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Contents

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10329-1, Session 1

Optical metrology in industry: exciting times and some history *(Invited Paper)*

John H. Bruning, Corning Tropel Corp. (United States)

No Abstract Available

10329-2, Session 1

Polarization and phase shifting interferometry

Sergej Rothau, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Klaus Mantel, Max-Planck-Institut für die Physik des Lichts (Germany); Norbert Lindlein, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

The spatially resolved polarization and phase distributions of a wave front are two important quantities of a light beam. For this reason it is often useful to characterize optical elements with respect to their impact on the polarization and the phase of an incoming light wave simultaneously and full field. Here a theoretical description and experimental results of a novel interferometric approach to solve this task are presented. With this method the phase and the polarization of a light wave with arbitrary polarization can be determined in one measurement.

The characterization of polarization state of a light wave, accomplished by a measurement of the Stokes parameters, resulting in the local phase retardation, but not the global phase. On the other side, for the phase measurement the well established method of the phase shifting interferometry (PSI) can be used, but without measuring any polarization results. PSI is furthermore impaired by the fact that for general polarization distributions, regions of vanishing contrast appear in the interferograms, making full field phase measurements impossible.

The newly developed method, called "polarization and phase shifting interferometry" (PPSI), solves these problems by measuring both quantities simultaneously and for the full field. The measurement strategy is based on the idea of changing the polarization of the reference wave in a way which is analogous to common phase shifting, combined with PSI. Several different algorithms were introduced, varying in the number of frames and variation steps and strategies. The minimal algorithm needs just five intensities to calculate the full description of the object phase and polarization in addition to the mean intensity and fringe contrast. An increase in the frame number leads to more stable and more precise algorithms. Therefore, one of the most metrologically interesting algorithms with high accuracy is a so called (5/2/1)-algorithm, working with 10 frames. This measurement procedure is based on two sets of five interferograms with an equidistant phase step of ϖ/2 (0; ϖ/2; ϖ; 3ϖ /2; 2ϖ) made for two reference polarization states, namely a horizontally and vertically linear polarization.

For the experimental verification, two different versions of the measurement setup as modified Mach-Zehnder-interferometers were realized, for a macroscopic and for a microscopic observation of the light fields. Both setups were designed for the measurement of objects in transmission for light of wavelength of 633nm. Moreover, both setups can be used for the classical PSI method and Stokes analysis without any and with minimal rearrangement, respectively. That allows to make a direct comparison between the PPSI results and results made by well established and commonly used methods. Measurement accuracies, calculated in that way, lie in the sub-lambda range and are comparable with the classical methods.

Furthermore, the PPSI method can be enhanced to the full characterization of the object, e.g. by the complete Mueller matrix. That allows us to characterize the impact on the phase front and the birefringence of the element under test. Therefore, the current investigations of this research field will be presented.

10329-3, Session 1

Increasing the accuracy of tilted-wave-interferometry by elimination of systematic errors

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In the last years, the Tilted Wave Interferometry (TWI) has evolved to a tool for the flexible and precise measurement of aspheric and freeform surfaces in non-null configuration. The key to the method has been the development of a sophisticated set of algorithms for the calibration of non-null interferometers [1]. This comprises a spatially and field dependent polynomial black-box description for the wave fronts in suitable reference planes, the selection of a set of positions in which interferograms of reference spheres are recorded and the solution of an inverse problem for the reconstruction of the model parameters.

Yet, the accuracy can be further increased if redundancies in the measurement process are used to correct for remaining systematic errors arising from the calibration of the system. Such calibration errors are identified and classified in simulations and by measurements of precisely characterized reference objects. The simulation environment allows representing typical error sources of the measurement and calibration procedure, such as misalignments of the instrument components, figure errors of individual lenses and calibration objects, positioning errors and phase noise. In contrast to the experimental results, the true state of system is known in the simulations and can be used in order to assess the accuracy of the calibration process. The accuracy of the calibration can be accessed experimentally if a sphere with known form errors is measured in a strongly defocused position and evaluated like an aspheric surface under test.

As the Tilted-Wave-Interferometry allows for large departures from the null configuration, a given specimen can be tested in a range of different positions and orientations. This includes lateral and axial shifts, rotations around the z-axis and small rotations around the x- and y- axis. The resulting redundancies are analyzed and models for the simultaneous reconstruction of surface and system parameters are proposed. Depending on the configuration, it is investigated which part of the calibration error can be eliminated. This is strongly linked to the symmetries of the system and the surface under test. The models are adapted such that the resulting inverse problems are sufficiently precise and well conditioned to allow for a unique solution.

The proposed evaluation strategies are validated by simulations and experimental results. Different benefits arise: Measurements in setups with changing environment conditions are facilitated and even for well calibrated setups an increase in accuracy can be achieved.

10329-4, Session 1

Full-field heterodyne dynamic interferometry based on hertz-level low differential frequency AOFS

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With the development of science and technology, especially aerospace?astronomy and high-power laser and other large-diameter, long-length optical system, requirements for manufacture precision of surface shape of optical components with large-diameter, and long-focal length are increasingly high. As it is known to all, measurement is the basis of processing. Because of longer cavity length measurement of long focal optical element, as well as vibration, airflow and other environmental impact on measurement accuracy, high precision

measurement of this kind of optical elements has been research focus and difficulty.

Optical interferometry is a non-contact, high-precision measurement technique utlizing the coherence of light, which is one of the most effective and accurate way to measure the precision of optical system and elements. The phase-shift interferometer, generated by laser technology, electronics, computers, precision machinery and traditional interferometer, has high precision of wavefront analysis and can achieve automatic measurement. But it is particularly sensitive to the environment. Vibration, airflow and other factors will affect the results for high-precision measurements of optical components with large diameter and long focal length.

In order to solve the above problem, we propose a full-field heterodyne interferometric measurement technique that could effectively suppress the environmental interference. In the early related research, a Hertz-class high-stability, low-differential frequency acousto-optic frequency shifter was successful developed, which is applied to heterodyne interferometry, instead of traditional phase-shifting intererometry. On this basis, a full-field heterodyne interference measurement system is developed. In the system, the reference light and measuring light respectively go through an acousto-optic frequency shifter, after that the heterodyne frequency of the two beams can by stabilized at Hertz level. The two coherent lights form full-field heterodyne interference signal, which could be collected continuously by array detector, and therefore we can obtain the ultra-multi-step phase-shift data of the whole interferogram. By processing the time line data of each pixel at a certain sampling time, phase information can be accurately extract, thereby accurately recovering the surface shape. Adopting full-field heterodyne interferometric measurement program, with direct phase calculation to heterodyne frequency, can be effectively isolated from spectral noise caused by vibration, airflow and other factors. Furthermore by average of certain measurement time, the interference of various environmental factors could be effectively suppressed, so as to achieve high-precision dynamic interference measurement.

This new dynamic interferometric measurement scheme can solve the problem of different optical paths of reference light and measuring light in dynamic interferometers, avoid the use of short-coherent lasers with performance not perfect enough, thereby simplifies the structure of dynamic interferometer and reduces the difficulty and cost of interferometers. It could effectively suppress the vibration, noise, airflow and other factors, and thus significantly improve the system's measurement accuracy and environmental adaptability. In the conventional non-vibration environment, the system can achieve technical indicators as follows: surface measurement accuracy is better than ?/10 and repeated measurement accuracy is better than ?/1000. As a result, the dynamic measurement problems of the need for large-diameter optical components and systems quality inspection, system installation correction, on-line measurement and other areas could be solved.

10329-5, Session 2

Phase imaging using a single-pixel camera

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Single-pixel camera is composed of optical coding masks and a photo detector. An object image is encoded on the masks displayed on a spatial light modulator (SLM) and the encoded image is detected by the single photo detector. The reconstruction image is built up from a number of the light detections. The most important feature of the single-pixel camera is a simple hardware structure, therefore it is useful for an imaging in broad spectral range, especially in temporal and spatial frequency ranges that have no good image sensor.

The masks decide the performance of the imaging system. The Hadamard mask is one of good choices for a small measurement time and a small calculation cost, but it has a weak point in optical intensity implementation that has no negative value. Therefore, it required the twice measurements and the subtraction calculation.

In this paper, the phase imaging method based on a single-pixel camera with a complex-amplitude representation to measure a surface profile of objects is demonstrated. The use of the complex-amplitude representation of the input signal enables us to perform the phase imaging of an object in combination with the phase-shifting technique. The masks are also represented by the complex-amplitude, the positive and negative values of the Hadamard patterns are represented by a phase, and the subtraction is performed by interference. The complex-amplitude masks are displayed on phase modulation using a liquid crystal on silicon spatial light modulator (LCOS-SLM). Furthermore, the residual area of the mask is used for the reference beam with the phase shifting. Therefore, the phase imaging system has high stability for external disturbances because it has the coaxial structure.

Firstly an object image was modulated by a mask. The modulated image was coherently summed up (interfered) on a photodetector. The -1 or 1 element of the Hadamard mask is expressed by $-\varpi/2$ or $\varpi/2$ phase modulation, respectively.

A reference beam was given a four-step phase shifting to get a phase of the object. It is performed with the outside area of the rectangle mask in the circular aperture. The object light and reference light were in the coaxial, therefore the optical setup has a vibration tolerance. The phase detections were iterated with changing the mask. Typically, the number of iterations is the same as the number of pixels. It is noted that the number of the optical detection is its 4 times. If it can be applied the compressive sensing technique with depending on a sparsity of the object, the number will be decreased. The object is easily reconstructed using the inverse matrix calculation.

An experimental single pixel camera with 256 pixels was composed of a liquid crystal on silicon spatial light modulator (LCOS-SLM) (X10468-07, Hamamatsu), photodetector (S2281-01, Hamamatsu), and a He-Ne laser as an illumination light source. The single-pixel phase imaging was successfully performed based on a complex single-pixel camera with the in-line interferometer with the phase-shifting method. We demonstrate the computer simulation of the phase imaging for some objects and the experimental verifications. We also demonstrate an estimation of the measurement accuracy.

10329-6, Session 2

Applications of digital interferometer

Sen Han, Univ. of Shanghai for Science and Technology (China)

Digital interferometer is widely used for evaluating optical surfaces due to its outstanding sub-nanometer accuracy and precision. In this paper, we will summarize its advantages and then describe its applications in industry, especially in both inner surface and absolute flat measurements. Inner surfaces measurement of cylindrical ring can be achieved without map stitching, by a Fizeau interferometer with a 90°conical mirror. The alignment of this arrangement, however, is very crucial to the accomplishment. Any small misplacement of 90° cone or hollow cylinder from their ideal settings may result in large measurement errors. These errors are not intuitive and hard to be removed if their origins are not well understood. In other words, it is very important to know how these measurement errors are generated from the optical misalignment in order to eliminate them. Transmission flat has normally 1/20 wavelength PV. However, when a flat surface under test is better or much better than the transmission flat, we need the absolute flat measurement. We developed a new method to be easily able to achieve the accuracy of 1/100 wavelength PV. We have dedicated our efforts to do so. The theoretical analysis, computer simulations, and experimental validation are presented in the paper.

10329-7, Session 2

Spatial-temporal phase shifting interferometry: suppressing phase errors in dynamic Fizeau interferometer

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Surface topography measurement plays an important role in many applications in engineering and science. The most commonly used method at present for surface topography measurement are temporal phase shifting interferometry [1]. However, phase shifting interferometry cannot be used effectively in the presence of unstable conditions such as vibration, air turbulence, or when the object under test is in motion. Recently, we proposed a dynamic Fizeau interferometer, which is based on lateral displacements of a point source array to obtain simultaneous phase shifting [2]. The proposed interferometer is immune to retrace error, poor contrast, and aperture restrictions compared with the prior technologies [3-7]. However, just like other dynamic interferometers, it is difficult for the proposed interferometer to avoid the phase errors induced by inaccurate phase shift, pixel mismatch and intensity [8]. In order to realize high-precision measurement, these errors must be suppressed. The temporal phase shifting interferometry often suppresses the errors by using more phase steps, but it not suitable for the dynamic Fizeau interferometry because the number of interferograms is limited by detector. Thus, there is an urgent need to suppress the phase errors contained in the dynamic Fizeau interferometer.

In this paper, we propose a new algorithm to suppress the phase errors in dynamic Fizeau interferometer. Since the proposed algorithm introduces temporal phase shifting into spatial phase shifting interferometry, we call this algorithm the spatial-temporal phase shifting interferometry. All the effects of the error sources will be viewed as a complex instead of being calibrated independently in the proposed interferometry, thus it provides a new way to suppress all the phase errors simultaneously.

The process of phase errors suppression can be divided into the following three main stage: (1) utilizing the spatial phase shifting interferometry to calculate the initial phase; (2) viewing all the effects of the error sources as a complex; (3) utilizing the temporal phase shifting interferometry to obtain multiple different initial phases and calculate the average phase. The spatial phase shifting interferometry is based on the lateral displacements of the point sources while the temporal phase shifting interferometry on the wavelength modulation.

Experimentally, the spatial-temporal phase shifting interferometry was achieved in the dynamic Fizeau interferometer with a semiconductor laser by measuring an optical flat. The phase errors are suppressed effectively in the measurement result, which verifies the validity of the proposed method. In addition, the high measurement accuracy of the proposed method is shown by comparing with the result measured by a Zygo GPI interferometer.

In conclusion, we propose a spatial-temporal phase shifting interferometry to suppressing phase errors in dynamic Fizeau interferometer. The proposed interferometry not only remains the benefit of vibration insensitive of the dynamic interferometry, but also has the error suppressing capability of the temporal method. In addition, it provides a good application for the wavelength modulation phase shifting interferometry because the main problems contained in the wavelength modulation such as the inconsistent intensities and modulations of the interferograms can be solved by spatial phase shifting interferometer. Moreover, the proposed spatial-temporal phase shifting interferometry is not only suitable for the presented dynamic Fizeau interferometer, but can also be applied to other kind of dynamic interferometers such as pixelated phase-mask dynamic interferometer [9] and low-coherence vibration insensitive Fizeau interferometer [10].

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10329-8, Session 2

Study on measurement accuracy of active optics null test systems based on liquid crystal spatial light modulator and laser interferometer

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With the increasingly applications of aspherical optics in modern optical systems, the wavefront measurement methods for aspherical optics are becoming more and more challenging due to the variation of complex-shaped optics. A common way to test high-quality aspherical lenses is to use a measurement system based on a set of null corrector and a laser interferometer. The null corrector can either be a combination of spherical lenses or be a computer generated hologram (CGH), which compensates the aspheric wavefront being tested. However, the null optics can’t be repeatedly used once the shape of tested optics changes. Alternative active null correctors have been proposed based on dynamic phase modulator devices. A typical dynamic phase modulator is liquid crystal spatial light modulator (LCSLM), which can spatially change the refractive index of the liquid crystal and thus modify the phase of the input wavefront.

Even though the measurement method based on LCSLM and laser interferometer has been proposed and demonstrated for optical testing several years ago, it still can’t be used in the high quality measurement process due to its limited accuracy. In this paper, we systematically study the factors such as LCSLM structure parameters, encoding error and laser interferometer performance, which significantly affect the measurement accuracy. Some solutions will be proposed in order to improve the measurement accuracy based on LCSLM and laser interferometer. Finally, experimental measurement on spherical optics will be implemented to testify the effectiveness of these partial improved methods.

10329-9, Session 3

Evaluation of refocus criteria for in holographic particle imaging

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Digital holography and digital holographic microscopy are techniques for recording and reconstructing three-dimensional images of objects. As a general rule, the object field is numerically reconstructed using a propagation operator (discrete Fresnel transform, angular spectrum) in which an important parameter is the refocusing distance. Thus, an in-focus image can be obtained under the condition that the focusing distance is closest as possible to the exact optical path in the experimental set-up. Therefore, a criterion to estimate if the reconstructed image is at the best focus has to be considered. A lot of refocus criteria were proposed in the past years. As a general rule, the best focusing plane is determined by the reconstruction distance for which the considered criterion function presents an extremum (maximum or minimum). A brief review of refocusing criteria deals with self-entropy, variance, integrated amplitude (L1 norm), Gradient, Laplacian, logarithmically weighted Fourier spectral function, correlation coefficient, complex ratio, Tamura coefficient, and finally Gini index. These criteria were widely applied to amplitude and phase and there is no rule to guide the choice for one or more of these criteria. It follows that a systematic approach for studying these criteria has to be implemented, in order to objectively compare them with the same set of data. In addition, such an approach has to test the criteria with both simulated and experimental data. Using simulated data is the most objective way to verify if the peak (or valley) of the metric is in good agreement with the exact best focus distance. Using experimental data is more powerful to test the robustness of the criteria according to noise and alias that cannot be always perfectly simulated. So, in this paper, for holographic particle imaging, we aim at comparing the refocusing criteria mentioned above for amplitude and phase images obtained from off-axis holograms, on one hand simulated and on the other hand experimentally recorded. Simulations were carried out to generate digital holograms of opaque and phase particles by taking into account some alias and noise. Refocus criteria were applied to both amplitude image and phase image obtained from off-axis digital holographic simulations. This was also conducted in the same way by considering experiments with a non-calibrated opaque particle. The computational costs were estimated for each criterion. In order to briefly summarize the results obtained within this study, it was found that the most robust criteria are the correlation coefficient and the complex ratio. Such criteria are able to systematically produce a regular curve with a peak or a valley at the correct focus distance; for this reason they are of major interest. Such regular curve could be fitted by analytical equation and this modelling would not require too much distance computations to determine the peak (or valley) and to determine the optimal distance by least square fitting with a reduced set of reconstructed images. Future work will consider such an approach for high-speed refocusing in digital holographic particle imaging.

10329-10, Session 3

Topography measurements of high NA aspherical microlenses by digital holographic microscopy with spherical illumination

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Digital holographic microscopy (DHM) is a versatile measurement technique applicable to metrology of microstructures. Conventional DHM systems use plane wave illumination of an object. The measurement of high numerical aperture (NA) object topography cannot be successfully realized because of discontinuity of the phase data and a problem with reconstruction of the correct profile [1]. Due to this fact, the use of the conventional DHM systems is limited to the objects with low gradient of shape. One solution to this problem is application of the directional illumination. Such an approach was proposed for transmission [2] and reflection [3] configuration of DHM. Second solution consist of use spherical illumination [4,5] that allows obtaining information from the areas with high spatial frequencies of high NA object without manipulation of the illumination direction. Thus the spherical illumination offers optimal illumination conditions for testing of objects with spherical-like surfaces.

In this contribution we propose a DHM configuration enabling measurement of high NA microstructures of spherical and aspherical shape. The novelty of the system is an application of an optimized spherical illumination scheme that simplifies the setup and special calibration procedure improving the measurement accuracy. The proposed method utilizes reflection of the spherical illumination beam from the concave or convex object surface and the interference with spherical reference beam of the same radius of curvature. In this case, the NA of DHM is fully used for illumination and imaging of reflected object beam. Thus, the system allows capturing the phase in entire area of the quasi-spherical object and, therefore, offers possibility of high accuracy characterization of its surface even in the areas with high surface inclination.

For reconstruction of the object shape we apply the algorithm based on Local Ray Approximation (LRA) [6], which was developed for the case of spherical object illumination. The proposed precise calibration procedure allows identifying all parameters required for the accurate shape recovery with the LRA method: location of the object focus point and the positions of the illumination and reference point sources. Additionally, the high measurement accuracy is ensured by spherical aberration compensation.

The utility of the proposed approach is demonstrated with characterization of surface of high NA focusing objects. The accuracy is firstly verified by characterization of known reference sphere with low error of sphericity. Then, our method is applied for characterization of spherical and rotationally symmetric aspheric surface of microlenses replicated in glass and polymer. The results provide a full-field reconstructed topography with resolution in nanometer range over NA up to 0.8. At the end of the measurement procedure we apply an effective method for extracting the important parameters of microlens: e.g.: radius of curvature and conic constant.

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10329-11, Session 3

Digital holography on moving objects

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Digital holography (DH) is a well-qualified technique for measuring 3D surface profiles due to its high precision with a resolution being in the range of nanometer. 100%-inspection of products is increasingly common in manufacturing processes. In order to improve the applicability of DH in production lines with high throughput, multiwavelength digital holography on moving objects is investigated.

The surfaces of many technical objects are optically rough with height differences in the micrometer range. Multiwavelength holography is used to achieve reliable height data with a height unambiguity of several micrometers despite the speckle pattern of diffusely reflecting surfaces. In production lines objects under test are usually transported on assembly lines or carried in reels. Up to now, it is essential for every interferometric measurement to prevent movements of the test object in the scale of a fraction of the wavelength, which is time consuming and thus expensive. Digital holography on moving objects would enable higher efficiencies and expand the field of application. For instance it would be possible to measure large scale components without loss of resolution, just by moving the object along the sensor. In this work we describe the impact of object motion on the interference contrast as well as height measurements of objects moving with more than 100 mm/s, using spatially phase-shifted multiwavelength holography with eye-safe cw lasers.

The interference contrast of a holographic measurement can be considered as a measure for data quality: The higher the contrast, the higher the maximum possible height resolution. In the stationary case, it

is given by the intensity ratio of reference and object beams. In case of a moving object, interference contrast depends mainly on the change of the optical path length during exposure time. If this change equals one wavelength, the contrast is zero. Therefore the interference contrast of a holographic measurement of moving objects depends on the distance covered during exposure and the direction of motion, as well as on the illumination and reflection angle of the object beam. Consequently, describing diffusely reflecting surfaces, the aperture of the imaging system is crucial, because it limits the scattering angles. We present theoretical considerations describing the dependence of the interference contrast on aperture size and object speed. We find that the contrast decreases with increasing velocity. The noise in the height measurement increases accordingly. However, even for large velocities exceeding one speckle diameter per exposure, the contrast decreases slowly, allowing useful height measurements at relatively high speeds.

The velocity dependence is investigated experimentally by performing height measurements of a metal object with heights of several micrometers. In the presented experiment two wavelengths (632 nm and 634 nm) are employed. This leads to a maximum height difference of 100 µm, which can be detected unambiguously. Spatial phase shifting is chosen because it requires just one camera frame per measurement. The dependence of resolution and accuracy of the height measurements on velocity are shown. Height resolutions of better than 5 µm are achievable at 100 mm/s using an exposure time of 2 ms.

10329-12, Session 3

Surface contouring digital holographic microscopy for shape measurement

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Elements of micro-optics are widely applied in both modern industry and consumer products, therefore there is a strong need for high precision measurement of their topography. The aim of this work is to develop a novel holographic method that provides the shape reconstruction with an extended measurement range (MR) and improved accuracy. An accurate measurement of three–dimensional deep topography of reflective micro-optics can be achieved with a non-contact digital holographic microscopy (DHM) system based on Twyman-Green interferometer. This technique ensures high resolution, short measurement time and outstanding flexibility of holographic tools. However, in DHM, the direct measurement result is an ambiguous modulo-2ϖ version of unwrapped phase distribution, which means that the measured phase is in the range from -ϖ to ϖ. Hence, beyond this range the information about fringe order cannot be determined from a single DHM measurement, i.e. the phase step cannot be higher than 2ϖ. Especially in reflective configuration of DHM, the height MR is limited to ?/2.

To overcome this problem, in this work we propose a DHM system that employs optical contouring [1-3]. The contouring technique is based on recording two holograms with slightly different inclination angles of the object illumination ?. The phase difference obtained from those two holograms enables the height measurement with MR?(?)(Δ? sin?). Our DHM system in reflective configuration ensures extended MR and provides high accuracy measurement of the phase objects with high numerical aperture.

The high accuracy is provided by developed here specialized shape reconstruction algorithm, which considers two inclined illumination angles in the shape reconstruction. Proposed algorithm is based on non-paraxial Tilted Local Ray Approximation (TLRA) [4]. The principle of the algorithm is based on precise reconstruction of optical path length using exact reflection law for a given condition of illumination. However, in order to ensure high accuracy of the shape reconstruction, there is a need to precisely determine the location of the imaging plane in reference to the measured object. For the phase object, the application of the conventional autofocusing methods, which are based on analysis of amplitude distributions in various axial locations, does not ensure sufficient accuracy in finding imaging plane [5]. Therefore, here we propose to take additional advantage of the two-directional illumination used in the proposed DHM system and utilize more accurate technique proposed by P. Gao [6]. In this algorithm, the location of the object plane is determined basing on interdependence of two optical fields reflected from the sample for two various directions. As it was shown in [6], the off-axis illumination based autofocusing outperforms the standard methods in terms of accuracy and possibility of application of the method for wide range of the sample types.

The precision of the proposed non-paraxial algorithm for shape calculating is evaluated with numerical simulation of the measurement process of continuous and step micro-objects. The validity of the proposed method is demonstrated experimentally with measurement of topography of selected challenging micro-objects.

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10329-13, Session 3

A method for total noise removal in digital holography based on enhanced grouping and sparsity enhancement filtering

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Digital Holography (DH) is a powerful imaging technique allowing to capture the complex information of an object, thus being suitable for optical metrology, e.g. for non-disruptive testing in industrial inspections and material science, or as a diagnostic tool for biology and medicine [1]. However, due to the coherent nature of the employed light sources, DH reconstructions can be severely degraded by a mixture of speckle and incoherent additive noise. These can affect both the visual quality in holographic imaging and display, and the accuracy of quantitative DH interferometry. In the framework of non Bayesian methods, the speckle problem is tackled by reducing the illumination coherence. Among them, the most intuitive way involves the recording of multiple uncorrelated holograms to be incoherently combined [2-5]. In particular, Multi-Look DH (MLDH) has been demonstrated to be very efficient to improve the quality of both numerical [2] reconstruction and optical display [3]. However, single shot recordings are highly desired in DH, and numerical methods are required to go beyond the improvement bound of ML techniques. Among the existing image processing methods, the 3D Block Matching filtering (BM3D) has shown the best performance, introducing the concepts of grouping and filtering the groups in a suitable 3D transform domain [4]. These are very effective in reducing the noise mixture provided that the observables present a minimum level of Signal-to-Noise Ratio (SNR). A too low SNR can provoke incorrect grouping and the algorithms fail. Here we present the MLDH-BM3D, a method specifically suitable to filter DH images that combines ML and BM3D to overcome their respective limitations. The use of ML preprocessing allows obtaining enhanced grouping of similar image fragments, so that a sparsity enhancement filtering can be applied to work without introducing image distortions and overcoming the typical ML improvement bound [4]. Numerical ML is performed by random resampling masks applied on the hologram to simulate the action of a moving aperture [2]. Thus, MLDH-BM3D is applicable to single-shot recordings. We will show both qualitatively and quantitatively that MLDH-BM3D achieves near noise-free DH reconstructions of single wavelength holograms and color holograms in the visible region. The performance quantification shows a level of improvement far beyond the current state of the art in DH [4]. Finally, the challenging case of far Infrared Digital Holography (IRDH) is faced, where the noise degradation is more severe due to the large size of the speckle grains [5]. We show the quasi noise-free reconstructions of large size objects captured by IRDH and processed by MLDH-BM3D.

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10329-14, Session 3

Extensive in-machine tool measurement with a miniaturized multiwavelength digital holography sensor

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In this paper we present a miniaturized digital-holographic sensor (“HoloCut”) for operation inside a machining center.

With state-of-the-art 3D measurement systems, short-wave structures such as tool marks cannot be resolved inside a machine tool chamber. Until recently, measurements had to be conducted outside the machine tool and thus processing data are generated offline [1, 2].

The sensor presented here uses digital multiwavelength holography to get 3D-shape-information of the machined sample. The underlying measurement principle is that of an interferometer where laser light is split up into an object beam, which illuminates the sample, and an unaffected reference beam. Both beam paths are superimposed on a camera subsequently, which enables us to extract amplitude and phase through temporal phase shifting. The light is coupled into the measurement system through a fiber from a switchable laser system with 3 wavelengths (633.41 nm, 633.82 nm and 638.37 nm). The measurement object is illuminated coaxially which is an essential requirement to resolve short-wave structures on complex object geometries. By using multiple wavelengths, we get a large synthetic wavelength with a large unambiguous measurement range of 492 μm and are able to suppress the effect of speckles on phase measurements on rough surfaces efficiently. In addition, a digital refocusing algorithm based on phase noise is implemented to extend the range of unambiguousness and depth beyond the limits of the synthetic wavelength and geometrical depth-of-focus. With complex wave field propagation [3], the focus plane can be shifted after the pictures have been taken and a sharp image is constructed consequently. Furthermore sharp image portions of an object at different digitally refocused planes are merged to get height measurement with extended depth of field up to several mm while the geometrical depth of field of the imaging setup is in the range of several 100 μm. With 20x20 mm? field of view it measures both macro- and micro-structure (such as tool marks) with an axial resolution of 1 μm, lateral resolution of 7 μm and consequently allows processing data to be generated online which in turn qualifies it as a machine tool control.

HoloCut is small enough for operation within a machine tool. To make HoloCut compact enough for operation inside a machining center, the beams are arranged in two planes: After splitting the beams on the bottom plane, the reference beam remains in the bottom plane whereas the object beam is transferred to the top plane, until both beams are combined onto the camera in the top plane. The sensor measures perpendicular relative to cutting direction and extends no more in height than a typical processing tool. Using a mechanical standard interface according to DIN 69893 and having a very compact size of 235 mm x 140 mm x 215 mm (WxHxD) and an approximate weight of 8 kg, HoloCut can be easily integrated into different machine tools.

In the future, microelectronics and software will be integrated into the sensor which will enable it to detect process errors and communicate with the machine tool as a stand-alone system.

10329-15, Session 4

Tomographical process monitoring of laser transmission welding with OCT

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Laser transmission welding as a contactless and locally limited joining technique is well-established in different production areas. It is used in a variety of demanding applications like for example parts which require a particle-free joining process. Sensitive parts demand a joining technique which does not affect the inner components. The welding process itself faces higher requirements concerning for example tightness of the weld joint or cleanliness of the produced part (no material must impurify the part during the process).

During the laser transmission welding process the laser radiation is locally focused on an absorbing surface. The joining is performed between a transmissive part (regarding the process laser wavelength) and an absorbing part. After solidification the weld seam is created at the intersection of both parts within the material. The weld seam is hermetically enclosed within the material and cannot be visually inspected.

A very narrow process parameter window during the laser process or process deviations have led to an increase on the requirements for the laser transmission welding process and on monitoring devices. A qualitative feedback for process adaptation is not given by today´s state of the art measurement systems. Pyrometers detect the process emission but return no tomographical information. Quality assurance of the fabricated product is done via destructive testing resulting in production of scrap parts.

Inline integrated optical measurement systems capable of providing non-invasive tomographical images of the transparent material, the weld seam and its surrounding areas with micron resolution would improve the overall process by providing more detailed information about the actual forming process. Hereby obtained measurement data enable qualitative feedback into the system to adapt process parameters to obtain a more robust laser transmission welding process. Non-destructive testing during the laser welding process would reduce the process cost as well.

Within the European-funded research project Manunet “Weldable” an inline monitoring device based on Fourier-domain optical coherence tomography was developed at the Fraunhofer IPT. This device, after adaptation to the laser transmission welding process is optically integrated into the existing laser machine. Pre-process analysis of the work piece can as easily be performed as well as post-process quality assurance inspection. The main target lies within the inline process control destined to extract tomographical geometrical measurement data from the weld seam forming process. Hereby process feedback is given to adapt prior set laser parameters as well as high resolution images are made available for quality inspection. In-process obtained data make obsolete the need for further testing and reduce the handling of the product. Usage of this non-destructive and non-invasive technology makes offline destructive testing of produced parts unnecessary as any defects occurring during the process can be identified and its information feedback for laser process adaptation, delivering hereby a reliable weld process and a safe product.

10329-16, Session 4

Nondestructive testing of layer-to-layer fusion of a 3D print using ultrahigh resolution optical coherence tomography

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No Abstract Available.

10329-17, Session 4

Applications of optical coherence tomography in the noncontact assessment of automotive paints

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The paint on cars serves two end purposes; firstly they protect against corrosion and secondly give the desired visual appearance. To achieve this, the paint systems of modern cars are composed of multiple layers. To ensure consistent corrosion protection and appearance, suitable Quality Assurance (QA) measures on the final product are required. Currently the most common assessment method for measuring the layer thicknesses of car paints is ultrasound sensor which only provides thickness information in single position and needs to be in contact with the sample for best performance.

Optical Coherence Tomography (OCT) is a 3D imaging technique with ?m resolution, which uses broadband interferometry for ranging. Since its inception, its main application has been for ophthalmological and other medical imaging. It has also found a variety of applications outside medicine [1], including the assessment of multiple coating layers in historic works of art [2]. However, it is only since 2016 [3, 4] that its potential applications to automobile paints have been reported. Whereas the current single point ultrasound method only returns information on one variable (i.e. the thicknesses of the layers at one position), OCT can provide multiple different pieces of information simultaneously.

Currently three applications have been reported. Firstly, though currently more limited by transparency than ultrasound, OCT can measure the thickness of the coating layers over a significant lateral distance instead of a single point. Secondly, 3D OCT can return information on the size, shape and quantity of metallic flakes within the base coat. Thirdly, the image signal decay properties of scattering layers are dependent on its scattering and absorption properties. Unwanted changes to a layer could lead to an identifiable change in the signal decay properties.

In this paper we will add two more novel applications of OCT to automotive paints. Firstly, the orange peel (Benard-Marangoni) effect usually leaves a low spatial frequency texture (roughness) to the top clear coating of modern car paint systems. Historically, this has been considered a visual defect. However, due to the inhibitive cost of removal it is now generally tolerated. Surface profile with nm measurement precision can be extracted by OCT, either by finding the centre of the axial PSF [5] or utilising the Fourier phase information [6]. Here we apply this method to quantify and characterise the orange peel on car paint samples. Secondly, the PSF and Fourier phase information could also be used to measure the rate of change of thickness of the clear coat, and thus determine how dry it is. Here we demonstrate this on a nail varnish – glass model.

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10329-18, Session 4

Single-shot multilayer measurement by chromatic confocal coherence tomography

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Oftentimes situations occur in industrial inspection, where samples consist of multiple semi-transparent layers, whose refractive index is either of interest itself or not exactly known. Even in the latter case, this refractive index has to be retrieved in order to correct the measured results of most optical measurement systems.

We introduce Chromatic Confocal Coherence Tomography (CCCT) as a single-shot manner for the simultaneous measurement of the layer thickness and its refractive index. Hereby we aim for multiple inspection tasks: Thickness and refractive index of thin semi-transparent materials or stacks of such shall be measured with high axial as well as lateral precision. Layers carrying possibly unknown refractive indices like varnish on machined surfaces shall be measured while giving raise to detailed topography of both surfaces. In inline measurement, precise topography inspection shall be possible without the need for removing contaminations like oil or drilling emulsion.

Most of these tasks are not easily achieved by well-known techniques like confocal or white light scanning microscopy, nor by their single-shot counterparts like chromatic confocal microscopy or spectral interferometry. All of these schemes are affected by the material's refractive index, but in different ways. CCCT utilizes the fact that confocal and interferometric information are disturbed in an reciprocal manner: On the one hand, Interferometers measure optical path lengths, which are increased in materials of higher refractive index. Confocal systems on the other hand underestimate axial lengths in materials of higher refractive index due to refraction at the material's surface.

As mentioned above, especially in situations where fluids are involved, it seems important to realise a single-shot system. This is obtained by a combination of chromatic confocal microscopy and spectral interferometry. The experimental setup is based on the corresponding topography measurement system, Chromatic Confocal Spectral Interferometry (CCSI). A superluminescent diode provides 50 nm of NIR illumination bandwidth. It's joined to the detecting spectrometer via a fibre-coupler, whose other end is connected to the sensor head, where it also acts as the confocal aperture. The linnik type sensor head provides a chromatically separated focal range in the measurement volume by the use of a refraction compensated diffractive optical element near the back focal plane of the microscope objective. The back propagated signal from layered specimen consist of super-imposed wavelets from each surface, where the envelope of each peak is defined by the confocal signal and the spectral frequency below is given by the corresponding difference in path length regarding the reference arm.

We will present first proof-of-concept measurements of different thin slabs of fused silica and diamond. Even using a rather simple frequency analysis for the interferometric information channel, discrepancies in the low percent range were met with respect to thickness and refractive index. Also, different sources of uncertainties and errors are evaluated. Here, mainly the system's numerical aperture is important, as it has a strong influence on the confocally measured thickness. Furthermore, the interferometric channel is severely affected by uncompensated dispersion due to the non-identical design of the two arms of the interferometer.

10329-19, Session 4

Tolerance of sphere radius for the calibration of the transfer function of coherence scanning interferometers

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Although coherence scanning interferometry (CSI) commonly achieves a sub-nanometre noise level in surface topography measurement, the absolute accuracy is difficult to determine when measuring a surface that contains varying local slope angles and curvatures. Traditional step artefacts that contain two parallel flat surfaces are, therefore, not considered sufficient for calibration of CSI systems for measuring complex geometry. One method to characterise a CSI system for three-dimensional (3D) measurement is by obtaining its 3D transfer function (TF). The 3D TF contains rich information about the metrological characteristics of a CSI system, for example both vertical and lateral resolutions can be derived from the TF and an inverse Fourier transform reveals the point spread function (PSF). It is not easy to measure the 3D TF of a CSI system. Coupland et al. have derived an approach to characterisation of surface measuring systems as 3D linear filtering operations in which the so-called "foil model" of a surface is linearly related to the interference signal obtained from the CSI system. Recent research has shown that it is possible to use a single sphere with a radius much greater than the source wavelength to calibrate the 3D TF of a CSI system. A major requirement of this calibration approach is the accurate knowledge of the sphere radius, but the 3D measurement of a sphere with nanometre level uncertainty is a highly challenging metrology problem, and is not currently feasible. Perfect spheres do not exist and every measurement has uncertainty. Without having a quantitative understanding of the tolerance of the sphere radius, the calibration method cannot be used confidently for calibration of the transfer function of a CSI system that may be used in research laboratories or industry. The calibration errors may occur when the TF is measured using, e.g. a 51 ?m radius sphere, that is measured/estimated to be a 50 ?m radius calibration sphere. The calibration errors of the ideal CSI instrument may cause additional tilt dependent errors when measuring the topography of a surface. In this paper, the effects of the tolerance of the radius of the calibration sphere on surface topography measurements are quantitatively analysed through a computational approach. For example, if 1 nm additional height error (due to the mis-calibration) is desired at 30˚ surface tilt, the radius error of the calibration sphere should be smaller than 6 nm. CSI measurements of sinusoidal and rough surfaces are also investigated in the presence of various degrees of radius error. For example, the mis-calibration due to 1 ?m radius error may cause an additional height error of a few tens of nanometre for the measurement of a sinusoidal surface with 5 ?m period and 0.2 ?m amplitude. In this paper, a lookup table that relates the surface height error as a function of the radius error and surface slope angle is provided. The users may estimate the required tolerances of the sphere radius for their specific surface measurements if this calibration approach is used. The output of this paper provides a feasibility analysis and the foundation for this calibration method for further development and applications.

10329-20, Session 5

New challenges for optical inspection in the times of industry 4.0 *(Invited Paper)*

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No Abstract Available

10329-21, Session 5

Underwater 3D measurement devices using Gobo-projection

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New developments of structured light based optical 3D scanners provide high-speed data acquisition and processing and make 3D reconstruction of dynamic processes or 3D measurements using moving scanners possible. Many fields of application, especially in industrial quality management require such quick 3D scanners. A necessary precondition for the realization of high-speed 3D scanners is the use of high-speed cameras and projection units. Whereas classical beamers are not suitable for high-speed projection, the Gobo principle is appropriate concept to realize 3D scanning in motion, e.g. at ROVs for underwater use.

Photogrammetric measurements of objects under water become more and more important in the application fields of archaeology, biology, and industrial inspection, especially for deep sea facilities. Structured light should help to overcome the big challenges of underwater photogrammetry namely the short visibility, spectral differences in ray refraction, and identification of corresponding object points.

Recently photogrammetric underwater setups or devices have been introduced and the power of these setups has been shown. However, this principle allows short measurement distances and limited measurement fields of approximately 0.5 m x 0.5 m so far using classical beamers for structured light projection. However, the Gobo projection principle allows using stronger light sources and hence is going to achieve larger measurement fields and measurement distances.

In this paper the Gobo projection principle is introduced, the use of aperiodic sinusoidal fringes for structured light projection is explained, and realizations of 3D scanners in air and water are shown as examples. The principle of aperiodic sinusoidal pattern for identification of corresponding points in two camera images requires a-priori-calibration of the system and the use of epipolar lines. However, these lines are not straight in the underwater case. This is a remarkable challenge of the use of the Gobo principle for underwater.

The calculation of the 3D measurement data will be obtained using the triangulation principle well known from photogrammetry. The usual pinhole camera modeling is extended by consideration of the refraction effects at the interfaces between air and glass and glass and water. Using the projection of aperiodic sinusoidal fringe patterns by a Gobo projector, epipolar curves are used for the realization of finding corresponding points in the two camera views. A special calibration procedure was developed in order to get the necessary geometric system properties which allow the calculation of the epipolar curves and the correct determination of the 3D measurement points.

The new principle was realized in a laboratory setup. The measurement accuracy was determined by experiments using certain specimen as plane ceramic tile and a calibrated ball-bar for the evaluation of flatness and length measurements. First underwater measurement examples are given showing the possibilities of the new methodology and the limitations of the currently used hardware configurations.

Future work will be addressed to the building up of different laboratory setups of 3D scanners with different measurement volume sizes in water basins using Gobo projection and the simulation of deep sea conditions. Many experiments have to be performed in order to evaluate the theoretic assumptions concerning 3D point calculation and measurement accuracy.

10329-22, Session 5

Verification of real sensor motion for a high-dynamic 3D measurement inspection system

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Inline three-dimensional measurements are a growing part of optical, contactless inspection. Considering increasing production capacities and economic aspects at once, dynamic measurements under motion are inescapable. Using a sequence of different pattern, like it is generally done in active fringe projection systems, relative movements of the measurement object with respect to the 3d sensor system between the single images of one pattern sequence have to be compensated. Therefore, motion estimation is one major task.

Based on the application of fully automated optical inspection of circuit boards at an assembly line, the knowledge of the relative speed of movement between the measurement object and the 3d sensor system should be used inside the algorithms of motion compensation. In an optimal way, this relative speed is constant over the whole measurement process and consists of only one motion direction to avoid sensor vibrations. The quantified evaluation of this two assumptions and the error impact on the 3d accuracy are content of the research project described in this paper.

The 3d measurement system under investigation consists of one monochrome camera and one LCoS system using for pattern projection. The combination of this two hardware elements is designated as 3d sensor head and represents the mobile part considering the 3d inspection systems as a whole. For our experiments we use a glass etalon with non-transparent, solid filled circles. Furthermore, we used a homogeneous transmitted light source in red spectrum to illuminate the etalon and create hard black-and-white contrasts of filled circles and transparent background in the camera images. Focused on the circle borders, this is one of the most reliable methods to determine subpixel positions using a couple of searching rays. Depending on the amount of border pixels of each circle, the number of search rays have to be increased up to the situation, that two rays intersect the same border pixel with high probability. The intersection point of all rays characterize the center of each circle.

Based on the circle centers determined with a precision of approximately 1/50 pixel, the motion vector between two images could be calculated and compared with the input motion vector. To further increase the reliability of the estimated motion vector, we use the arithmetic mean of five circle positions. These verifications were firstly realized for a constant input velocity and secondly motion with an acceleration phase. To confirm the results, experiments were done with two opposite motion directions and five different values of velocity. Overall, the results are used to optimize the weight distribution of the 3d sensor head and reduce non-uniformly vibrations. Finally, there exists a dynamic 3d measurement system with an error of motion vectors about ±4 micrometer. Based on this outcome, simulations result in a 3d standard deviation at planar object regions of 6 micrometers. In comparison, the same system yields a 3d standard deviation of 5 µm with static setup and 9 µm without the optimization of weight distribution.

10329-23, Session 5

High speed imaging for assessment of impact damage in natural fibre biocomposites

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Enhancement in imaging technologies and the development of ultra high speed cameras has made possible the use DIC methods for dynamic event testing [1]. High speed DIC has been used for many experiments including for fracture, and impact testing [2]. Tiwari et al. [1] used a 2D-DIC method to make full field measurements during high speed impact conducted using the split Hopkinson Pressure Bar (SHPB) setup. High speed imaging (HSI) is nowadays commonly used even on production site thanks to rugged high speed sensors. In the industrial sector, high-speed camera experiments were conducted on Printed Circuit Boards to fine-tune drop impact simulations [3]. However, Liu et al. [4] reported that synchronization difficulties and poor image resolution from high-speed camera limited the use of high speed imaging under impact loading rates. For example, in ballistic testing high speed cameras were used to measure the initial and residual velocities of the projectile but not for damage assessment [5]. The assessment of impact damage is typically done after the impact using visual inspection, ultrasonic C-scan or other NDI methods. The evolution of damage is identified from the force-displacement curve obtained from the impact experiment. The creation of cracks results in the loss of stiffness and a corresponding drop in the force history. However, the force-displacement data is not correlated to the actual creation and propagation of damage due to difficulties of setting up high speed camera equipment to observe the bottom surface of the impacted plate. For this application, the HSI integration is really specific and enables the user to better depict the successive events occurring upon the crack propagation. Indeed, post mortem inspection of the cracked plate does not always show if the impactor was completely piercing the plate under study.

In this paper, a method is presented to correlate the force- displacement data from the sensors to the slow motion tracking of the cracks in natural fibre reinforced composites. Natural fibres are considered a potential replacement to traditional composite reinforcements such as E-glass due to their low density, high specific properties, relative abundance, low cost of raw material, and positive environmental profile. Bensadoun et al. [6] reported that the use of natural fibres for high performance applications has been limited in part by a lack of data for loading conditions such as fatigue and impact. Impact loading can occur during the service life due to dropped tools, or collisions with loading and unloading fixtures and the resultant damage, such as delaminations and back-face splitting, can severely reduce the mechanical properties.

The low velocity impact tests were conducted using a CEAST instrumented drop tower. Flax composites with thermoset and thermoplastic matrix were chosen for the project. Woven flax / polypropylene (PP) commingled fabric was supplied by Composites Evolution as Biotex Flax/PP. Dry flax woven fabrics (Biotex Flax) also from Composites Evolution were chosen for the manufacture of Flax-Epoxy composites. The thermoset matrix was a two part epoxy resin supplied by Resoltech (1800 epoxy resin and 1805 aliphatic amine hardener). Both the thermoset and thermoplastic composites were fabricated using a compression moulding method.

The drop tower setup consists of an instrumented impactor that is secured to a carriage that falls along guideposts and collides with the plate. The weight of the impactor was 3.1 kg with a hemispherical impactor of diameter 20 mm. The drop height varied from 0.1 m to 0.3, 0.35, 0.4, and 0.5 m to give a range of kinetic energies of 3 J to15 J. The impact tests were conducted until complete perforation of the plate was observed, in order to assess the absorbed energy behaviour of flax composites. Three specimens were tested at each condition to ensure the repeatability of the experiment. A Phantom V2512 high speed camera, coupled with long distance macrozoom lens, was used for slow motion observation of the bottom surface of the composite plate during the impact event. A mirror setup placed at 45° below the composite plate allowed the camera to safely capture the impact event without fear of damage and also to shine about 15000 lumens from superLEDs cold light device. The images were acquired at a frame rate of 39000 fps and exposure time of 25 ?s with a resolution of 786 x 786 pixels. Photoelectronic switches acted to trig the camera and was also used to measure the initial velocity and rebound velocity of the impactor. The bottom surface of the (dark) composite plate was painted with a thin layer of white powder to allow the skeletonisation of the images during the cracking of the plate. The crack lengths were measured from each image using a skeletonisation algorithm in ImageJ software. The evolution of damage observed in the plate was correlated to the mechanical response of the composite plate. Additionally, some composites were painted with a fly-speckled pattern and the results of the digital image correlation were compared to the results obtained for the white paint. For clear color composite, no preparation of the samples is required as dynamic range of the V2512 is really high. The proposed method can be a valuable tool to study the impact behaviour of fibre-reinforced composites and better depict the successive events that lead to their breakage.

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10329-24, Session 6

Miniaturization of an optical 3D sensor by additive manufacture of metallic mirrors

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In automated inspection tasks multiple sensor technologies are available for purchase. The diversity of systems includes intelligent cameras and 3D acquisition systems based on photogrammetry, laser triangulation and fringe projection. All these systems have in common that they have fixed properties concerning field of view, accuracy and sensor size. For many applications these properties can fulfill the requirements of industrial manufacturing control, but for inspection tasks with exceptional inspection part geometries sensor size and field of view are insufficient and standard devices fail. With use of additive manufacturing technologies optical elements can be generated cost efficiently in low numbers to build sensor devices which adapt to requirements of the inspection part. By printing optical elements the design of the sensor system is not limited anymore because freeform optics of almost any shape can be printed and utilized for the application in mind. In this article a solution for an inspection application is presented which cannot be solved with standard technologies. Focusing on the customized, additive manufactured illumination optics opportunities of additive technologies for automated inspection are exemplified. Utilizing selective laser melting technology metallic mirrors are generated to miniaturize a laser triangulation setup. With the miniature device the interior of plastic parts manufactured by injection molding is inspected. These parts to be inspected are components of fluid pumps which are characterized by an up to four meter long but only 26 millimeter in diameter undercut. By integrating this micro optical system in a robotic kinematics the sensor device can be inserted into the inspection part and a 3D point cloud of the interior can be generated. Beginning with the optical design and the additive manufacture of the optical element the complete process chain to manufacture such customized optical elements is illustrated by this example optics. So far it is not possible to generate surfaces with optical quality by 3D printing. Therefore different methods to rework surfaces are compared. In addition to the manufacture of the optical element a simple but highly accurate 3D acquisition algorithm and calibration setup is explained to analyze laser lines and calculate 3D data time efficiently. The setup is finished with the electronical components of the device. Also the camera module as well as the illumination unit include approaches to minimize the size of the optelectronical device by using laser diodes with diffractive optical elements and cameras in millimeter size. To minimize not only the sensor device itself but the complete measurement setup efforts are being made to execute the 3D acquisition algorithm as well as an analyzing software on a miniature Raspberry Pi computing device. Finally an evaluation of the sensor device is presented illustrating the 3D point output and comparing the output data with the CAD model of the inspection part.

10329-26, Session 6

Platform for 3D inline process control in additive manufacturing

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3D - Inline - Process - Control is getting more attention in any fields of manufactures processes to increase productivity and quality. Sensor systems are necessary to capture the currently process status and are basement for Inline-Process-Control. The new fields for Inline – Process – Control are given together with the establishment of new manufacturing methods like the additive manufacturing. Adjusted process parameters in additive manufacturing are necessary for proper final results. Other currently published papers used 2D – image processing methods or measure only the final 3D – shape of the additive manufactured part.

This approach uses the 3D – inline – scanning in additive manufacturing processes like melt layer forming methods such as Fused Filament Fabrication (FFF) for Inline – Process – Control. Reasons are findable in the initial cost of the different additive manufacturing machines. The higher costs for metal-based manufacturing allows earlier the application for Inline – Process - Control and amortize the extra initial cost for the necessary hard- and software in an acceptable relation. But sensor systems, for example image sensors, are getting cheaper and cheaper and getting more interesting for lower priced additive manufacturing processes like FFF. Furthermore the large variety of available filaments for an FFF manufacturing system requires adapted machine parameters for an acceptable manufacturing result. The parameters are normally only adjustable with the help of iterative manufacturing process steps or the machine operator has high expertise in handling with different filament. The number of possible process failures is very diverse and can be reasonable in different causes.

The aim of the presented work was to accomplish a 3D - Inline – Processing – Platform to evaluate objectively additive manufacturing processes in Fused Filament Fabrication. The own created and adaptable hardware platform for the Inline – Process – Control is able to output 3 – dimensional information about the manufactured object during processing time. The developed 3D Sensor system using pattern projection method is currently build in an Ultimaker 2 extended+, but adaptable in other additive manufacturing systems with requirement to have an free field of view to the manufacturing process on the upper side. A 3D scan in a bird eyes view arrangement is captured after every finished manufactured layer and is the basis for the subsequent image processing. The image processing of the several captured layer point clouds constitutes the Inline – Process – Control and can manipulate the manufacturing machine in only a few seconds. If a manipulation has no success and the manufacturing result is disappointed, the Inline – Process – Control can decide to stop the manufacturing process. The automatic stop process allows to reduce raw material, manufacturing time and other costs.

Additionally the separate layer scans are also use to transform a complete point cloud stack of the manufactured part to get a filled point cloud of it like a tomographic dataset. This procedure allows to takes a look inside the manufactured part and gives more possibilities to assess the manufacturing process. The analyzation of the several layer and the layer stack offer (tomographic dataset) a great potential to characterize the additive manufacturing result in dimensional accuracy, stability and finishing. For the geometry reference the STL file of the manufactured part is used.

The presented research provides a suitable solution to 3D monitoring and regulate an additive manufacturing process – in example of Fused Filament Fabrication. The main parts of the work are the developing and integration of an adaptable 3D hardware platform and the analyzation of captured layer point clouds and the filled point cloud stack to regulate inline the manufacturing process.

10329-27, Session 6

Flexible registration method for light stripe sensors considering sensor misalignments

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In many application areas such as object reconstruction or quality assurance it is required to measure the complete shape of an object or at least a whole cross section. For complete measurements of 3D objects, multiple views are needed to avoid undercuts. Hence the developed measuring system consists of several light stripe sensors surrounding the

measurement object. The final number of sensors depends on the object geometry and dimension. Each light stripe sensor is mounted on an adjustment unit to align the laser planes. In order to create a uniform 3D data set from individual sensor data, a registration of each individual data set into a common global coordinate system has to be performed.

A common method is to use 3D reference objects with well-known geometry in advance. The registration is performed by measuring the reference objects in different positions and orientations. After fitting a spare geometry or a CAD model in the range data, the corresponding points in each individual data set will be manually determined. Subsequently a rigid body transformation of the corresponding points is performed to calculate the transformation between two adjacent sensors by minimizing the squared error. For this method the alignment of the reference objects as well as of the sensors play a major role, because possible misalignments or offsets of both reference objects and laser planes will not be considered.

Another widespread approach is to use an iterative closest point (ICP) algorithm directly on the range data of a 3D reference object, so that the alignment of the reference object is no more important. There is also no need for fitting the measurement data to get the corresponding points. The corresponding points are located in the overlap of the projected laser planes and can be specified either as a part of the data or as a percentage. The ICP searches for corresponding points of a part of one dataset in the other one and then performs a rigid body transformation. The procedure repeats until the stopping conditions have been reached. Usually a good initial guess transformation has to be applied in order to avoid local minima, which will cause the registration to fail. For successful registration, this method also requires good sensor alignments, because similar to the previous approach misalignments and offsets of the laser planes will not be considered as well.

In this paper a new registration method based on 3D pose estimation using the camera calibration data of the sensors will be presented. The developed method is flexible regarding to the position and orientation of the reference object and considers possible misalignments of the sensors. This method is especially interesting for the object reconstruction, where is no need for perfect cross sections, cause of polygonising the measured points to a mesh. So an accurate adjustment of the sensors becomes incidental. As reference object a 2D checkerboard pattern is used. The results of the developed registration method will be discussed and compared with the other methods.

10329-73, Session PS1

Parallelism measurement of plane glass at oblique incidence by interferometry

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Parallelism is an important parameter of plane glass in high power solid-stat lasers such as SG-III and NIF etc which consists of many large rectangular plane glasses with slight wedge angle. It will influence the collimation of laser beam.

This parameter should be measured at full aperture. To realize high measurement accuracy, these glasses is tested by interferometers. Parallelism measurement is often done at 0° incidence by interferometers, so the size of large rectangular plane glasses which can be tested is limited to the interferometer aperture. Subaperture stitching is a well known method which could enlarge the size of testing aperture, but the positioning inaccuracy bring much error and the algorithm should be improved, and also, subaperture stitching testing will take too much time.

If position a plane glass at an oblique incidence angle in interferometer, the parallelism of the glass could be obtained at full aperture, but the result is quite different from the result obtained at 0° incidence angle.

In this paper, a new method is proposed to parallelism measurement that plane glasses can be measured at oblique incident angle. This method is based on least square method and refraction law, and the parallelism testing modeling is built. Each transmission wavefront of plane glass at oblique incidence and interferometer empty cavity can be obtained by interferometry testing, then they will be fitting to two planes by least square method, so the included angle ? of the two planes and the included angle ? between ? and X axis could be obtained. With angle ? and ?, the emergence direction of the testing beam light at different incidence angle and with different glass rotation could be calculated, the direction of tilt could also be obtained, and the optical path difference between different testing angles could be obtained too. With these 3 factors mentioned above, the relation equation of the results of parallelism with different testing incidence angle could be figured out. So those rectangular plane glasses could be qualified at incidence angle, the results of parallelism could be converted to the results obtained at 0° incidence angle---that means the dimension of sample measured at horizontal direction is enlarged, those rectangular plane glasses could be measured at some oblique angle by full aperture but with a smaller aperture interferometer.

This method will not take anymore equipment nor extra measuring time. In this paper, a same plane glass is measured at 0° angle and at other angles, and the testing results are matched with each other. The error sources of this method are discussed, and the ways to avoid these errors are also pointed out.

10329-74, Session PS1

New technique for generating light source array in tilted wave interferometer

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Smaller and lighter optical systems with better performance can be built by the use of freeform optics. However, most optical imaging systems were constrained to traditional surfaces for the accurate metrology of freeform surfaces is a challenge so far unsolved. One high-precision approach to measure freeform surfaces with less time and expense is using tilted wave interferometer (TWI). In the test path of the interferometer, an element is placed, which can generate light source array that act as test beams. But each source generated by lens array is not ideal spherical wave which contains aberrations. In addition, the sources cannot be activated individually during the measurement, so that it is impossible to perform an irregular source array according to the gradient variation of each test surface. Thus, a novel technique based on fiber array is proposed for generating irregular source array. Whereas, some system errors that affect the measurement accuracy are introduced by the use of fiber array, such as the position deviation of each fiber and phase difference produced by the length of each fiber. In this paper, the consequences of the above system errors are analyzed. With regard to position deviation of each fiber, we conclude that it must be controlled within 15um to make the wave error of each test beam less than?/10 (?=632.8nm). Based on the imagine theory in geometrical optics, a calibration method can obtain the exact spatial coordinates of the center of each fiber is suggested. In the experiment, a known magnification lens was used to image the fiber array onto the CCD. Then the spatial coordinates of each fiber of the developed fiber array is calculated by Newton's Formula in geometrical optics. The calculation results show that the position deviation of each fiber is less than 3um, which satisfies the requirements of the tilted wave interferometer. In order to calibrate the phase difference produced by the length of each fiber, as long as we measure the length difference of the each fiber. So a Mach-Zehnder interference system is built based on the principle of excess fraction method, which can get the value of length difference accurately. During the measurement, the center fiber of fiber array is selected as the reference fiber, and the length difference in the order of millimeters between the other fiber and the reference fiber is obtained. Afterwards, the data obtained by the two calibration methods are introduced into the mathematical model of system error for eliminating the measurement error introduced by the use of fiber array. A non-coaxial ellipsoid mirror is measured by our tilted wave interferometer based on fiber array showing the feasibility of the proposed methods.

10329-75, Session PS1

Absolute test using the conjugate differential method

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The conjugate differential method we presented before, has been applied to the absolute test of flat, cylindrical, and axicon surfaces. The basic idea is to make the data difference between the adjacent positions be an approximation of the differential data of the test surface. And the absolute shape of the test surface can be reconstructed. To achieve the goal, two interferometric measurements at conjugate positions along two orthogonal directions need to be carried out to get the difference data along each direction. With the numerical calculation, it is possible to remove the systematic error from the original test result. The schematic diagram is indicated below.

In the previous work, we have made simulations for the flat, cylindrical, and axicon surfaces, and given the experimental test cases to verify the feasibility of conjugate differential method. For analysis and calculation convenience, we combine both the reference error and systematic error together. In fact, their influences upon the measurement result are different from each other. We will discuss the conjugate differential method in detail according to the following aspects.

First of all, we will discuss the application possibility of the conjugate differential method. Surface types of the test surfaces in the previous work have a similarity that the difference along two orthogonal directions can be obtained by a certain minimal shift. For cylindrical and axicon surfaces, an additional compensator, like computer generated hologram (CGH), is normally inserted to fulfill the null test criteria. In this paper, we will take the flat surface as an example in the analysis.

Secondly, the reconstructed spatial frequency information of the test surface is mainly restricted by two aspects. One is the characteristic of the interferometer, and the other is the algorithm limitation of the conjugate differential method. Interference system can be considered as a linear system approximatively if the frequency band is mainly low. The corresponding ingredient are linearly addible. In addition, the distortions caused by interferometric imaging, coherent noise, electronic noise in interferometric image acquisition and so on, will make the test results deviate from the ideal ones. These factors are static factors relatively, and they will be introduced into the difference calculation in the conjugate differential calculation process. In order to obtain higher test precision, the difference amounts obtained by subtraction of two measurements should be as close as possible to the actual differential amounts. This means that the translation amount between the conjugate positions must be as small as possible to ensure better approximation. However, at the same time, the influences of systematic errors will be increased when the translation amount decreased. Furthermore, if the test piece is a large aperture element, the sampling frequency has to be reduced, in order to maintain effective aperture. So the translation amount will be increased, and the bandwidth of the test surface reconstructed by the conjugate differential method will be further limited. We will focus our current research on how to choose an appropriate translation amount and sampling frequency, and explore the range of the shape that the conjugate differential method can be applied.

10329-76, Session PS1

Experimental comparison of photogrammetry for additive manufactured parts with and without laser speckle projection

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The ability to measure highly complex, freeform parts manufactured from a range of materials typical in additive manufacturing (AM) is a difficult challenge. Mechanical contact techniques can provide accurate 3D measurements, but for complex parts, measurement times can be substantial. Optical techniques, however, can provide the fast and high accuracy form measurements and are suitable for the types of surfaces produced using AM. For instance, fringe projection has already been adopted widely by both the aerospace and automobile industries (Salvi et al. 2010, Gorthi and Rastogi 2010). Unfortunately, many optical techniques are still subject to their own limitations due to surface geometries, material properties and optics (Stavroulakis and Leach 2016).

Photogrammetry is a passive triangulation technique based on the matching of points between many images of an object (Luhmann and Robson 2011). Through the matching of points over the surface of an object, photogrammetry is able to triangulate a point cloud for which geometric information about the object may be extracted. Using this technique with commercial DSLR cameras, 3D point measurement uncertainties in the order of tens of micrometres are possible with a very low-cost system. A requirement of photogrammetry is that some texture must be observable on the object surface, making the highly textured surfaces of many AM parts ideal for finding point correspondences. For AM parts that do not display sufficient surface texture for correspondences to be found, we have developed a laser speckle projection system to project observable texture onto the object surface (Sims-Waterhouse et al. 2016). By using a combination of typical and laser speckle projection photogrammetry, a vast range of AM parts with different geometries, materials and post-processing finishes can be measured to high accuracies.

In this paper, we have experimentally determined the measurement uncertainties for a series of AM test artefacts. The test artefacts were produced in three materials: polymer powder bed fusion (nylon 12), metal powder bed fusion (titanium 64) and polymer material extrusion (ABS plastic). Each test artefact was then measured with the photogrammetry system in both normal and laser speckle projection modes and the resulting point clouds compared with the artefact CAD model. The traceability of all measurements was also ensured by scaling the reconstructions using a calibrated ball bar. Each artefact was also measured using a commercial fringe projection system, for which the same comparison with CAD data has been made. The aim of this paper is to show that laser speckle projection is able to increase the density and accuracy of photogrammetry measurements and provide form measurements comparable to a commercial fringe projection system.

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10329-77, Session PS1

Phasing piston error by analyzing the intensity distribution on image plane

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As the demand for space exploration increasing, telescope's resolution has become higher and higher. In order to get a high resolution, the telescope primary mirror's aperture must be enlarged. This makes optical processing and testing, and transportation or launch very difficult. A segmented and deployable primary mirror was adopted to address this problem. Segmented mirror telescopes provide a high resolution, but introduce the cophasing problem. Piston error between the segments must be reduced from an initial state of 100 microns to several tens of nanometers to realize a diffraction-limited imaging. This makes cophasing detection vital. Several methods have been adopted, some of them fit coarse detection and the others fit fine detection. Consequently, cophasing is divided into coarse and fine regimes which involve separate dedicated hardware solutions. In this paper we propose a novel method to address this issue. We detect the piston error based on analyzing the intensity distribution on the image plane of a segmented telescope, which is of a large capture range and high accuracy. A mask with a sparse sub-pupil configuration is set on the exit-pupil plane to sample the wave reflected by the segmented primary mirror. The relation between the piston error and the heights of MTF's surrounding peaks is derived by analyzing the intensity distribution on the image plane according to the Fourier optics principle. Simulation has been done to verify the relation is correct. Thus, the piston error can be obtained by using this relation after measuring the heights of MTF's surrounding peaks. This method's capture range is the input light's coherence length, the accuracy is of nanometer scale. But this relation, derived theoretically, is complex to be used directly in a realistic piston error measurement. We try to find out a kind of function similar to this relation and it could be used to measure the piston error easily. We fit it with Gaussian, linear, parabola, cubic polynomial, quartic polynomial, and piecewise quartic polynomial functions. The best fitted one is the piecewise quartic polynomial function. By a fit error analysis, the difference is 1.8nm RMS. Thus, the piston error between the segments can be retrieved by using the piecewise quartic polynomial function. Finally, experiments have been carried out on the ACAT (Active cophasing and aligning testbed with segmented mirrors) which was set up before to validate the feasibility of this method. ACAT was set up to validate some methods for cophasing errors detection. It consists of a source module (SM), beam splitting module (BSM), piston error detection module (PEDM), tip-tilt error detection module (TEDM), sensitive micro-displacement actuator module (SMAM), segmented mirror module (SMM), FISBA spherical interferometer, laser plane interferometer (LPI), and computer control system (CCS). And the process of the cophasing errors detection and correction can be carried out under the computer closed-loop control in nanoscale. The validation experiments show that our method can capture segments with the piston errors as large as the coherence length of the input light and reduce these to 0.026 wavelength RMS (wavelength=633nm).

To show the potential of this method, it can be used to realize piston error parallel detection for a multi-segment primary mirror telescope with a high accuracy in a large capture range, and just need to set a mask with a sparse multi-subpupil configuration on the exit-pupil plane of the telescope or rotate the mask to cophase the entire segmented mirror. The design principle for the sparse multi-subpupil configuration is to avoid overlap of the MTF's surrounding peaks which formed by each pair of subwaves sampled by corresponding subpupils. This method can be adapted to any segmented and deployable primary mirror telescope, whatever the shape of the segmented mirror and the number of the segments is.

10329-78, Session PS1

Development of a width and camber measurement system in a steel plate mill

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Quality is one of the most important issues for both producers and customers. Camber is one of the most significant defects in the steel plate mill. Conventional methods for characterizing product parameters fail in these unfavorable measurement conditions. An alternative is optical measurement technique. It is non-contact and can be positioned in a safe location. The design and implementation of an optical-based width gauge and camber measurement system in the steel plate mill will be described in this paper.

The system has three main functions, such as width measurement as well as sidewalk and camber measurement. In this system two high-resolution line-scan cameras configured with a stereoscopic view are used to measure the silhouette of the strip. With this configuration, the influence factors for measurement, such as vibration, tilt and wandering of running steel plate, are greatly diminished. The accuracy of width measurement is ±2mm for widths in the range of 900 to 4100mm.

The system has been currently installed and working in the steel plate mill for one year without any problem. By using this system, it not only can lighten the load of the inspectors and acquire on-line measuring data in time but also very helpful for quality and process control.

10329-79, Session PS1

Optical scanner system for inline high resolution measurement of lubricant distributions on metal strips based on laser induced fluorescence

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Current trends in metal processing industry require forming procedures with increasing deformations. Thus a sufficient amount of lubricant is necessary to prevent the material from rupture. However a surplus of the lubricant layer causes dints as well as problems in post-deforming procedures, like welding, gluing and soldering. For monitoring this sensitive process a spatial resolved measurement for the thickness of the lubricant layers is required. Measurement systems for the thickness of lubricant layers are either based on infrared spectroscopy or laser induced fluorescence. Information on the lubricant distribution is achieved by moving the sensor heads along the object on a linear axis. The spatial resolution of these systems is insufficient at strip speeds, which are typically more than 1 m/s in the forming processes, e.g. at press plants.

In this article we present a new optical setup, which uses scanning mirrors in combination with laser induced fluorescence to monitor the spatial distribution of lubricants on metal sheets. Although scanner systems for laser induced fluorescence have been published before mostly in microscopy applications, there are no systems known for inline analysis in industrial environments.

By using fast rotating scanner mirrors combined with a fast analogue digital conversion, data rates of 200 lines/s consisting of 1000 data points each can be reached. In the presented setup the beam of a 405 nm diode laser is used to excite autofluorescence of investigated lubricants. The fluorescence signal is collected by a coaxial optic, spectrally filtered and recorded using a photomultiplier. From the acquired signal a two dimensional image is reconstructed in real time. As the trajectory of the scanned laser beam is nonlinear, the position of the laser spot on the metal surface, depending on the deflection angle of the scanning mirror, is calculated to gain undistorted images.

Special care has been taken on the quantitative measurement of the thickness of the lubricant layers. The presented system has been calibrated using reference samples. These samples are made both using a spray system and a spin coater. For calibration reference samples are weighted. Standard lubricant oil from German Federal Institute for Materials Research and Testing (BAM) is used for the experiments. Calibration results in the range of 0.1 to 5 g/m? will be presented.

Linearity and stability of the presented system were characterised using a target made of Spectralon® fluorescence material. Using this standard, a linearization of the photomultiplier output at different gains for fluorescence intensities of six orders of magnitudes is achieved. The drift of the system is less than +/- 1 % over 60 hours. An etched aluminium stencil is combined with the fluorescence standard to characterise the spatial resolution. At a scan rate of 50 lines per second and a scan field of 0.3 m the spatial resolution is 0.5 mm.

For using the system inside production sites, a concept for a laser safe housing was implemented. Furthermore the influence of ambient light on the fluorescence signal was analysed.

10329-80, Session PS1

Characterizing the quality of the fiber optic reference for cylindrical wave testing

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With continued advances in cylindrical optics manufacturing capability, interferometric testing of such optics is difficult and continues to be a challenge. The primary reason of this challenge is the lack of a well characterized cylindrical reference surface. One approach that has been investigated is the fiber optic reference. The fiber optic reference test utilizes a specially processed optical fiber to provide a clean high quality reference wave from an incident line focus from the cylindrical wave under test. However, to date, there is not sufficient information about the quality of the fiber optic reference surface; one publication has discussed the accuracy of using the fiber as a cylindrical reference, stating only that the fiber is " lambda/15 P-V" or better" along the plane axis. Due to asymmetry, a discussion of cylindrical wavefront accuracy would not be complete without a description of the accuracy along the powered and the plano axes.

In this paper, the Random Fiber Test (RFT) is used to experimentally quantify the quality of fiber surface as a cylindrical reference. The basic method of the experiment is to take measurements at different rotations about and translations along the axis of the fiber. From these measurements, the quality of the fiber surface in both direction can be determined. The experimental setup consists of an interferometer with a transmission flat and a computer generated hologram (CGH). The CGH cylindrical null diffracts the collimated wavefront from the interferometer into a high quality F/4 cylindrical test wavefront. A specially prepared fiber reference with a radius of curvature of ~ 62.5 µm placed at the focus line ~ 285mm from the CGH . This fiber is fixed in a two degree of freedom adjustment stage controlling tilt and clocking, but neither adjustment is particularly smooth or capable of fine motion. To measure different patches of the fiber surface, the fiber stage is then mounted to crossed translation stages that enable motion in x (perpendicular to the focused line), y (fiber axis direction) and z (defocus). Finally, a rotation stage was added to enable rotations about the fiber axis. A series of 60 different patches of the fiber surface were randomly measured by y-shifting and rotating the fiber about the y-axis. The interferometer testing system error and the misalignments error were subtracted from each of the 60 measurements leaving only the individual fiber test measurement errors. The results of these fiber reference quality tests are presented in two different ways. One is simply in terms of PV and RMS. However, for many applications, PV and RMS are not sufficient to describe the surface quality as they provide no information about the form of the surface error. Cylindrical-wave tests are often over rectangular apertures, which is not amenable to Zernike decomposition. Therefore, the 60 measurements were decomposed into Chebyshev polynomials.

Experimental results show that the performance using one specific fiber depends highly on what portion of the fiber is illuminated. However, for the fiber tested, results ranged from "lambda /13 to "3 lambda / 4" .

10329-81, Session PS1

Fiber Bragg grating vibration measurement device

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Vibration monitoring is an important area in mechanical and civil engineering. Presence of vibration in any mechanical system or civil structure is not desirable as it reduces the efficiency of the system. It is imperative to measure these vibrations in order to evaluate the stability of the structure. Vibration measurement can be carried out by either inertial response of the Vibration Measurement Device or by a contact type Vibration Measurement Device. The present study proposes a Fiber Bragg Grating Vibration Measurement Device (FBGVMD) which will comprise the ability to measure vibrations of varying acceleration. Frequency response scan and amplitude response scan is carried out with the developed FBGVMD. Also, the developed FBGVMD can be employed for displacement measurement. With the inherent advantages of the FBG sensor (fiber optic sensor) such as insensitivity to electromagnetic interference, passive sensor element and ultra-fast response making the developed FBGVMD as an effective means for measurement of vibration and displacement in any kind of industrial environment

10329-82, Session PS1

Analysis of the fractures of metallic materials using optical coherence tomography

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Forensic in situ investigations, for example for aviation, maritime, road, or rail accidents would benefit from a method that may allow to distinguish ductile from brittle fractures of metals - as material defects are one of the potential causes of such accidents. Currently, the gold standard in material studies is represented by scanning electron microscopy (SEM). However, SEM are large, lab-based systems, therefore in situ measurements are excluded. Also, they are expensive and time-consuming. We have approached this problem and propose the use of Optical Coherence Tomography (OCT) in such investigations in order to overcome these disadvantages of SEM. In this respect we demonstrate the capability to perform such fracture analysis by obtaining the topography of metallic surfaces using OCT. Two types of metallic materials have been analyzed: low soft carbon steel (with a carbon content ranging between 0.20% and 0.22%, lamellar graphite cast iron, and an antifriction alloy. An in-house developed Swept Source (SS) OCT system has been used, and height profiles were generated for the sample surfaces. These profiles allowed for concluding that the carbon steel samples were subjected to ductile fracture, while the cast iron and antifriction alloy samples were subjected to brittle fracture. A validation of the OCT images obtained with a 10 microns resolution has been made with SEM images obtained with a 4 nm resolution. Although the OCT resolution is much lower than the one of SEM, we thus demonstrate that it is sufficient to obtain clear images of the grains of the metallic materials and thus to distinguish between ductile and brittle fractures. This study analysis opens avenues for a range of applications, including: (i) to determine the causes that have generated pipe ruptures, or structural failures of metallic bridges and buildings, as well as damages of machinery parts; (ii) to optimize the design of various machinery; (iii) to obtain data regarding the structure of metallic alloys); (iv) to improve the manufacturing technologies of metallic parts.Selected References:
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10329-83, Session PS1

A novel white-light interferometry using low differential frequency heterodyne system

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The optical surface profilers, offering fast, non-contact, high-precision 3D metrology for complex surface features, widely used in the field of precision machining manufacturing, such as automobiles, aerospace, high-brightness LEDs, solar energy and semiconductors. The optical surface profiler traditionally adopts white light interference, mainly including optical interference system and high-precision displacement stage. The accuracy of the displacement table determines the longitudinal resolution of the instrument. But the displacement with both high precision and large range is very expensive, which, in the meantime, could not avoid the hysteresis effect of piezoelectric materials. By matching the zero-path difference and detecting the intensity of the interference fringes, the height information is extracted. The direct inversion of the intensity signal is susceptible to all kinds of noise and meanwhile reduces the measurement accuracy.

In this paper, a novel white-light interference technique is proposed, i.e. full-field heterodyne white-light interferometry, which combines common displacement stage, low differential-frequency heterodyne system and optical interferometry system. The displacement stage achieves full-scale scanning, and stay still in discrete Positioning during measurement. The low differential-frequency heterodyne system generates heterodyne signal and in the range of laser coherence length, by using the digital phase shift in substitution for the mechanical phase shift, the vertical resolution increases from the sub-nanometer level to the sub-angstrom level. The frequency shift of the laser beam with center wavelength of

520nm and line width of 10nm can be achieved by using the developed dual-band wide-band acousto-optic frequency shifter. After the frequency shift, it generates two homologous beams. The center frequency difference of the two beams is 10Hz and the phase noise of frequency shift is controlled below -110dBc. One beam is irradiated to the surface of the measured object by the imaging lens, and the diffuse reflection light is received on the detector. The other beam is used as a reference light to directly interfere with the signal light. Due to the low difference frequency technique, the common area array detector acquisition is available. In principle, any frame rate that is greater than 20fps can be used. In order to improve the detection accuracy, a 100fps CCD detector is used for acquisition in this experiment. A fixed displacement stage position obtains a set of three-dimensional data cubes. Through Fourier-Transform process of the time series data, the initial phase of each pixel at a specific heterodyne frequency is calculated and transformed into surface height information. By using phase unwrapping, the object surface profile can be restored within the laser coherence length. With 10 nanometer displacement stage scanning, it is available to achieve full range of high-precision contour acquisition.

The experimental results show that the accuracy of longitudinal repetitive measurement of silicon wafer groove measurement is 0.37 Å. Through digital phase-shifting, phase extraction technology replaces the intensity extraction technology, the moving distance of the displacement can be calibrated with high precision. Thus it can achieve a large range of high-precision contour measurement and reduce the cost of the instrument.

10329-84, Session PS1

Fiber Bragg strain sensor calibration system on the basis of mechanical nanomotion transducer

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Fiber Bragg Grating (FBG) strain sensors are powerful tool for structural health monitoring. However, it should be noted that for fabrication of Bragg sensors special glue joints, metal structures, polymeric and composite materials with elastic properties are usually used, that leads to a non-linear component of the transmission characteristic of the Bragg sensor, that have an impact on an accuracy of strain measurements.

Here we present a novel, non-destructive calibration technique for FBG strain sensors using a mechanical nanomotion transducer. Mechanical nanomotion transducer is a commercially available high-precision sensor based on the Michelson's interferometer (Intellegent Technologies Ltd., Moscow, Russia). The accuracy of mechanical motions is 0.02 nm.

A customized calibration setup was designed on the basis of dovetail-type slideways mechanized by a stepping motor. For the initial calibration of the FBG strain sensor the calibration setup was placed into a heat chamber to maintain temperature. At each point of the strain variation range mechanical deformation of the sensor is measured by the mechanical nanomotion transducer and the reflected wavelength is measured by the wavelength meter. The wavelength meter is a part of State Special Standard for Metrological Support of Measurements of Optical Fiber Transmission System at VNIIOFI (Root-Mean-Square Error is of 9.1?10–8, Systematic error is of 9.1?10–7). The wavelength meter has been developed specifically for operation with optical fiber and possesses a number of specific features related to fiber properties (small sizes and power levels, specific spectral range of operation of 1100--1700-nm).

During the calibration, the difference between the strain obtained from the measuring system and from the precision mechanical nanomotion transducer was calculated. According to the results of measurements a table of values of the transfer characteristics of the sensor under calibration was obtain.

The resulting transfer characteristic for each FBG strain sensor records in the computer memory and uses for further strain measurements.

10329-85, Session PS1

Evaluation and tolerancing of irregularly shaped interferometric test regions

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The evaluation of non-circular test ranges poses an unusual but tricky problem to interferometric testing since typical polynomial decompositions of the measured wavefront like Zernikes are only valid in a circular region. Despite the fact that of course non-circular polynomial decompositions exist they still rely on regular regions like ellipses or rectangles. For irregular shapes of test ranges no widely accepted general decomposition exists.

Unfortunately it is necessary in some cases to test completely irregularly shaped test ranges. May it because the optics simply is of this shape and needs to be tested in this state or because the used area is irregular and it is undesired to extend the test region to a larger, but regular shape.

We present a simple method that not only provides a possibility to evaluate any arbitrary shaped test region but also to have a tolerance model that gives reasonable and worldwide accepted specification standards.

Certain interferometer software may be suited for an appropriate data analysis. An overview over some commercially available interferometer software is given with respect to the requirement of the presented method.

10329-86, Session PS1

Remote sensing of atmospheric turbulence profiles by laser guide stars

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Atmospheric turbulence has a important influence on optical wave, and results in beam spreading, jittering or wandering, and scintillation. Characteristics of atmospheric turbulence varies temporally and spatially, so remote sensing of atmospheric turbulence profiles in real time is important and necessary for applications such as performance analysis of astronomical adaptive optics systems, astronomical sites surveys and selection, validation of atmospheric turbulence prediction model, free space laser communication, and laser beam propagation in the atmosphere. The astronomical and adaptive optics communities have established several optical techniques for remote sensing Fried parameter, a parameter of path-integrated structure constant of refractive index of atmosphere, but few techniques has been applied in remote sensing ranged-resolved information of atmospheric turbulence. Laser guide stars technique is used commonly in adaptive optics community, and differential image motion method is a matured technique in astronomical community. So, a new technique is put forward for remote sensing atmospheric turbulence profiles. Combined with laser guide stars and differential image motion method, remote sensing of atmospheric turbulence profiles in real time is realized in experiments effectively.

To validate the remotesensing technique, a experiment was carried out. The configure of experiment consist of a powerful pulsed laser, a beam-expanding lens and a negative lens for beam-focusing, a reflective mirror for beam-projecting, a optical device for receiving and imaging of returned signals, a ICCD camera for recording images of laser guide stars, and a computer for controlling and data processing. By expanding and focusing laser beam projected from a powerful pulsed lasers, laser guide stars are formed at several successive altitudes. A optical system with two receiving telescopes is developed based on differential image motion method. The laser guide stars are observed with the optical system developed, and images of laser guide stars with two spots at a receiving ICCD camera. The images with two spots at the same altitude are processed and centroids of two spots at every images are given. Differential image motion variance of distance of centroids could be derived from the images at the same altitude. So, the motion of the images of the laser guide stars from each altitude is characterized as the differential image motion variance.

Based on a inversion algorithm, atmospheric turbulence profiles could be retrieve from differential image motion variance of distance of centroids at various altitudes. Experiments of remote sensing have been performed, and the profiles of atmospheric turbulence are obtained. The structure constants of refractive index of atmosphere range from 10-14m-2/3 at lower altitudes to 10-16m-2/3 at higher altitudes. The results show it is a effective method that combined laser guide stars with differential image motion method and could sense atmospheric turbulence profiles remotely in real time and the profiles data remote sensed are reasonable.

10329-87, Session PS1

Laser-line scanning speckle reduction based on a one-dimensional beam homogenizer

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Laser-line scanners have become ubiquitous in many forms of automation and measurement systems. Despite this fact, these systems are still susceptible to speckle or interference on rough scattering surfaces. In general, post-processing algorithms are used in most modern line-scanning devices in order to smooth out speckle and enhance the resolution through sub-pixel interpolation. However, these post-processing techniques come at a cost of increased CPU time and a subsequent decrease in bandwidth.

The culprit behind speckle is the laser's coherence length in both space and time. There have been numerous attempts to correct speckle while maintaining a sharply focused line. However, applications such as a 2D rotating diffusor plate or a saturated multimode vertical cavity surface emitting laser (VCSEL) fall short on these goals because these methods destroy the spatial coherence of the laser, which in turn removes the ability to tightly focus this light to a line. In this paper, we present a low-cost, high resolution solution to generating speckle-free sharply focused laser lines. The key to this technique relies on only removing the spatial coherence in one dimension using a 1-D cylindrical lens array as a beam homogenizer. This beam homogenizer is then wrapped around and rotated about a central axis in order to remove the temporal component of the laser's coherence. Since the plane-wave-like behavior is maintained along one dimension, this beam can still be sharply focused to a line. However, the spatial coherence and temporal coherence are reduced to the point that speckle is minimally visible.

The device itself, pictured in Fig. 1, consists of a cylindrical lens focusing a collimated laser beam through a 1-D lenticular array. This is a common setup for beam homogenizers. The lenticular array is then shaped around a rotating disk which provides a mechanism to generate a time-averaged random phase variations which remove speckle as long as the image integration time is long enough. Because the optics are all cylindrical lens based, the laser maintains its focusability along the transverse direction. This dynamic beam homogenizer will be tested in a laser-line scanning system in an attempt to maximize resolution while minimizing computational costs.

10329-88, Session PS1

High-power LED light sources for optical measurement systems operated in continuous and overdriven pulsed modes

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The rapid progress of light emitting diode (LED) technology has recently resulted in the availability of high power devices with light emission intensities comparable to those of visible laser light sources. On this basis two versatile devices have been developed, constructed and tested.

The first one is a high-power, single LED illuminator (Fig. 1) that provides continuous light (CW) as well as light pulses of programmable width and intensity. The apparatus can be used for both light field as well as dark field imaging in high-speed videography and in image based measurement techniques such as PIV (particle image velocimetry), LPT (Lagrangian particle tracking), BOS (background oriented schlieren), IPCT (image pattern correlation technique), shadowgraphy and schlieren [1].

The device generates extremely bright, non-coherent and narrow band monochromatic light. The CW-intensity is up to 2100 lm and reaches 14,000 lm (at 528 nm) in overdriven (250 A) pulsed operation. Available colors are red (623 nm), green (528 nm) or blue (462 nm), UV (390 or 400 nm) and white light. The mode of operation and all parameters can be programmed over a USB interface and stored in an internal non-volatile memory. The pulse width can be set in the range from 50 ns up to 300 ?s or switched to CW mode. The programmable delay allows the flashes to be precisely synchronized with camera triggers or other trigger sources by means of an external TTL-trigger signal input. The double pulse mode for PIV is also provided. The device is equipped with interchangeable projector lenses providing homogenous light spots of various diameters. Moreover the light can be coupled with the experimental set-up using light guides and accompanying optics, e.g. light sheet lenses.

The device supply voltage is 24-28 V DC and 230 V AC, which enables the optical measurements not only in the laboratory and industry but also in vehicles and in aviation.

The second device (Fig. 2) is a multi-LED illuminator consisting of a number of high-power LEDs, each equipped with a separate collimating system of ± 3 degree. This device can likewise emit R, G, B, UV or white light. It can be operated both in pulsed or CW mode. The pulse width can be selected from 1 µs up to CW. The maximum light energy is 9 mJ at 10 µs pulse width. The pulse repetition rate can reach up to 50 kHz. An example of application of the multi-LED device in a pulsed overdriven mode at 1.25 kHz to a large scale Lagrangian particle tracking investigation of an impinging turbulent jet using tracer particles of Helium-Filled-Soap-Bubbles (HFSB) with 300 µm diameter and a volumetric velocity field reconstruction is shown in Fig. 3.

The principle, construction and application examples of both devices will be discussed in the paper and presented at the conference.

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10329-89, Session PS1

The research of structured reflective surface of matrix sensor according to generalized scheme of ellipsometry

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The matrix receivers of optical radiation on basis of CCD and CMOS sensors apply in many video information and measuring devices. The main parameters affecting the quantity of the been taking electrical signal is sensitivity. During the analysis of the researching object it is necessary to take into consideration the fault brought in with the elements of electronic signal processing part. Errors appear because of noise of the receiver and due to the irregular distribution of the sensitivity of the sensor platform. Therefore, during the faults' analysis of these devises, the dissimilarity of the optical characteristics and their elements must be taken in consideration.

To research this type of fault and its registration in the scheme of a particular device it is necessary to generate a mathematical model of the multilayer pixels' structure; its options can be determined by according to the generalized scheme of an ellipsometry. The aim of the work is to adapt the solution of the inverse ellipsometry problem for a single-layer system of pixel, forming the structure of a color matrix of a video information receiver.

To get the initial data, which are necessary to solve the inverse problem, the ellipsometric measurements of the polarization angles for the radiation reflected from the air-surface interface of the sensor. These angles characterize a pixel structure of the matrix.

Solving the inverse problem of ellipsometry for such a system, it is possible to determine the thickness and refractive layers' indexes, forming the structure under study. That problem has no analytic solution in general form (except for the case of a clean surface without any covering). Thus, a large diversity of the numerical nonlinear methods are involved to solve it. Their basis – the multiple solution of the direct problem with the system options selected by some rules and comparing the calculated values of the polarization angle with the experimental one. The procedure continues till the difference between the calculated and experimental values of the polarization angles becomes less than some predetermined value. The inverse problem of ellipsometry for the multilayer system (in that case three layer), at each stage is solved within the limits of a single-layer model. The refractive indexes are determined with the reflection coefficient, expressing with the admittances Abele. Layer thickness is determined by the method of Holmes. The measurements are carried out at two or more angles of incidence. That allows to specify the adequacy of the model and the real object on the convergence of the results at different angles of incidence.

Thus, within an algorithm of the solution of the return problem of an ellipsometriya for multilayered system of pixel of the matrix receiver of optical radiation the mathematical model of the reflecting sensor surface is developed for determination of parameters of layers of pixel.

10329-90, Session PS1

A metrological comparison of Raman-distributed temperature sensors

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Since the early beginning of the 80's, Distributed Temperature Sensing (DTS) technologies by optical fibres have been continuously developed and improved. The most known and mature technologies are based on the Raman scattering which enables to measure a temperature profile along the whole length of an optical fibre with a length up to 30 km (for a multimode fibre) and even up to 70 km (for a single-mode fibre). These techniques have found very promising and useful applications in the fields of the structural health monitoring (nuclear reactor containments), fire detection (tunnels), subsea cables monitoring, and fluid leakages (earthen dams and dikes, oil-gas-water pipelines). Another specific application envisaged is the temperature monitoring of the future French deep geological nuclear waste repository site.

In the framework of the Joint Research Project (JRP) ENV54 MetroDecom, LNE works in a close partnership with the French National Radioactive Waste Management (Andra) and the Electricité de France Company (EDF) for developing a metrological infrastructure devoted to the Raman-DTS technologies.

Despites of some actions leaded at the international level (i.e. IEC and ASTM standardization committees, the US Seafom platform), the dissemination of the DTS-Raman technologies to the concerned industries is suffering of a lack of standardization in this field. For that reason, users are often bring to confusion about the performances of a Raman-DTS system which are only based on the specifications proposed by a manufacturer (as resulting of a heterogeneous – sometimes mistaken – vocabulary used for describing the characteristics of the Raman-DTS systems).

In order to avoid this problem, LNE with Andra and EDF have defined a set of metrological characteristics, and developed some dedicated experimental facilities and protocols for characterizing DTS-Raman devices. The objective is to enable the users to perform a relevant comparison of such systems with a great confidence.

In this paper, the results obtained from a first benchmark of few DTS-Raman devices (including both single-mode and multimode sensing optical fibres) are presented and discussed. The perspectives provided by these works in terms of standardization are also introduced.

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10329-91, Session PS1

Phase A: calibration concepts for HIRES

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The instrumentation plan for the E-ELT foresees the High Resolution Spectrograph (HIRES). Its main aim is the detection of atmospheres of exoplanets. Therefore a radial velocity precision of about 10 cm/s is required.

Despite its extraordinary intrinsic stability, HIRES will experience systematic errors like intrapixel variations and random errors like fiber noise which need to be calibrated. One of the main tasks is to develop, how a slit consisting of individual fibers can be calibrated. We list the main requirements for the calibration of the spectrograph. Based on this we discuss different calibration sources available and show possible solutions for the frequency calibration. We outline the frequency calibration strategy for HIRES.

10329-92, Session PS1

Femtosecond Z-scan measurements of the nonlinear refractive index of fused silica

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The self-focusing effect introduced by optical nonlinearities of optical materials plays an important role in the high power laser system, which will change the phase and amplitude distribution of the laser beam. As a result, the focused window on target plane will decrease and the risk of damage to the optical components will increase. In the ultra-fast pulse regime, the laser damage process is very complicated, because fast electronic, as well as opto-mechanical and thermo-optical processes may be involved. Z-scan technology is an experimental technique for determining the nonlinear refractive index based on the principle of transformation of phase distortion to amplitude distortion when a laser beam propagates through a nonlinear material. In the case of fused silica, the nonlinear refractive index is quite small, which is about two orders of magnitude below the nonlinear refractive index of most of the materials usually studied with the Z-scan method. The change of refractive index introduced by accumulation of thermal effects cannot be neglected in nanosecond and picosecond Z-scan measurements. In order to study the impact of self-focusing on laser damage of fused silica optics, it is crucial to have a reliable measurement of the nonlinear refractive index. For this purpose, we developed a metrology bench based on the femtosecond Z-scan technology. In femtosecond regime, the refractive index is quite sensitive for different kind of mechanisms that may lead to change of the refractive index. Moreover, the maximum intensity that can be reached is limited by the damage fluence of the fused silica. The conflict of maximum intensity and minimum detectable energy is a big challenge. In this work, the intensity modulation component is used to overcome this problem.

In the femtosecond Z-scan system, spectra-Physics Spitfire Ace amplifier is used in order to provide 37fs pulse duration, the wavelength is 800nm and repeat frequency is adjustable from 4Hz to 1000Hz. A intensity modulation component consist of a attenuator, polarizer and half wave plate is used to tune finely the power of the laser beam. In order to eliminate the distorsion of the beam due to the power fluctuation, a reference arm is used to measure the Z-scan incident power exactly and account for beam fluctuations. The sample is placed on a motorized translation stage (range:0-200mm, resolution:0.1um) controlled by a computer and the photodiodes are connected to the computer via a digital dual channel optical meter. This setup could make the "Open-aperture " and "Closed-aperture" measurements simutanously and is automatized. In this work, we perform femtosecond laser Z-scan technique on fused silica which have a size of 5mm?5mm?3mm. After the sample scanning through the focus of the laser beam, the "open aperture Z-scan curve" and the "closed aperture Z-scan curve"---the transmittance changes with different sample positions on "open aperture" and "closed aperture" conditions are obtained. According to the Z-scan theory, the nonlinear refractive index of Fused silica is evaluated to be 9.4039?10-14esu for 800nm, 37fs pulse duration at I0=50GW/cm2 (I0 is simply the peak irradiance at the focus). Six measurements are performed on fused silica with same parameters to illustrate a relative standard deviation of 6.7‰.

Since the nonlinear refractive properties are related to the beam irradiance. Therefore, the nonlinear refractive properties of fused silica with different irradiances have been analyzed. As depicted in the open aperture measurement, we found the reverse phenomenon of the nonlinear absorption at 37fs pulse duration with irradiance increasing which can not appear in nanosecond regime. This could be explained by four-level system when the pulse duration is shorter than the lifetime of excited state. For closed aperture measurement, the peak-to-valley of the normalized transmittance increases with irradiance increasing. However, the distance between the peak and valley is always equal to a constant?Z=1.7z0 (z0 is the Rayleigh range). Because the change in total refractive index ?n is directly proportion to the beam irradiance, by performing the same calculation for different beam irradiance, we could plot a graph of ?n against I0. From the linear fitting, the nonlinear refractive index n2=8.6482±1.1923?10-14esu was obtained. This is a more accurate method to calculate because it is based on average measurement of several experiments rather than from a single experiment. This result shows a good agreement with A.J Taylor's work at 804nm using frequency-resolved optical gating technology (n2=8.5929±0.7969?10-14esu).

As a conclusion, we developed a very sensitive metrology setup based on the femtosecond Z-scan measurement that can measure nonlinear refractive index as small as fused silica and this is in femtosecond regime and close to the damage threshold of the sample. Besides, linear fitting of the ?n against different beam irradiance allow us to provide a more reliable value of the nonlinear refractive index. Moreover, this work also provides a potential application on the femtosecond time-resolved nonlinearities measurement to distinguish the mechanisms of nonlinear absorption and refraction in femtosecond regime.

10329-93, Session PS1

Neural network and optical fiber sensor as intelligent heart rate monitor

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This paper presents a design and fabrication of an intelligent fiber-optic sensor used for examining and monitoring heart rate activity. It is found in the literature that the use of fiber sensors as heart rate sensor is widely studied. However, the use of smart sensors based on artificial neural networks is very low. In this work, the sensor is a three fibers without cladding of about 1 cm, fed by laser light of 630 nm of wavelength. The sensing portions are mounted with a sensitive diaphragm to transfer the pulse pressure on the hand. The influenced light intensity will be detected by a three photodetectors as inputs into the neural network algorithm. The latter is a backpropagation net, which is a multi-layer structure with input and output layers. The prior training weights are stored in the net memory for the standard recorded normal heart rate signals. The sensors' heads work on the reflection intensity basis. The novelty here is that the sensor uses a pulse pressure and a neural network in an integrity approach. The results showed a significant output measurements of heart rate and counting with a plausible error rate.

10329-94, Session PS1

Development of hydrogen sensors based on fiber Bragg grating with palladium foil for the dissolved gas analysis in transformers

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Optical fiber sensors (OFS) are good candidates for hydrogen gas sensing in oil immersed electrical power equipment. They are usually intrinsically safe in combustible gases, comparably insensitive to electromagnetic noise and provide distributed, or quasi-distributed sensing, [1].

DGA is a common tool used for fault detection[2, 3] mainly applied to larger, expensive, power transformers. OFS provide an economical solution that could be integrated into smaller, inexpensive distribution transformers (including step up transformers for wind turbines).

Hydrogen is a dominant fault gas in the DGA and a strong indicator of transformer health [2, 3]. Palladium (Pd) is a common material used for H2 sensing[1] as hydrogen absorption leads to an expansion of the lattice structure. The gas solubility, and therefore expansion, increases with increasing partial pressure of hydrogen and decreasing temperature. This reversible expansion (outside material phase change regions) can be utilized to impart strain into a sensing element[4].

Fiber Bragg gratings (FBG) are a well-established OFS used for temperature and strain sensing. A safe, inexpensive, reliable and precise hydrogen sensor can be constructed using an FBG strain sensor to transduce the volumetric expansion of Pd (due to hydrogen absorption). FBG hydrogen OFS using this principle have been widely reported [5-12].

The reported hydrogen sensing OFS rely on 1. bonding a rigid Pd element to the FBG [11, 12], or 2. direct deposition of Pd film on fibers[5-10]. Responsivity has been observed to be higher, but response rate lower, with increasing Pd cross-section [11, 12]. Recent reports of some Pd based FBG hydrogen sensors for DGA use thin coatings[5, 6] to deliver rapid response rates. But DGA does not require rapid response rates due to the relatively slow production of dissolved hydrogen in the transformer oil. A response time of hours or even days would be acceptable as standard sampling intervals are annual, or monthly and seldom weekly or shorter[13].It is more important to have relatively accurate indication

of the hydrogen concentration. Therefore, the response/resolution of the sensor is the main optimization parameter.

In this paper we improve the sensitivity of the Pd based OFS through the use of greater cross-section metal foils and improved strain transfer to the fibers. This paper reports on the development, and evaluation of fiber optic hydrogen sensors based on FBG and an experimental measurement system for long term testing of fiber optic gas sensors in oil. Two types of palladium metal sensors were manufactured using modified palladium foil with 20 and 100?m thickness. The sensors were tested in transformer oil at 90°C and over a hydrogen concentration range from 0- 2000 ppm.

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10329-95, Session PS1

Development of a low-cost, 11 μm spectral domain optical coherence tomography surface profilometry prototype

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A spectral domain Optical Coherence Tomography (OCT) surface profilometry prototype has been developed for the purpose of surface metrology of optical elements. The prototype consists of a light source, spectral interferometer, sample fixture and software currently running on Microsoft® Windows platforms. In this system, a broadband light emitting diode beam is focused into a Michelson-type interferometer with a plane mirror as its sample fixture. At the interferometer output, spectral interferograms of broadband sources were measured using a Czerny-Turner mount monochromator with a 2048-element complementary metal oxide semiconductor linear array as the detector. The software performs importation and interpolation of the spectra to pre-condition the data for image computation. One dimensional axial OCT images were computed by Fourier transformation of the measured spectra. A first reflection surface profilometry (FRSP) algorithm was then formulated to perform imaging of step-function-surfaced samples. The algorithm re-constructs two dimensional colour-scaled FRSP B-scans by concatenation of 21 and 13 axial scans to form a 10 mm and 3.0 mm slice length respectively. Measured spectral interferograms, computed interference fringe signals and depth reflectivity profiles were comparable to simulations and correlated to displacements of a single reflector linearly translated about the arm null-mismatch point. Surface profile images of a double-step-function-surfaced sample, embedded with inclination and crack detail were plotted with an axial resolution of 10 μm. The surface shape, defects and misalignment relative to the incident beam were detected to the order of a micron, confirming high resolution of the developed system as compared to electro-mechanical surface profilometry techniques.

10329-96, Session PS1

Gas monitoring onboard ISS using FTIR spectroscopy

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In the confined, enclosed environment of a spacecraft, the air quality must be monitored continuously in order to safeguard the crew's health. The currently performed standard gas monitoring approach by sending gas samples for analysis to Earth is cumbersome, has an unrealistic long delay between taking the sample and receiving analysis results and is not possible on future missions, e.g. to Moon or Mars.

For this reason, OHB was awarded to build the ANITA2 (Analysing Interferometer for Ambient Air) technology demonstrator for trace gas monitoring onboard the International Space Station (ISS) by the European Space Agency (ESA). The operation of ANITA is based on the Fourier Transform Infrared (FTIR) technology, which is in turn based on a Michelson interferometer. The measuring principle uses gas-specific absorption characteristics in the infrared range for detection and quantification of trace gases. The gas analysis software was developed and is continuously improved by the Norwegian partner SINTEF. It successively proved to monitor concentrations of 33 trace gas simultaneously.

In comparison to the predecessor ANITA1, which operated onboard ISS in 2007 and 2008, the spectrometer which is currently being build, features significant reductions in mass, volume and power consumption, as well as an improved gas analysis sensitivity.

An important part of this instrument is a laser source based on a semiconductor laser, whose beam is entering the interferometer; enabling interferometric measurement of the optical path difference in the two Michelson interferometer arms. The requirements for the Laser wavelength are very high, so that self-calibration methods will be implemented to compensate ageing effects, having an impact on the Laser wavelength.

The gas analysis sensitivity depends on the strength and spectral position of the characteristic signatures of each specific gas, but also on the interaction length of the radiation with the gas. In order to gain a high sensitivity, ANITA2 features a 10 meters gas cell, which is achieved by reflecting the radiation back and forth 39 times inside the gas cell, having a mechanical length of 250 mm.

The optomechanical components are designed in a robust manner, to withstand shock and vibration loads at launch, which is verified by simulations and experiments. The moving interferometer parts are critical components for recording high-quality spectra and are developed in cooperation with Bruker Optics GmbH. The movement needs to be performed very precisely and smoothly. To enable this, these parts are designed as a pendulum with the center of mass close to the rotation axis, so that impacts from external influences such as vibrations are minimized. In addition, the pendulum has bearings without wear or friction, which eases the control of the interferometer and makes ANITA2

suited for long-lasting, maintenance free operations.

Although the first application of ANITA is monitoring cabin air, it is very well suited for measuring gas concentrations in industrial environments, e.g. for process and quality monitoring. Due to the optical measurement principle, no consumables are required and measurements can be performed at very high repetition rates.

The paper/talk describes the optomechanical elements of ANITA2, achievements in optical and mechanical stability and presents first results of the newly set-up instrument.

10329-97, Session PS1

Experimental light scattering by small particles: system design and calibration

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We describe a setup for precise multi-angular measurements of light scattered by mm- to µm-sized samples. We present a calibration procedure that ensures accurate measurements. Calibration is done using a spherical sample (d = 5.556 mm, n = 1.5) fixed on a static holder. The ultimate goal of the project is to allow accurate multi-wavelength measurements (the full Mueller matrix) of single-particle samples which are levitated ultrasonically.

The system comprises a tunable multimode Argon-krypton laser, with 12 wavelengths ranging from 465 to 676 nm, a linear polariser, a reference photomultiplier tube (PMT) monitoring beam intensity, and several PMTs mounted radially towards the sample at an adjustable radius. The current 150 mm radius allows measuring all azimuthal angles except for ±4° around the backward scattering direction. The measurement angle is controlled by a motor-driven rotational stage with an accuracy of 15'.

10329-98, Session PS1

Light section measurement to quantify the laser light deflection in an inhomogeneous refractive index field

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In the manufacturing process of Tailored Forming components, the inline-inspection of the joining zone directly after each single process step (joining, forming, tempering, finishing) can yield advantages – such as early error detection, real-time process control and thus a reduction of production costs. Since measuring times need to be synchronized with the production chain, there is no time to cool down the component in between two hot forming processes.

Therefore the chosen inspection method needs to comply with special requirements. On the one hand, the method needs to be non-tactile due to the heat of the measurement object. On the other hand, the object's areal surface texture needs to be captured rapidly to realize a fast inline inspection. These requirements are only matched by an optical metrology system.

Additional challenges arise due to the high temperature of the Tailored Forming components: the ambient air is heated up and results in a density gradient field around the component which again causes an inhomogeneous optical refractive index field. A ray of light traversing such a field is deflected towards the more dense air layers, resulting in a deviation from the linear path of the ray.

The described effect applies to all kinds of optical triangulation techniques, such as laser light section, fringe pattern projection and stereo-photogrammetry. It decreases the reachable accuracy of the optical sensor. In dependency of the required measurement precision, a compensation or restriction of the described deflection is indispensable.

We present a measurement setup based on the laser light section method to quantify the measurement accuracy loss induced by the convectional heat flow from a cylindrical measurement dummy. The dummy consists of a stainless steel pipe uniformly heated by an inlaying heating rod. The ceramic rod can realize heating temperatures up to 1000 °C – matching the temperature of rolled specimen directly after the forming process. A monochrome camera with a 2048x2048 pixel-matrix is used, optimized for extreme environments and fluctuating lighting conditions.

In order to achieve the highest possible contrast on the red glowing dummy, a high power 20mW green laser with cylindrical optic has been implemented. To separate the measurement signal from incoming radiation induced by self-emission of the hot specimen, a bandpass filter for green light (523nm) and a NIR filter are used.

To attain a direct validation of our measurement results, measurements are performed with and without the influence of the inhomogeneous refractive index field induced by the convective heat flow of the dummy.

For this purpose, a controlled reduction of the convective heat flow above the dummy has been achieved by imposing a slow, external laminar flow sideways. The laminar flow is realized by a double-pipe system with a flow straightener and two ventilators.

10329-99, Session PS1

Digital holographic inspection for drying processes of paint films and ink dots

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The techniques to investigate drying processes of paint and ink dot using digital holography is presented. The proposed technique based on holographic interferometry can analyze local variation of paint films in drying process by using a phase change between two subsequent reconstructed complex amplitudes of the reflected or transmitted light from the film. The technique has been applied to assess the drying process of commercial paint using the temporal variation of films.

For monitoring the drying processes of commercial paints, phase-shifting digital holography was applied and data acquisition was conducted with a constant interval T. In the holographic system, the diffusely reflected laser beam from the paint film was recorded using phase-shifting digital holography.

To follow the temporal variation of the paint film, the subsequent reconstructed complex amplitude of object wave was obtained with the interval T. After the reconstruction of subsequent holograms, the phase difference between two adjacent reconstructed phases was calculated after the speckle noise reduction. To evaluate the temporal variation, the standard deviation ?t of phase difference distribution between the successive reconstructed phases was calculated. For evaluation of the dryness of paint, the time history of the standard deviation in the phase-difference has been used. By investigating the temporal variation of the standard deviation, it was possible to evaluate the drying process of commercial paints up to tack free state.

For monitoring an ink dot of a few hundred micrometer in size, a digital holographic microscope has been applied. In the experiment, a water-based magenta ink was used and applied to an OHP (Over-head projector)-sheet by an ink-jet nozzle. The OHP-sheet was pasted on a glass plate having optically flat surfaces and inserted in the object optical path of the Mach-Zehnder interferometer. The light transmitted through the ink dot was expanded by an objective lens having the magnification of 20 and collimated by a lens. The transmitted wave became an object wave recorded with off-axis configuration. The off-axis angle for the reference wave was introduced by tilting the mirror.

The hologram was captured by a monochromatic CMOS camera having 1024?1024 pixels with each pixel size of 5.2?5.2 micrometer. The image data was sent to a PC via USB2.0 interface. The data acquisition was conducted with the interval of T = 0.25 s for a period of 2000 s. Most of the optical system was set in a closed box to reduce environmental disturbances as described previously.

The ink dot having a diameter of 0.28 mm was used for a sample. By expanding the time interval for the phase difference calculation, it is possible to enhance the detectable variation in the film. In addition, the integration of phase difference within a relatively long time interval was introduced to analyze the activities for making the ring-like pattern seen in the picture of the ink dot taken after completely dried. By expanding the time interval for calculating the standard deviation of the phase-difference in the ink dot area, it was possible to follow the small variation occurring in the ink dot surface, which was difficult to detect using the time intervals shorter than T = 1.0 s. In addition, the integration of phase difference over the period of 100 s enabled us to investigate the process for generating the ring-like pattern observed in the dried ink dot. These techniques seem to be very useful especially for both the drying stage in the falling rate period and the analysis of convection current in the paint films.

This paper describes the outline of these holographic techniques and shows some experimental results for commercially available paint and ink.

10329-100, Session PS1

Development of optical-electronic autocollimation sensor for industrial inspection with an increased measurement range

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During the installation and operation of large-scale objects, need to use an angle measurement devices, which allow to control the deformation of these objects. For example, such measurements are required to create high-speed railways, radio and telescopes coordinate stands charged particle accelerators. The reasons for such deformations are own weight structures, as well as external weather conditions. Optical-electronic autocollimation angle measurement systems are effective for such measurements. Their advantage is absence of electrical connection with the controlled objecton with small-sized reflector as a flat mirror. After considering the optical-electronic autocollimator sensors on the market, can conclude that these autocollimator sensors have insufficient measurement range (up to 5 meters), one of the reasons of the limited distance is error due to vignetting of the reflected beam, because with increase in the measurement range, accuracy of the measurement is reduced, because there is no means of compensating beam vignetting.

For the solution of this problem, effectively use optoelectronic sensors with autocollimation schemes. The autocollimation system allows measuring a mirror turning angle as sensitive element in a point of angular deformation with a potential accuracy up to 0.05 arc. sec. Actually the error can exceed considerably the specified value because of existence of systematic error, one of which main components is the error owing to vignetting of a working beam. The reason of vignetting error is changing of irradiance distribution of the image on the autocollimator analyzer owing to cutting of a bundle of optical beams at a mirror deviation in case of angular deformation.

The component of systematic error due to vignetting of the beam can be eliminated in case of existence of the analytical description of changes in irradiance distribution of the analyzed image. Because of the complexity of the analytical description of the vignetting processes proposes the use of computer models. The modelling is based on approximation according to which each point of the finite image of a source of radiation essentially is the focused area of intersection of the entrance pupil and the elementary beam reflected by a mirror, and its energy is proportional to integral (the general energy) on this area.

As this systematic measurement error unacceptably large (30 arcsecs), there is a need to compensate for this error. The algorithm compensate for systematic error consists of four steps: 1) definition of the formed image radius 2) measurement the value of displacement the energy center of image after a mirror rotation 3) calculation the ratio of the displacement and the radius then determined the values of relative and absolute measurement errors 4) the value of the measured angle is calculated after determination of the refined image shift value.

After using the compensation algorithm, the error due to the vignetting amounts to a negligible value 0.4 arcsecs.

Using a computer analytical modelling of image processing was investigated systematic error due to vignetting. The designed algorithm compensation systematic error due to vignetting allows increasing the measurement range of the autocollimation sensor up to several tens of meters.

10329-101, Session PS1

Nondestructive inspection method of vertical semiconductor devices using multilayer optics analysis

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There have been intense research and development efforts on three-dimensional vertical semiconductor devices in recent years. Compared to traditional two-dimensional devices, three-dimensional devices can achieve higher densities, smaller footprints, and lower power consumption. As the number of layers increases, however, the inspection of such vertical devices is becoming more difficult. The widely used electron microscopy techniques, such as scanning electron microscopy (SEM), is a destructive inspection method and cannot be used for total inspection in the manufacturing processes.

In fact, there is a high structural similarity between vertical semiconductor devices and multi-layer thin-film coated dielectric mirrors. Therefore, we can apply well-developed analysis methods for such multi-layer thin-film optics to vertical semiconductor devices. In this work, we show that the measurement of spectral reflectance enables the detection of <10 nm change in a single layer inside 80 layer vertical semiconductor devices.

The vertical semiconductor devices that we target to inspect in this work have 80 quasi-periodic (between high and low refractive indices) layers on a silicon substrate, where each layer thickness lies in the range of 40 nm to 120 nm. Exact layer thickness is characterized by the SEM, and the refractive indices and absorption coefficients of high- and low-index materials are also measured from 200 nm to 800 nm.

Once these characteristics are known, we can calculate the spectral characteristics such as reflectance using a thin-film mirror design software. Note that we used OptiLayer software for calculating spectral characteristics in this work. The spectral reflectance measurement from 200 nm to 800 nm using a spectrophotometer (Lambda 1050, PerkinElmer) shows a fairly good agreement with the simulated reflectance result.

Then we first examined whether we can detect a simple defect case (for example, a single layer thicker or thinner than the targeted device design) using the reflectance spectrum analysis. With simulations, we found that the wavelength shift in reflectance peaks in the 500 nm – 600 nm range is the most sensitive and reliable parameter that reflects the layer thickness changes. For example, when the thickness of a high-index layer is increased or decreased by 10 nm, the reflectance peaks are shifted by ~2 nm in wavelength [see Fig. 1]. Considering commercial spectrophotometers have a wavelength measurement accuracy better than 1 nm, we can expect to detect sub-10-nm-level manufacturing error in a single layer by monitoring the reflectance spectrum.

As a demonstration experiment, we tested two samples with defects: one with 20-nm thicker 18th layer (high index) and the other with 20-nm thicker 38th layer (high index). As expected, due to the 20-nm thicker high-index layer, the measured reflectance peaks in the 500 nm – 600 nm range are red-shifted by ~4 nm compared to the normal sample. This reflectance peak wavelength measurement result also agrees well (within ±0.5 nm error) with the predicted peak shifts using OptiLayer simulation [see Fig. 2]. Note that we can use the reflectance amplitude information to identify the approximate location of the defect layer as well. In addition to the spectral reflectance measurement, high-resolution and broadband group-delay dispersion (GDD) measurement (with <10 fs^2 error) can further improve the accuracy in identifying the location and amount of manufacturing errors.

10329-102, Session PS1

Influence of sampling parameters on spatial variations of reconstruction accuracy in holographic tomography

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Holographic tomography (HT) is a dynamically evolving technique, which allows noninvasive 3D imaging of transparent microobjects. In this method, digital holographic microscopy is used to acquire multiple complex fields that are collected at various viewing angles of a sample. This is usually achieved either by rotating a sample (the object rotation configuration – ORC) or altering the illumination direction (the illumination scanning configuration – ISC). Then, the acquired complex waves are processed with a tomographic reconstruction algorithm, which results in a quantitative, 3D reconstruction of refractive index distribution in a sample. The outlined 3D imaging technique has found numerous application in many areas of industry and science, most importantly, in biomedicine for noninvasive analysis of cell morphology [1,2] and in fiber optics research [3,4].

During the recent decade we have witnessed great progress in the field of HT. The advances in the experimental setups include among others speeding up the data acquisition process, applying sophisticated scenarios of the sample views alternation [6-8] and proposing new systems for handling a sample [9,10]. A substantial progress has been also made in the numerical part of HT, e.g. with accurate diffraction models for tomographic reconstructions [11,12], new methods for numerical correction of the rotation errors in ORC [13,14] and solutions to the limited-angle problem of ISC [15-17]. The progress happening now, and not yet finished, enables application of HT to more demanding samples and achieving better measurement parameters such as improved resolution, accuracy and larger reconstruction volume. This advancement requires us to look further for newly emerging challenges, which in the near future of HT may become of crucial importance.

The recent works [10-12] brought the attention to the problem of spatially variant accuracy of the HT reconstructions, which is higher in the central region of the reconstructed volume and decreases for the off-center areas. In the works [10-12] this disadvantageous effect was attributed mainly to the limitation of the state-of-the-art tomographic reconstruction algorithms, such as filtered backpropagation [18] and direct inversion algorithm [19], which apply an approximated model of diffraction. In [10-12], as a solution, extended depth of focus filtered backpropagation algorithm was proposed, which was proved to enhance the reconstruction accuracy in the off-center regions. In the present study we continue investigating the issue of spatially variant quality of the HT reconstructions. However, we are now focusing on the discrete nature of the tomographic data as a source of spatially-variant accuracy of the reconstructed images. In our analysis, two key parameters are considered: sampling rate and size of the complex wave data. Moreover, the study also considers nonuniform distribution of holographic data in the 3D Fourier spectrum of the reconstructed object. In our work, we investigate both basic tomographic configurations: ORC and ISC as well as the recently proposed hybrid tomographic system [8] combing object rotation and off-axis illumination. The analysis, basing on the Wigner distribution [20] and the Ewald sphere approach [21], allows us to quantitatively characterize spatially-depended resolution and aliasing errors related to the sampling parameters.

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10329-103, Session PS1

High-precision surface measurement of long-radius concave sphere with diverging transmission

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With the development of optical technology, it demands higher and higher of optical surface accuracy . Interferometer measurement of long radius concave sphere interferometer using common convergent transmission requires long optical cavity. The effect of air on the measurement results is proportional to the square root of the cavity length, therefore, a divergent transmission was used in our measurement. The RMS error of system and reference surface is 600nm and 3nm respectively, which meets our design requirements. Repeatability of surface shape measurement reaches sub-nanometer.

10329-104, Session PS1

Lateral scan position correction in ptychography

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For high resolution imaging, X-rays and electron beams are being used. However, for such a small wavelength, imaging with lenses becomes difficult as lenses must have very low aberrations and a stable set-up. Ptychography is a lens-less imaging technique which uses intensity information of the multiple diffraction patterns in the far field. These multiple far field diffraction patterns are generated by an unknown object which is scanned by a localized illuminated spot (probe).

Accurate knowledge of initial parameters is important for a good reconstruction of the object. Robustness of the Ptychography Iterative Engine (PIE) has already been studied for inaccurately known initial parameters, where the success of the algorithm was found to be sensitive to the accuracy of the estimate of lateral positions of the probe. A small error in lateral positions of the probe can lead to the stagnation of the algorithm at wrong solution. There are a few existing modified PIE algorithms which overcome this problem. These methods relax the requirement for the experimental set-up.

We have come up with a new method to correct the lateral position of the probe with respect to the object. Simulations for different values of feedback parameter are performed to know the effect of feedback parameter. To know the maximum allowable initial lateral position error and to investigate the robustness of this method against different level of noise, simulations are performed. It has given satisfying results for the object reconstruction. This method has achieved a very low lateral position error and has given an accuracy of sub-pixel.

It has been observed that this method is more straightforward to implement and converges faster than other existing algorithms while achieving comparable accuracy for the lateral position.

10329-105, Session PS1

Holographic prism based on photo-thermo-refractive glass

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New application of photo-thermo-refractive glass (PTR) named “holographic prism” is presented. This element provides multivalued measure of plane-angle and allows measurements of current rotation angle of rocking platform. A conventional plane-angle measure is a regular fused silica prism, where the angles are set by the normals to prism faces. Each normal is implemented physically by the autocollimator axis when the cross hairs in its focal plane are aligned with the image arising because of collimated beam reflection from the prism face. The angle between two normals is reproduced by rotating the prism around an axis perpendicular to the autocollimator measuring plane. In the holographic prism angles between directions are set by the holograms which create fan of signal beams. Initially, such prism was developed and realized based on additively colored calcium fluoride crystals with color centers. This kind of prism creates several signal beams which are equal to the reflections from facets of the conventional silica prism. But this kind of holographic media has several disadvantages which lowers sensitivity and confine the. possibilities of such measure. Implementation of PTR glass as a holographic medium for this device brought us several advantages and new features. First it leads to decrease in overall size of the prism that positively affects the identification process of the beam’s cross-point. Thus, it increases sensitivity and accuracy of the measure. Second, greater value of the refractive index change in PTR glass in comparison with calcium fluoride crystal allows us to increase quantity of the recorded reference beams for the measure which leads to sensitivity increase. Since the process of recording in PTR glass is much easier than that in fluorite we implemented several new modifications of the prism. Original prism created the fan of signal beams laying in one plane. In our work, we updated this functionality to several fans which are orthogonal to each other or even have some predefined angle between their planes. In addition, we included beam identification based on the difference in diffraction efficiencies of individual beams within the fan. This identification eases the process of signal analysis and monitoring of the device. Plane-angle measure excludes the effect of platform orbital motion and provides highly accurate measurement. We believe that the use of PTR glass will make the design of such measuring element more flexible and suitable for wider range of plane-angle measurements.

10329-106, Session PS1

Component-level test of molded freeform optics for LED beam shaping using experimental ray tracing

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Due to the high demand of LED light sources, the need to modify their radiation pattern to meet specific application requirements has also increased. This is mostly achieved by using molded secondary optics, which are composed of a combination of several aspherical and freeform surfaces. Unfortunately, the manufacturers of these secondary optics only provide output information at system level, making impossible to independently characterize the secondary optic in order to determine the sources of erroneous results. For this reason, it is necessary to perform a component-level verification leading to the validation of the correctness of the produced secondary optic independently of the light source.

To understand why traditional inspection methods fail, it is necessary to take into account that not only errors due to irregularities on the lens surface like pores, glass indentations or scratches affect the performance of the lens, but also differences in refractive index appear after the compression during fabrication process. These internal alterations are generally produced during the cooling stage and their effect over the performance of the lens are not possible to be measured using tactile techniques. Additionally, the small size of the lens and the freeform characteristics of its surface introduce additional difficulties to perform its validation.

In this work, the component-level test is done by obtaining the ray mapping function (RMF) which describes the deflection of the light beam as a function of the input angle. To obtain the RMF, firstly a collimated light source is held fix and the lens is rotated. Thus, a virtual point source is created and subsequently by using experimental ray tracing it is possible to determine the ray slopes, which are used to the retrieve the RMF. Under the assumption that the optical system under analysis is lossless and considering the principle of energy conservation, it is possible under specific conditions to use this new approach to obtain the output of the complete set, composed of light source plus secondary optic. Thus, for different LED models, combining their radiation pattern with the RMF allow us to obtain the resultant modified radiation pattern. By following this procedure, the correct functionality of the secondary optic is verified independently of the light source. This method brings the opportunity to the final product manufacturer of defining fail regions over the desired resultant output radiation pattern as a combination of different LED sources and then verify if the secondary optic fulfill the requirements.

10329-107, Session PS1

Classification and separation of particles in size and speed for inline particle measurement in industrial ion implantation systems

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The technical realizations of particle measurement equipment for industrial applications are typically based on optical scattering effects. The principle of the measurement procedure is a detection of scattered light from the surface of a particle. The initial laser radiation is typically transmitted over the measurement array and afterwards, will be absorbed/dissipated on the end of the detection array. Under standard pressure conditions, particles are transported by the gas/air stream. The speed of the particles is therefore predefined and the detection of the particles can be realized in combination with estimation of the size of the particle. The application of the described measurement method in pressure conditions which are typical for a PVD/ion-implanter will cause problems with the speed and size separation. The motion of particles is induced by a randomized process. The typical detection of scattered light is basically the measurement of a changing in direction of incident radiation. In the following work, the numerical methods and algorithmic implementation for solving the described problems are presented. Different signal-detection approaches were proposed, compared and evaluated. The fixing points for the evaluation of different algorithms were a linear and/or parallel optimization and robustness of the algorithm. With the measurement setup described in the paper, the estimation of the size of particle was analyzed and, based on the signal detection algorithms, the size estimation algorithm was implemented. The implementation of a second routine was also realized in combination with linear and/or parallel optimization. The dynamic detection and analysis was a necessary requirement for the planned wide array of applications of the system in vacuum. The issues for the coordination of dynamic detection, correction of contamination and self-calibration of the measurement system are analyzed. The realization of controlling loops was implemented to solve the contamination problems by using the described measurement equipment in the environment of the PVD/Implantation-processes. An adapted signal detection technique was realized based on the analysis of these described implementations and technical problems. This technique builds on the combination of

high-speed and low-speed digitalization. The evaluation of acquired data was implemented on a FPGA. After optimizing the algorithms, the implementation of the subroutines described above was converted in FPGA form. The necessary evaluation model for the size and speed classification was realized based on the information about the geometry of the initial laser beam and measurement array. Allowance of this model was prepared, analyzed and summarized with regards to the detection cases and detection problems. This information was applied for optimization of the mechanical and optical structure of developed measurement equipment. On other side, the analysis of detectable cases directly depends on the particle size and geometry distribution. Classical scattering methods are based on the radial symmetrical partial model. The results of a randomized geometry of the detection objects have been analyzed and the typical shapes of the measurable signal were generated. Based on these effects, the detection method was modified. Therefore, the realized measurement procedure includes the self-calibration and compensation of contamination effects which build a robust routine for a wide range of applications for the described measurement system.

10329-108, Session PS1

Characterization of batwing effects in precision low-coherence interferometry using broadband light sources

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The manufacturing of power semiconductors, MEMS and thin-film structures does benefit from use optical metrology. Especially the measurements of surface topographies in the nanometer-regime which can be performed along the production line of wafers are of great interest. In order to fulfil all demands regarding accuracy, appropriate in-line ready and integrated characterization methods are required. One of the key requirements is the ability to resolve structures of high aspect-ratios and precise edges which were produced by etching or lithographic processes.

Within this work an alternative approach based on a low coherence interferometer is presented which is designed to comply with these requirements. Special emphasizes is placed on the characterization of so called batwing effects, which influence the measurement data on sharp edges and slopes. In contrast to other works, this examination focuses on the influence of very broadband light sources such as a supercontinuum white-light source (380-1100 nm) and a laser-driven plasma light source (200 - 1100 nm) on the formation of these effects. The interferometer is equipped with one of these broadband light sources and defined dispersion over the given spectral range. The spectral width of the light sources in combination with the dispersive element defines the possible measurement range and resolution. Instead of detecting the signals only in a one-dimensional manner, a two-dimensional spectrometer on the basis of a high resolution CMOS camera is set-up. Through the introduction of defined dispersion, a controlled phase variation in the spectral domain is existent. This phase variation is dependent on the optical path difference between both arms and can therefore be used as a measure for the height of a structure which is present in one arm.

Due to the known dispersion characteristics, it becomes possible to calculate the surface profile with nm-precision from the phase-varied spectral data. In the two-dimensional approach the surface profile is encoded in one dimension as spectral modulations (z-coordinate) while the second dimension holds information about the spatial distribution of the profile (y-coordinate). When gathering spectral information at sharp edges the data gets influenced by the diffraction at these edges which results in error in the determination of the height difference as well as of the slope.

The work describes the calculation of theoretical resolution as well as the experimental setup and its results. In different experiments with both light sources it is evaluated how batwing effects develop when using different spectral widths (FWHM 10 – 200 nm and full spectrum) at different central wavelengths. The experiments where done on a Si-based height standard of 100 nm step height. Apart from the examination of the edge effects on a single height step it is also investigated how the effects form when measuring multiple successive steps on a 100 nm deep, 250 μm wide step pattern.

In conclusion, an alternative image acquisition strategy is developed where multiple images are combined under the usage of different spectral ranges. This enables the reduction of edge effects at the same time with keeping the necessary measurement range and resolution.

10329-109, Session PS1

In-line full-field optical 3D surface inspection and metrology for mass production system

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Contemporary production systems of mechanical precision components show challenges as increased complexity with a reduction of tolerances to sub microns when yield losses must be mastered as wel. The goal is better process control that is often realized by means of feedback control. Special attention is required for inspection often limits the overall system throughput and sensor output is required to have the shortest delay after the production process to allow for stable feedback on tights error budgets. The developed sensor technology leads to a future generation of instruments with specifications that are unknown before in inline inspection. Sub second surface metrology images of 300x300 pixels with nanometer height resolution. Millimeter height range. Highly robust to vibrations and ambient light. Up to 3 hertz repetition rate. High dynamic range, allowing for metrology of transparent, black and high reflective objects in a single shot. The novel technology is based on the well-known full field time domain white light interferometry that enables to demodulate 250x103 fringes per second, for each pixel, allowing for a maximum axial scan rate of 20mm/sec while maintaining nanometer resolution.

The project challenge is a demonstration of system capability in a relevant industrial environment. In this case by setting up a production line comprising of a 50ton progressive die stamping press that is required to produce micrometer accurate metal parts at rate of 2 products per second. (vibration spectrum to be included) The OCT metrology system is setup directly next to the production equipment as to have minimal time delay in the control loop and is therefore directly exposed to vibrations created by the stamping machine. This to endure for 15 months.

Careful analysis of the error budget and error sources led to a system design which is a combination of optics and mechatronics that is capable to withstand these circumstances and still capable of delivering sub micrometer accuracy. Care has been taken to have motion-, thermal- and optical axis to be aligned allowing for a robust and scalable design.

Transfer functions: (optics)

OSnoise = f(Image quality, optics stability)

OInoise = f(Product, angle, pixel size)

Transfer functions: (camera)

Cnoise = f(Signal, triggering)

Transfer functions: (mechatronics)

Mnoise = f(Disturbances, Bandwidth, Parasitic motions)

Total Uncertainty = sqrt(OSnoise2 + Cnoise2 + Mnoise2 + OInoise2)

Gage R&R repeatability test show a measurement system performance with a standard deviation of 50nm for the measurement instrument. Different product where created with min-max experiments. Gage R&R analysis shows that the measurement error is significant smaller than the product defects. (graphs to be shown) Therefore the sensor is suitable to be used to measure and qualify the products. For traceability to standards a method has been devised with certified test objects that calibrate both the optical magnification and the axial scale of the measurement system.

Future development will allow for more pixels (1000x1000) and more accurate measurement under rough conditions. Applications of this technology are to be found in many fields, among which are inspection and metrology of composite fibre reinforced plastics, mass manufacturing of optical lenses, semiconductor die and via defect inspection and alignment of complex optical systems as space telescopes.

10329-110, Session PS1

Compact DPSS-laser source for LIBS analysis of steel

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The chemical analysis of cast steel products is important in the steel production process. Typically the analysis is performed discontinuously in dedicated laboratories using arc/spark emission spectrometers. LIBS-technology holds the potential for on-site real-time measurements of steel products. However for a mobile and robust LIBS measurement system, an adequate small and ruggedized laser source is a key-requirement. In this contribution, we will present tests with our novel and compact high power laser source, which, initially, was developed for ignition applications.

The CTR HiPoLas® laser is a diode pumped Nd:YAG solid-state laser with a passive Cr:YAG Q-switch. The active laser medium, the Q-switch, and the cavity mirrors are all integrated in a monolithic, optically bonded crystal which is driven in a side pumped configuration using a pump ring with several high power diodes. This enables an extremely robust system with dimensions of less than 10 cm? for the laserhead. The laser generates 2.5 ns-pulses with 30 mJ and a collimated beam diameter of 2.5 mm. A power driver unit enables operation of the laser at a maximum continuous repetition rate of about 30 Hz and a burst rate of up to 100 Hz. Laser stability was proven among others by tests on piston engines and for the ignition of satellite thrusters. While initially developed for laser ignition, the relevant optical parameters should be perfectly suitable for LIBS spectroscopy.

This was experimentally verified for the analysis of steel. Samples, for which the chemical composition was known from spark emission spectroscopy, were provided by SMS Concast. In the experiment presented here, we focused on two samples, with different Al content. (The Al contents of the two samples were 0.001% and 0.6%, respectively). The laser beam was focused at the sample target and the emitted radiation was collected and measured with a commercial fiber based spectrometer with a resolution of 0.15 nm.

The results clearly showed that plasma generation on the surface of steel samples is easily possible and confirmed the feasibility of quantitative LIBS measurements with our novel laser source by easy means. Most importantly, the spectra we obtained were identical to spectra reported for standard LIBS set-ups, which indicates, that similar plasma conditions were obtained.

More recently we also performed tests using an Echelle spectrometer and a set-up purged with nitrogen. The high resolution achieved in these experiments enables quantitative multi-element analysis for a number of additional elements. In particular, purging with nitrogen allowed measuring the carbon content using a line at 193nm. Quantitative evaluation of these measurements is still ongoing and also these results will be presented.

The results show that the laser with its current optical output parameters is very well suited for LIBS real-time measurements of steel products, even though it was developed for ignition purposes. We believe that the miniaturized laser presented here will enable very compact and robust portable high-performance LIBS systems.

10329-111, Session PS1

Defect detection in translucent materials by thermal stressing using lensless Fourier transform digital holography

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Increase in industrialization gave rise to the need of locating and quantifying defects in the final product as well as in its individual components. The task of measuring defects can be performed either by employing a non contact method (NDT) or by the conventional contact methods. NDT works on the principle of measurement without disturbing the functionality of the object. Both these methods find their utility in industry as each technique offers advantages over the other, for certain kind of applications. But the requirement of having non contact measurements of various physical parameters is fulfilled by using NDT techniques. Out of many NDT techniques, optical techniques stand out as they have improved the measuring capability by providing non-contact, sensitive and accurate ways of achieving precise values specially in case of transparent as well as translucent mediums.

Phase objects such as gaseous systems, temperature distributions produced by flames, plasmas, objects under thermal stress, biological specimen etc. produce a spatial variation in the phase of the wavefront passing through them due to the refractive index variations. Factors such as density, temperature, impurity distribution etc affect the refractive index distribution of a material. So any discontinuity in the material can be imaged or detected by mapping the refractive index of a translucent object. Many optical methods like the shadow, schlieren and interferometric technique are used to map the refractive index profile of phase objects. While the other two techniques give the derivatives of the refractive index, the interferometric technique provides its direct value.

Holography is an interferometric imaging technique for recording and reconstructing the amplitude and phase of a wave field, where a hologram is the record of interference pattern produced by the wave field passing through or scattered by the object under study (object or signal beam) and a coherent background (reference beam, usually a plane wave front). Conventionally holograms are recorded on photographic plates but in case of digital holography, they can also be recorded using CCD/CMOS chips, which are collection (array) of large number semiconductor detectors.

Digital holography is an interferometric imaging technique in which digitally recorded holograms can be reconstructed numerically using scalar diffraction theory yielding the complex amplitude of the object wavefront. It is one of the most versatile tools for the whole field imaging of wavefronts as both the phase and amplitude information of the object can be obtained from the complex amplitude. Thus it finds immense potential applications ranging from shape measurement to microscopy. Phase objects when exposed to visible radiation do not show any substantial change in the amplitude of the interacting wavefront and hence are difficult to image. So it becomes necessary to image their phase that in turn gives information regarding refractive index distribution across them. The fact that a defect or any form of optical inhomogeneity will show discontinuity in the refractive index distributions on change in temperature can be used to detect defects. In order to detect and map such defects, the object is subjected to thermal stress which brings about a variation in the refractive index distribution. The wavefront passing through such a region of non-uniformity of refractive index will carry the information about it as a spatially varying phase and thus will lead to defect detection in phase objects. Here we describe our efforts in the development of lens less Fourier transform digital holographic interferometric techniques for imaging of spatio-temporally evolving refractive index distributions under thermal stressing and its application in defect detection.

10329-112, Session PS1

Design and fabrication of microsilica sphere cavity force sensor based on hybrid Fabry Perot interferometer

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In recent years, demands for force measurement especially in medical application have been growing dramatically. Force information can help the diagnostic and prognostic procedures to be more accurate and more reliable. For some especial medical applications, there is a need to focus on parameters like immunity to electromagnetic interference, small size and chemically inert structure to be able to measure force. To address this issue, Optical Fiber Force Sensors (OFFSs) were utilized in some applications such as eye surgery , dental application , compression therapy , and so on, which all were relied upon in Fiber Bragg Grating (FBG)

In this work, we have developed a novel OFFS based on a hybrid Fabry-Perot Interferometer (HFPI) integrated with a micro silica sphere cavity (MSSC). The interferometric spectrum of the HFPI was fromed based on interference between reflected light beams from SMF cleaved end and a MSSC, which was fabricated on tip of a silica capillary tube. To bind the SMF to the MSSC a PDMS layer was utilized. In this configuration, PDMS has been considered as a simple elastic material especially for small loads in mechanical model . In addition, stiffness of PDMS is a function of curing parameters, weight ratio of prepolymer to hardener, and aging . Consequently, different force ranges can be addressed with modifying the mechanical properties of PDMS. The ratio of length / thickness for PDMS layers is a key point parameter in our configuration. For obtain the effective length of bonding on the sensor sensitivity to the force, the sensor was simulated with Finite Element Methods (FEM). The length of PDMS for bonding the SMF to MSSC was obtained 500 ?m.

To characterize the sensor to the force an electrical load cell was used. The voltage from load cell was calibrated based on standard weights, to be used as a force indicator in labVIEW program. In addition, a step motor with micro translation stage in z direction was used to push sensor head toward the load cell surface. To interrogate the sensor spectrum and study the effect of force on MSSC-HFPI, an optical spectrum analyzer was used with wavelength resolution of 1 pm. Light beam was guided from our interrogation system into SMF, and its reflection spectrum from sensor head was saved with labVIEW program.

For measuring the sensitivity of the sensor different force in range from 0 N to 6 N was applied to the sensor. When the force applied, MSSC-HFPI spectrum was shifting toward shorter wavelengths due to the effect of gap changes. With linear fitting to the obtained data the sensitivity and limit of detection of the MSSC-HFP was obtained of -0.155 nm/N and 6 mN, respectively. The MSSC-HFPI sensor has promising applications to study stiffness of different biological tissue such as brain and skin.

10329-113, Session PS1

Fast searching measurement of absolute displacement based on submicron-aperture fiber point-diffraction interferometer

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The submicron-aperture fiber point-diffraction interferometer (SFPDI) can be applied to realize the measurement of three-dimensional absolute displacement within large range, in which the performance of point-diffraction wavefront and numerical iterative algorithm for displacement reconstruction determines the achievable measurement accuracy, reliability and efficiency of the system. A method based on fast searching particle swarm optimization (FS-PSO) algorithm is proposed to realize the rapid measurement of three-dimensional absolute displacement. In the proposed FS-PSO, the number of sample points on CCD detector increases nonlinearly in the iterative process, and it enables the suppression of random noise as well as the improvement of measurement efficiency. Besides, two submicron-aperture fiber pairs are applied to achieve the high measurement accuracy both in x and y directions. Four single-mode fibers with submicron aperture are laterally displaced to generate two laterally-sheared fringes in x and y directions, respectively, and all of them are integrated in a target. Both the numerical simulation and comparison experiments have been carried out to the feasibility of proposed SFPDI system for the rapid measurement of three-dimensional absolute displacement, high measurement accuracy, convergence rate and efficiency have been realized with the proposed method.

The point-diffraction spherical wavefront from submicron-aperture fiber is critical in the SFPDI system, for it determines the achievable measurement accuracy of the system. The sphericity of point-diffraction wavefront is mainly determined by the exit aperture size, cone angle and NA of the submicron-aperture fiber. Both the numerical analysis based on finite difference time domain (FDTD) method and experimental measurement based on shearing interferometry have been carried out to analyze the point-diffraction wavefront, by which the achievable measurement accuracy can be evaluated. According to the analysis results, both the point-diffraction wavefront error and displacement measurement error grow with the exit aperture, taper angle and NA. The point-diffraction wavefront error is in the order of 1?10-4? (the wavelength ? is 532 nm), and the corresponding displacement measurement error introduced by point-diffraction wavefront error is smaller than 0.03 ?m.

In the laboratory experiments, both the repeatability and accuracy of the proposed measurement method are evaluated. The RMS value in 30 repeated measurements with the proposed measurement method is 0.87 ?m, and the convergence rate reaches 90.0%. Besides, the rapid measurement is realized with the proposed measurement method, and the consuming time is only 1.61 s to finish the reconstruction of three-dimensional displacement. In the control experiment, a high-precision CMM (HEXAB global classical) is carried out to evaluate the accuracy of the proposed method. A good agreement between the CMM results and those from the proposed method is obtained. The RMS values of measurement error for the x, y and z axes are 0.71 ?m, 0.51 ?m and 0.80 ?m with the target moving from (0 mm, 5 mm, 150 mm) to (100 mm, 5 mm, 150 mm) in x axis, and those are 0.67 ?m, 0.69 ?m and 0.79 ?m with the target moving from (0 mm, 5 mm, 20 mm) to (0 mm, 5 mm, 320 mm) in z axis.

In conclusion, a fast searching method based on modified model of SFPDI system and FS-PSO algorithm have been proposed to measure the three-dimensional absolute displacement. With the application of submicron-aperture fiber as point-diffraction source, the point-diffraction wave with both high NA and large light intensity is obtained, and the achievable measurement range of the measurement system can be greatly extended. A modified FS-PSO method with a fast searching method is proposed to improve the measurement accuracy, reliability and efficiency performance of the SFPDI system. Both the numerical simulation and comparison experiments have been carried out to demonstrate the accuracy and feasibility of the proposed SFPDI system. High measurement accuracy, convergence rate and efficiency can be realized with the proposed method, providing a feasible way to measure three-dimensional absolute displacement in the case of no guide rail.

10329-114, Session PS1

Autocollimation system for measuring angular deformations with reflector designed by quaternionic method

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High-precision measurements of angles are one of the most important operations in instrument and mechanical engineering. Optic-electronic autocollimators for non-contact angular measurements are used effectively. The autocollimation system includes autocollimator, mounted on the fixed base, and a controlling reflection element, placed on inspected object.

The stationary XYZ coordinate system is specified by the autocollimator. The axis OZ coincides with its optical axis, passing through the rear nodal point of the lens and the center of the matrix analyzer. The XOY plane is parallel to the plane of the matrix analyzer, and the OX and OY axes, respectively, are parallel to the rows and columns of the matrix analyzer.

The mobile coordinate system X1Y1Z1 is associated with a reflection element, which is placed on inspected object. The pitch, yaw and roll axes of the coordinate system X1Y1Z1 are parallel to the axes of the coordinate system XYZ when the initial position of the inspected object.

When the reflection element rotates, the reflected beams are deflected

from its original direction. This results to a change in position of image on the matrix analyzer. Deformations of the object are determined by three angular dimensions simultaneously. They are pitch ?1, yaw ?2 and roll angles ?3.

For calculating the parameters of the autocollimators different mathematical methods are used e.g. spherical trigonometry, vector and vector-matrix calculus. When using these methods necessary repeated recalculation of orientation parameters between different coordinate systems. It increases the complexity and reduces the resulting measurement accuracy. More simple problems of determining the angular spatial orientation are solved by using quaternions. The paper deals with application of quaternions for calculating parameters of reflector in autocollimation measurements.

Researches on the mathematical model have shown, that the orthogonal arrangement of two basic constant directions for autocollimator tetrahedron reflector is optimal with respect to criterion of measurement error reduction at bisection arrangement of actual turn axis against them. The obtained results enable to synthesize the reflector for the autocollimation dimensions of the turns relative to a known axis, the optimal criterion to reduce measurement error.

In many practical cases approximately known position of the axis of actual rotation object. When performing the high-precision laboratory experiments in the case setting of basic rotation with using angular measuring progress and availability relatively small angular deformation its shaft relative to orthogonal axes or monitoring measurements of deformations the shafts or the piping. The method of synthesis reflector for autocollimation measurements under this condition in the first stage includes the calculation its parameters. These parameters are implemented by mutually perpendicular arrangement of the two main unchanged direction. In the second stage of synthesis the values between the angles of tetrahedron reflector are selected so that the bisection plane of the right angle is formed by the two unit vectors of the main unchanged direction most closely located to the approximately known position of the axis actual rotation. On the base of the found ratios between tetrahedron reflector angles and angles of its initial orientation parameters we have developed a practical method of reflector synthesis for autocollimation measurements in case of aprioristic information on an actual turn axis at monitoring measurements of the shaft or pipelines deformations.

10329-115, Session PS1

Steps towards traceability for an asphere interferometer

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Aspherical optical components are currently used in many optical imaging systems. While polishing techniques for optical surfaces enable corrections at the nanometer level, adequate metrology needed to produce and verify aspheric surfaces with an accuracy of some ten nanometers is still a challenge. The reason for this is the large deviation of as much as 1 mm (or more) from an asphere to a sphere. Current measurement systems have the potential to reach measurement accuracies well below 100 nm (see e.g. European project “Optical and tactile metrology for absolute form characterization”, http://www.ptb.de/emrp/ind10.html), but there is still a lack of traceability of the measurement results to the SI unit of the meter. At PTB, the national metrology institute of Germany, we are currently developing strategies to establish traceability for aspheres and freeform surface measurements.

In this article, we introduce the concept of traceability and then analyze interferometric asphere measurements using the example of the Tilted-Wave Interferometer. This measurement technique combines a special measurement setup with model-based evaluation procedures. Therefore, simulations are part of the evaluation procedures. We use the SimOptDevice simulation tool, which has been developed at PTB to investigate optical measurement systems. The tool is based on object-oriented programming in MATLAB and combines the geometric modelling of a measurement device with ray tracing and ray aiming methods. We apply SimOptDevice to investigate and evaluate Tilted-Wave Interferometer measurements, and point out the resulting challenges as well as the first steps towards establishing traceability for this measurement technique. One important issue is how to identify and investigate all significant uncertainty sources. In addition to typical uncertainty sources like environmental influences, the uncertainty of the evaluation software has to be identified. Here, the uncertainty of the interferometer calibration, which is used to adapt the interferometer model to the real measurement system, also has to be determined. Additionally, the uncertainty of SimOptDevice itself has to be considered. In this article, these uncertainty sources are itemized and the steps towards traceability are discussed.

Furthermore, we briefly introduce the concept of metrological reference surfaces, which is an alternative way to check the measurement capability of an asphere measurement system for characteristic surface features of the metrological reference surfaces.

10329-116, Session PS1

Three-dimensional refractive index distribution measurement by digital holography

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Digital holography (DH) includes to the acquisition and processing of hologram with a digital sensor array, where reconstruction of data is performed numerically from digitized holograms. DH is used to measure three-dimensional (3D) shapes, and to measure local refractive indexes of materials. In particular, one can measure the 2-dimensional refractive index distribution without lateral scanning by DH.

Recently, the direct writing of waveguide and other integrated photonic components inside the volume of transparent materials by focused laser pulse has gotten much attention. This laser process is simple, flexible, and low cost, allowing for the fabrication of efficient 3D index modified structures as compared the traditional photolithographic process. The 3D index modified structures, such as Bragg grating, wave-guide laser, and directional couplers were successfully demonstrated. However, the conventional techniques, such as Abbe refractor, interference method, and ellipsometry have their own limit in measuring the 3D refractive index distribution. Although the measurement of 3D refractive index distribution is very important to control the fabrication process in integrated photonic components, techniques above only measure the average refractive indeIn this regard, we have developed the method for measuring 3D refractive index distribution using sectioning DH. Optical sectioning is the very important process for 3D imaging in microscopy. We used the depth of focus (DoF) of lens for sectioning thickness. The contrast of the interference pattern depends on the location of the object, which is located within DoF or not. If the object is located in the DoF, the contrast of the interference pattern would be strong. Using optical axis scanning, the multiple section of the object were recorded on a 2D hologram. Generally, the hologram is complex-valued and contains the information from all the sections. Therefore, the suppression of defocused phase noise is mandatory in the reconstruction of sectional phase images from the hologram. We have discarded the hologram, which has smaller contrast value to suppress the defocused phase noise. After discarding the defocused noise, we were capable of retrieving the phase information. This resulting phase is regarded as one of the in-focus sections. Normally, the phase unwrapping process is necessary for obtaining 3D information from the phase. We use two-wavelength DH for obtaining 3-D information without unwrapping process since the thickness of sectioned area is a few times of wavelength. We can obtain the 3D refractive index distribution information at each section. By stacking the refractive index information of the focused section, the entire 3D refractive index information was revealed.

In this study, we have experimentally demonstrated new approach in measuring the 3D refractive index distribution by Digital holography microscopy (DHM) and optical scanning, and have proposed two-wavelength DHM for fast measuring 3D information. We achieved an accuracy of ~?10?^(-3) for refractive index measurements.

10329-117, Session PS1

Principles of radiation terrain mapping with SiPM gamma spectrometer

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Detectors of gamma radiation are the most effective instruments in emergency situations, for evaluation the extent of radioactive damage of the equipment, as well as for personal dosimetry. Gamma detectors are used to measure the weak geophysical fields when moving or by stationary installation. Since the measurements are often carried out in the natural environment, far from settlements, they are required to be power-efficient, steady and easy to use. In addition, pedestrian instruments should be lightweight and compact.

Gamma spectrometer based on the vacuum photomultiplier, which is traditionally used for geophysical measurements, have low spectral resolution and unsatisfactory by modern ergonomics standards. Considering these drawbacks it can be seen, that vacuum photomultipliers are unsuitable for pedestrian gamma spectrometer. Therefore, it is reasonable to develop a device, which is free from the above mentioned drawbacks. The active development of SiPM in the last decades has led to the fact that at this moment it can be a complete alternative to the vacuum photomultiplier. SiPM have such advantages as small size and low supply voltage, low cost, as well as independence of the influence of magnetic fields and high impact resistance. Therefore, the purpose of this research is to provide a pedestrian field gamma-spectrometer based on solid-state silicon photomultiplier.

The solution of the problem is connected with a number of difficulties, both at the level of design and by the development of algorithms for data acquisition and processing. One of the actual problems arising in the second step is to develop a method for radiation terrain mapping.

The process radiation terrain mapping in the field consists in measurement of gamma background, executing in a pedestrian version, and the subsequent eduction of the general level of radiation background and the content of individual gamma-emitting radionuclides. According to the results of field research are made maps of gamma field parameters and radionuclide contamination.

In this paper we will focus on the methods and features of radiation terrain mapping with pedestrian method for estimation of gamma background caused by both natural causes and anthropogenic pollution. We will show how to solve this problem in several stages, including initial terrain evaluation using GIS, elaboration of grid spacing, direct radiation measurement and visualization. We propose ways of solving the difficulties related to the accuracy, speed and other factors.

10329-118, Session PS1

The spatial concentration of dust emissions measured by using 3-D scanning lidar in the open storage yards of steel-making company

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The wind-blown dust emissions frequently occur in the open storage yards of steel-making companies. Tracking the dust source and monitoring their dispersion are rather difficult. This type of open-air storage yards poses many environmental hazards. The 3-D scanning Lidar system is effective in environmental monitoring (e.g., dust) with high temporal and spatial resolution, which is lacking in traditional ground-based measurement. The objective of this paper is to make an attempt for the flux estimation of dust concentration by using lidar system. Further, we investigate the dynamical process of dust and their relationship with local air quality monitoring data.

The results show that the material storage erosion by wind (~ 3.6 m/s) could cause dust to elevate up to 20m height above the material storage, and produces the flux of dust around 674 mg/s. The flux of dust is proportional to the dust mass concentration (PM10) measured by commercial ambient particular monitors. The dust control efficiencies of wind screen are also estimated and compared with numerical simulations in an open storage yard. Details will be presented in the upcoming symposium.

10329-119, Session PS1

Super-resolution photonic nanojet interferometry: photonic nanojet interaction with polymer sample

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Super-resolution photonic nanojet interferometry is a new modality for 3D label free super resolution imaging. We present a comparative study of the photonic nanojet interaction with a layered polymer sample. The aim is to use 3D numerical modelling to reproduce the results observed in our experiments. The numerical model employs the same set of input parameters (sphere with a diameter of 11 μm and a refractive index of 1.68, and sample refractive index of 1.5-1.6), as in our experiments. The interaction is described using the finite-difference time-domain method applied on a finely discretized mesh. The knowledge gained using the verified and validated model, will be used to conduct numerical simulations in wider parameter space enabling to optimize the design of 3D-interferometric super-resolution microscopes.

10329-120, Session PS1

Optoelectronic joined-channel autocollimator for measuring three angular coordinates

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Optoelectronic devices are an effective instrument for non-contact measurement deformations of such environmentally hazardous facilities as pipelines, fuel reservoirs, power settings and no less effective while the proper installation of the transportation modules is being verified, environmentally hazardous substances are being carried. The issue of increasing the measuring range of the optoelectronic autocollimation sensor is being considered.

The study presents the results of research aimed at investigating the possibility of establishing single-channel autocollimator for measuring three angular coordinates at the same time. The principle of autocollimation scheme consists in placing autocollimator to the base object and the control element of the controlled object. The control element does not require a power supply to the control point and it is usually a conventional flat mirror. However, the flat mirror can measure only one angle at the same time and has a large value of the optical reduction coefficient. New types of control elements are designed to increase the number of measured angles at the same time, reduce the size of the system and increase the accuracy characteristics. New control elements are typically different combinations of prisms. When such control elements are being used, in the plane of the image analysis may happen marks overlapping which make measurement the angles impossible. To resolve this problem, add additional channels for the autocollimator and CCD, which affects the overall dimensions the system and its cost.

To study the possible solution of this problem, the model for the processing of overlapping arrays of irradiance has been developed and implemented in technology MatLab. This model has allowed investigating the influence overlapping marks on the measuring accuracy of the coordinates. An algorithm for measuring the coordinates of the centre mark was proposed and developed during the study. This algorithm can measure the coordinates with an accuracy of 0.5 pixels, even in a case of large marks overlapping. Currently a fully functional algorithm, based on circle Hough transform, is being developed. This algorithm enables to expand the metrological performance of the angle measuring sensor by addressing the problem of malfunction of the device when the marks are overlapping.

The algorithm is based on the idea using the Hough transform. Hough Transform can solve the problem of grouping boundary points by the use of particular voting procedures to a set of parameterized objects in the image. This is particularly significant when it is necessary to detect objects whose boundaries are crossing. For this purpose, Accumulation array is used for detects the presence of the required object. The dimension of the Accumulation array is equal to the number of unknown parameters of the Hough space. In the case of circular marks, the number of unknowns is equal to three. These will be X and Y, and the radius of the mark. The algorithm is sufficiently flexible and can measure the marks centres while the various parasitic reflections, the inhomogeneity of the background, etc are being ignored. Algorithm determines whether the weight of the boundary at this point is sufficient for each point and its neighbourhoods. This method is based on an assessment of the normal orientation of the voting contour points. The first step of the process is finding edge pixels which are surrounding the perimeter of the object. Evaluation of the amplitude and direction of the gradient vector is used for this purpose. The voting contour point is considered regarding high modulus gradient. The second step, position estimate and the orientation of the circuit to evaluate the centre of a circular object of radius R by the movement over a distance R from the edge of the pixel in the direction normal to the contour is being used for each edge pixel.

If this operation is repeated for each edge pixel, a variety of positions alleged points of the centre, which can be averaged to determine the exact location of the centre will be found. After that, the algorithm used a threshold filter and search of the local maximum in the accumulator array for determination the centres of the circles.

Application of the proposed algorithm allows keeping the device efficiency when marks are overlapping without significant loss of accuracy. The algorithm has successfully passed functional testing on real devices with different control elements and showed the error of less than 0.5 pixels, stable performance, versatility.

The use of this algorithm extends the metrological characteristics of the entire system, reduces its overall dimensions using a single channel and as a result reduce overall system costs. All of this allows the use of autocollimation system where previously this was not possible.

10329-121, Session PS1

The method of increasing accuracy of dynamic goniometer

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Angle encoders are widely used in all spheres of human activity. Using dynamic goniometers you can calibrate angle encoders with high accuracy in wide dynamic range. Raising of accuracy of angle encoders and dynamic range extension cause the increasing of requirements for their calibration facilities – dynamic goniometers. Increasing the accuracy of dynamic goniometers can be achieved by the improvement of technical equipment that requires large material costs, as well as by measurement techniques, and the use of new measuring methods of information processing.

The dynamic goniometer consists of one or two angle transducers forming its circular scale. Those angle transducers are mounted on the rotor which rolls in bearings. Ring laser can be used as angle transducer, because its scale has high uniformity and resolution. But it can’t meet all dynamic range requirements applicable to up-to-date angle encoders. Ring laser’s dynamic range, which ensured it’s precision characteristics, is 60°/c ? 360°/c. Goniometer’s dynamic range can be widened using optical encoder as circular scale. In the same way continuous monitoring of the metrological characteristics of both transducers can be provided. High accuracy can be achieved by applying of time interpolation and elimination of angle encoder’s uncertainty.

In the construction of the dynamic goniometer different types of bearings can be used. For super high precision dynamic goniometers air bearings are used. But in this case it is necessary to have such additional techniques, as compressor, also it needs to take measures to maintain bearing’s stable operations at high speeds. Ball bearings have a good value for money and performance. The dynamic goniometers with radial angular contact precision ball bearings was investigated. It is shown that the use of a ball bearing gives rise to nonstationary dynamic goniometer measurement results. It is definded, that in the results there is periodic component. In this case it is impossible to use the standard way to decreasing random error – conduction of multiple determinations. To eliminate the nonstationarity of the results of measurements we analyzed the measurements error with the methods of mathematical statistics, Allan variance and wavelet analysis. The features of the application of these methods for the analysis of errors of measurements dynamic goniometer are presented. Allan variance allows to determine types of noise. Wavelet analysis shows the change of frequency characteristics of the signal over time, and in contrast to the Fourier analysis is applicable for nonstationary process. Its use allows to obtain additional information about the processes occurring in the system.

The complex method to analyze and eliminate the dynamic goniometers errors is presented. This method has increased the accuracy of the dynamic goniometer with ball bearings to the level of precision dynamic goniometer with an air bearing.

10329-122, Session PS1

Interferometric signals analysis based on extended Kalman filter tuned by machine learning technique

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High-resolution non-invasive optical investigation methods are widely used in material science, medical research, microbiology, metrology, criminalistics, and others. The greatest precision among optical methods is provided by interferometric techniques [1].

The valuable information about structure of experimental objects is kept in signals registered by interferometric system. Extraction of this information requires high-quality, high-rate, and noise-immune data processing algorithms.

The conventional processing methods based on Fourier transform do not take into account available a priori information about mathematical signal model and optical characteristics of the interferometric system [2]. The phase-shifting methods are not stable to noise that constricts the area of their application [2].

An alternative approach to interferometric data processing is recurrent algorithms of parameters estimation [3]. In these algorithms each discrete sample of an interferometric signal is represented as output of non-linear dynamic system [3]. It is a mathematical abstraction which contains a priori information about signal formation model, its parameters evolution, and noise characteristics that leads to high quality of estimation results. Step-by-step mode of data processing by recurrent algorithms usually promises high calculation rate.

Non-linear dependence between observed signal and its estimated parameters (i.e. amplitude, frequency, phase) justifies the application of non-linear algorithms of parameters estimation such as extended Kalman filter, particle filter and others [3]. Data processing quality is influenced by input parameters of these algorithms such as initial vector of signals parameters, system and observation noise covariance, parameters evolution model. The accurate tuning of the algorithms for data processing in specific interferometric system needs high qualification of the user and availability of a priori information about the system.

The work deals with automatic selection of input parameters for the extended Kalman filter in application to interferometric data processing by non-linear optimization methods such as Monte Carlo method and gradient descent [4, 5]. The optimization criterion is represented as difference between learning set of signals of the same type (i.e. signals with the same phase variation law or some different pixel lines on interference pattern image) and results of signals restoration using parameters estimated by tuned algorithm. The features of proposed approach are considered and discussed.

The presented technique for automatic tuning of the extended Kalman filter allows to obtain accurate parameters estimation results in conditions of a priori uncertainty about specific interferometric system. It opens way to the use of recurrent algorithms for data processing in various types of interferometric systems.

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10329-123, Session PS1

The small-sized ultraprecision sensor for measuring linear displacements

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The article describes a new optical scheme of noncontact sensor for measuring linear displacement - linear encoder. This sensor is an optical device in which the measurement of displacement is performed by analyzing the optical signal, which pass through two diffraction gratings, one of which is moved relative to the other. The optical signal is obtained by the diffraction of light in these diffraction gratings and subsequent interference of diffracted beams. Often this type of sensors are multi-channel devices with symmetrically positioned of detectors. This scheme is proposed to use a multi-section diffraction grating that allows to make a small-sized sensor. The analyzed diffraction grating is multi-section optical component in this sensor. The diffraction gratings made of the same frequency in each of the sections of this component, but are shifted relative to each other in phase. The number of sections in the analyzed diffraction grating can be varied. Estimated sufficient number of sections is from two to four.

10329-124, Session PS1

Die misalignment determination in LED illumination optics using an artificial neural network

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Misalignment in optical systems is considered to be one of the most detrimental factors to achieve the required image properties [1]. The presence of misalignment in an optical system has been widely studied in the field of imaging applications. Several contributions have been presented to align lenses and optical groups [2-4]. As has been pointed out [5] aligning optical groups is a really time-consuming process that is highly sensitive to misalignments of the reference axis.

In this work we present a strategy based on artificial neural networks that allows us to determine the degree of die misalignment in LED illumination optics. The use of artificial neural networks (ANNs) in misalignment determination strategies has previously been tested in imaging optical devices [6]. In particular, ANNs have been successfully applied to align objectives of cinematography cameras [7].

The main contribution of the present work lies in the use of a well selected set of points in space, placed near the LED illumination optics device, where we can determine the difference between the directions of the ray propagation when the die is on the nominal design position and when the die is misaligned. The developed strategy is based on the assumption that different degrees of misalignment will produce specific, reproducible deviations in the directions of propagation of the rays.

Our ANN is then trained with a large collection of cases (covering the maximum misalignment ranges) for which the misalignment value is known. The input used to train the ANN for each degree of misalignment consists in the following information pair; misalignment value and matrix of the deviations of the director cosines in the selected set of points. A different collection of cases, in the same misalignment range but with different misalignment values, together with the corresponding values of the matrix of the deviations of the director cosines is then used to test the ANN strategy performance.

Summarizing, this work presents a strategy based on artificial neural networks to determine the degree of misalignment of the die in LED illumination optics. The simulated results show fairly good capabilities in the prediction and quantification of the misalignment by the trained ANN.

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10329-125, Session PS1

Simulation of multispectral multisource for device of consumer and medicine products analysis

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The main distinguishing feature of the era of capitalism is market economy,which is characterized by market competition and the struggle for the capital, that one always reflected well on buyers. People make purchases in different stores or on marketplacesand often don't check the quality of products, such as fruits, vegetables, meat, fishand etc. So each time they, buying products of unknown quality, have a risk of negative impact on their health. Today there are a few methods for testing consumer products, based on the following: the assessment of visual appearance; the taste and the results of chemicallaboratory analysis.These methods are allowed todetermineexactlythe current state of the object, but they have main disadvantage likethe duration and the unpopularity. The most promising is the method, based on analysis of infrared spectroscopy. Device, using in this analysis, highlightsthe object, determinesthe spectral composition in the reflected radiation and finds "markers" of amino acids and proteins disintegration substances, such as ammonia, hydrogen sulfide and secondary amines, which correspond to a specific wavelength. This technology is not widely spread in the area of products consumption.

This research focuses on the development and simulation of special source aimed at solving analysis problems of food, medicines and water for suitability inconsumption.

In this research it is provided the mathematical model of the lighting area

and the model of the spatial irradiance source on the basis of several diodes types with different wavelengths. In the process of this kind source's creation it is taken into accountthe following factors: spectral component, power settings, spatial and energy components of the diodes.

The research results can be applied in quality control, pharmaceuticals and medicine. The device can be part of the unit, identifying not only product quality but also its exact chemical composition. The device will be in demand not only in the production and procurement, but in shopping by ordinary buyers.

The research is acontinued explorationof authorsgroup, specialized in creation of special lighting devices for opto-electronic systems, instrumentation and industrial control systems in order to ensure optimal conditions for observation and analysis; in creation of the corresponding automated measurement devices and control parameters and characteristics of the radiation sources.

10329-126, Session PS1

On-line hyperspectral imaging system for evaluating quality of agricultural products

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The domestic consumption of fresh-cut agricultural produce in Korea has been growing, and the types of materials used in these products have expanded from vegetables to various fruits. The browning of fresh-cut vegetables that occurs during storage and foreign substances such as worms and slugs are some of the main causes of consumers' concerns with respect to safety and hygiene. The purpose of this study is to develop an on-line system for evaluating quality of agricultural products using hyperspectral imaging technology.

The online evaluation system with single visible-near infrared (VNIR) hyperspectral camera in the range of 400 nm to 1000 nm that can assess quality of both surfaces of agricultural products such as fresh-cut lettuce was designed. The on-line evaluation system consists of the sample input unit, a pair of conveyor units, the quality determination unit, a pair of low-quality sample removal units, the flipping unit, outlet unit, and system control unit. Hyperspectral images of the moving samples are obtained by the line scanner in the quality determination unit. Low-quality samples with defects on one side are determined by the detection algorithms using the hyperspectral images and are removed by the low-quality removal unit. The other samples are reversed using the flipping belt of the flipping unit and placed on the outlet conveyer belt. The hyperspectral images of the other side of the reversed samples are measured and quality on this surface are similarly determined and eliminated.

Algorithms to detect browning surface on lettuce were developed for this system. Single-waveband and multi-waveband algorithms to assess the quality on the lettuce surface were developed using the VNIR reflectance spectra extracted by hyperspectral images. Algorithms to discriminate browning lettuces and conveyor belts, browning lettuces and the gap of the chains of the conveyor belts (GCCB), and browning and sound lettuces were developed. The optimal wavebands for discriminating browning lettuce were investigated using the correlation analysis and the one-way analysis of variance (ANOVA) method. The optimal wavebands found by spectra data were used to develop imaging algorithms for the browning detection. The imaging algorithms to discriminate the browning lettuces were developed using the combination of three algorithms: the two-waveband ratio image (RI) algorithms to discriminate between browning lettuces and conveyor belts, the two-waveband subtraction image (SI) algorithms to discriminate between browning lettuces and GCCB, and the two-waveband image algorithms to discriminate between browning and sound samples. The RI algorithm of the 533 nm and 697 nm images (RI533/697) for abaxial surface lettuce and the RI algorithm of the 533 nm and 697 nm images (RI533/697) and SI algorithm of the 538 nm and 697 nm images (SI538-697) for adaxial surface lettuce had the highest classification accuracies. The classification accuracy of browning and sound lettuce was 100.0% and above 96.0%, respectively, for the both surfaces. Two-waveband imaging algorithms obtained better enhanced misclassification accuracy of browning lettuces and classification accuracies of sound lettuces than the single waveband image algorithm.

The overall results show that the online hyperspectral imaging system could potentially be used to assess quality of agricultural products.

10329-127, Session PS1

Enhancement of spatial resolution in digital holographic microscopy using speckle field generated from ring-slit apertures

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Digital holographic microscopy is actively investigated in the field of bio-imaging as a quantitative phase microscopy. In the research area of microscopy, one of the main issues is an enhancement of the spatial resolution. In recent years, the method for enhancing the spatial resolution using a structured illumination in digital holographic microscopy has been reported by several research groups. In this study, we report the enhancement of the spatial resolution in digital holographic microscopy using speckle illuminations generated from a ring-slit aperture.

Now, we consider the optical system of the off-axis Mach-Zehnder digital holographic microscopy. When a laser light is incident on an amplitude modulated aperture and a diffuser, a speckle field is generated. The sample is illuminated by the speckle pattern and the object wave is generated. It is magnified by an objective lens and is coupled with a plane wave, which is used as a reference wave, by a beam splitter. The object and reference waves interfere and a digital hologram is detected on an image sensor. The spatial resolution of this digital holographic microscopy is given by the numerical apertures of the illumination system and the optical system between the sample and the image sensor. While the numerical aperture NAg between the sample and the image sensor is given by the objective lens, the numerical aperture NAs of the illumination system is determined by an average diameter of a speckle pattern incident on the sample. This implies that the spatial resolution of digital holographic microscopy can be enhanced by changing the average diameter of the speckle pattern.

A circular aperture and a ring-slit aperture are used in this study. In the case of the ring-slit aperture, the outer and inner diameters are 1.05mm and 1.01mm. The diameter of the circular aperture was adjusted to fit the outer diameter of the ring-slit aperture. A He-Ne laser (632.8nm, 20mW) is used as the optical source and the CCD camera (1392 ? 1040 pixels, pixel pitch 4.65 ? 4.65?m2) is placed at 100 mm after the sample. The holographic diffuser (Edmond, # 47-676) is placed at 30 mm before the sample and 30 holograms are recorded under different speckle illuminations by changing the position of the holographic diffuser in the in-plane direction. Each of hologram is reconstructed using the angular spectrum method and the reconstructed intensity images are averaged. A negative resolution test target (Sigma-koki, TRN-003) is used as a sample. The numerical aperture NAg of the optical system is reduced to NAg = 0.124 by changing the distance between the sample and the objective lens (x40, NA=0.65) as it is able to resolve the bars of G7-3 but not G7-4 of the test target. On the other hand, the numerical apertures NAs of the optical systems in the circular and ring-slit apertures are 0.0167 and 0.0266.

To confirm the enhancement of the spatial resolution in speckle fields using the ring-slit aperture, we carry out the experiments in the case of the non-structured illumination, the speckle illumination using the circular aperture and the ring-slit aperture. It is confirmed that the spatial resolution is the highest when the speckle illumination generated by the ring-slit aperture is used.

In conclusion, we demonstrated the enhancement of the spatial resolution in digital holographic microscopy using speckle illuminations generated from a ring-slit aperture theoretically and experimentally.

10329-128, Session PS1

Phase and group refractive indices of air calculation by fitting of phase difference measured using a combination of laser and low-coherence interferometry

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The majority of interferometric measurements are carried out under the ambient atmosphere. Hence, the light wavelength that is used as the basic scale of the length is affected by the refractive index of air. This phenomenon causes a multiplicative systematic error to the results of length measurements. In order to obtain accurate results, the knowledge of the refractive index of air is essential. There are two different approaches to the measurement of the refractive index of air. Indirect methods involve calculation of the refractive index of air from measured temperature, pressure, relative humidity and in some cases also carbon dioxide concentration employing Edlén's, Ciddor's or similar equations. The other group of methods are direct methods that are based on monitoring the variability of the optical path. The refractive index of air is usually obtained from the optical path difference between air and a reference environment, usually vacuum.

We present a new direct technique for the refractive index of air measurement that is based on measuring the phase difference between air and vacuum using a combination of laser and low-coherence interferometry.

In our experiment, we use Michelson interferometer as the experimental setup. The light source is carried out using a collimated beam of red LED and HeNe laser radiation. These beams are combined at the input of the interferometer and split at the output. That allows us to measure the laser interference signals separately from the low-coherence interference signals. The key component of the experimental setup is a double-spaced vacuum cell placed in the measuring arm of the interferometer. The cell transversally divides the beam into two parts, one of which travels trough vacuum and the second one through the ambient atmosphere. The different environment in both parts of the cell causes a phase shift between the interference signals measured in both parts of the beam. This phase shift is wavelength-dependent, and it is proportional to the refractivity of air. While the interference of the laser radiation occurs in both parts of the beam at any measuring mirror position, the interference of the white light occurs in each part of the beam at a different discrete position. The distance between these positions is proportional to group refractive index of air for the LED central wavelength.

During the measurement, we measure two laser and two low-coherence interference signals. The goal of the signal analysis is to calculate the phase difference between the two laser interference signals and convert it to phase refractive index of air for the laser wavelength. This phase difference can be calculated directly from the two laser interference signals, however, then the value is known only modulo 2ϖ. In order to resolve the 2ϖ ambiguity, we use the low-coherence interference signals. Moreover, we use the phase of one of the laser interference signals to calculate the measuring mirror position. Since the laser wavelength in air is unknown at this stage, the position is expressed in interference fringes, while two fringes correspond to measuring mirror shift of one laser wavelength (633 nm). To calculate the dependency of the phase difference on the vacuum wavelength from the measured low-coherence interference signals, we calculate discrete Fourier transform of both of these signals and subtract their unwrapped phases. This dependency is then fitted by a theoretical dependency based on modified Edlén equation. The phase value for the laser wavelength obtained from the regression is then used to calculate the phase refractive index for this wavelength. To obtain more accurate air refractive index value, also the phase difference between the two laser interference signals (known only modulo 2ϖ, but more accurately) is taken into account.

The proposed method was experimentally verified by comparison of the measured refractive index values with two different techniques—direct technique based on measuring laser interference signals during the cell evacuation and indirect technique based on the calculation of the air refractive index value from atmospheric conditions. We were able to reach uncertainty level comparable to other direct methods.

10329-129, Session PS1

Very high aspect ratio through silicon via reflectometry

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Through Silicon Via (TSV) technology is a key feature of new 3D integration of microelectronic devices. The high aspect ratio opens up potential of smaller packaging, stress reduction, and low costs for advanced 3D integration. The high aspect ratio is advantageous for reduction of bending stress effects by wafer thinning and thermal stress inside the TSV by mismatch of thermal expansion of Si and the filling material [1-2]. As presented in this paper, we have developed an experimental setup and a respective evaluation algorithm for the control and monitoring of very high aspect ratio TSV profiles by spectroscopic reflectometry.

For this purpose square via arrays with lateral dimension from 3 to 10 µm have been fabricated by a highly selective Bosch etch process. Vias depth of up to 160 µm were achieved by using a SiO_2 hard mask. A series of scallops on the TSV sidewalls are formed due to the alternating etch and sidewall passivation steps. The profiles are defined by critical dimensions at the top, depth, and scallop size (period and amplitude). All measurements were carried out using an experimental setup consisting of a multimode fiber bundle including condenser and focusing objective with variable aperture. The results obtained by our setup are compared with data obtained by commercial wafer metrology tool [3-5], where our own evaluation algorithm was applied. The Pearson correlation coefficient between measured and calculated reflection is used as a quality criterion of the fit. Using our setup, the reflection data for patterns with aspect ratios of up to 30 were safely evaluable, whereas the commercial tool provided evaluable data for patterns with aspect ratios of up to 17 [5]. The limiting factors of optical TSV depth measurements will be discussed, as well as further improvements.

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10329-130, Session PS1

Application of identifying transmission spheres for spherical surface testing

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We developed a new application on Microsoft Foundation Classes (MFC) to identify correct transmission spheres for Spherical Surface Testing (SST). Spherical surfaces are important optical surfaces (e.g. flat, asphere, free-form), and the wide application and high production rate of spherical surfaces necessitates an accurate and highly reliable measuring device. A Fizeau Interferometer is an appropriate tool for SST due to its

sub-nanometer accuracy. It measures the contour of a spherical surface using a common path, which is insensitive to the circumstances. The Fizeau Interferometer transmits a wide laser beam, creating interference fringes from re-converging light from both the transmission sphere and the test surface. To make a successful measurement, the application calculates and determines the appropriate transmission sphere for the test surface. There are 3 main inputs from the test surfaces that are utilized to determine the optimal sizes and F-numbers of the transmission spheres: (1) the curvatures (concave or convex), (2) the Radii of Curvature (ROC), (3) the aperture sizes. The application will firstly calculate the F-numbers (i.e. ROC divided by aperture) of the test surface, secondly determine the correct aperture size of a convex surface, thirdly verify that the ROC of the test surface must be shorter than the reference surface's ROC of the transmission sphere, and lastly calculate the percentage of area that the test surface will be measured. However, when there's a requirement to measure a large amount of spherical surfaces, the amount of interferometers and transmission spheres should be optimized. The users can't buy one interferometer and transmission sphere for each test surface. The smart application can optimize results and advice the users to buy and use as less interferometers and transmission spheres as possible. Current measuring practices involve tedious and potentially inaccurate calculations. This application eliminates human calculation errors, optimizes the selection of transmission spheres (including the least number required) and interferometer sizes, and increases efficiency.

10329-131, Session PS1

Investigation of accuracy characteristics of circular photodetector "Multiscan"

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In different areas of science and engineering there are necessity to measure linear and angle motions of different mechanical parts (assembly units, designs) and data acquisition from manipulators and robotic systems. The biggest part of utilized technical solutions is based on linear scales and optical raster systems. Their main disadvantages are following: complicated manufacturing process, relatively low rate of performance and efficiency, high cost. In The Ioffe Institute (Saint-Petersburg, Russian Federation) the circular position sensitive Multiscan detector intended for definition of angular data of a light spot on the basis of the principle of the relative frame aperture is developed. These problems could be solved by utilization of position-sensitive detector also known as "Multiscan". Multiscan will improve structural scheme of the device and will reduce some disadvantages of other systems. But for using of such sensor in actual metering circuits requires a research of its potential precision characteristics. In this study, we evaluated the characteristics such as nonlinearity "Multiscan" output voltage, repeatability and stability of the photodetector.

The experimental solution was realized in original experimental setup based on reference angle movement detector (goniometer) and high sensitivity voltmeter as indication system. Accuracy performances of the system were studied in the range of 0 to 140 degrees.

The value 11% of output voltage nonlinearity was obtained. Because of highly dependence of nonlinearity factor from the eccentricity of experimental setup, the value of nonlinearity was algorithmically corrected to 1%.

In the process of experimental studies had revealed a strong influence of the eccentricity installation of the circular "MultiScan" on turntable of goniometer. As a result of development of special algorithmic measures of correction of eccentricity the size of nonlinearity of angular measurements by means of circular "Multiscan" less than 1% has been reached at high temporary stability of the detector. The conducted researches and the received results allow to count on a possibility of creation of a small-size absolute angular encoder on the basis of the circular Multiscan sensor.

10329-132, Session PS1

Optical measurement system of microcomponents flatness by Moiré interferometry

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The automation, speed and precision in the quality control of surface shape require, the development of control methods suitable for this purpose. The technique proposed in this paper provides a quality control components surface flatness by non-destructive and contactless way, with high resolution and increased sensitivity. The control is done in real time and instantaneously on all inspected surface. The accuracy of components geometry is the one of parameters which influences precision of the function. Moiré topography is full-field optical technique in which the shape of object surfaces is measured by means of geometric interference between two identical line gratings. The technique has found various applications in diverse fields, from biomedical to industrial and scientific applications. In many industrial metrology applications, contactless and non destructive shape measurement is a desirable tool for, quality control and contour mapping. This method of optical scanning presented in this paper is used for precision measurement deformation in shape or absolute forms in comparison with a reference component form, of optical or mechanical components, on surfaces that are of the order of few mm2 and more. The principle of the method is to project the image of the source grating to palpate optically surface to be inspected, after reflection; the image of the source grating is printed by the object topography and is then projected onto the plane of reference grating for generate moiré fringe for defects detection. The optical device used allows a significant dimensional surface magnification of up to 1000 times the area inspected for micro-surfaces, which allows easy processing and reaches an exceptional nanometric imprecision of measurements. According to the measurement principle, the sensitivity for displacement measurement using moiré technique depends on the frequency grating, for increase the detection resolution. This measurement technique can be used advantageously to measure the deformations generated by the production process or constraints on functional parts and the influence of these variations on the function. The optical device and optical principle, on which it is based, can be used for automated inspection of industrially produced goods. It can also be used for dimensional control when, for example, to quantify the error as to whether a product is good or rubbish. It then suffices to compare a figure of moiré fringes with another previously recorded from a product considered standard; which saves time, money and accuracy. This optical device control has advantageous features allows non-destructive and contactless testing, real time speed inspection and measurement; possibility of image tracking in motion analysis and surface deformation, high spatial resolution and high sensitivity may vary depending of the importance of defects to be measured.

10329-133, Session PS1

High-accuracy laser photometer for laser optics

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Development of laser systems requires optical components with high performance, and a high-precision double-beam laser photometer was designed and established to measure the optical performance at 1064nm. Double beam design and lock-in technique was applied to decrease the impact of light energy instability and electric noise. Pairs of samples were placed symmetrically to eliminate beam displacement, and laser scattering imaging technique was applied to determine the influence of surface defect on the optical performance. Based on the above techniques, transmittance and reflection of pairs of optics were obtained, and the measurement precision was improved to 0.06%. Different types of optical losses, such as total loss, volume loss, residual reflection and surface scattering loss, were obtained from the transmittance and reflection measurement of samples with different thickness. Comparison of optical performance of the test points with and without surface

defects, the influence of surface defects on optical performance was determined. The optical performance of Nd-glass at 1064nm was evaluated, and different types of optical loss and the influence of surface defects on the optical loss was determined.

10329-134, Session PS1

Analysis of optical heterodyne frequency error of full-field heterodyne interferometer

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The full-field heterodyne interferometric measurement technology is beginning better applied by employing low frequency heterodyne acousto-optical devices instead of complex electro-mechanical scanning devices. The optical element surface could be directly acquired by synchronously detecting the received signal phases of each pixel, because standard matrix detector as CCD and CMOS cameras could be used in heterodyne interferometer. Instead of the traditional four-step phase shifting phase calculating, Fourier spectral analysis method is used for phase extracting which brings lower sensitivity to sources of uncertainty and higher measurement accuracy.

The full-field heterodyne interferometer is easily implemented in the Mach-Zehnder type interferometer and Tyman-Green type interferometer. It is also possible to be Fizeau type interferometer by using short coherent light source or the spatial filtering method. The full-field heterodyne detection is also conveniently designed as a point diffraction interferometer. In this paper, two types of full-field heterodyne interferometer and one heterodyne point diffraction interferometer are proposed whose advantages and disadvantages are also specified. And the described full-field heterodyne Tyman-Green interferometric schematic is used for analyzing.

Heterodyne interferometer has to combine two different frequency beams to produce interference, which brings a variety of optical heterodyne frequency errors. Frequency mixing error and beat frequency error are two different kinds of heterodyne frequency errors which any type full-field heterodyne interferometers can't avoid. In this paper, the effects of frequency Mixing error and beat frequency error to surface measurement are analyzed respectively.

The frequency mixing error is usually generated by factors such as beam splitting, combination and stray light. We simulate the change of the interferograms and the signals on time-domain and frequency-domain with frequency mixing error. It could be a guide to the determination of interferometer error source. The relationship between the surface measurement accuracy, repeatability and the error is given. The tolerance of the extinction ratio of polarization splitting prism is proposed.

Heterodyne interference signal is usually generated by acousto-optical modulator. The full-field heterodyne interferometer requires the beat frequency is as low as several hertz to tens of hertz so that even an ordinary CCD or CMOS could detect the beat signal. The acousto-optical modulator driver pairs are easily affected by environmental temperature, circuit noise and other factors that causes the super-low beat frequency shifts. The error of phase extraction by Fourier analysis that caused by beat frequency shifting is derived and calculated. And the degradation of surface measurement reconstruction is simulated. We propose an improved phase extraction method based on spectrum correction. An amplitude ratio spectrum correction algorithm with using Hanning window is used to correct the heterodyne signal phase extraction. The simulation results show that this method can effectively suppress the degradation of phase extracting caused by beat frequency shifting error and reduce the measurement uncertainty of full-field heterodyne interferometer.

10329-135, Session PS1

An optical flow-based method for velocity field of fluid flow estimation

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The aim of this paper is to present a method for estimating flow-velocity vector fields using the Lucas-Kanade algorithm. The optical flow measurements are based on the Particle Image Velocimetry (PIV) technique, which is commonly used in fluid mechanics laboratories in both research institutes and industry. This technique consist in illuminating the flow containing tracer particles with, usually, a high-energy pulsed laser beam. A sequence of images of the light scattered from the flow is acquired by a high-speed digital camera at successive time steps and then post-processed using the proposed algorithm. Several approaches for an optical characterization of velocity fields base on computation of partial derivatives of the image intensity using finite differences. Nevertheless, the accuracy of velocity field computations is low due to the fact that an exact estimation of spatial derivatives is very difficult in presence of rapid intensity changes in the PIV images, caused by particles with small diameters. The method discussed in this manuscript relies on an image model, wherein the particle image complies with an Airy disc, which is well approximated using a Gaussian function. The PIV images are interpolated using Gaussian radial basis functions having small width (sigma < 1 px) whose centers are located at positions of all image pixels. As the result of interpolation, a matrix of Gaussian coefficients is obtained allowing for the evaluation of partial derivatives analytically, without the use of discrete methods. This provides a significant improvement in the accuracy of the velocity estimation but, more importantly, allows for the evaluation of the derivatives in intermediate points between pixels. Doing so an iterative velocity vector estimation becomes feasible. The algorithm for radial basis function interpolation (PetRBF) uses a GMRES iterative solver with a restricted additive Schwarz method (RASM), that exhibits O(N) complexity, requires O(N) storage, and is parallelized as the smaller independent tasks, which significantly accelerates calculations on multiprocessor (or multicore) machines. Another distinguishing feature of the proposed method is that it localizes the centers of interrogation windows at particles' centers. This is to significantly improve a spatial resolution of the estimated velocity vector field at the expense of having to perform the calculations at points of an irregular grid, which can lead to additional interpolations. Numerical analysis proves that the method is able to estimate even a separate vector for each particle with a 5x5 px window, whereas a classical correlation method needs at least 4 particles within the window. A set of numerical examples will show the most important features of the presented method. The first part of the analysis is devoted to uniform velocity fields. The calculations include root-mean-square (RMS) error of the estimated velocity as a function of reference-field velocity, particle density, noise level, window size, and number of intensity quantization levels. The case of a turbulent velocity field generated by kinematic simulation of turbulence is also discussed. Finally, a multi-step hybrid approach is also presented aimed at improving the estimation of the particle displacement far above 1 px. The velocity field is initially estimated using the correlation with a large interrogation window (32x32 or 16x16 px) and then much more precisely using a combination of the proposed method, a pyramidal decomposition, and an image deformation.

10329-136, Session PS1

Phase detection model and method for SPR effect modulated by metallic thickness

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A mathematic model based on surface plasmon resonance (SPR) effect is presented to measure the nano metallic film thickness with the coupling device of Kretschmann configuration composed of K9 prism-gold film-air. Four modulation modes of SPR method, such as intensity, phase, wavelength and angle, are numerically analyzed. Their detection principles, the measurement range and sensitivity of different modulation type sensors are discussed.

The simulation results show that the SPR intensity detection method has the highest measurement range and the SPR phase detection method has the highest sensitivity. In practical applications, not only the measurement range and sensitivity, but the optical signal processing mode, experiment devices, the complexity of the algorithm and cost factors should be considered to research and develop the appropriate thin metallic film's thickness measurement SPR sensor with higher sensitivity and stability.

The above analyses based SPR phase detection model and system are put forward. As surface plasmons are the transverse magnetic (TM) mode waves, it is common to use the transverse electric (TE) mode waves (TE-polarized light) for the reference. The prism coupler is coated partially with Ag/Au metallic layers on the bottom surface and the uncoated part is used as reference substrate. The He-Ne Laser beam passes through a laser beam expander and a polarizer firstly. The linear polarization direction of the polarizer is at 45° from both TM and TE polarization. Then the light beam is incident upon the SPR prism coupler clamped onto a rotation stage which adjust the resonance angle. A Mach-Zehnder type interferometer is used to receive the reflected TM and TE light from the prism to form polarized beam interferometer to measure the phase changes modulated by the metallic film's thickness. Here, the reflected light beam is separated into TM and TE mode waves by a polarizing beam splitter. After reflections of the mirrors, the two light beams converge together with orthogonal polarizations in another polarizing beam splitter. The polarization analyzer can make the TM and TE mode waves change to the same polarization direction in order to gain interference fringes. By filtering out stray light with a band-pass filter, the interference pattern is recorded by a CCD camera and processed by a computer to obtain the phase difference ??. And the phase difference with different angles of incidence can be acquired by moving the rotation stage.

Theoretical analysis and experimental results show that the range of metal thin thickness measurement can be 0-100nm, and the resolution can be better than 1nm. Easy to operate, less measurement error and higher anti-interference ability make the application prospects of this system broad.

10329-137, Session PS1

Combined narrowband imager-spectrograph with volume-phase holographic gratings

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In the present work we discuss a possibility to build an instrument with two operation modes - spectral and imaging ones. The key element of such instrument is a dispersive and filtering unit consisting of two narrowband volume-phase holographic gratings. Each of them provides a high diffraction efficiency in a relatively narrow spectral range of a few tens of nanometers. Besides, the position of this working band is highly dependent on the angle of incidence. So we propose to use a couple of such gratings to implement the two operational modes. The gratings are mounted in a collimated beam one after another. In the spectroscopic mode the gratings are turned on such angle that the diffraction efficiency curves coincide, thus the beams diffracted on the first grating are diffracted twice on the second one and a high-dispersion spectrum in a narrow range is formed. If the collimating and camera lenses are corrected for a wide field it is possible to use a long slit and register the spectra from its different points separately. In the imaging mode the gratings are turned to such angle that the efficiency curves intersect in a very narrow wavelength range. So the beams diffracted on the first grating are filtered out by the second one except of the spectral component, which forms the image. In this case the instrument works without slit diaphragm on the entrance. We provide an example design to illustrate the proposed concept. This optical scheme works in the region around 656 nm with F/# of 6. In the spectroscopic mode it provides a spectrum for the region from 641 to 671 nm with reciprocal linear dispersion of 1.4 nm/mm and average spectral resolving power of 9400. In the imaging mode it covers linear 12mm X12mm field of view with resolution not less than 18 lines/mm. We consider different cases for the gratings diffraction efficiency profiles. Results for an ordinary grating with sinusoidal fringes and symmetrical efficiency profile are provided. It's shown that they can be significantly improved is edges of the efficiency curve are sharp. Possible ways to implement such a profile are discussed. In our opinion, an instrument implementing the described concept can be used for different applied measurement tasks, e.g. for optical diagnostics in nuclear fusion. Moreover, it can be of a special interest for a few other areas like astronomy and astrophysics.

10329-138, Session PS1

Heterodyne grating interferometry based on sinusoidal phase modulation for displacement measurement

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In this study, a heterodyne grating interferometer based on the sinusoidal phase modulation method for displacement measurements was proposed. The interference beams were modulated using a sinusoidal oscillating grating, and the proposed frequency-domain quadrature detection method was used to detect the optical phase of the interferometer and determine the displacement. Experimental results were consistent with the strain gauge results for several displacement ranges. When only high-frequency noise was considered, our method achieved a measurement resolution of approximately 2 nm.

The measurement system comprises a laser source, an oscillating diffraction grating, a reflective mirror, and a photodetector. A beam from the laser is incident on the diffraction grating with an incident angle ?. The partial reflected beam from the grating is back-reflected by the target mirror and is redirected to the grating. Both of the incident light beam and the back-reflected light beam from the target mirror are diffracted by the grating. With the specific incident angle, these two diffracted beams can superpose and interfere with each other. According the theory of the optical interference and Doppler effect, the interference signal will be the function of the grating displacement, and the optical path difference between the grating and the target mirror.

If the grating is driven with a sinusoidal vibration with angular frequency ? and amplitude a, the interference signal can be expressed as Fourier–Bessel series expansion. This is a multi-frequency signal, and the optical path difference between the grating and the target mirror is coded in the amplitudes of the fundamental and the harmonics frequencies signals. Here, we were interested in the signals with the fundamental frequency (cos?t) and double frequency (cos2?t), because the amplitudes of these two signals are quadrature components. We can detect the amplitudes of these two signals by using the lock-in technique to determine the optical path difference or displacement.

In our experiments, the light from a He–Ne laser (wavelength, 632.8 nm) was incident on the grating with a 1.67-?m pitch. According to the grating equation, an incident angle ? = 22.27° was selected, and the two diffraction beams superposed and interfered with each other. The interference intensity was detected by the photodetector. The sinusoidal signal with a frequency of 40 Hz is used to drive the grating oscillation. Both the signals from the photodetector and the sinusoidal signal were sent to the computer-based lock-in amplifier for detecting the amplitudes of the fundamental frequency and double frequency signals. The displacement of the target mirror can be determined with the measured amplitudes of these signals.

Several experiments included micrometer and nanometer scale displacements, were conducted to demonstrate the feasibility and effectiveness of this proposed SPM interference system. A strain gauge sensor was used to simultaneously verify the displacements. The measurement results obtained using our method agrees with those obtained using the strain gauge sensor. These results confirm that our system can measure several micrometer displacements with excellent precision.

Because of the heterodyne interferometric phase measurement, this method has the advantages of a high measurement resolution and relatively simple operation. The feasibility of this method is demonstrated in this paper. Furthermore, we discussed and analyzed the periodic nonlinearity error caused by the electronic signal processing.

10329-139, Session PS1

Optical exploration of micro-/nanoscale irregularities created on metallic surfaces by femtosecond laser irradiation

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Success or failure of many industrial components is in a direct relation with their surface characteristics. Surface irregularities such as roughness or waviness are among the most important and effective features in this regard. Not only mechanical properties such as wear or corrosion resistances and hardness characteristic, but also biocompatibility features such as surface wettability or osseointegration are the sensitive functions of its irregularities. So the surface irregularities measurement is one of the essential quality control processes.

The statistical parameter which is frequently used in surface roughness investigations is Root Mean Square (RMS) height. However, the surface irregularities cannot be specified only by the RMS roughness. In the other words the height distribution is insufficient to categorize a surface but another parameter which is called correlation length "T" is also needed to distinguish surface smoothness. T parameter can be considered as the average value of the spacing of the adjacent crests and sometime is called "surface spatial wavelength".

Numerous contact type inspections such as DEKTAK profilometer, Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) are more common for measurement of these surface irregularities. But in some cases they lack lateral resolution due to the tip geometry and they may also cause surface damage through the forces exerted on the surface. On the other hand none of them is capable of being used for on-line measurements. Optical techniques which are mainly based on Total Integrated Scattering (TIS), Angular Distribution (AD), interferometery and speckle pattern recognition also offer fast measurements of the surface features without any contact or unwanted damage.

Hereby, we suggest a direct method based on light scattering and Beckmann formulation for the surface RMS roughness and correlation length measurements. Metallic steel samples irradiated under controlled interaction conditions with ultrafast femtosecond laser system are selected as the random rough surfaces for investigation. A collimated low intensity laser and a CCD camera are the main elements of the experimental measurement probe. The light source and camera are located symmetrically around the surface normal and camera is placed close to the laser spot on the sample surface to have an appropriate view angle. Taking the picture of the scattered light intensity distribution, the total amount of the scattered intensity is calculated by the image processing techniques. In the following, the dependency of the surface scattering to the illumination angle is investigated.

In the next step, theoretical approach that was suggested by Beckmann which correlates the intensity of scattered light with surface parameters i.e. roughness and correlation length was utilized to extract the surface features. Then by inserting the intensity data of the experiments in the Beckmann formula, the surface RMS and T parameter could be extracted. AFM microscopy is also assessed to evaluate the precision of the determined values. Due to the simplicity and accuracy, this method seems to have enough potential to be used in the on-line investigations.

10329-140, Session PS1

Universal dynamic goniometer for rotary encoders

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A precise evaluation of geometrical parameters of parts and mechanical components is an up-to-date problem. It is necessary to develop easy designed dynamic goniometers with high resolution. The majority of systems used for measuring parameters of angular movement based on the method of a polygon mirror. This classic measuring method to determine the encoder error has a resolution limit. The limit depends on the amount of the polygon edges. In general this method is relatively time-consuming. The encoder error depends on the angular position. For this reason multiple measurements of the measured angle has to take place. The development of a dynamic goniometer on the basis of high-precision optical rotary encoders or a ring laser is the next scientific effort in the field of technology. The method provides high performance of measurements for a large number of controlled positions. One problem of this measuring principle is a coupling method of the rotation axis of the reference rotary encoder with a rotary axis of rotary encoder under test. A precise compensation coupling device has to be used to connect two rotary encoders to minimise the coupling errors. These coupling devices have errors itself and it is problematic to consider their influence to the entire process accuracy. For this reason, the concept of designing a modern dynamic goniometer has been revised: removing of the compensation coupling [1]. The compensation coupling has two principal functions: transmit the rotation angle and compensate the radial runout. The transmission of the rotation angle could be done with a rigid coupling by connecting one shaft with the other. For dynamic goniometers new constructions have been designed called compensation coupling devices [2]. Those devices based on the constructing principles of the compensation coupling and they are assembled at the case of one encoder. Furthermore the coupling device is moveable and does not rotate around the rotation axis of the rotary encoder. That allows registering the spatial position of the rotary encoder at any time with a digital autocollimator. It is also possible to optimise the measured accuracy of the rotary encoder. At the moment this is not feasible with a goniometer with compensation coupling.

Research tests have confirmed the opportunity to use the coupling devices for angular measurements and high efficiency of the compensating method of encoder errors. That shows great options for future optimisation of dynamic goniometer and increases its measured accuracy to less than 1% of an angular second. The developed dynamic goniometer together with the proposed correcting method for instrumental and systematic errors, reduce the requirements for the production and the assembly of the elements of goniometers, increase the accuracy of the calibration and reduce the time consumption for measurement preparations. The time saving is achieved because it becomes unnecessary to determine the errors of the compensation coupling itself and the angle transmission of the rotation axis of the reference and the rotary encoder under test.

The set-up of the goniometer considers all constructive and informative characteristics of measured encoders. The design of the novel goniometer is suitable for common models of all kind of rotary (angle) encoders, step motors and servo motors.

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10329-141, Session PS1

Estimation of clearances in the design and adjustment of the lens

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Estimation of probable clearances in the fit of the installed lenses and the impact from mounting and adjustment of units on system alignment and the resulting imaging quality has been considered. The characters of dispersion fields and acceptable deviations in mating dimensions of parts and their allowance have been analyzed for the estimation of probable clearances. Very commonly existing deviations in the clearances have a considerable systematic component due to systematic components of errors in the mated dimensions of parts. It has been shown that the assembly of lens based optical systems in horizontal position of its body allows vast reduction of the impact given by clearances on the accuracy of the alignment of the lens parts as compared to assembly in vertical position of its body, as in the this case the lens misalignment is due to errors in the diameters of lens components. For the adjustment of the quality of the image generated by the optical system it is necessary to take into account both the impact from misalignment of lens components on edge and central aberrations of the image field.

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10329-142, Session PS1

Self tunable phase shifting algorithm for images with additive noise

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Phase-shifting (PS) is a well-established technique for phase retrieval in interferometry (and three-dimensional [3D] profiling by fringe projection) that requires a series of intensity measurements with known or unknown phase-steps. The intensity measurements Ik(x,y)(with k=1,2,...,N) are given by

Ik(x,y)=I0(x,y)[1+K(x,y)cos(?(x,y)+k?)]+nk(x,y),

where (x,y) are Cartesian coordinates, I0(x,y) is the mean intensity, K(x,y) is the contrast, ?(x,y)is the phase to be retrieved,? is the phase-step, and nk(x,y) is the additive noise.

We will take the case where the phase-step is unknown. The objective of this work is determinate a self-tunable PS algorithm that minimize the error in the reconstructed phase when the images have additive random noise.

The algorithm works as a nonlinear phase-step estimator first, and then, with the calculated phase-step, a linear tunable PS algorithm is applied. The phase-step estimator and the PS algorithmare designed to minimize the propagation of the additive noise.

The phase-step estimator is based in a novel ellipse fitting that we will show is quite insensitiveto noise. The method is easy to implement and it works well still with very small signal-to-noise ratios (SNR), e.g. SNR ≈ 0.1 or even smaller.

The linear tunable PS algorithm is based in a previous work in witch we deduce the algorithm that minimize the noise propagation for images with certain phase-steps. [1,2]

Simulations to show the performance of the algorithm will be presented.

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10329-143, Session PS1

Revealing features of different optical shaping technologies by a point diffraction interferometer

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Low-frequency and mid-frequency features left on an optical surface after final processing can characterize what way of shaping had been used. It is evident that hardly the same technology is suitable for fabrication medium precision optics of wavelength/4 – wavelength/20 and highest precision optics of wavelength/40 and better. The target of the paper is to eliminate probable preconception about ability of such peculiar tool as a point diffraction interferometer to display the map of a surface under test (SUT) both with low- and mid-frequency defects. This sub-nanometer accuracy tool is mostly engaged to display the figure of a surface or wavefront with paying attention to low-frequency profiling. Such technique is suited to EUV or X-ray optics testing. Nevertheless the tool, considered in the paper, detects characteristic features upon the SUT which disclose either grinding or diamond turning had been used to form the substrate.

In the paper there are given examples of inspecting surfaces polished after grinding and diamond turning. The inspected surfaces after diamond turning had different quality – better and worse – so that different views of them could help reveal technological specifics. For the surface inspection we used the Bruker GT-I white light interferometer and the point diffraction interferometer D7. It is important that in point diffraction interferometers stray interference is a very blurring effect making fine-structure details of the SUT difficult to notice. This happens because of intermediate stray images appearing due to high coherence and large angles of incidence of rays inside the high aperture imaging optics. As a rule, in practice of exploiting point diffraction interferometers mostly fine surfaces are measured and therefore no high- and mid-frequency effects are under consideration. Such effects are ignored using low-band filters in fringe pattern processing, so that neither stray interference artifacts nor mid-frequency features of the SUT remain in measurement results. In the interferometer D7 there is used optical ZOOM system with different magnifications of mid-frequency defects, and also a special hardware means for damping stray interference effect in the imaging system. The CCD camera resolution is sufficient to display tens of micrometer sized features under an appropriate ZOOM setting.

Results obtained by both interferometers differ from each other in resolution and scale. The errors detected by the white light interferometer are drawn with micrometer (x, y) resolution giving tens nanometers for the hights of irregularities. Similar hights of irregularities are detected by the point diffraction interferometer except that (x, y) resolution is tens micrometers. In addition this interferometer notices some profile features ultimately characterizing diamond turning but are invisible for the white light interferometer because of low field of view (FOV) available to it at once. In contrary to the white light interferometer the D7 with large FOV can observe much greater part of the SUT and detect alternate diamond turning effects.

Results of inspection by both kinds of interferometers are given in the paper with analyzing advantages of using the point diffraction interferometer in observing simultaneously low- and mid-size features. We conclude this may help avoid incorrect decisions at the first stage of shape forming before final polishing.

10329-144, Session PS1

Pointwise intensity-based dynamic speckle analysis with binary patterns

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Non-destructive detection of physical or biological activity through statistical processing of speckle patterns on the surface of diffusely reflecting objects is a perspective branch in optical metrology [1]. Dynamic laser speckle method is sensitive to microscopic changes of the surface over time and needs simple optical means. Technological advances in computers and optical sensors made possible pointwise processing of a temporal sequence of correlated speckle images. The output is a 2D spatial contour map of the estimate of a given statistical parameter chosen to characterize activity. The most popular pointwise estimates are the intensity-based estimates due to simple acquisition of the raw data [2,3]. They build each map entry from a time sequence of intensity values taken at one and the same pixel in the acquired speckle images. Efficiency of the pointwise intensity-based approach is strongly deteriorated by the signal-dependent nature of the speckle data, non-uniform illumination and the limited number of the acquired speckle patterns. As a whole, processing is qualitative and allows only for indicating regions of higher or lower activity. Therefore, search of new algorithms with a narrow spread of fluctuations of the estimates they produce, reliable performance at non-uniform illumination and a quantitative output is a pressing task.

We propose to transform the acquired speckle images into binary patterns by using for a sign threshold the mean intensity value estimated at each spatial point from the temporal sequence corresponding to this point. In this case, activity is characterized by the 2D distribution of a polar correlation function estimated at a given time lag from the formed binary patterns. The preliminary results confirmed that, besides the accelerated computation, the algorithm provided correct activity determination at non-uniform distribution of intensity in the illuminating laser beam without the necessity to apply normalization. This study considers statistical properties of the introduced new estimate. Firstly, to check efficiency of the applied threshold, we found distributions of the temporal intensity fluctuations around the mean intensity value in spatial regions of different activity. Secondly, we built the probability density functions of the estimate of the polar correlation function for spatially varying activity and compared them to the distributions obtained for the normalized correlation function. Calculation of the latter required at each point not only evaluation of the mean intensity value but also calculation of the intensity variance. As a third task, we evaluated ability of the proposed algorithm for quantitative characterization of activity through applying a smoothing filter to the output activity map. Filtering is a tricky task in view of the activity dependent spread of probability density function of the estimate of the polar correlation function similarly to all intensity-based estimates [2]. The fourth task was to determine the minimum required number of captured speckle images for reliable evaluation of activity. When it is small, this number of patterns has a strong impact on accuracy. Statistical analysis was made by using synthetic speckle patterns. Efficiency of the algorithm was also checked by applying it to experimental data.

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10329-145, Session PS1

Full-field wafer warpage measurement technique

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Light-emitting diodes (LEDs) are the preferred light source in many lighting application fields, due to their high flux efficiency, low power consumption, and long operation life. LED wafers are usually manufactured using metal organic chemical vapor deposition, wherein temperatures can reach 1000 °C. Under these conditions, thermal stress and intrinsic stress often leads to wafer warpage. Warpage will compromise uniformity and the quality of the resulting LEDs wafers. This shows the significance of monitoring wafer warpage in real-time during the manufacturing process in order to adjust the growth procedures with the aim of eliminating warpage.

An innovative moiré technique for full-field wafer warpage measurement is proposed in this study. The wafer warpage measurement technique is developed based on moiré method, Talbot effect, scanning profiling method, stroboscopic, instantaneous phase-shift method, as well as four-step phase shift method, and high resolution, high stability and full-field measurement capabilities can be easily achieved. According to the proposed full-field optical configuration, a laser beam is expanded into a collimated beam with a 2 inch diameter and projected onto the wafer surface. The beam is reflected by the wafer surface and forms a moiré fringe image after passing two circular gratings, which is then imaged and captured on a CCD camera for computation using a self-developed image analysis module. The corresponding moiré fringes reflected from the wafer surface are obtained by overlapping the images of the measuring grating and the reference grating. The moiré fringes will shift when wafer warpage occurs. The phase of the moiré fringes will change proportionally to the degree of warpage in the wafer, which can be measured by detecting variations in the phase shift of the moiré fringes in each detection points on the surface of the entire wafer. The phase shift variations of each detection points can be calculated via the instantaneous phase-shift method and the four-step phase-shift method. By adding up the phase shift variations of each detection points along the radii of the circular gratings, the warpage value and surface topography of the wafer can be obtained. Measurement resolution can be controlled by adjusting the pitch size of the circular grating or the focal length of the focusing lens.

Experimental results demonstrate that the proposed technique is capable of measuring wafer warpage and surface topography. As can be found from the experimental results, the proposed method is able to achieve angular resolution of approximately 0.2 μrad. The minimum relative warpage value that can be detected is approximately 0.04 ?m under the experimental conditions of 200 ?m grating pitch and 150 mm focal length of the focusing lens. The proposed measurement device can be mounted directly on the equipment under test or the outside of the testing chamber, avoiding adverse effects on the quality of epitaxial wafer fabrication. As compared to current warpage measurement methods such as the beam optical method, confocal microscopy, laser interferometry, shadow moiré method, and structured light method, this proposed technique has the advantage of full-field measurement, high resolution, stability and adaptability.

10329-146, Session PS1

On the issue of creating a movable housing for the encoder alignment axis of rotation and correction angle

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In modern science and industry commonly used variety encoders. They are used in set of different measuring structures, control systems, robotized complexes, metal working and other machines. In general terms, the encoder consists of two parts - a stationary housing and a rotating cylindrical solid or hollow shaft. There were widespread encoders with hollow shaft and the inclusion of a compensation coupling. The presence of coupling the encoder simplifies its installation. For example, on the machine, allows the axis of rotation of the encoder with small shifts and at small angles to the axis of the machine without losing functionality of the encoder. Another way to solve the problem by simplifying installation while retaining high measurement accuracy can be the use of an encoder with movable housing and rotating shaft. The idea of work consists in replace the built-in encoder compensating coupling to the compensation housing.

It gives several alignments:

- The housing gives possibilities to correction a measuring results;
- The housing gives great opportunity to shift than coupling and saves the measurements accuracy.

The experiment results make it possible to talk about realization moveable self-compensation encoder`s housing. At this moment encoder case is enough compact but error correction can be possible only with optical measurement devices. The main direction of the current work is to try to create a complete and all-sufficient encoder's housing which will include all necessary sensors to determine the displacement of the housing parts during work, without using additional measurement devices. This is the only solution to create a compact and high precision encoder.

The reduction of the measuring errors will not only be done exclusively with modern electronic methods, such as test data interpolation, but also by hardware corrections.

10329-147, Session PS1

Vibration compensated high-resolution scanning white-light Linnik-interferometer

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Scanning white-light interferometers (SWLI) are well-established optical instruments for 3D measurement of micro- and nanostructures. The measuring procedure is based on a so-called depth scan, whereby the distance between the interferometer and the specimen varies continuously. During this scanning process, a camera captures several hundred images at equidistant axial positions. By evaluation of the interference contrast and phase of the signal from each camera pixel along the scanning direction, the 3D topography is obtained. The measurement accuracy in sub nanometer range can be reached under laboratory conditions. In presence of environmental vibrations the accuracy decreases rapidly till no usable results can be obtained.

To overcome the problem of vibrations on measurement results we developed a passive vibration compensation technique to minimize measurement uncertainty even in presence of high mechanical distortions. The particular feature of this technique is a combination of SLWI and distance measuring interferometer (DMI) in the same optical path and usage of the common oscillating reference mirror for white-light as well as for distance measurements inside the same field of view. This approach was already successfully realized in a Michelson SWLI with low magnification and resolution (5x, NA=0.14) and was verified in presence of artificial vibrations generated in the laboratory as well as on the shop-floor level inside a fatigue testing machine [1, 2].

In this contribution we present a high-resolution Linnik-interferometer with integrated DMI. The distance, measured by DMI during the depth-scan, is used for vibration compensation of SWLI signals. This system is the further development of our previously presented Michelson-interferometer. Each technical feature was improved significantly. We increased the lateral resolution by a factor of 4 by using of 50x, NA=0.55 objective lenses. The distance acquisition rate increased from 2 kHz to 40 kHz. For image acquisition we use a camera providing 500 fps instead of 60. But also the signal evaluation was subjected of different improvements and optimizations. We perform a real-time SWLI signal preprocessing on GPU during the depth-scan. This enables to reduce the amount of data to the constant size independent on the scan range and to decrease the subsequent signal correction and evaluation time significantly.

With this system we are able to compensate for arbitrary vibrations up to several kilohertz and amplitudes in a lower micrometer range. Completely distorted SWLI signals can be reconstructed and the surface topography can be obtained with high accuracy. We demonstrate the feasibility of the method by examples of practical measurements with and without vibrational disturbances.

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10329-148, Session PS1

Modern approaches for optical multisensor systems design

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One of the main trends in modern device engineering is integration of multiple sensors in one network. Such distributed systems in optical devices are used in many problems from closed-circuit television to navigation systems for automatic transport and spherical cameras. All of those systems are characterized by operating with data cannot be obtained from single device.

Depending on purposes of distributed system there are various possible architectures, but the set of their structural elements is permanent, regardless of their designation. The main structural elements are: sensors, data transmission channels and data processing units.

The main purpose of this paper is developing the most complete systematization of possible distributed systems of optical devices topology types depending on their designation.

Research described in this paper was done as a part of research and development of swarming visual sensor network for multiple object tracking. In this paper, the review on different types of distributed systems topologies was done. For each reviewed system architecture advantages and disadvantages were shown. Depending on mechanism for producing output data optimal system topologies and their applicability were proposed. Analysis shown in this paper can be useful for better understanding the distributed system design and optimal data processing mechanism development.

10329-149, Session PS1

Features of the estimation of temperature distribution on the bead formed by the laser aided metal powder deposition

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The diagnostics of the dynamics of the laser radiation effect on the melt in the process of the bead formation during laser aided metal powder deposition is critical to correlate process parameters to microstructural evolution.

The multisensor spectral ratio pyrometer with a bundle of optical fibers was used to estimate the distribution of the temperature on the bead formed by the laser aided metal powder deposition. The setup comprised CO_2 laser with output power up to 1800 W. The substrate surface was illuminated by laser radiation with uniform distribution and spot diameter 1.8 mm while using the lens with focus distance of 300 mm. Part of the experiments was carried out with use of gauss-shaped radiation with the spot size of the 0.47 mm using the ZnSe lens of 190 mm focus. The powders of two types were utilized: PG-S27 (40Cr28Ni2WMo) and PR3-20CrNiMo (4320 steel analog) of different granulometric composition.

The lined-up end faces of the optical fibers were located at the place of image formation by the pyrometer lens of the heated surface. Fibers with an inner diameter of 50 μm were located at a distance of 0.3 mm from each other. The thermal radiation from the area of about 100 μm transferred through one of the five optical fibers and illuminated corresponding two-color sensor of InGaAs -photodiodes. The temperature data digitizing sampling rate was 10 kHz in each channel.

The dependences of temperature behavior in five points of the forming bead on the scanning speed, laser power and powder flow rate are obtained. Number of measurements of the temperature distribution in the area of the bead formation during laser aided metal powder deposition was carried out with the specific energy input value up to J = 90 MJ/kg.

It is shown that the temperature in the region of laser radiation action is changed slightly in the wide range of estimated specific energy input J = 4...20 MJ/kg, while the width of the bead increases with J growth. Increasing J above a certain threshold J1 leads to an increase of the temperature on the axis of the bead. The evaluation of J1 = 24 MJ/kg is obtained for certain experimental conditions. It is shown that the threshold J1 depends on the width of the track. A narrow bead of about 0.65 mm width was formed in the case of small powder PG-S27-M flow rate and the corresponding value of J = 45 MJ/kg was lower than J1 for certain thickness of the bead. The range of the measured temperature data variation in the heated area is not exceeded ±180°C.

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10329-150, Session PS1

Optical fiber sensors measurement system and special fibers improvement

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We present method for the improvement of the measurement accuracy in the optical frequency spectra measurements based on tunable optical filters. The optical filter was used during the design and realization of the measurement system for the inspection of the fibre Bragg gratings. The system incorporates a reference block for the compensation of environmental influences, an interferometric verification subsystem and a PC - based control software implemented in LabView. The preliminary experimental verification of the measurement principle and the measurement system functionality were carried out on a testing rig with a specially prepared concrete console in the UJV ?e?. The presented system is the laboratory version of the special nuclear power plant containment shape deformation measurement system which was installed in the power plant Temelin during last year.

On the base of this research we started with preparation other optical fiber sensors to nuclear power plants measurement. These sensors will be based on the microstructured and polarization maintaining optical fibers. We started with development of new methods and techniques of the splicing and shaping optical fibers. We are able to made optical tapers from ultra-short called adiabatic with length around 400 um up to long tapers with length up to 6 millimeters.

We developed new techniques of splicing standard Single Mode (SM) and Multimode (MM) optical fibers and splicing of optical fibers with different diameters in the wavelength range from 532 to 1550 nm. Together with development these techniques we prepared other techniques to splicing and shaping special optical fibers like as Polarization-Maintaining (PM) or hollow core Photonic Crystal Fiber (PCF) and theirs cross splicing methods with focus to minimalize backreflection and attenuation. The splicing special optical fibers especially PCF fibers with standard telecommunication and other SM fibers can be done by our developed techniques. Adjustment of the splicing process has to be prepared for any new optical fibers and new fibers combinations. The splicing of the same types of fibers from different manufacturers can be adjusted by several tested changes in the splicing process. We are able to splice PCF with standard telecommunication fiber with attenuation up to 1 dB. The method is also presented.

Development of these new techniques and methods of the optical fibers splicing are made with respect to using these fibers to another research and development in the field of optical fibers sensors, laser frequency stabilization and laser interferometry based on optical fibers. Especially for the field of laser frequency stabilization we developed and present new techniques to closing microstructured fibers with gases inside.

10329-151, Session PS1

Broadband interferometric characterisation of nanopositioning stages with sub-10 pm resolution

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Ultraprecision nano-positioning stages with displacement resolutions down to sub-100 pm belong to the essential components of metrological instruments for nanomechanical and nanodimensional surface characterization at the atomic scale. Especially for nanomechanical measurements based upon dynamic nanoindentation, it is required that the ultraprecision stage should have adequate bandwidth (e.g. up to kHz). For the quality control of these stages, traceable displacement measurement approaches with a resolution down to sub-10 pm and relatively broad bandwidth are therefore required.

In this abstract, a reliable calibration setup for investigation of the quasi-static and the dynamic performance of nano-positioning stages has been established in our laboratory. As one of key components of the calibration setup, a differential plane-mirror interferometer with double-pass configuration from the National Physical Laboratory (NPL) [1] is utilized to measurement the displacement of a nano-positioning stage.

The laser light (? = 632.8 nm) coming from a frequency-stabilized He-Ne laser (SOIS GmbH) is firstly coupled into a polarisation-maintaining single-mode fiber and then delivered to the interferometric calibration setup, enabling high flexibility of the calibration system. To further reduce the potential systematic errors, the mechanical system of the calibration setup has been well designed so that the interferometric measurement system has zero-path difference.

The phase-quadrature interferometer signals (i.e. sin and cos) are acquired by a FPGA data acquisition (DAQ) board (National Instruments, 16 Bits) with the DAQ sampling rate of 250 kHz, and decoded by a LabView-based program. Here the Heydemann correction [2] is intergrated into the decoding program for the purpose of nonlinear correction of the interferometer signals. The fast DAQ hardware and decoding algorithm enables fast interferometric calibration of nano-positioning stages with a high resolution and broad bandwidth.

To investigate the frequency-response of a nano-positioning stage, an AC signal coming from a function generator (e.g. AFG 3022, TekTronix) is used to drive the nano-stage. This modulation signal is simultaneously sent to a Lock-in amplifier (SR 830, Stanford Research) as reference signal. The interferometric readout of the stage movement is sent to the input of the Lock-in amplifierfor further analysis. This DSP lock-in amplifier allows a modulation signal with the operating frequency ranging from 1 mHz to 102 kHz and down to 100 dB of drift-fre dynamic reserve, can therefore be used for quatitative characterization of both quasi-static and dynamic performance of a nano-positioning stage.

First experimental results have proven that the calibration setup can achieve under nearly open-air conditions a resolution of 14 pm and a noise floor of 10 pm/sqrt(Hz) over a 2 Hz bandwidth. A pico-positioning stage, which is used in the PTB for nanoindentation with indentation depths down to a few pico-meter, has been characterized with this calibration setup, and the measurement results together with the uncertainty budget will be reported. Further improvement of the calibration system concerning bandwidth will be outlined.

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10329-152, Session PS1

Optical measurement system to determine the tool center point in ultraprecision shaping

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In ultra-precision machining tools are mainly made of natural or artificial diamonds with geometrically defined cutting edges. For fly cutting tools the polished diamonds are glued or soldered onto ?" metal shanks. Fly cutting is normally used for generating optical surfaces or linear grooving and therefore a defined lateral position of the diamond on the shank is not necessary and also the varying thickness from several hundreds of microns till several millimeters does not count. Compared to fly cutting, shaping has non-rotational tools which are pushed directly through the surface of the workpiece. Shaping is enabled for bidirectional structuring and for generating grooves which follow arbitrary curvatures. The tools are mounted on an indexed spindle axis in order to position the cutting edge in shaping direction. Therefore, the position of the tool tip is crucial for the contour accuracy of the shaped surface and should be on the rotation axis of the spindle. An alignment is realized by an additional XY-stage to center the tool tip according to the rotation axis.

In this work, an optical measurement system for determining the lateral misalignment of the tool tip according to the rotation axis is presented. The developed measurement system consists of a camera with optics and a blue backlight concerning the absorption spectrum of diamonds. It is integrated into the ultra-precision shaping machine. The X-axis of the machine is used for focusing while the Z-axis is for adjusting the height of the tool tip in the camera image. The misalignment between the machining and the camera coordinate system is compensated by a lookup table. The basic principle is the measurement of the tool tip in the camera image at four positions (0°, 90°, 180° and 270°) by positioning the tool with the spindle. By comparing the opposite positions, orientation and lateral misalignment of the tool tip in the orthogonal plane to the rotational axis can be calculated. At the beginning of each measurement the cutting face of the tool must be aligned parallel to the image plane of the camera system. This is done by an initial autofocus to move the tool into the focal plane, afterwards the tool is slightly rotated with the spindle and an autofocus algorithm is used for calculating the tilt angle of the cutting plane towards the image sensor plane. The evaluation of a single position of a tool tip is then effected by means of digital image processing algorithms (edge filter and Hough transform) combined with the correlating position on the linear axis defined by an autofocus. By comparing the results of the image at 0° to 180° and 90° to 270° the lateral misalignment in the plane orthogonal to the rotation axis is calculated. An accuracy of the whole measurement system in the submicron range is achieved. In addition, the height and orientation of the tool tip in the camera plane is also defined and thus the tool is completely registered in the coordinate system of the ultra-precision shaping machine.

10329-153, Session PS1

Signal-to-noise ratio for mode-mode fiber interferometer

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Mode-mode fiber interferometer (MFI) is one of fiber optic sensors types. Its operation principle is based on measuring of the speckle pattern changes at the output of a multimode optical fiber (MMF). One of important MFI characteristics is signal to noise ratio (SNR). However, in our opinion, it is investigated only partially and not enough [1]. In this work, we present modelling results of SNR using averaged amplitude characteristics method [2, 3]. For this purpose, let us write the SNR expression for MFI with coherent laser source and interference contrast close to unity:

SNR=S/(N_s+N_t+N_I+N_RIN+N_p)

Where S=(s?P??ACH?_I (?L_s))^2 – sensor signal, s – photo detector sensitivity [A/W], P – averaged optical signal power, ?Ls – fiber length change as a result of external fiber perturbations, ACHI – intensity MFI response for fiber length change, so called "amplitude characteristic" [2]. Amplitude characteristics depend on various MMF parameters such as number of propagating modes, fiber profile parameter, etc. N_s=2?e??f(s?P+I_D) – shot noise of optical signal and dark current ID. N_t=4Δf(kT⁄R) – thermal noise of photo diode load resistor R. Ns and Nt can be neglected for typical parameters of the MFI sensor detection scheme. N_RIN=(s?P)^2 RIN??f – relative intensity noise of the laser for bandwidth ?f. ?N_I=(s?P??ACH?_? (??_n))?^2 – noise caused by parasitic laser frequency fluctuations ??n which can be characterized by ?orresponding amplitude characteristic ?ACH?_? (??_n). ?N_p=(s?P??ACH?_I (?L_n))?^2 ?f – noise, caused by parasitic fiber length fluctuations [3].

Thus neglecting Ns and Nt components and reducing the multiplier (sP)2 the SNR can be written as

SNR=(?ACH?_I (??L?_s))^2/((?ACH?_? (????_n))^(2)+(RIN?Δf)+(?ACH?_I (??L?_n))^2?Δf)

This equation can be analyzed for different cases of MFI operating modes.

First of all let us consider the simplest case when laser frequency noise and parasitic fiber length fluctuations can be neglected, so (RIN?Δf) >> (?ACH?_? (????_n))^(2)+(?ACH?_I (??L?_n))^2?Δf. In fig. 1 are represented SNR dependency from signal amplitude ?L_s for different amount of propagating modes in parabolic MMF (fig. 1 (a)), from fiber profile parameter ? for different amount of propagating modes (fig. 1 (b)) and from amount of propagating modes for different signal amplitudes ?L_s (fig. 1 (c)). As it can be seen in fig. 1 SNR significantly depends on signal amplitude, amount of propagating modes, and fiber profile parameter (especially for lower number of propagating modes).

Another case is SNR with consideration of laser frequency noise as the most common situation of MFI operation. Fig. 2 demonstrates SNR dependency from fiber profile parameter (fig 2 (a)) and from laser frequency fluctuations amplitude (fig. 2 (b)). In particular, it can be seen from fig. 2(a) that SNR is the greatest (>103) for the case of parabolic fiber profile while it is dozens times less for step-index MMF. Fig 2(b) shows significant SNR decrease when laser frequency fluctuations amplitude exceed a certain value.

Thus, in this work SNR for MFI was analyzed using MFI amplitude characteristics method approach. This approach allows to perform effective and detailed analysis of MFI SNR with respect to important MFI parameters (fiber profile parameter, amount of propagating modes, laser noise parameters etc.) The analysis demonstrates the need of correct MMF (with maximal frequency band) and laser (with minimal RIN) choice for achievement of maximal SNR (>103).

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10329-154, Session PS1

A layout of faceted multichanneled electro-optical spatial coordinates measuring instrument for point-like bright objects

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As is generally known, problems related to opportunities of obtaining information about environment within large spatial areas were and remain important for solution different practical tasks. These tasks may include, for example, searching for small ignitions which give rise to large fires, searching for missing persons in the vast terrain with the help of aviation, problems solved security systems.

Obviously, such a device must have high speed, sensitivity and accuracy.

And they must have a minimum possible size and weight.

There are so many methods of obtaining information with the help of electro-optical systems which operating over a wide angular field: mechanically scanned area, static systems with special lens panoramic round view, which allows to obtain an image of the annular zone.

An alternative approach is to implement a multi-channel system with a discrete angular field and potentially high sensitivity to movement of objects. Implementation of such a system design is to place an array of photodetectors in a certain way on the surface, which is not flat (for example, this may be spherical or cylindrical surface). Thus, design of the electro-optical system with a discrete angular field imitates the visual apparatus of insects.

Multi-channel system with a discrete angular field may have a number of advantages:

– a large (up to a full sphere) angular field;

– a feature of stereoscopy (because the information comes from multiple channels, located at different distances from the object and with various orientations relative to this object);

– a specific construction, where it is possible to implement the angular fields overlap of adjacent channels, as well as to increase the area of the entrance pupil (which allows energy and information advantage);

– potentially high sensitivity to movement of objects, since if photodetectors have the small size and high density in their arrangement, that with a small moving of the object perception moves to adjacent photodetectors of the array of sensors;

– potentially small size of system, since it is not involve the use of large optical components;

The aim of this work is to implement the layout of facet type multi-channel electro-optical system for measuring coordinates of point targets, as well as the development of the operation algorithm of this system. Each channel is represented by a photodiode in conjunction with lens.

In the course of this work an analytical review of existing analogs was carried out. It was shown that there were only a few experimental samples, which may be used in endoscopy, systems vision of robots, aerial photography, in security systems.

Mathematical models of the multi-channel electro-optical system were developed. So, a preliminary layout of the system with three photodetectors channels consisted of by photodiodes in conjunction with the lens (to establish a minimum number of channels for a clear definition of the position of object) was created for developing raw data. Electrical connection circuit and calibration program for layout were designed. So, the dependence of signal from the position of the radiation source in space was obtained.

An algorithm to determine the position of the radiation source was implemented using three calibration matrices. Configuration features in the used arrangement of photodiodes were investigated with the help of this algorithm. The advantages and disadvantages of used amplification circuits were practically evaluated as well. In addition, the three-dimensional model of the structure in which photodiodes are placed on the surface of the sphere had been developed.

10329-155, Session PS1

Wide-angle solar-blind UV optical system for power transmission line monitoring

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Ultraviolet sensors and their applications are one of the most fast-growing areas in optical devices. This is due to the fact that some industrial, medical, ecological and otherproblems can be effectively resolved through sensors of ultra violet spectral range.

In particular such systems are widely used for monitoring of air lines electricity transmissions because it allows to record glow of corona discharges and find accident-prone lots beforehand.

When installing the equipment on the aircraft it is possible promptly evaluate the technical condition of the stretches electricity transmissions. The multispectral optical electronic system was designed and assembled by the branch of JSC “PA” UOMZ” in St. Petersburg “Ural-GOI”. This system was intended for automatic operational control of power transmission lines technical condition. During the inspection of power transmission lines, anomalously bright light sources in ultraviolet and infrared region of the spectrum are detected and registered.

In this paper, experimental data of corona discharge monitoring optical system prototype are shown. Measurement data ofultraviolet source signal level using different receivers and optical band-pass ultraviolet filters were presented.Analysis was conducted and elementsoptimal configuration requirements ofpower transmission linesteleediagnosisoptical electronic systems were developed.

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Analysis and 3D inspection system of drill holes in aeronautical surfaces

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Nowadays the companies are subjected to a constant pressure to improve the quality of the products that they manufacture, as well as the efficiency in the production procedures. In this competition the final position reached, will establish the market share and, in a long term, the everlasting of the company.

In the industry, the significant magnitudes of the manufactured parts are denoted using a value and a tolerance. The tolerance stablishes the range where the value of the magnitude is admissible in the manufacturing process. The values of the tolerances are defined in the design process and they depend on the parameters such as the materials used in the process, the assembly of them as well as from the systems used in the final inspection process. Reducing the manufacturing tolerances results in more reliable parts, less investment in manual adjustment operations in the final assembly, and increasing the added value of final products. The advantage is both technical and economic.

The investment in the quality control processes and the reduction of the range of tolerances have become a priority for the industry, especially in those were the final products have a high added value, like aerospace industry, or where the product requirements are focused in the reliability, like automotive industry.

In aerospace industry, the structure of the aircraft is assembled using a small part or a combination of them that are made with different materials, such as for instance aluminium, titanium or composites. The union between these small parts is a critical point for the integrity of the aircraft. The quality of this union will decide the fatigue of adjacent components and therefore the useful life of them. For the union process the most extended method is the rivets, mainly because their low cost and easy manufacturing. For this purpose it is necessary to made drill holes in the aeronautical surface to insert the rivets.

In this contribution, we present a 3D inspection system [1] for drill holes analysis in aeronautical surfaces. The system, based in optical triangulation, was developed by the Group of Optoelectronic Image Processing from the University of Valencia in the framework of the Airbus Defence and Space, MINERVA project (Manufacturing industrial - means emerging from validated automation). The capabilities of the system permits the end user to generate a point cloud with 3D information and GD&T (geometrical dimensions and tolerances) characteristics of the drill hole. For the inner surface defects detection, the system can generate an inner image of the drill hole with a scaled axis to obtain the defect position. In addition, we present the GR&r (gauge reproducibility and repeatability) analysis performed for the drills in the wing station (STATION 72) of the A-400 M in Sevilla. In this analysis the system was tested for diameters in the range of [10 – 15.96] mm, and with three different materials (Carbon Fibre, Titanium and Aluminium) and a combination of them.

1. European Patent: No.15 382237.4, US Patent: US 2016/0327775 A1

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Measuring horizontal atmospheric turbulence at ground level from optical turbulence generator (OTG) over a 1D sensor

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Different theories including Kolmogorov have been valid to explain and model physic phenomenal like vertical atmospheric turbulence. In horizontal path, we still have many questions, due to weather problems and consequences that it generates. To emulate some conditions of environment, we built an Optical Turbulence Generator (OTG) having spatial, humidity and temperature, measurements that were captured in the same time from optical synchronization. This development was made using digital modules as ADC (Analog to Digital Converters) and communications protocol as SPI. We all made from microcontrollers. On the other hand, to measure optical signal, we used a photomultiplier tube (PMT) where captured the intensity of fringes that shifted with a known frequency.

Outcomes show temporal shift and phase drive from dependent samples (in time domain) that correspond with frozen turbulence given by Taylor theory. Parameters studied were , scintillation and inner scale in temporal patterns and analysis of their relationship with the physical associated variables. These patterns were taken from Young Interferometer in laboratory room scale. In the future, we hope with these studies, we will can implement an experiment to characterize atmospheric turbulence in a long distance, placed in the equatorial weather zone.

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Absolute measurement of surface figure of rotationally symmetrical aspheric surfaces

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Optical metrology is a critical and complicated technique for the fabrication of the aspheric optics which are tested interferometrically with refractive, diffractive, or hybrid null optics systems. It shall calibrate the errors of the experimental setup including intrinsic systematic error. Nevertheless, the measured consequence also includes surface deformation caused by mounting supporter and gravity effect, which may result in a misleading judgment for surface figure correction. This study proposes an absolute measurement methodology for the aspheric surface which can identify the manufacturing form error, and gravity and mounting resulted distortions. This method adopts the frequency of peaks and valleys of each Zernike coefficient grabbed by the measurement with various orientations of the mirror in horizontal optical-axis configuration. In the end of this study, we will experimentally verify the proposed absolute measurements by using different experimental test configuration and mounting mechanism for the optic

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The analysis of methods to calculate the measurement error of coordinates for optical-electronic system for real-time position control of roof's supporting structure

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The paper reports the results of computing and physical modeling of measurement optical-electronic system for real-time position control of extended objects with an active tags. We proposed an original method for solving systems of differential equations to calculate the coordinates of the objects. We offer an original multichannel monitoring optical-electronic system based on orthogonal channels. We create the physical model of this system for controlling the position of the pool's roof.

During the construction and operation of extensive engineering facilities is particularly important task of monitoring their spatial position in real time. This task is often complicated by variable external conditions, fluctuations in ambient temperature, humidity, wind speed, level of background illumination, etc.

To solve these problems, we can use the optical-electronic systems based on triangulation scheme, they have undoubted advantages: high accuracy, simplicity and cheapness. There is the resection method, built on a single triangulation scheme with a "made base" chosen for controlling the position of the supporting structure elements of the pool's roof .

The elements of the bearing structure of the roof with a certain step are fitting out by several active targets bases of three infrared LEDs. Targets radiation is captured by two or more cameras installed in order to see all the targets. The structural system consists of active targets on the test object, the lens, the matrix analyzer, the coupler and the computer, allowing you to measure linear and angular displacement of the object.

To calculate the coordinates of the active targets and identify measurement errors we need to solving the system of equations, which associates the position of the targets in the space and their images on the matrix analyzer. The result of solving the system of equations are six parameters: three angular coordinates of the object, three linear coordinates. In the General case the system of equations does not have an analytical solution but can be solved numerically by iteration method.

In analysis of methods for solving system of nonlinear differential equations we considered the following methods: method of simple iteration for the solution of nonlinear systems, Seidel method, Newton method, Broyden method (secant method), etc.

In calculations by the method of simple iteration for finding the unconditional extremum of functions of many variables the iterative process corresponds to a parallel iteration, so as to calculate the k+1 approximation of all unknown are taken into account previously calculated their k approximation.

Seidel method is a modification of the method of simple iterations, where after specifying the initial approximation instead of parallel iteration is sequential iteration, in each iteration in each subsequent equation are substituted for unknown values obtained from previous equations.

Newton's method (tangent method) also uses successive iteration with the computation of the Jacobian for the system of equations at each step. The disadvantages of Newton's method include: the need to ask a good enough initial approximation; lack of global convergence for many problems; the need to solve at each iteration a system of linear equations which can be ill-conditioned. The advantage of this method is quadratic convergence from a good initial approximation provided that the Jacobian matrix neirogenna.

The idea of the secant method (Broyden method) is to approximate the Jacobian matrix using the already computed values of functions forming the system.

It's easy to see that one measurement channel with three infrared LEDs gives an unequal sensitivity of the system to different types linear and angular displacement. This drawback can be avoided by adding a second measuring channel, perpendicular to the first and second of the three LEDs. So we have the original active target in the form of a cube with three LEDs on nearby faces.

At a small angle of rotation around the longitudinal axis of the mark image on the matrix of orthogonal channel is shifted much stronger than the longitudinal matrix, which significantly increases measurement accuracy while maintaining a wide measurement range. When you move the mark along the longitudinal axis of the image matrix orthogonal channel is shifted, in contrast to the longitudinal matrix, which captures the movement of the work at distances of more than several meters.

The proposed optical-electronic system has a simple structure to measure the full spatial position of a floating object, we developed an original algorithm for determining the six spatial coordinates. The results of the experiments with the layout of the optical-electronic system confirmed the possibility of implementing high-precision system for 6DOF measuring the spatial position of the object.

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Superresolution imaging in spatially multiplexed interferometric microscopy by using time multiplexing

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Digital holographic microscopy (DHM) allows the great advantage of visualization of phase samples. DHM layouts can be found ranging from customized versions of classical interferometric configurations on an optical bench at the lab to commercially available microscopes at the market. The first option is normally more concise, specific and cheap but requires optical design, experimental implementation and specific algorithmic/software development while the second one enables robustness, versatility and easy-to-implementation at the expense of increased price.

Somewhere in the middle, there are ways to proceed in order to achieve holographic imaging in a robust, compact and concise way keeping the price to a reasonable level. Aimed to this, SMIM (initials incoming from Spatially-Multiplexed Interferometric Microscopy) proposes a low cost, extremely simple, and highly stable scheme to update a standard microscope into a holographic microscope [1-2] by using a common-path interferometric setup [3] implemented in a real microscope embodiment with only three modifications: i) the replacement of the broadband light source by a coherent one, ii) a one-dimensional diffraction grating properly inserted at the microscope embodiment, and iii) a clear region at the input plane for reference beam transmission. With these minimal modifications, a regular microscope is converted into a holographic one working under off-axis holographic recording with Fourier filtering [1] or slightly off-axis recording with phase-shifting algorithm [2].

However, the main drawback of SMIM is the FOV restriction imposed by the need to transmit a clear transparent reference beam. As consequence, modest/low NA objectives having a poor resolution limit are additionally restricted in FOV. But is it possible to synthetically increase the NA value without modifying a given optical imaging configuration in SMIM? In such a positive case, the FOV is penalized using SMIM but the resolution will result improved in that limited FOV.

In this contribution, we report on the additional capability of merging SMIM with superresolution imaging by angular multiplexing, thus allowing S2MIM (initials incoming from Superresolved SMIM). Taken the basic layout proposed by SMIM [1-2], superresolution enables at least a resolution gain factor of 2 based on tilted beam illumination [4] which is achieved by lateral displacement of the coherent source to a set of off-axis positions. The set of tilted beam illuminations is implemented sequentially using time multiplexing and SMIM technique recovers the complementary spatial-frequency content provided by each tilted illumination. All this information is used to generate a synthetic aperture expanding up the cutoff frequency of the system and, thus, allowing superresolution imaging. Experimental validation of the proposed S2MIM concept using resolution test targets to quantify the resolution gain factor is presented.

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10329-161, Session PS1

Water turbidity optical meter using optical fiber array for topographical distribution analysis

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This work is presenting an analysis study for using optical fiber array as turbidity meter and topographical distribution. Although many studies have been figure out of utilizing optical fibers as sensors for turbidity measurements, still the topographical map of suspended particles in water as rare as expected among all of works in literatures in this scope. The effect of suspended particles are highly affect the water quality which varies according to the source of these particles. A two dimensional array of optical fibers in a 1 litter rectangular plastic container with 2 cm cladding off sensing portion prepared to point out 632.8 nm laser power at each fiber location at the container center. The overall output map of the optical power were found in an inhomogeneous distribution such that the top to down layers of a present water sample show different magnitudes. Each sample prepared by mixing a distilled water with large grains sand, small grains sand, glucose and salt. All with different amount of concentration which measured by refractometer and turbidity meter. The measurements were done in different times i.e. form 10 min to 90 min. This is to let the heavy particles to move down and accumulated at the bottom of the container. The results were as expected which had a gradually topographical map form low power at top layers into high power at bottom layers. There are many applications can be implemented of this study such as transport vehicles fuel meter, to measure the purines of tanks, and monitoring the fluids quality in pipes.

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Uncertainty analysis of optical components absorption coefficient measurement using an intracavity device

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In order to measure the absorption coefficient and performance degradation characteristics of optical components which used in high power laser system, an intra-cavity device was established based on a discharge-drived CW chemical laser. Two pieces of 45 degree reflecting mirrors were tested. Each mirror was tested for more than twenty times, and high power laser irradiation on the testing mirrors lasted 100 seconds continuously in each test. The dependence of absorption coefficients on irradiation times was acquired. The testing results of both reflecting mirrors showed that, the differences between the experimental absorption coefficients and their fitting curve were up to 30.7% and 21.6% respectively, and the differences were independent of irradiation condition, such as irradiation energy, irradiation power and beam cross-sectional area. The uncertainty of absorption coefficient was composed of two parts. For one thing, the uncertainty of the direct measurement results, such as the temperature rise of optical components, can cause the uncertainty of absorption coefficients. This part of uncertainty was about 11.3%. For another, the resonant cavity need to be adjusted again when other optical components were replaced, which lead to the change of the incident angle of the optical components to be measured. A typical film system of 24 layers (12 pairs) was calculated by Thin Film Design Software called TFCalc, which showed the absorption coefficients increased with the increase of incident angle. When the angle of incidence was 0.5 degree from the design value, there would be -60~71ppm difference of absorption coefficient from the original one, and the uncertainty was 14.5%. When there was a deviation of 1 degree, the difference of absorption coefficient and the uncertainty were -112~155ppm and 31.7% respectively. This results showed that, the deviation of incident angle was between 0.5~1 degree in the test. In order to reduce the testing uncertainty of absorption coefficients, the deviation between the incident angle of optical components and the design value should be reduced as much as possible. This provides guidance for measuring the absorption coefficients of optical components with an intra-cavity device.

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Invariant electro-optical system for deflection measurement of floating docks

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Invariant electro-optical system developed for measurement of large-scale object deflection is analyzed.

Commonly deflection control of large-scale object, for example, a floating dock, is performed in severe conditions, like mist, rain, etc. A floating dock is a special vessel of 100-200 m long, designed for ships maintenance. When docking a ship, the dock partially submerges to let the ship come in, then the dock emerges holding the ship. During this process different dock parts are under different pressure, therefore floating dock body is deformed. If a critical deformation limit is exceeded, the dock fails. To avoid it, the floating dock has a ballast system to balance pressure on different dock's parts. However, to ensure proper work of the ballast system, it is necessary to measure the pressure or the deflection at different points of the dock.

One of deflection control methods is optical. It is shown that invariant electro-optical systems are useful in the said application as they are easily mounted and, at the same time, provide high accuracy.

The considered system has two measurement channels for monitoring opposite directions of the dock. It consists of a base unit, reference marks, an industrial computer and a display. The base unit contains an optical system and a CMOS camera. The base unit is usually mounted at the center of a floating dry dock top deck while the reference marks are at ends of the top deck (if the dock length is greater than 100 m, the reference marks are mounted one at the bow, one at the stern, and two in the middle of distance from the said marks to the base unit). A mark contains IR LED (940 nm) for better performance in mist.

The base unit may turn during deformation of the dock. It can lead to deflection measurement error. To eliminate the effect of the base unit turn, invariant systems can be applied. Such systems allow to keep parameters of output measuring data independent on external and internal conditions.

Thus, the structure of the invariant optical system shall contain a long focal lens and a beam deflection system. The beam deflection system can be made with mirrors or prisms.

Mirrors are typically used in the following cases: there is a large transverse size of rays at the location of reflective elements, a light-weight optical system, no chromatic aberration, and small light losses in a wide spectral range. An implementation with prisms is preferred to an implementation with mirrors as angles between faces of a prism remain constant during the operation.

An analysis of mirror systems revealed that these systems are invariant to the turn around one of the three axes. The turn of the system around other two remaining axes can be compensated mechanically.

Thus, use of the beam deflection system together with a CMOS camera in the base unit reduces the deflection measurement error.

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3D shape measurement of specular surface by speckle reflection method

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Non-contact three-dimensional (3D) shape measurement constitutes an increasingly important topic in modern industry. For diffuse surface, the fringe projection method is commonly used. For specular surface, fringe projection method also works by spray scattering material onto the surface under investigate, this method usually cause error and may damage the object. Another method is using fringe reflection technique. The accuracy of fringe reflection technique is mainly affected by phase unwrapping algorithm and system calibration accuracy. It is a simple and robust technique but limit the topology of the specular surface to be partly continuous and smooth. In this paper, a 3D shape measurement method for specular surface, which combines speckle feature extraction method, path-integration technique, and multi-view registration algorithm, is presented. A speckle pattern, which is generated by a monitor, is projected onto the measured object. The deformed speckle patterns modulated by the specular surface were captured by multiple camera system (MCS). It is obvious that any tilt of the object surface changes the angle of reflection, therefore the normal of any area of the surface can be indicated as the surface gradient at the same area, then the gradient field of the surface 3D shape can be extracted. To acquire the complete 3D shape, the MCS was carefully calibrated by ultra-precision plane mirror, and MCS is of benefit to identify the reflection angles on the object for every camera pixel from different view, which enable capability of the measuring object with complex topology. To realize that, the features of deflected speckle were extracted by feature detection algorithm and their corresponding reflective angles were obtained, and the relationship between deflected speckle and the gradient values of the object surfaces was analyzed. Since the surface topology is delivered by local gradients which were calculated by using path integration of these reflection angles, the whole 3D shape of object was obtained by register these gradient fields from different view together. The region of interest (ROI) of the captured images were also preprocessed to speed up the computational time of 3D shape and to improve the boundary integrity and accuracy. Moreover, a global optimum algorithm is adopted to reduce the noise and improve the calibration accuracy, thus improves the accuracy of the reconstructed 3D shape. The proposed method is insensitive against rigid body movement and environmental disturbances, but in return it needs well calibrated MCS to calculate the object 3D shape from different view. Thanks to the MVS, this method can measure freeform object with no constraints on its topology.

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Numerical analysis of nonlinear multimode interference waveguide as a refractive index sensor

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The numerical analysis of a refractive index sensor based on multimode interference (MMI) waveguide is designed using optical simulation (OptiBPM). The nonlinear refractive index of graphene in the proposed sensor was investigated by applying external electric field on the graphene cladding layer. Graphene is chosen because of its outstanding properties in electro-optics and it has already been shown to possess a giant nonlinear refractive index. The designed waveguide was constructed using silicon as substrate and silicon oxide (SiO2) as a core while graphene is coated on top of the waveguide slab. The response of the sensor in the output power was examined and validated by changing liquid samples with different refractive index. The guided modes of the 1550nm input plane source at the absence of external electric field were used as the initial reference point. The phase change and power at the output waveguide against refractive index were analysed and discussed. It is found that there was a threshold magnitude of the field which makes graphene sensitive to the relative change in the refractive index of the solution. The output results showed a promising indication that this design is appropriate for environmental monitoring.

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Investigation of the relative orientation of the system of optical sensors to monitor the technosphere objects

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Purpose: Developing of the methods of relative orientation of industrial robots and construction of three-dimensional scenes areas of interest using optical sensors. Results: Developed the method of construction of the relative orientation of industrial robots to meet the challenges of reconstruction of three-dimensional mapping and image-set received from the optical sensors. The basis of this technique is the problem of finding the solution of the global position of each industrial robot on the relative orientation of each of them. The global position of the industrial robot characterized by a matrix of rotation and transfer vector in a coordinate system (adopted as a global). As a result of the global positioning possible to solve the major problems of vision such as detection, tracking and classification of objects of the space in which these systems and robots operate. Practical significance: Continuous qualitative monitoring of technosphere objects.

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Evaluation of laser ablation crater relief by white-light micro-interferometer

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The laser ablation method applied to solids is widely used for synthesis of nanoparticles. As a result of pulsed laser interaction with material surface, a laser ablation crater is being created. Assessment of crater's micro relief allows to optimize a mode of sample surface modification at different conditions of laser radiation and to improve the efficiency of ablation process [1]. We investigated craters with typical lateral size 30-50 mkm and depth within the range 1-5 mkm. Some instruments for laser ablation crater relief evaluation employs the principle of white light interferometry due to wide range of measurement unambiguity. Recording of video frames sequence acquired at different sample axial positions allows to recover a relief at each point in lateral directions by evaluating interferometric signals envelope maximum position [2]. It should be noted that the surface of a sample is being modified by high-temperature influence, shockwaves and micro particles deposition that leads to destruction of a surface structure and considerable variability of light reflection at some crater points. Due to reflection inhomogeneities, light reflection flares and shades can appear at some points. In such points a crater relief can not be evaluated properly by single view measurement.

To overcome difficulties mentioned above, it is suggested to apply multi view method of a surface relief evaluation at different observation angles. A sample is slightly tilted and then turns around vertical axis. At different rotation positions, a video frames series is being recorded, and subsequent processing of video frames allows one to obtain information about 3D crater relief over all relief points. Data processing algorithm contains the step of matching the relief data obtained at different observation directions. This allows to provide relief data recovery for the object points where single scan results are poor.

There was utilized white light Michelson interferometer with Linnik configuration equipped with video camera. The device provided accurate axial scans within the field of view 200?160 mkm. Experiments have been conducted for ablation craters obtained in the mono-pulse irradiation mode when modifying surface of metals (titanium, steel), semiconductors (silicon, chrome oxide) and dielectrics (fused silica, calcium fluoride). To avoid relief recovery ambiguity, each specimen was scanned eight times with observation at different angles.

The obtained results testified increasing of the quality of laser ablation crater relief recovery with using multi view relief evaluation method in comparison to known single view method.

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10329-168, Session PS1

Relationship of parameters of optical equisignal zone system

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Means of electro-optical remote control are widely used in industry, construction, geodesy, etc. A type of systems that may be used is a system based on optical equisignal zone.

Such a system contains a projector forming the base plane, and a receiver, which determines its position relative to the base plane. Traditionally the base plane is created by two light sources (e.g. LEDs) modulated with different frequencies, thus creating a required spatial-temporal distribution. Their fluxes are condensed on the edge of a splitting prism, thus halves of the original sources compose one light source on the edge. The prism reflects these fluxes in the same direction. Thus, two fields of irradiance divided by the base plane are formed in the plane of the sensor. The difference between fluxes un the plane of the sensor results in a difference signal on the receiver, proportional to the displacement. The value of the signal will depend on the distance and transmission of the air-path. The receiver is attached to an object under control and the object is kept in a required position.

For the most applications the difference signal is required to be independent on the distance. The purpose of the study is to find interrelation of parameters of an optical system, of sources and of a detector for registration of objects while changing the distance to the detector to enable constant difference signal.

It is known that if the source has a uniform radiance and an ideal objective (without aberrations) is used, in order the width of the transitional zone be independent on the distance, the objective must be focused on infinity. In practice homocentricity of the pencil of rays is influenced by the spherical aberration. Study of impact of the 3th order abberrations on the width of the transitional zone, and as a result, on radiance distribution, allowed to find equations linking the width of the transitional zone, exit pupil diameter, and irradiance of the sources. It is shown that the relative difference signal depends on relation of the product of spherical aberration value and distance to the exit pupil diameter, thus relative difference signal can be reduced with refocusing on a required distance.

On the basis of obtained relations and experimental results we conclude that using an appropriate processing of the difference signal, correction of spherical aberration of the objective and focusing the projector on infinity, constant static characteristics may be achieved.

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Estimation of the particle concentration in hydraulic liquid by the in-line automatic particle counter based on the CMOS image sensor

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The reliability of hydraulic systems depends on the regular monitoring of their state. One of the most effective ways to address this task is utilizing in-line automatic particle counters (APC) built inside of the system in order to get information about wearing processes inside of it. The information about the state of the system can be obtained by investigation of parameters of particles floating in the hydraulic liquid. The measurement of particle concentration is the crucial part of such monitoring because increasing numbers of particles with particular sizes should mean that some part of hydraulic system does not work properly or is near to break down. In spite of the fact that several automatic particle counters exist, they have significant limitation for the precise measurement of relatively low concentration of particle in case of utilizing it inside of aerospace systems or they are unable to measure highest concentration in industrial ones. Both issues can be addressed by implementation of the CMOS image sensor instead of single photodiode used in the most of modern APC.

Firstly, the accuracy of the particle concentration measurement is influenced by the accuracy of measurement of the volume of liquid to be investigated. Usually, the velocity of the particle is used for determination of the flow rate and the time of analysis whereas the volume is fixed (100 ml). The velocity of the particle is measured by APC using the duration of the electric pulse at the output of the photodiode. However, the velocity of the particle varies throughout the tube as in the centre we have got the maximum speed compared to the lower one near to the pipe wall. This issue cannot be resolved by using photodiode as it cannot measures the position of the particle inside of the tube. Generally, the assumption that the average speed is measured by each particle gives sufficient results for high concentrations. Nevertheless, in case of pure systems like aerospace the error of particle concentration estimation cannot be lower than 30 per cent or might be higher. In case of using matrix image sensor the position of the particle in the tube can be determined by image analysis and the real velocity can be calculated. In our study we represent the method and results of particle concentration determination based on assumption that the distribution of particle velocity is parabolic throughout the channel. Calculations based on the proposed algorithm show that the total error in concentration estimation is not exceed 10 per cent and does not depend on liquid viscosity and temperature.

Secondly, the errors of particle concentration estimation are caused by matches of different particles inside of measurement volume. The photodiode measures several particles inside of measurement volume as one. Typically, the restriction of the maximum measured concentration is put for APC based on photodiodes. It is about 1500 particles per cm3, which is not sufficient for the industrial hydraulic systems. We proposed the algorithm of estimation of the accuracy of the APC based on matrix sensor. Calculations made by using Poisson distribution prove that the improvement of the resolution (or the limit of concentration to be measured) can achieve in average 20 times more compared to the APC with single photodiode.

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The research of the cross-links effect influence in the color matrix photodetector on an error of the air tract vertical temperature gradient determination

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The use of the optical-electronic systems of the spatial positioning control allows us to get the required accuracy of measurements in a wide range of the spatial displacements. Among the sources of the errors that affect the measurements process, the main role is played be the influence of the air tract, especially at long distances. The aim of the paper is the research of the possibilities to minimize or compensate the influence of the air tract in opticalelectronic systems of the spatial positioning control. There is a way to compensate the influence of the air tract vertical temperature gradient based on the dispersion method. There are a lot of difficulties conducted with theoretical air tract temperature gradient determination because it is difficult to research the heat convection process in the air tract. We conduct the research of the dispersion method to determine the vertical tempretature gradient based on spectrozonal method. Using the photoreceiver with the Bayer filter allows to measure the difference between the images from two color channels (red and blue) using some possibilities of an image processing. In this case the influence of the air tract parameters and the photodetector system has some features caused by presence of the cross-links effect in the color matrix photodetector.

Using the spectrozonal method it is possible to estimate the influence of the air tract temperature gradient on the measurements accuracy by the value of the coordinate difference between the energy centers of two source images differing in the wavelength. But there is the cross-links effect almost in all photodetectors color channels that has the systematic error, that's why the information about object position is distorted.

Theoretical research showed the possibility to take into account the cross-links effect by received dependence. The coefficient of the cross link of the adjacent channel from the main is the ratio of the amplitude of the video signal in the adjacent color channel to the amplitude of the video signal in the main color channel.

The analysis of the spectrozonal difference error from the value of the cross-links effect showed that if the cross-links effect is more than 0.3 the error has the value of 100%. The experimental research showed the reliability of the results from the theoretical research and the possibility to estimate the minimization of the air tract vertical temperature gradient influence by the variations of the storage time and the frames number.

10329-171, Session PS1

Parameter optimization of measuring and control elements in the monitoring systems of complex technical objects

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Optical-electronic methods and means for the contactless control of the position of objects relative to the linear base are relevant in many areas of technology. This is because the non-contact, distance and the ability to fully automate the processes of measurement combined with high speed makes extensive to use of optical - electronic systems (OES) for the active control of the spatial position of objects (disposition). Of particular interest for this class of systems is called invariant optical-electronic system for alignment control (OESAC).

Because such systems allow preventing (warn) technological disasters, the urgency of the problem increases in proportion to the technical progress of all mankind, to prevent the recurrence of tragedies have occurred, for example, the Bhopal disaster (1984), the Chernobyl disaster (1986), the Sayano-Shushenskaya power station accident (2009), pipeline spill in Israel (2014), which served as the impetus for the development of systems of this trend.

Invariant devices - devices that are insensitive to external mechanical impacts (insensitive to changing external conditions) that do not require prior verification or verification before starting work, always ready for use and guarantee the required accuracy of control. The use of a single planar photodetector matrix fields for the analysis of the representations of natural and specially created spatial distributions of informative features of the object of control are widely used for the implementation of robotic tasks in machine vision. In this case, the application of computer vision algorithms, in combination with the properties of optical systems, enables to implement invariant to environmental influences and changes the distance of the OES for alignment control.

This class of systems allows to register transverse displacement with an accuracy of tens of microns, changes in the distance of several tens of meters and the range of transverse displacements of a dozen millimeters. Special interest is to use of the application of the autoreflection schemes for alignment control with the control elements like different types of reflectors.

When using the reflectors in geodesy, systems, road safety, security systems, gas analyzers, and meters visibility range and so on, very often, the incident radiation flux on reflector is generated by transmitting optical system, which consists of a collimating lens and emitting area.

Expected scientific novelty will consist in the optimization methods of control parameters and measuring elements used in optical-electronic vision system controls basic structured test object in the form of a combination of retroreflectors, and also in approaches to processing information reception channels of non-destructive testing systems using cloud technologies, providing a given magnitude of error and the measurement range of the coordinate measuring element.

10329-172, Session PS1

Advanced defect classification (ADC) by optical metrology

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Particle defects are important contributors to yield loss in semi-conductor manufacturing. Therefore the particle count has to be minimized and, to this end, to be characterized in order to determine their root cause. Figure 1 outlines the general approach for advanced defect classification in three consecutive steps; detection, review and classification. For defect detection, TNO has developed the RapidNano (RNx) particle scanner [1]. The RNx scans large flat areas like blank wafers or reticles at a high throughput. The optical column, which is at the heart of the RNx, is based on a sensitive dark-field microscope. For each sample, the lower detection limit (LDL) is verified by an analysis of the speckle signal strength. The detected defects are ranked on their importance, thereafter the defects of interests (DoI) are redetected and reviewed. In previous work, the redetection process (R.2) has been simplified by the production of a stealth fiducial marker system [2]. The RapidNano3 particle inspection system is capable of detecting 42 nm Latex Sphere Equivalent (LSE) particles on XXX-flat Silicon wafers [3]. This sensitivity is achieved by illuminating the sample from multiple angles. In detection-mode (RN3.1) the signal from all these angles is added. In review-mode (RN3.9), signals from all nine individual arms are analyzed to derive the shape, material and size of deep sub-wavelength defects. Via this analysis we are able to classify and select defects for further analysis on much slower metrology tools that offer more details, e.g. SEM or AFM. A first experiment with the RN3.9 showed that it is indeed possible to extract information on e.g. the defect aspect ratio and orientation, which is not available from the RN3.1 signal.

Using electron beam lithography and a standard lift-off technology, a 2D pattern is applied to an XXX-flat Si wafer blank. The 2D pattern comprises both large "stealth" markers for easy navigation in optical, atomic force, scanning probe and scanning electron beam microscopes (OM, AFM, SPM, respectively SEM) as well as a sub-micron set of programmed defects with a rectangular or elliptical shape at aspect ratios ranging from 1:1 to 1:5.

In summary, this paper will report on the feasibility, benefits and limitations of optical metrology-based Advanced Defect Classification (ADC) using both modelling as well as experimental results for a set of programmed defects on a silicon wafer, using other review tools (SEM, AFM) to verify the ADC as made using the RN3.9.

10329-173, Session PS1

Effects of the density and homogeneity in NIRS crop moisture estimation

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Near-infrared spectroscopy (NIRS) is widely used in fruits and vegetables quality evaluation. This technique is also used for the analysis of alfalfa, a crop that occupies a position of great importance in the agricultural field. In particular for the storage, moisture content is a key parameter for the crops and for this reason its monitoring is very important during the harvesting phase. Usually optical methods like NIRS are well suitable in laboratory frameworks where the specimen is properly prepared, while their application during the harvesting phase presents several difficulties. A lot of influencing factors, such as density and degreee of homogeneity can affect the moisture evaluation. In this paper we present the NIRS analysis of alfalfa specimens with different values of moisture and density, as well as the obtained results. The measurements were performed in two different optical configurations, transmission and reflection, in order to compare the achievable information from the two setups.

A FT-NIR spectrometer (ARCoptix S.A.,Switzerland) with spectral range from 900 to 2600 nm and a resolution ranging from 6 to 10 nm is used for both the setups. In the reflection setup an Integrating Sphere ARCSphere-50-HAL (ARCoptix S.A.,Switzerland) with an internal 5 W halogen lamp is used. The measurements were performed with a specimen holder that allows density regulation. In the transmission setup a fiber bundle coupled with a 5 W Halogen Lamp (Avantes BV) is used for the first analysis, while a second set of measurements were performed using a 50 W halogen lamp. The measurement procedure consists in an initial warm-up of the light source. After that, the reference is taken with a 99 % NIST standard Diffuser (Labsphere Inc.,USA) in the reflection configuration, while for the transmission setup the light source spectrum was measured directly. To avoid the spectrometer saturation a neutral density filter was used. Then the alfalfa specimens were measured.

In order to determine the behavior of the alfalfa sample avoiding the effects of the influencing factors preliminary reflection spectra were acquired on milled alfalfa Fig.1.

The spectra baseline is due to the light scattering that depends on the specimen particles size while the peaks are due to the molecular vibrations. Molecular vibrations exist in the NIR region in the form of X-H where X is carbon, nitrogen or oxygen, X-H functionalities are due to hydrogenic stretching, bending, or deformation vibrations. The major bands in the NIR region are second and third harmonics of fundamental O-H, C-H and N-H stretching vibrations found in the mid-IR region. After the preliminary analysis the measurements were performed on the alfalfa collected from the field after the mowing phase. In order to obtain different moisture contents in a natural way the alfalfa is collected in sequential time after the mowing. Initially the leaf and the stem were measured separately, the moisture content and the density was changed in the range of interest. Each specimen was measured multiple times, and after each measurement the specimen was mixed in order to determine the effect of the homogeneity.

10329-174, Session PS1

Automatic inspection system for photovoltaic solar concentrator based on Fresnel lens collector

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Quality control in fabrication of modules for solar concentration systems requires focused solar energy in a small area of a solar cell. A number of concentrators systems are based on the well alignment of three optical elements, i.e. a Fresnel lens, a diffractive homogenizer and a multijunction solar cell. In this paper we present an automatic technique to determine the magnitude of the misalignment between the centers of these three elements. The method uses a rotary prism system, and a camera as image acquisition system. Simulations and experimental results are presented.

10329-175, Session PS1

Direct fabrication of polymer microlens arrays

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Microlens and more in general microstructures made of polymer material are useful for a large number of applications ranging from the integral imaging for 3-D displays, optical communication, OLEDs and high-resolution imaging [1,2]. In response to their extended use in different fields of technology, a great emphasis is being placed on research into simple manufacturing approaches for these micro-optical components as well as on the characterization of their performance. Many ways have been developed for the fabrication of polymer lenses, such as hot embossing, soft replica molding, rapid laser-based patterning, ink-jet printing, and UV-nanoimprint lithography. Some of these methods are expensive, require the use of clean-room facilities and highly trained staff with a limited selection of suitable materials. An interesting property of microlenses would be the possibility to tune their focal length [3]. Many procedures have been developed for assembly arrayed microlenses with a variety of materials with different geometry and optical properties. For example, swellable polymer microlenses upon exposure to solvents create a tunable range of focal lengths, or also the generation of microlenses by virtue of the photopolymerization, wherein the employment of a surfactant has broadened the range of substrates for the microlens formation. Recently direct alternative methods have been proposed for the fabrication of microlens arrays utilizing the electrohydrodynamic (EHD) patterning technique in case of polymer solution [4-6]. In this work we present a simple multiscale process for the fabrication of micro-optical elements using high viscous polymer materials. In particular the pyro-electric effect activated onto a Lithium Niobate crystal is exploited for the fabrication on demand of microlens array and the high resolution pyro-inkjet printing is proposed for the fabrication of 3D micro-optical elements [7]. Both the methods proposed for the fabrication of polymer microlens arrays are driven by the pyro-electric process and the electrohydrodynamic (EHD) pressure activated by a temperature gradient. This method could offer a simple alternative to the conventional soft lithography techniques reaching high resolution in terms of microns. Here we demonstrate a systematic investigation for fabrication of microlens arrays in a multiscale range (i.e., between 25 to 500 ?m diameter) with high degree of uniformity. By controlling the polymer instability driven by EHD, we report on two different micro-optical shapes, spherical or toroidal. Active filler such as nanoparticles or semiconductor QDs could be introduced inside of polymer solution in order to produce functionalized microlens arrays on a free-standing flexible polymer films. The optical behavior of the microlenses has been characterized in terms of the optical aberrations intrinsically present in the lens array by digital holographic microscopy (DHM).

10329-176, Session PS1

Optical fibre-based reflective displacement sensor: computer modelling and application to impact detection in aeronautical structures

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The present contribution aims at evaluating the performance and validity of a computer model to simulate the behaviour of an optical fibre-based reflective displacement sensor beyond the scope for which it was initially designed.

The model, originally designed to simulate a trifurcated optical fibre bundle displacement sensor used in tip-timing and tip-clearance measurements, also allows us to predict that a tetrafurcated optical fibre bundle is a more convenient geometry if we are committed to a displacement sensor with different specifications in terms of measurement distance and linear operation range. The structure of a trifurcated optical fibre bundle consists of a central transmitting fibre and two rings of receiving fibres set concentrically around the transmitting fibre, whereas the tetrafurcated design incorporates three rings of receiving fibres around the transmitting one. Based on the predictions made by the computer model, a tetrafurcated optical fibre was fabricated and tested, and the experimental results show that the simulations results fit well the experimental ones.

The computer model relies on Gaussian optics to simulate the sensor under ideal circumstances, but as these are not the real ones, it becomes necessary to adjust some simulation parameters in order to stick to the actual specifications (target roughness, actual specifications of equipment used in the implementation of the displacement sensor, etc.) that were measured in the laboratory. The simulation results fit well the experimental results in the linear region of the calibration curve of the displacement sensor, and no matter what exact configuration is used, almost no differences are observed between simulations and experimental data measured in the laboratory.

The aforementioned tetrafurcated optical fibre bundle displacement sensor was fabricated not only to confirm the validity of the computer model, but also because its working specifications are more in line with the requirements needed for impact detection in aeronautical structures than the specifications offered by the trifurcated version of the sensor. We are carrying out impact tests in the Aeronautical Technologies Center (CTA) facilities with different projectiles used to simulate real impacts, and for the detection we are using four different technologies (three optical and one electrical): Doppler vibrometry, Fibre Bragg Gratings, Strain Gauges and our reflective displacement sensor. The results that will arise from the tests, and their analysis and discussion will be presented in the conference.

10329-177, Session PS1

Characterization of laser damage performance of fused silica using photothermal absorption technique

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The subsurface damage and metal impurities have been the main laser damage precursors of fused silica while subjected to high power laser irradiation. Light field enhancement and thermal absorption were used to explain the appearance of damage pits while the laser energy is far smaller than the energy that can reach the intrinsic threshold of fused silica. For fused silica optics manufactured by magnetorheological finishing or advanced mitigation process, no scratch-related damage site occurs can be found on the surface.

In this work, we implemented a photothermal absorption technique based on thermal lens method to characterize the subsurface defects of fused silica optics. The pump beam is CW 532 nm wavelength laser. The probe beam is a He-Ne laser. They are collinear and focused through the same objective. When pump beam pass through the sample, optical absorption induces the local temperature rise. The lowest absorptance that we can detect is about the order of magnitude of 0.01 ppm. When pump beam pass through the sample, optical absorption induces the local temperature rise. Spatial refractive index will vary due to thermal expansion. Probe beam is deflected by the modulated refractive index gradient. The deflection of the transmitted probe beam is measured by a position sensor. We measured optical thermal absorption in scanning mode with the area of 3 mm2 for every sample. The mean value, maximum value and three-dimensional profiles were obtained. Then we used a tripled Nd:YAG laser at a wavelength of 351 nm to test the laser damage density of fused silica samples. The photothermal absorption technique would not produce irreversible damage to fused silica optics compared with laser damage test.

The photothermal absorption value of fused silica samples range from 0.5 to 10 ppm. The damage densities of the samples were plotted. The damage threshold of samples at 8J/cm2 were gived to show laser damage performance of fused silica.The results show that there is a strong correlation between the thermal absorption and laser damage density. The photothermal absorption technique can be used to predict and evaluate the laser damage performance of fused silica optics.

10329-178, Session PS1

Compensation of optical system distortion and image perspective deformations for the projection lens

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In the article takes up the possibility of optical system distortion compensation for projection lens by making predistortions into projected digital image. Image processing is producing for main types of optical system distortion, which can be described both as power polynomial and as Zernike polynomials.

Special attention is given for perspective deformations which arise in the deviation of the optical axis from perpendicular to the plane of projection. In processing takes into account both as horizontal and as vertical perspective deformation.

For possibility of optical system distortion compensation there is a need to provisional certification of lens by Abbe grid for taking polynomial description of distortion. According to certification results performed image processing on the points corresponding to the nodes of the grid Abbe. As a result of processing a digital image deformations introduced, the reverse occurring when deformations are projecting.

Pre-made image deformations allow to compensate for distortion of optical system and the perspective deformation caused by the projection lens used, therefore, when projecting the image will largely corresponds to the original image.

The results of the work is planning to use in the preparation of digital image mapping show, namely the projection on objects of complex geometric shapes.

10329-180, Session PS1

A flexible 3D laser scanning system using a robotic arm equipped with a MEMS scanner

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In this paper, we present a flexible 3D scanning system based on a MEMS scanner mounted on an industrial arm with a turntable. This system has 7-degrees of freedom and is able to conduct a full field scan from any angle, suitable for scanning workpieces with complex shape. The existing non-contact 3D scanning system usually uses laser scanner that projects fixed stripe mounted on the Coordinate Measuring Machine (CMM). These existing systems have some drawbacks. First, the CMM is bulky, and requires critical environmental conditions, not applicable for industrial online inspection. And CMM has only 3-freedom, less than industrial robots, and fails to measure workpieces with complex shape . Second, the most laser scanners mounted on the CMM are based fixed stripe projection and need mechanical movement to implement fullfield scanning, thus increasing the difficulty of path planning and reducing the flexibility, especially in the case of scanning complex parts or the lack of CAD models.

To overcome the drawbacks of conventional techniques we propose a robotic 3D scanning method which uses a MEMS scanner mirror to project laser stripe onto object's surface. The MEMS laser projection module is mainly composed of a scanning mirror and a laser diode, which is programmable and capable of projecting 2D scanned stripes. The fullfield 3D point cloud can be generated by a triangle setup. When the robotic arm is still, this method allows it to hold the probe to scan the parts, while the CMM equipped the fixed-stripe scanner must keep moving . Apparently, the latter increases the difficulty of path planning and control. In order to increase the fexibility of the scanning system, we have added another axis, a turntable, to the robot. The turntable has one rotational joint.

Before we measure the object, we must calibrate the whole system. First, we need to calibrate the orientation of the turntable center relative to the robotic arm by flat plate with checkerboard pattern. Second, we have to calculate the Hand-Eye matrix to represent the relationship between the coordinate of the scanner and the coordinate of the robot hand. When the system starts working, place the object on the turntable and keep the robotic arm stationary. Then the scanner projects stripes modulated by the MEMS scanner mirror to the object while the camera in the scanner shoots the images. When all the stripes are projected, the scanner reconstructs the point cloud model of the object's surface covered by stripes at the current position with these images captured by the camera with depth information. After completing the measurement of the current position of the robotic arm, the scanner mounted on the robot move to another position and repeat the previous step. Throughout the scanning process, the machine arm moves N positions, so we get the N vectors of point cloud data. The measurement data of each position is converted into the coordinate of the robot base. Finally we get a complete model.

This system we proposed is mainly to quickly and easily measure the workpieces with complex shape, and improve the measurement efficiency. We are committed to applying industrial robots to industrial inspection, so as to replace the coordinate measuring machine for 3D scanning.

10329-181, Session PS1

A high performance fringe projection profilometry using a biaxial MEMS scanner

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Fringe projection profilometry (FPP) has been one of the most popular non-contact methods for 3D surface measurement in recent years. DLP is the most widely used fringe pattern projection technology. Some researchers proposed a new method, using a single axial MEMS scanning mirror, to produce the fringe pattern in recent years. However, they all have their inherent problems. In this paper, we proposed a high-quality fringe projection method using a biaxial MEMS scanning mirror and a laser diode (LD). And did a contrast between the proposed method and these two methods.

The basic steps involve that laser diode beam is conducted to MEMS mirror, and the reflected beam is scanned by fast and low-speed rotation of two axes to form a 2D light field. With the help of synchronizing laser intensity modulation, a sinusoidal analog grating with continuous intensity distribution and large depth of field is generated and projected onto object's surface. Capturing the deformed grating image from a triangular-positioned camera the surface height distribution can be calculated. By using this method, we can obtain a fringe pattern which has a quality.

A contrast between proposed methods with DLP system had been done in this paper. When we project a fringe pattern, the pattern we get is the convolution of the original image and the PSF (point spread function) of the system. As to DLP projector, every pixel is a micro-mirror unit. The PSF of a DLP system consists of the optical blur, the optical transfer function (OTF), and the shape of a micro-mirror. Unfortunately, the radius of OTF in a DLP system increase rapidly when the imaging plane is away from the focal plane. So the Depth of field of a DLP system is very shallow. The situation to a biaxial MEMS projection system is quite different. The PSF of this system determined by the shape of the spot produced by the laser diode. It approaches a 2D Gaussian function. And radius of the spot changes little when the imaging plane is away from the focal plane. Due to the difference in PSF, the fringe pattern produced by proposed method have a longer depth of field, which is almost 10 times that of DLP system. The extension in depth of field increases the measurement range of FPP.

Some researchers using a single axial MEMS scanner and prism to produce a 2D fringe pattern. In this paper, we did a contrast between the fringe pattern produced by single axial MEMS scanner and biaxial MEMS scanner. By using single axial MEMS scanning mirror, it can just project a single direction of the fringe pattern, which limits the applications of FPP. Moreover, each column (the direction of phase line) consist only one spot (for LD) in single axial MEMS scanner. However, there are more than 500 spots in each column in biaxial MEMS scanner, which weakens the speckle effect. In addition, because of the prism, it is difficult to guarantee the uniformity of the fringe pattern. Besides, the noise coming from the prism will be amplified as well.

Due to these factors. Biaxial MEMS scanner can produce higher performance fringe pattern, which brings a higher accuracy and longer measurement range in FPP.

10329-182, Session PS1

A high-speed full-field profilometry with coded laser strips projected by a MEMS scanning mirror

Guanliang Zhang, Xiang Zhou, Rui Jin, Chang da Xu, Dong Li, Xi'an Jiaotong Univ. (China)

Recent years, optical three-dimensional measurement technology is widely used in industrial detection, medical health, digital entertainment and many other fields, especially in the field of industrial on-line

inspection. 3-D reconstruction using coded structured light is considered one of the most reliable techniques to reconstruct object surfaces because of its non-contact, high precision and fast speed.

Fringe projection profilometry with surface structured light has the advantages of fast, high speed and full-field scan. But it is easily disturbed by the surface reflection of the object, and in case of dark objects, it is not reliable. Line structure light measurement, using stripe laser, is more robust in case of scanning reflective metal objects or dark objects. But it needs mechanical device to control its movement, which decides the accuracy of the result. And camera with high frame rate is requested in order to increase the speed. Accurate mechanical movement device and high-frame-rate camera are difficult to realize.

To solve these difficulties, we propose a high-speed full-field profilometry, which uses coded laser strips projected by a MEMS scanning mirror. The MEMS scanning mirror with red (R), green (G) and blue (B) laser sources, which is focused on full-field imaging display application recently, gives another choice of projectors. The mirror could take place of the mechanical movement device with its high speed and accurate, and color laser sources support more coding method of light. Besides, a method with gray code and color code is used to decrease the frames number of projection, retaining the advantage of line structure light measurement. At first, the gray code divides the projector's field of view into four parts; and then, seven stripes coded by different color (R, G, B, RG, RB, GB, RGB) are projected on every part. Thus, 28 stripes in total are projected at the same time, and a 1 000-pixel scan can be completed in 36 frames. An ordinary camera could reach the frame rate of 30. The scan time is no more than 1.5 seconds.

In the experiment, we use a laser MEMS scanner and two color cameras. The laser MEMS scanner projects gray code and coded stripes, with two color cameras collecting the modulated pattern on the measured object. Every laser stripe is distinguished by gray code of the part and hue of the stripe color. The color cameras compose a stereo vision system so that the three-dimensional data is reconstructed according to triangulation. The sum of three - dimensional data reconstructed from every single frame image is the full-field surface through the scan.

This profilometry uses a MEMS scanning mirror to take place of accurate mechanical movement device, which could deal with the surface reflection and scan the full field with high speed. The stripes coding method of gray code and color code makes the profilometry fast, robust and reliable.

10329-183, Session PS1

A hybrid structured-light measurement using a laser MEMS scanner

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The Fringe Projection System (FPS) and the Laser Stripe Projection System (LSPS) both have the limitations in 3D measurements. If we need to obtain the accurate 3D structure of a complex and uneven surface, which is composed of reflective parts,

diffuse parts and black parts together, neither of the systems could manage it individually in a low cost. To bypass these difficulties, we propose a system combining these two ways of projections together using a Laser MEMS Scanner?which could project fringe patterns and scanning-laser-stripes both.

The Laser MEMS Scanner and the principle of the measuring structure is introduced.

Here is a brief introduction of the measuring procedures. Get the disparity map and quality map in FPS model?then get two maps in LSPS model?combine two disparity maps into a reliable one according to the quality maps?reconstruct the surface of the object with the disparity map. The procedures are detailed in the paper.

We also propose two methods for the measuring procedures: The method for extracting the laser stripe correctly in the low-contrast images and from the reflective noise and the method for calculating the quality map.

Finally, the experiments to verify the proposed method and evaluate the system performance are ongoing at this moment. The simple objects can be reconstructed successfully. The black-and-white objects and the metal-plastic-combined objects will be reconstructed in the system?with the estimated accuracy less than 0.5mm . We'll show the experimental results in the presentation.

10329-28, Session 7

Suppression of contrast-related artefacts in phase-measuring structured light techniques

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Optical metrology using phase measurements has benefited significantly from the introduction of phase-shifting methods, first in interferometry, then also in fringe projection and fringe reflection. As opposed to interferometry, the latter two techniques generally use a spatiotemporal phase-shifting approach: A sequence of fringe patterns with varying spacing is used, and a phase map of each is generated by temporal phase shifting, to allow unique assignments of projector or screen pixels to camera pixels.

One ubiquitous problem with phase-shifting structured-light techniques is that phase artefacts appear near regions of the image where the modulation amplitude of the projected or reflected fringes changes abruptly, e.g. near dirt/dust particles on the surface in deflectometry or bright-dark object colour transitions in fringe projection. Responses in the phase maps will appear that are not plausible as an actual surface feature. The phenomenon has been known for a long time but is usually ignored because it does not compromise the overall reliability of results.

In deflectometry, however, often the objective is to find and classify small defects, and of course it is then important to distinguish between bogus phase responses caused by fringe modulation changes, and actual surface defects. We present, for what we believe is the first time, an analytical derivation of the error terms, study the parameters influencing the phase artefacts, and suggest some simple algorithms to minimise them.

10329-29, Session 7

3D geometry measurement of hot cylindrical specimen using strucctured light

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Inline process control by 3d geometry measurement is an important part of the cost-effective production of high precision components. Within the Collaborative Research Centre (CRC) 1153, funded by the German Research Association (DFG), a production chain for high performance hybrid components is developed. These so called Tailored Forming components are composed out of two or more materials, bonded at a discrete joining zone. The inspection of the components is needed to early detect errors and exclude defective components from further processing steps to save costs e.g. through reduction of wear of the used tools. Measurement times are key while developing efficient inline inspection systems in a production chain since the measurement process needs to sync with other processing steps.

Many of the production steps in the CRC 1153 are hot forming processes, so conventional tactile measurement systems cannot be used due to the requirement of standard ambient temperature. State of the arts on the topic of non-tactile 3d geometry measurement are current setups of structured light techniques, e.g. based on fringe projection or laser light-section. It is usually used to analyse geometry deviations of specimen. In this case the acquired data can also be used to localise the joining zone and to monitor the shrinking process during scheduled cooling phases. This may lead to a non-destructive prediction on residual stress without using a high cost diffractometer.

We present a fringe projection system to measure hot Tailored Forming specimen in between production processes. The used, high power, green light projector is based on TI DLP technology to create the highest possible contrast between fringes on the red glowing specimen. It has a resolution of 1140 x 912 pixels, arranged in a diamond shape and can project up to 120 images per second. We use green bandpass (532 nm) and NIR filters on the camera optics to block unwanted incoming radiation from the specimen due to self-emission. Commercial measurement standards are not calibrated for temperatures other than 20 °C, so they cannot be used to validate measurement data at the required temperatures up to 1050 °C. We use a uniformly heated pipe made of stainless steel as a dummy specimen to examine the measured geometry data. A thermal imaging camera secures the exact temperature and the homogenous heating of the pipe so the expansion can be easily calculated using the thermal expansion coefficient. Different angles of impact and triangulation angles are investigated to identify the effects of hot ambient air on the measurement of hot specimen. The impact of different surface qualities is examined to check the need for pre-processing steps in the measurement routine.

10329-31, Session 7

Phase-shifting profilometry using binary patterns projection with projector defocusing

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Phase-shifting profilometry using binary projection is the most promising technique for high-speed 3D measurement. The 3D profile is constructed by using phase information determined from the camera captured patterns. A phase-shifting algorithm is used to calculate the wrapped phase. The calculated phase is always wrapped in the interval (-ϖ, ϖ], and contains 2ϖ phase discontinuities. To retrieve the continuous absolute phase, a temporal phase unwrapping method using the so-called Gray-code patterns is widely used. In this technique, when the projector is properly defocused, sinusoidal patterns can be generated by projecting binary patterns. To calculate high-quality phase, binary patterns should be specially designed to generate high-quality sinusoidal patterns. The squared binary patterns have been used. Because squared patterns generate lots of high-frequency harmonics, which result phase error in the calculated phase. A high defocusing level can suppress these high-frequency harmonics but reduces fringe contrast. A large step phase-shifting algorithm can improve the phase quality but uses a large number of binary patterns. The pulse width modulation (PWM) technique is introduced to suppress high-frequency harmonics and improve phase quality using a small number of binary patterns. The dithering technique performs better than the squared and PWM modulated binary patterns for fringe patterns with a large fringe period. In this paper, a simple method is introduced to design binary patterns based on the symmetry and periodicity of sinusoidal distribution. A small binary patch is flexibly selected to generate the whole size of binary patterns. The projector defocusing can be approximated by a Gaussian filter. The selected binary patch is optimized by randomly assigned "0" or "1" values for each pixel. Because the size of the binary patch is much smaller compared with the previous method, the optimal binary patterns can be easily obtained, and high quality phase can be calculated even for the projector with a slight defocusing level. The calculated phase needs to be retrieved before 3D reconstruction. In the real measurement, the temporal phase unwrapping methods are commonly used. The Gray-code method is more practical as its robustness. However, owning to the defocused projector and the discrete sampling of the camera, the Gray-code method always generates unwrapping errors near 2ϖ phase discontinuities. The unwrapping errors can be deemed as impulsive noise in the absolute phase map. To remove this kind of noise, a few methods have been proposed, which work well for the object with smooth surface. However, for the objects with complex surface, it is difficult to remove noise and preserve edges. The median filter works effectively to remove impulsive noise. Therefore, an adaptive median filter is introduced to effectively remove this noise. A small-size of 1D median filter is first applied to the retrieved absolute phase. A large-size of 2D median filter is then applied to some remaining noise close to the edges. Because the median filter reduces the measurement resolution, a congruent operation is presented in the context of precision measurement, which makes that the output of the current pixel is expected to be indeed its own value. By projecting the designed binary patterns and introducing the adaptive median filter, high-quality phase can be determined for the high-speed 3D measurement.

10329-179, Session 7

High-throughput single-shot hyperspectral interferometer for areal profilometry based on microlens array integral field unit

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Scanning white light interferometry (SWLI) has become an established technique to measure absolute distance and surface profile of components with height steps and steep height gradients. The use of a broadband source eliminates the need for phase unwrapping and increases the unambiguous measurement range with respect to systems that use monochromatic light. In SWLI, the object or a Mirau objective is scanned axially while keeping the reference beam stationary. The surface height with respect to a datum is then found by detecting the point of maximum fringe modulation on a pixelwise basis. In a closely related technique, known as wavelength (or frequency) scanning interferometry (WSI or FSI), the optical path difference between both arms in the interferometer remains fixed while the wavelength is scanned over time.

The scanning nature of these approaches imposes stringent environmental stability requirements during the acquisition of typically hundreds of interferograms. To overcome this limitation, a 'single-shot' method has been proposed in which all the spatial and spectral information is recorded simultaneously in a single exposure [1, 2]. Known as hyperspectral interferometry (HSI), the output of a white-light interferometer provides the input to a hyperspectral imaging system to spatially separate, onto a photodetector array, a set of narrowband interferograms from a single white-light interferogram. Previously proposed implementations, however, based on an etalon filter and a diffraction grating use only ~2% of the available pixels. This limits the number of measured coordinates to ~200 pixels with an unambiguous depth range of ~0.3 mm.

In this paper, an alternative way to spatially separate the spectral information onto the photodetector array is presented. It is based on a microlens array integral field unit developed in astronomy for spectral imaging applications where high space-bandwidth product and throughput are required, and can lead to a pixel usage of over 40%, i.e. a 20? improvement on previous HSI setups. Using a Linnik type interferometer, the object is imaged onto a microlens array, where it interferes with the reference beam. Behind the microlens array white light spots are produced, which are then dispersed by a grating and imaged as an array of linear spectra onto a large area photodetector array (see Fig. 1). For each microlens, the optical path between its corresponding point on the object and the reference beam determines a modulation frequency along the wavelength axis of its spectrum. Fourier transformation along these (in the wavenumber domain) leads to a 2-D map of surface height.

Experimental results from various samples are presented, including validation tests, specular surfaces (see Fig. 2) and rough surfaces that produce speckle. An array of 35x35 independent points was measured simultaneously in a square grid with a pitch of 0.1 mm, covering a FOV of 3.5x3.5 mm^2 and with a depth range of 0.88 mm. An rms height error of 490 nm was achieved for a flat mirror, mainly dependent on lens aberrations, and a 15x throughput increase compared to previous implementations.

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10329-32, Session 8

Comparison of astrophysical Fabry-Perots with respect to the requirements of HIRES

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The detection of atmospheres of exoplanets is one of the aims of HIRES - the High Resolution Spectrograph, an instrument which will be used at the E-ELT. To reach the required radial velocity precision of about 10 cm/s, calibration with more precise sources will be mandatory. Possible calibration sources are Fabry-Perots (FP). It has already been demonstrated that the FP perform better than 10 cm/s per night. We give an overview of the currently used FP in different surveys and compare their individual features. For the FP which may be used in HIRES we discuss different configuration, including ring-resonators and pasive or active length-stabilization. We show that the Finesse and FSR of the FP needs to be optimized with regard to the resolution of the spectrograph and we outline a possible solution to meet the requirements of HIRES.

10329-33, Session 8

Comparison of astrophysical laser frequency combs with respect to the requirements of HIRES

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Precise astronomical spectroscopy with the forthcoming E-ELT and its High Resolution Spectrograph (HIRES) will enable detection of atmospheres of exoplanets. HIRES will experience systematic errors like intrapixel variations and random variations like fiber noise, caused by the non-uniform illumination of the coupling fibers. All these errors will affect the performance of the spectrograph. One goal is to achieve a radial velocity precision on the order of 10 cm/s. Here, we describe the requirements for calibration sources which may be used for HIRES. Precise wavelength calibration with Laser Frequency Combs (LFC), so called AstroCombs, has been demonstrated with different astronomical spectrographs and we show a comparison of currently used AstroCombs. We outline a possible solution to meet the requirements of HIRES with a single broadband AstroComb.

10329-34, Session 8

The end-to-end simulator for the E-ELT HIRES high resolution spectrograph

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We present the design, architecture and results of the End-to-End simulator model of the high resolution spectrograph HIRES for the European Extremely Large Telescope (E-ELT).

The End-to-End simulator can be used both by engineers and scientists to help the design and the building of the spectrograph since it allows predicting the instrument performance for any given hardware set.

In particular, the photons of any scientifically relevant input source are traced across the spectrograph down to the detector. The resulting 2D spectrum can, then, be analyzed by the Data Reduction Software to check that the designed spectrograph is compliant with the HIRES science cases requirements.

In this paper, we will detail the architecture of the simulator and the computational model which are highly modular, ensuring flexibility. This is a crucial aspect of any next generation astronomical project like E-ELT in view of their complexity and realization time-scales.

Eventually we present the synthetic spectra obtained by the current version of E2E based on the HIRES accuracy requirements. The aim is to feed these spectra into DRS (Data Reduction Software) to close the loop and prove that the achieved accuracy in the final radial velocity measurement is the one expected and compliant with the HIRES very demanding science cases.

10329-35, Session 8

Calibration of astronomical infra-red spectrographs: from VLT/CRIRES to the E-ELT

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CRIRES+ is the premier astronomical high-resolution, infra-red spectrograph at the European Southern Observatory Very Large Telescope coming online in 2018. The project provides a state-of-the art IR spectrograph in a unique and highly anticipated parameter range, tailored to tackle exoplanet science in the 1-5um range at highest spectral and spatial resolution. This is facilitated by new and innovative IR calibration techniques in CRIRES+, including a novelty IR etalon, infra-red gas-cells, and a metrology system that enables self-calibration of the spectrograph.

The instrument is currently being integrated and under test in the laboratory. The talk will dicuss the calibration unit strategy and implementation, and report first performance results. Emphasis will be put on lessons learnt and how to meet the challenges imposed by calibration units of E-ELT IR spectrographs.

10329-36, Session 8

Atomic layer sensitive in-situ plasma etch depth control with reflectance anisotropy spectroscopy (RAS)

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Reflectance anisotropy spectroscopy (RAS) allows for in-situ monitoring of reactive ion etching (RIE) of monocrystalline III-V semiconductor surfaces.

During RAS the sample to be etched is illuminated with linearly polarized light under nearly normal incidence. Commonly the spectral range is between 1.5 and 5.5 eV. Typically the spectrally resolved difference in reflectivity for two orthogonal linear polarizations of light is measured - for example for cubic lattices (like the zinc blende structures of most III-V semiconductors) polarizations along the [110] and the [-110] direction.

The signal is caused by local anisotropies on the surface due to ablations on the etch front and comes along with an elliptical polarization of the reflected light.

The time and photon energy resolved spectra of RAS include reflectometric as well as interferometric information. Hence light waves with wavelengths well above 100 nm (even inside the material) can be successfully used to monitor surface structures with characteristic heights or resolution of some tens of nanometers. The shrinking layers act as optical interferometers and lead to Fabry-Perot oscillations in the signal.

Our experimental data show even better resolution in an etch regime with very low etch rates and high RAS scanning rate. For certain photon energies we detect monolayer oscillations in the mean reflectivity, which gives the best possible resolution in etch depth monitoring and control, i.e. the atomic scale.

10329-37, Session 8

Photo-vibrational spectroscopy using quantum cascade laser and laser Doppler vibrometer

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Photoacoustic/photothermal spectroscopy is an established technique for detection of chemicals and explosives. However, prior sample preparation is required and the analysis is conducted in a sealed space with a high-sensitivity sensor coupled with a lock-in amplifier, limiting the technique to applications in a controllable laboratory environment. Hence, this technique may not be suitable for defense and security applications where the detection of explosives or hazardous chemicals is required in an open environment at a safe standoff distance. In this study, chemicals in various forms were excited by an intensity-modulated quantum cascade laser (QCL), while a laser Doppler vibrometer (LDV) was applied to detect the vibration signal resulting from the photocoustic/photothermal effect. The photo-vibrational spectrum obtained by scanning the QCL's wavelength in MIR range, coincides well with the corresponding spectrum obtained using typical FTIR equipment. The experiment in short and long standoff distances demonstrated that the LDV is a capable sensor for chemical detection in an open environment.

10329-38, Session 9

Three-dimensional Dammann confocal microscopy *(Invited Paper)*

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Distorted and three-dimensional (3D) Dammann confocal microscopy is proposed based on introducing distorted and 3D Dammann gratings into traditional confocal microscopy. Distorted Dammann grating is developed from distorted grating whose grooves are curved for achieving multiple axial imaging at one single plane according to the Dammann-encoded distorted grooves. 3D Dammann grating is a combinative diffractive optical element which could produce three-dimensional array around the focal point of a microscopic lens. Here the combinative means that 3D Dammann grating is composed of two diffractive optical elements, one is a usual Dammann grating and the other is a Dammann zone plate. Dammann grating is a well-known diffractive optical element that could produce multiple equal-intensity light spots at the Fourier-transforming plane, while a Dammann zone plate is a circularly-encoded diffractive optical element which could generate equal-intensity focal spots along the axial direction symmetrically from the original focal point of a microscopic lens. Dammann zone plate is called "Dammann" zone plate because its encoding data of the circularly phase-modulated plate is directly from the original data of Dammann gratings, based on the fact that the axial direction at the focal spot of a lens and the radius' square of the circular diffractive zone plate has a Fourier-transforming relationship. Since Dammann grating is a Fourier-transforming binary diffractive optical element, and Dammann zone plate is also a Fourier-transforming optical element with its radius' square encoded in binary phase modulation, so it is not necessary to re-optimize such a binary phase modulation of the circular zone plate, and it is simple to directly borrow the optimized data from Dammann grating for encoding the circular radius of Dammann zone plate. It should be noted that Dammann zone plate is different from the conventional Fresnel zone plate. Fresnel zone plate is a classical diffractive optical element which has been introduced in almost every optics class book in university course. Fresnel zone plate is based on the diffractive orders of a circular phase plate, while Dammann zone plate is based on the Fourier-transforming relation between the axial direction around the focal point of a microscopic lens and the radius' square of its phase modulated aperture of the lens. The conventional confocal microscopy usually has a single focal point, it could obtain three-dimensional profile of object by scanning the object. But it is hard to get an overall imaging of the changing cell with a single shot. Dammann STED microscopy, including 3D Dammann STED microscopy, could achieve 2D/3D superresolution using two wavelength lasers. Using distorted and three-dimensional Dammann gratings, it shows a new confocal microscopy which could obtain three-dimensional information of object faster and more convenient than the usual single-focal-point confocal microscopy, therefore, novel Dammann-based microscopy should be useful for practical applications.

10329-39, Session 9

Optical inspection of hidden MEMS structures

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Nowadays, micro-electro-mechanical-systems (MEMS) are contained in almost every modern device. In vehicles, the airbag or electronic stability program operates on MEMS-based sensors. MEMS pressure sensors in the automobile engine ensure less fuel consumption and modern cellphones become "smart" only with MEMS-based devices, which are used for detecting or controlling of motion, pressure or camera focus among others.

The production of MEMS is a fully automated process. The basic process flow of the MEMS structures consists of material deposition, lithographically pattering and etching techniques. In these steps, the structures are still optically accessible for inspection or error localization. A final step is the bonding of a silica cap wafer on top to protect the MEMS. Afterwards the functionality can be influenced, since the capping can induce tension. In addition to the electronical test, an optical inspection of the MEMS through the cap would be helpful, because more than 90 % of the production costs occur only during the dicing and packaging of the entire device. Further, in case of a failed electronic test the defect cannot be localized. In order to analyze the topography using state-of-the-art optical metrology techniques, the silica cap has to be removed prior to the measurement. However, this step is quite complex and the structure of the MEMS might change again.

In this paper, an optical sensor is presented which is able to register the topography of the MEMS structures inside the already closed wafer-stack. In order to achieve this, the boundary conditions for optical inspection of these MEMS structures are first discussed. As most crucial limitation, this is only feasible with short infrared light (SWIR), since the absorption of silica drops rapidly for wavelengths above 1.1 μm. Additionally, high axial accuracies are required in order to resolve slightly bent MEMS fingers. Various known measurement techniques in the field of optical surface metrology are therefore analyzed and compared with regard to their applicability for these requirements. Promising candidates are confocal microscopy (CM), which is suitable for the inspection of multi-layer reflective objects, as well as low-coherence interferometry as an established technique for high precision measurements in the sub-micron range. Examples hereby are the optical coherence tomography to resolve multi-layered technical or biological objects or the scanning white-light interferometry (SWLI) to detect one layer with sub-lambda accuracy.

The most appropriate sensor is a Linnik-type SWLI sensor, operating in the SWIR wavelength range, whose design and setup is presented in the second part of this publication. Since the MEMS cover is considered as a plane-parallel plate, spherical aberration badly influences the imaging performance. However, this can be corrected by using special microscope objective lenses. The axial scan of the sensor is done by a piezo actuator

in order to receive the desired SWLI wavelet. The final height information is then obtained by applying a phase-accurate signal evaluation based on a lock-in technique. First height measurement of MEMS are shown, where the topography of the smallest MEMS fingers with a structure size of 2 μm is resolved.

10329-40, Session 9

Confocal unrolled areal measurements of cylindrical surfaces

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Confocal microscopes are widely used for areal measurements thanks to its good height resolution and the capability to measure high local slopes. For the measurement of large areas while keeping few nm of system noise, it is needed to use of high numerical aperture objectives, move the sample in the XY plane and stitch several fields together to cover the required surface. Other technologies such are Coherence Scanning Interferometry (CSI) and Focus Variation (FV) are also widely used for the measurement of technical surfaces. Each technology has its own advantages and disadvantages. For instance, Inteferometry provides the highest vertical resolution independently of the numerical aperture of the objective, but I has the drawback of being highly sensitive to vibration and requires large amount of acquired images to extract the areal information. Focus Variation has the benefit of being very robust for the measurement of rough surfaces, but it requires high numerical aperture to achieve high vertical resolution. For low magnification objectives, Focus Variation is more suitable for the measurement of the form and waviness components of a surface more than its texture. In this paper we are proposing the measurement of cylindrical surfaces, which in principle can be measured with any of the above technologies. We have selected Confocal as the first step in our research to implement this new acquisition methodology, despite this does not limits the use of CSI or FV in future developments.

On cylindrical surfaces a rotational stage is used to measure fields along the round surface and stitch them in order to obtain a complete 3D measurement. The required amount of fields depends on the microscope's magnification, as well as the cylinder diameter. However, for small diameters, if the local shape reaches slopes not suitable for the objective under use, the active field of the camera has to be reduced, leading to an increase of the required number of fields to be measured and stitched. This is even more evident when measuring the cylinder shape with low magnification optics, where the maximum permissible local slope is relatively low, and thus the amount of image used is even less. Calibration of Confocal measurements on tilted surfaces is not as simple as removing the residual flatness error taken on a flat reference mirror. The original raw aberration of the optics changes the field curvature amount with the tilt of the imaging object, making to appear a low frequency error that increases in amplitude with the tilt. On cylindrical surfaces this is a continuous effect and it is difficult to correct, and despite this error most of the times lies lower than the texture components of the surface, it appears on the stitching between fields. Such error may be considered as a low frequency error of the surface itself, but in reality it is not.

In this paper we show a new approach for areal measurements of cylindrical surfaces that uses a rotational stage in combination with a slit projection confocal arrangement and a high-speed camera. An unrolled confocal image of the cylinder surface is build by rotating the sample and calculating the confocal intensity in the center of the slit using a gradient algorithm. A set of 360º confocal images can be obtained at different heights of the sample relative to the sensor and used to calculate an unrolled areal measure of the cylinder.

This method has several advantages over the conventional one such as reduced measurement time, and no stitching required, making the previous described error not appearing and thus much more reliable data for post-processing. In addition, the result shows less residual flatness error since the surface lies flat in the measurement direction in comparison to field measures where the highest slope regions will show field distortion and non-constant sampling.

We have also studied the influence on the areal measurements of wobble and run-out introduced by the clamping mechanism and the rotational axis. This two errors manifest on the measured topography as low frequency components that most of the times have a wavelength equals to one full turn of the surface. By identifying such form errors from the series of the confocal images, it is possible to predict their amplitude and isolate the components on the topography corresponding, subtracting them from the raw data. This method provides closer areal surface topography to the real one than any other existing method today.

10329-41, Session 9

Transfer characteristics of optical profilers with respect to rectangular edge and step height measurement

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Optical profilers are mature instruments used in research and industry to study surface topography features. Although the corresponding standards are based on simple step height measurements, in practical applications these instruments are often used to study the fidelity of surface topography.

In this context it is well-known that in certain situations a surface profile obtained by an optical profiler will differ from the real profile. With respect to practical applications such deviations often occur in the vicinity of steep walls and in cases of high aspect ratio.

In this contribution we compare the transfer characteristics of different 3D optical profiler principles, namely white-light interferometry, focus sensing, and confocal microscopy. Experimental results demonstrate that the transfer characteristics do not only depend on the parameters of the optical measurement system (e. g. wavelength and coherence of light, numerical aperture, evaluated signal feature, polarization) but also on the properties of the measuring object such as step height, aspect ratio, material properties and homogeneity, rounding and steepness of the edge, surface roughness. As a result, typical artefacts such as batwings occur for certain parameter combinations, particularly at certain height-to-wavelength ratio (HWR) values. Understanding the mechanisms behind these phenomena enable to reduce them by an appropriate parameter adaption. However, it is not only the edge artefacts, but also the position of an edge that may be changed due to the properties of the measuring object.

In order to investigate the relevant effects theoretically, several models are introduced. These are based on either an extension of Kirchhoff's diffraction theory, and Richards-Wolf modeling as well as rigorous coupled wave analysis (RCWA). Although these models explain the experimental effects quite well they suffer from different limitations, so that a quantitative correspondence of theoretical modeling and experimental results is hard to achieve.

Nevertheless, these models are used to study the characteristics of the measured signals occurring at edges of different step height compared to signals occurring at plateaus. Moreover, a special calibration sample with continuous step height variation was developed to reduce the impact of unknown sample properties. We analyzed the signals in both, the spatial and the spatial frequency domain, and found systematic signal changes that will be discussed. As a consequence, these simulations will help to interpret measurement results appropriately and to improve them by proper parameter settings and calibration and finally to increase the edge detection accuracy.

10329-42, Session 9

Focus-variation microscopy for measurement of surface roughness and autocorrelation length

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Spatial bandwidth limitations frequently introduce large biases into the estimated values of RMS roughness and autocorrelation length that are extracted from topography data on random rough surfaces. The biases can be particularly severe for focus-variation microscopy data because of the reduced lateral resolution (and therefore dynamic range) inherent in the technique. In this paper, we describe a measurement protocol – essentially a deconvolution algorithm – that greatly reduces these biases. The measurement protocol is developed for the case of surfaces that are isotropic, and whose topography displays an autocovariance function that is exponential, with a single autocorrelation length. The protocol is first validated against Monte Carlo-generated mock surfaces of this form that have been filtered so as to simulate the lateral resolution and field-of-view limits of a commercial focus-variation microscope. It is found that accurate values of roughness and autocorrelation length can be extracted over a four octave range in autocorrelation length by applying the protocol, whereas errors without applying the protocol are a minimum of 30% even at the absolute optimum autocorrelation length. Then, microscopy data on eleven examples of rough, outdoor building materials are analyzed using the protocol. Even though the samples were not in any way selected to conform to the model's assumptions, we find that applying the protocol yields extracted values of roughness and autocorrelation length for each surface that are highly consistent among datasets obtained at different magnifications (i.e. datasets obtained with different spatial bandpass limits).

Fig. 8a(left). Deviation between extracted values of RMS roughness from a 512x512 pixel mock topography and the actual value. Red points indicate first-order estimates (i.e.) from the unfiltered topography, that has a resolution pixel. They show a ~5 octave wide plateau of accuracy, where . Green points indicate first order estimatesfrom the mock topographies that have been filtered to simulate the instrument's actual lateral resolution. The plateau has disappeared, and all estimates are biased low by a large factor. Blue points indicate the corrected estimates, i.e., after the correction protocol of §III is applied. Most of the plateau of accuracy is recovered. Fig. 8b(right) The corresponding deviation between extracted values of autocorrelation length and the actual value . Again, the first-order estimates on filtered mock topographies show no plateau of accuracy whatsoever, although for smallthe estimates are biased high and for largethey are biased low. Again, the correction protocol of §III recovers most of the plateau of accuracy.

10329-43, Session 10

Sub-diffraction surface topology measurement using a microsphere assisted Linnik interferometer *(Invited Paper)*

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Microscopic surface topology measurement is an important aspect of industrial inspection. Optical and near field scanning techniques are increasingly replacing the use of the traditional mechanical stylus. The reasons for this are that they provide better lateral resolutions and higher measurement speeds. While near field techniques provide lateral resolutions down to several nm, they are fundamentally limited in measurement speed by the need for lateral tip scanning. The different far field optical techniques typically used are interference microscopy, confocal microscopy, structured illumination microscopy (SIM) and tomographic diffractive microscopy (TDM). The advantages of remaining in the far field [1] are the larger fields of view of hundreds of µm to several mm and the higher measurement speeds, ranging from several seconds to several minutes depending on the volume measured. The main disadvantage compared with near field techniques is the lateral resolution that is limited by diffraction to about lambda/2, or between 200 nm to 500 nm in the visible region. Improvements in lateral resolution to better than 100 nm have been achieved by means of increasing the synthetic aperture, in the case of SIM by using a projected high resolution grid [2], and in TDM, by changing the solid angle of illumination [3].

One of the most commonly used far field techniques is interference microscopy, mainly because of its very high axial measurement sensitivity of less than 1 nm and its ease of use. Nonetheless, the disadvantage remains the limited lateral resolution which is over two orders of magnitude worse than the axial measurement sensitivity. In the field of high resolution 2D imaging, an important technique introduced several years ago is the use of a microsphere placed on the sample in front of the microscope objective, with a lateral resolution of 50 nm in the best conditions [4]. More recently, in 2016, the microsphere technique was successfully combined with interferometry by several groups in a major step forward in reducing the gap between lateral resolution and axial measurement sensitivity [5-7]. In this paper we present some of our own first results of combining the microsphere technique with a white light Linnik interferometer and demonstrate a lateral resolution of lambda/4 and an axial measurement sensitivity of several nm.

Results are shown on the measurement of calibrated square profile gratings with periods ranging from 300 nm to 1.2 µm, with minimum feature sizes from 150 nm to 600 nm and heights from 140 nm to 190 nm, with a field size of several µm, dependent on the microspheres used (6 µm to 35 µm). While the smaller period structures are not visible directly, they become visible and measurable through the microsphere. Some first results are also shown on small more random structures such as anodised aluminium. An analysis using rigorous electromagnetic simulations is also given to help understand the imaging process of the technique and the implication of the photonic nanojet phenomenon. These first experimental and simulation results clearly indicate that this is a significant new technique that opens new possibilities for surface metrology beyond the diffraction limit.

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10329-44, Session 10

Measurement, certification and use of step height calibration specimens in optical metrology

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An important routine task in industrial inspection is the calibration of the height scale for surface topography instruments. For dimensional measurements, calibration involves comparison with a reference value that provides traceability to the SI unit of length, the meter. Potential outcomes of calibration include adjusting the instrument to provide data with greater accuracy, or simply verifying that the instrument is working properly and is reporting results with the expected uncertainty.

There are many ways of calibrating surface height measuring instruments, ranging from interferometry with a known reference wavelength to comparison with a reference or primary metrology instrument. A convenient technique is the use of material measures that have been examined and certified using a primary instrument at a National Metrology Institute or at a qualified lab. For surface height calibration, the most common technique relies on a type PGR (or type A1) material measure, consisting of a flat reference area with a rectangular groove or plateau offset by specified step height.

Somewhat surprisingly, there is not as yet a standardized procedure for measuring step heights and interpreting the results of 3D measurements. Published standards, including ISO 5436-1 and ASME B46.1, govern the use of step specimens for 2D profile instruments such as stylus gages. There is currently a discussion on this topic in the context of the emerging ISO 25178 documents related to areal surface topography instruments such as confocal, focus variation and interference microscopes. Key questions relate to the reference and measurement evaluation areas, the use of filtering, definition of valid data points, error sources, and the determination of the step height value from the processed topography data. The discussion is complicated by the reality that the existing contact profiler standards are not entirely consistent with each other, nor with established practice, even for laboratories that certify specimens for use by industry.

This paper proposes definitions for the reference and measurement areas of type PGR (A1) material measures for areal surface topography instruments. The definitions are logical extensions of trace lengths employed in the 2D profile measurements in the ISO and ASME standards. The proposed measurement protocol is to acquire and process the surface topography map, define reference areas 1 and 2 and groove or plateau measurement area 3. A linear least-squares fit plane to the topography data within the reference level areas 1 and 2 establishes a reference plane, followed by a calculation of the step height d as the average depth (or height) of the measurement region 3 with respect to this reference plane. The proposed procedure includes error reduction techniques, including minimizing residual flatness error and averaging of multiple measurements. The complete paper will describe alternative methods and guidance for the calibration, adjustment and verification of areal surface topography instruments. The paper will also report procedures and results for the certification of PGR standards in our laboratories to an uncertainty of 0.3% with a goal of achieving 0.1% in the future.

10329-45, Session 10

Surface profile measurement by using the integrated Linnik WLSI and confocal microscope system

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To accurately measure the three-dimensional (3D) surface profile (SP) of different industrial applications, optical methods have been widely used. In comparison with contact methods, optical methods are characterized by possessing non-contact, high resolution and whole field measurement capability.

The white-light scanning interferometer (WLSI) and confocal microscope (CM) are the two major optical systems for measuring 3D SP of micro specimens. Since the vertical scanning signals must be sufficient and complete to calculate zero optical path difference positions, WLSI is suitable for measuring smooth and low-slope surfaces, such as semiconductor and thin-film-transistor liquid-crystal display. CM is suitable for measuring rough, uneven-reflective and low-reflective surfaces in which the depth information is analyzed by using signal intensity and image sharpness. CM is popular in printed circuit board industry as well as assembly and test processes of semiconductor industry. Nevertheless, before implementing WLSI and CM, both vertical and horizontal scans are needed. Therefore, in this paper, Linnik white-light scanning interferometer (Linnik WLSI) and CM were integrated into an optical microscope system to accommodate the measurement needs of 3D SP of specimens of different micro structures.

A common part assembled by tubes, lenses and interferometer was used to conjunct finite and infinite optical systems for Linnik WLSI and CM in the self-assembled optical microscope. By adopting the flexibility of tubes and lenses, switching to perform two different optical measurements can be easily achieved. Furthermore, based on shape from focus method, CM was developed with energy of Laplacian filter. The on focal information of each pixel was enhanced so that all-in-focus image for 3D SP can be measured and analyzed simultaneously in the CM. As for Linnik WLSI, eleven-step phase shifting algorithm was used to analyze vertical scanning signals and the 3D SP within DOF was also determined. The magnifications of Linnik WLSI and CM are 40X and 60X, respectively. The associated horizontal spatial resolutions of Linnik WLSI and CM are 0.2 ?m/pixel and 0.15 ?m/pixel, respectively.

10329-46, Session 10

Application of a multilayer surface approach for the estimation of material-dependant optical properties for ellipso-height-topometry

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When coherence scanning interferometry is applied for the high-resolution topography measurement of micro-structured technical surfaces, phase changes on reflection may occur due to the different optical properties of the measured sample. The measured interference fringe phase and the position of the modulation envelope are influenced by material contrasts. Ellipso-Height-Topometry is a measurement technique which can measure material-specific ellipsometric angles and topography both at high lateral resolution on the same pixel raster leading to maps of height H(x,y) and ellipsometric angles ?(x,y) and ?(x,y). Based on the measured information, it is possible to evaluate the material composition of the surface, the thickness of covering layers and a height correction which considers the influence of the material contrasts. Currently it is possible to calculate the ellipsometric parameters for at most two layers. In practice there are often more layers. One example is an aluminum layer which covers an oxidized silicon surface leading to the three layers of silicon oxide, aluminum and aluminum oxide. Until now we assume that the basic material and the aluminum layer do no feature oxide which reduces the number of layers to two. Since there are more and more applications with diverse surface layers in order to meet different demands towards engineering surfaces for industrial and research applications, a robust and efficient algorithm for multiple layers and an accurate correction of topography height information for different materials are required.

In our paper, an extended multilayer approach which is capable of handling additional layers based on a parallelized ray tracing algorithm using graphic processing units is introduced. For this more accurate description numerical approaches are utilized since it is not possible to give an algebraically closed solution for three or more layers. It is possible to evaluate the layer thicknesses for multiple layers efficiently when the complex refractive indices of the different materials are known. Using these considerations, a numerical algorithm is introduced which evaluates the thickness of multiple layers for known complex refractive index and measured intensity of reflected rays which were transmitted or reflected by the optical system of layers before. By applying a damping threshold in the ray tracing algorithm, the intensity of a finite number of reflected and transmitted rays can be estimated. The new approach for Ellipso-Height-Topometry measurement technique is compared with the current procedures which neglect the existence of an oxide layer for the basic material.

To experimentally verify the approach and according algorithm, it is applied for the evaluation of actual surfaces with multiple plane layers and different materials. With the aid of lithography and sputtering, test samples of multi-layer surface structures are manufactured with different materials in order to evaluate the complex refractive index, the distribution of identified materials and the layer thicknesses within actual Ellipso-Height-Topometry measurements. The results of the measurements are compared towards the predicted theoretical results.

10329-47, Session 11

Combination of a fast white light interferometer with a phase shifting interferometric line sensor for form measurements of precision components

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With improved precision machining methods, more precise mechanical or optical components and surfaces can be produced, for example by diamond turning, polishing, high-precision impression processes or by ion beam processing. For mechanical precision components and precision optics very low form tolerances in the sub- micrometer range are required. Aspherical or free-form surface optics is used to reduce aberrations in optical systems (e.g. objectives) and to achieve high optical performance at the same time with a small number of optical surfaces. Correspondingly accurate and non-contact form measurement technology is the key for the use and the application of the precision-machined surfaces.

The line sensor system, which is developed in a research project funded by the Deutsche Forschungsgemeinschaft (DFG), measures the form of the specimen by several overlapping circular rings using a line sensor. This concept is very flexible and can be adapted to many different specimen geometries. The interferometric line sensor is based on a Michelson configuration. It consists of a fast oscillating reference mirror in combination with a line scan camera. The sensor has a measurement range of about 18 ?m in the axial direction and a working distance of 14 mm. It measures the heights with interferometric accuracy in the nanometer range. Due to the overlapping areas, movement errors can be corrected during the stitching process for the 3D topography. In order to obtain an interference signal with the interferometric line sensor, the measured surface section must be within the depth of field of the objective. A white light source and an additional scanning axis are integrated into the system. Hence, a white light interferometric measuring mode offers the possibility of finding the best focus position for the subsequent highly accurate phase shifting measurements. “Best focus position” means that the optimum distance between sensor and specimen as well as the optimum angle of the sensor head have to be found. The optimum angle is the angle where the optical axis of the interferometer is perpendicular to the surface of the specimen.

The setup of the line-based form measuring system which combines fast WLI and phase shifting interferometry (PSI) will be shown. The measurement strategy to find the optimum distance and the optimum angle of the sensor head will be presented. The traceability of the system and the main error influences are discussed. Exemplarily, form measurements of precision components are shown.

10329-48, Session 11

Birefringence measurement in complex optical systems

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State of the art microscope objectives become increasingly more complex. There are more lenses required in the optical design and optical coatings have more layers. These complex designs are prone to induce more thermal stress into the objective which causes birefringence. In addition, there is a certain degree of freedom required to meet optical specifications during the assembly process. The mechanical fixation of these degrees of freedom can also lead to mechanical stress in the objective and therefore to birefringence. To be able to distinguish those two types of stress a method to image the birefringence in the objective is required. There are also methods in microscopy where already very little amounts of birefringence reduce image contrast and therefore birefringence has to be controlled and contained on a level under 10 nm RSM over the whole pupil in the assembly process.

A classic Sernamont setup as well as any other setup with a unidirectional light path has many disadvantages when measuring immersion type objectives with high NA since the pupil cannot be fully illuminated without using immersion liquids. For this case a setup is needed which can measure the birefringence in reflection. An approach to measure birefringence in a complex optical system is presented, which is adapted to the needs of the manufacturing process of microscope objectives.

In the proposed setup light is polarized by a circular polarization filter and then is transmitted through a rotatable linear retarder and the tested optical system. Light then is reflected back on the same path by a mirror. After the light passes the circular polarization filter on the way back, the intensity is recorded. When the rotatable retarder is rotated the recorded intensity is modulated depending on the birefringence of the tested optical system. This modulation can be analyzed in Fourier domain and the linear retardance angle between the slow and the fast axis as well as the angle of the fast axis can be calculated. From the amplitude of the modulated signal, the retardance angle can be derived and the phase is connected to the angle of the fast axis. The retardance distribution over the pupil of the optical system then can be analyzed using Zernike decomposition. From the Zernike decomposition the origin of the birefringence can easily be identified. Since it is required to quantify small amounts of retardance below 10nm, the birefringence of the measurement system has to be characterized before the measurement and considered in the calculation of the resulting birefringence. This characterization is performed by measuring the birefringence in the setup against a flat mirror. Small changes in retardance angle or the orientation of the fast axis (due to temperature drift) are producing some very typical artefacts. Where usually a rotational symmetric birefringence distribution with the lowest birefringence in the middle is expected, these changes lead to a result which has two distinct minima. These artifacts can be compensated for under the assumption of primarily radial stress in the measured optical system. The assumption enables a self-calibration of the measurement due to assumed zero birefringence in the central part of the aperture.

10329-200, Session 11

TBA1 (Joint Session Presentation w/EOS) *(Invited Paper)*

Peter Lehmann, Univ. Kassel (Germany)

No Abstract Available

10329-201, Session 11

TBA2 (Joint Session Presentation w/EOS)

Peter Lehmann, Univ. Kassel (Germany)

No Abstract Available

10329-49, Session 12

Dynamic interferometry: metrology of space optics and structures *(Invited Paper)*

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No Abstract Available

10329-50, Session 12

Preliminary results of a new proposal for objective human independent striae measurement

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Optics and photonics are key enabling technologies and are important components for the approaching industry 4.0. As a matter of fact optical glasses with certain inner quality e.g. high homogeneity combined with low striae content are essential for such applications. A striae is a small local change in the refractive index of a glass due to (small) local chemical inhomogeneity of the glass composition. Striae inside a glass cause a wavefront distortion and thus can cause a blurring of the image. Therefore, optical glass is quality controlled during production with respect to striae. For this a sensitive striae measurement system is needed. SCHOTT uses a simple, robust and efficient measurement technique the so-called shadow graph method for measuring striae. Here stronger striae deflect light more and this results in a shadow with more contrast on a screen. An operator evaluates the contrast by comparison with references.

In order to have a human independent and objective measurement system a new approach is presented. The proposed new approach uses the shadow graph method which was proven to be reliable since more than 100 years. Instead of a human eye the image of the striae on a screen is taken by a digital camera. The following image processing includes an image pre-processing (shading, cutting and noise reduction), striae detection (with e.g. labeling and reconstruction) and analyzing using a look-up table from a reference plate. It turns out that two quantities are needed for a unique striae measurement: structural information about the striae width and the amplitude from the grey level of the striae contrast. A striae diffracts light and in the far-field (Fraunhofer diffraction) the diffracted striae is found as a shadow on the screen of the shadow graph method. Thus a Fourier transform and its first zero-point crossing (root) will give structural information of the striae width. A reference plate is used for calibration of the grey level. This reference plate consists of different artificial rectangular striae of different width and amplitude (defined wavefront distortion). This calibration has to be done only once. Using this calibration and the structural width and grey level scale both obtained from the measurement (i.e. the image taken by the digital camera), the striae level can be uniquely determined using image processing tools. Afterwards the striae level are analyzed, and categorized.

A first comparison is made between results obtained from the new proposed method and the reliable one using experienced human quality operator which show more than about 80% agreement. A first repeatability measurement shows wavefront deviation of less than +/- 8 nm (!) – maximum deviation! Such an unexpected small deviation suggests a further investigation of the new method based on shadow graph method and image processing. This new method has the big potential to be used as a human independent objective striae measurement with relatively low expenses that can be used during production and even for future standardization. Additional work is needed and already in progress to further prove reliability.

10329-51, Session 12

Development of wavefront sensor for in-situ measurement of freeform optics

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The freeform optical surfaces are increasingly becoming integral part of optical systems as they offer higher degrees of freedom to the designer in order to improve the performance. Particularly benefited systems are illumination systems, compact projection systems, head-up-displays, ophthalmic systems, and surveillance systems. The increased range of manufacturable freeform surfaces offered by the new fabrication techniques is giving opportunities to incorporate them in the optical systems. However, the success of these fabrication techniques depends on the capabilities of metrology procedures and a feedback mechanism for optimizing the manufacturing process. Therefore, a precise and in-situ metrology technique for the measurement of freeform optics is in demand.Though all the technicques available for asphers have been extended for the freeform surfaces by the researchers, but none of the techniques has yet been incorporated into the manufacturing machine for in-situ measurement. The most obvious reason is the complexities involved in the optical setups to be integrated in the manufacturing platforms. Shack-Hartmann sensor offers the potential to be incorporated into the machine environment due to its vibration insensitivity, the small size and the simple principle of operation for form error measurement.

A scanning Shack-Hartmann Sensor has been developed and used as a metrology tool that can be integrated to the manufacturing platform. A method based on sub-aperture stitching is applied to characterize the full surface.The interpretation of the metrology data in the context of the fabrication system has also been be made. It is required to develope an interface between the metrology and the fabrication systems. To know exactly the fabrication error on the freeform profile, a measurement in reflection mode is required.

The presented work is divided into two: the design and construction of a compact sensor assembly which can be integrated on the machine and a development of feedback mechanism between the manufacturing and the test environment. Presently, the experiments have been conducted for measurement of freeform in off-line mode by using the scanning subaperture stitching scheme. The methodology and first experimental results are presented here. The more detailed analysis and in-situ measurements will be presented in the conference.

10329-202, Session 12

TBA3 (Joint Session Presentation w/EOS)

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No Abstract Available

10329-203, Session 12

TBA4 (Joint Session Presentation w/ EOS)

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No Abstract Available

10329-204, Session 12

TBA5 (Joint Session Presentation w/EOS)

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No Abstract Available

10329-52, Session 13

Deformation measurements by ESPI of the surface of a heated mirror and comparison with numerical model

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2. Principle of the experiment

Our experimental setup is designed to determine the deformation of a heated parabolic off axis monolithic aluminum mirror. The mirror is placed on a nylon plate to prevent heat loss by conduction while heating from the back of the lateral side (Cf. Figure 1).

ESPI is used in combination with temporal phase unwrapping to measure the mirror surface displacements. This technic requires a diffusing surface to create speckle: the object beam is sent to a diffuser before it illuminates the mirror. The experimental setup is shown hereunder (Cf. Figure 2).

The measurements performed by ESPI allow us to determine the displacements between the camera and the mirror. In order to discriminate the RBM from the mirror and the RBM due to the environment (optical table dilatation e.g.) the displacements of an invar reference plate are also recorded by ESPI by the same camera.

3. Results

The experimental results have been compared to theoretical simulations performed with a multiphysics tool (OOFELIE developed by OpenEngineering). For a heating power of 0.5 W, the maximum error is about 0.03µm which is in the range of the experimental measurement precision.

4. Conclusion and perspectives

The experimental results are in agreement with simulation: the difference is in the range of the experimental precision. The next step will be the comparison between the experimental and theoretical wavefront error.

(test have been done, comparison will be presented during the congress)

10329-53, Session 13

Reduction of phase singularities in a speckle Michelson setup

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Speckle interferometry is an established technique in optical metrology. One particular application is the deformation measurement of rough objects in a Michelson interferometer. When phase measurements are taken before and after a load is applied, the deformation of the specimen can be made visible in the form of deformation fringes. The surface roughness of the specimen, however, leads to the appearance of phase singularities in the deformation phase, which impair the following unwrapping step. Indeed, applying standard unwrapping algorithms used for the testing of smooth surfaces fails completely. Therefore, smoothing or filtering operations are often applied, or sophisticated unwrapping algorithms are used in order to overcome the limitations imposed by the presence of the phase singularities.

In this work, however, we aim at reducing the number of phase singularities by physical means. By spatially forming the intensity distribution of the light source, an incoherent averaging is realized, which leads to an effective decrease in the number of phase singularities. The most straightforward realization of such a partially coherent light source is obtained by defocusing the light of a laser onto a rotating scatterer, forming a disc shaped source. In the experiment, this leads to a deformation phase that is indeed much smoother, almost resembling the results from two-beam interference. The deformation phase can even be unwrapped almost completely by the standard unwrapper mentioned above; only a few disturbances are left.

However, due to the partially coherent illumination, the interference phenomenon is located around the plane of optical path difference zero, limiting practical applications. Therefore, an alternative setup has been used to overcome this constraint. This time, a periodic light source is used. The laser light is focused onto the rotating scatterer, and multiple copies of the focus spot are generated by a Dammann grating. In this way, optical path differences of several centimeters can be introduced without any noticeable loss of visibility. Again, a huge improvement over the fully coherent case of the point source is achieved.

The experiments are also supported by computer simulations. In particular, the influence of the light source geometry is a topic of current investigation. By chosing the light source appropriately, the simulations suggest that the phase singularities can even be eliminated completely. It is a part of current work to see if such a complete elimination of the phase singularities can also be achieved in practice. Furthermore, the underlying mechanism behind the reduction in the number of phase singularities is currently being investigated. It can be shown from the experimental evidence that the application of the spatially extended light sources increases the correlation between the phase singularities of the measurements before and after the deformation takes place. During the combination of both raw phases into the deformation phase, the phase singularities then tend to cancel more than for the less correlated, fully coherent case. In addition, it is still to be determined why an analogous procedure for the shearing case, presented at this conference in 2015, did not show a corresponding effect.

In our contribution, we will describe the status of our investigations, present computer simulations and experimental results that provide insights into the reduction mechanism, and give a more extensive discussion of the results presented above.

10329-54, Session 13

Fast phase-shifting electronic speckle-pattern interferometer with a diode laser for detecting 3D deformations

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The analysis of materials and geometries under tensile stress and the extraction of mechanic parameters is an important field in solid mechanics. Our application addresses a biaxial tensile test of thin polymer specimens, since the thickness change is an unsolved problem. Currently, a commercial photogrammetric system measures the in-plane strain components. Due to the homogeneous polymer surface, elaborated surface treatment is required, which influences the image correlation results. Since there are only slow processes, vibrations and drift complicate precise deformation measurement. Additionally, no accurate out-of-plane deformation can be measured. Due to the rough surface of the technical surfaces, speckling occurs, which only allows for analysis of the out-of-plane deformation by ESPI approach. Commercial ESPI systems for strain measurement require several seconds to measure the 3D deformation, whereas phase-mask interferometers are expensive and complex.

We present a phase-shifting electronic speckle-pattern interferometer (ESPI) of Twyman-Green type for measuring the 3D deformation in tensile tests. A 65 mm optical path difference leads to a phase-shift by fast wavelength tuning of a diode laser via current. The utilized coherent source is a DBR laser diode with 10 mW at 632 nm and a linewidth of few MHz. For each quasi-static topography a set of four interferograms is acquired with equidistant phase shifts of $\varpi/2$, which corresponds to a wavelength tuning of approximately 1.5 pm or 1.1 GHz. The out-of-plane deformation (difference in topography) between consecutive sets of interferograms is calculated by the complex-division method. Then, a 2D unwrapping algorithm is applied. Due to the strong current dependence of the emission power, an intensity compensation has been implemented, which automatically adjusts the exposure time of the camera. Our algorithm normalizes the interferogram intensities subsequently in the digital regime. We calculate 2D in-plane displacement from two consecutive speckle pattern on the test surface while blocking the reference light. Applying a 2D cross-correlation algorithm the mean in-plane displacement is calculated for each segment on the surface assuming smooth deformation between adjacent segments. As a detector we employ a 2.3 MPixels CMOS camera to measure a field with maximum 14 mm in diameter with sufficient spatial resolution. The frame rate of 40 fps allows for a short image acquisition time. The temporal limitation for the image acquisition is mainly dependent on the exposure time for rough and uncooperative surfaces. The high quantum efficiency of the camera in combination with large apertures enables exposure times of tens of milliseconds even on uncooperative polymer specimens.

Due to wavelength tuning for the phase shifting via current, settling times faster than conventional piezo actuators are achieved in order to utilize the high frame rates of modern digital cameras. The combination of ESPI with speckle correlation enables fast 3D-deformation measurements. Therefore, our measurement system allows successive deformation measurements with nanometer spatial resolution and temporal resolution of considerably less than 1 s for the aimed application. In the paper we present our system, the performance analysis, and the application measurements on thin polymer specimens.

10329-55, Session 13

Uncertainty of scattered light roughness measurements based on speckle correlation methods

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The surface quality of technical components is an essential feature with regard to their applications. Surface characterization is based on well-defined statistical or deterministic parameters describing the micro topography in terms such as waviness, roughness or counts of structure elements (e.g., peaks). Typical roughness parameter values are in the micrometer and nanometer range and should be within defined close tolerances to enable an error free part function. Standardized measuring devices assess the topography and specify geometrical surface textures only under laboratory conditions (mechanical and optical stylus instruments, atomic force microscope) or at least under low vibration conditions (mobile roughness measuring systems). Scattered light measuring techniques overcome this confinement and enable a roughness characterization near to a production process (in-situ) and in a running production process (in-process). This opportunity is of increasing interest for manufacturers in order to establish a continuous quality inspection. A prototype roughness measuring devices reveals a roughness differentiability of delta_Sq = 1 nm for lapped surfaces within the roughness measuring range of Sq < 70 nm for a laser wavelength of 532 nm, a laser beam diameter of 10 mm or less, and a moving object with a velocity up to 90 m/min. The measuring results agree with simulation results based on a scattered light measurement process model according to the Kirchhoff theory. This indicates a principal applicability of the optical roughness measuring system. However, the experimentally determined resolution is probably not the limit and the determination of the corresponding measurement uncertainty is still an outstanding task, which is the object of this article.

Parametric optical surface characterization, as a subgroup of the scattered light techniques, is based on the evaluation of statistical properties of partially developed speckle patterns. They occur, when a technical surface with a roughness of less than 1/8 of the illumination wavelength diffusely reflects or scatters a coherent light beam of a few millimeters in diameter. A camera records a single speckle intensity distribution in the far field of the illuminated measuring object surface. Due to the statistical behaviour of laser speckles the speckle intensity modulation or the speckle contrast, respectively, carry information about the surface heights and the lateral correlation length of the measured micro topography area. Both parameters increase for larger roughness values, but decrease for a larger lateral correlation length in the case of the same surface roughness. As the later effect is minor compared to the roughness dependence of the parameters and, furthermore, is less significant in the case of in-process measurements within a specific production process, it is neglected here.

A suitable optical roughness parameter is based on the calculation of the two dimensional discrete autocorrelation function (ACF) of a camera image showing a speckle intensity distribution of the surface under investigation. Compared to the speckle contrast value the calculation of the ACF offers the opportunity to determine direction dependent roughness values, which is advantageous in the case of anisotropic rough surfaces. A roughness measure is, for example, the slope of the normalized ACF near to the ACF maximum. It can be estimated by the difference of only two ACF values: the ACF maximum and a neighbour value in the predominant roughness direction. As all ACF values – except for the maximum - result from multiplications and summations of uncorrelated camera pixel intensity values the propagated uncertainty of the ACF slope follows directly from the single pixel intensities and the corresponding uncertainty. The uncertainty of a single detector element depends on the uncertainties of many uncorrelated parameters (e.g., pixel size, detector sensitivity, detector noise, and laser photon shot noise) and is the result of propagated uncertainties, too. However, it is assumed to be the same for all camera pixels.

This article describes the assessment of the measurement uncertainty budget of parametric optical scattered light measuring systems and determines the combined measurement uncertainty according to the guide to the expression of uncertainty in measurement (GUM) methods A and B. The presented investigations consider for the first time the uncertainty propagation of features that are immanent to optical measurement techniques using lasers and electro optical devices. These features are based on physical effects, which result for example in the photon shot noise of lasers and the direction instability of laser beams. Furthermore, the readout noise, thermal noise, dark current noise and quantization noise of photo detectors and cameras are taken into account. The aim is to show that the single component uncertainties do not affect the measurement resolution of at least 1 nm for the Sq-Value.

Simulation results with an extended scattered light measurement process model according to the Kirchhoff theory, which takes into account the different uncertainty parameters, demonstrate the influence significance of single parameters on the appearance of speckle patterns and on the measurement uncertainty of the optical roughness parameter. The simulation results are verified by a comparison with scattered light measurements.

10329-56, Session 13

Pre-treatment for preventing degradation of measurement accuracy by speckle noise in speckle interferometry

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In the 1960s, deformation measurement method based on the speckle phenomenon was developed as speckle interferometry. ESPI (electronic speckle pattern interferometry) was also developed by introducing the TV-camera technology into speckle interferometry. Furthermore, fringe scanning technologies were introduced to the speckle interferometry for improving the measurement accuracy. As a result, the resolution power of the speckle interferometry was improved to approximately 1/100 of the wavelength of the light source. Recently, the deformation measurement method by using only two speckle patterns has been proposed in ESPI by using Fourier transform. Furthermore, three-dimensional deformation of the object was able to be measured with the same sensitivities in each direction of three-dimensional axis. However, the measurement results of a complex shape deformation are not always a smooth distribution of phase map. It can be thought that this trouble is caused from the effect of speckle noise which is included in speckle pattern. In this paper, the solution of the problem concerning the speckle noise is investigated.
In this discussion, speckle noise reduction is tried in a basic speckle deformation measurement using the new speckle interferometer that uses only two speckle patterns before and after deformation of the measured object. It is confirmed that the degradation of measurement accuracy in speckle interferometry is caused by some speckle noise. It becomes clear that the speckle noise influences the bias component and the amplitude of the speckle pattern. Furthermore, it is confirmed that the spatial movement of speckles of speckle-pattern during the deformation also influences into the measurement accuracy. An idea for the noise reduction is proposed by using a simple model of intensity distribution of speckle pattern. In this paper, the pre-treatment for the speckle interferometry is proposed in order to reduce such influence by speckle noise. In the experimental results, it is confirmed that the influence of speckle noise can be reduced by using the features of the reference and the object beams' intensity distributions in interference measurement process.
It is confirmed that the proposed method can reduce the influence of speckle noise to 1/1000 in comparing with the results of conventional method. The method is applied to the measurement of the deformation distribution of the circular plate that is fixed along the surrounding circular boundary. The validity of the proposed method in the practical operation is confirmed from the experiments.

10329-57, Session 14

Optical residual stress measurement in TFT-LCD panels *(Invited Paper)*

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The residual stress of the glass substrate might be one of causes to

produce the non-uniform light distribution defect, i.e. Mura, in thin film transistor-liquid crystal display (TFT-LCD) panels. Glass is a birefringent material with very low birefringence. Furthermore, the thinner and thinner thickness request from the market makes the traditional photoelasticity almost impossible to measure the residual stresses produced in thin glass plates. Recently, a low-level stress measurement method called transmissivity extremities theory of photoelasticity (TEToP) was successfully developed in the National Tsing Hua University, Taiwan. The concept of TEToP is to integrate the photoelasticity and spectrometer to analyze and reconstruct the spectroscopy of photoelasticity. Since systematic relationship of transmissivity with stress and wavelength can be constructed from TEToP, the stress can be directly determined from the transmissivity spectrum obtained by the spectrometer. In this paper, three commercially available glass plates with 0.33mm nominal thickness were inspected to verify the feasibility of this systematic setup. The experimental results illustrated that maintaining the consistent quality residual stress level in glass plates is critical.

10329-58, Session 14

Calibration of the incident beam in a reflective topography measurement from an unknown surface

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The precision of measurements as well as the need for precise measurements are increasing more and more. Thus, the importance of a good calibration of a setup is increasing, too. In the world of topography measurement a huge variety of techniques are available. Some of these techniques are using known shadow patterns reflected by the device under test (DUT). The reflected patterns are recorded using a camera with imaging optics. From the changes of the patterns, the topography can be resolved. Other measurement techniques are using a tactile sensing head, which is in contact with the surface to determine its topography. However, these techniques need a reference surface to calibrate movements. If this reference surface presents deviations from its expected form, errors are introduced.

We have developed a calibration method for reflective surface measurements based on experimental ray tracing (ERT) without the need of a reference surface.

In our measurement setup, a narrow laser beam introduced in the measurement under a certain angle is reflected by the device under test. After the reflection the position and the direction of the ray in terms of the coordinate system of the camera is detected. Thus, no errors are introduced by using an additional imaging optic. To calibrate position and direction of the incident ray in respect to the coordinate system of the camera, the reflected rays from the measurement are used only. From these rays, the incident ray is determined by detecting the line, all reflected rays are intersecting with. This leads to two major advantages. First, there is no calibration run needed, since the measurement data can be used directly for the calibration. Second, for the calibration no well-known reference surface is needed. However, some regulations have to be considered for a stable process of this calibration method. In terms of peak-to-valley values of the sag of the surface as well as of the change of the surface slope, the surface has to show values deviating from zero. If a surface like this is measured, a separate measurement run can be performed using another surface fulfilling these requirements. Since the DUT is scanned by moving the DUT itself, the position and the direction of the incident ray is not changed from one measurement to another and can be reused.

we describe the newly introduced calibration method for the incident ray in detail and present the necessary boundary conditions. The calibration has been tested using simulations and has been implemented in a measurement setup. Within this measurement setup, the expected performance resulting from the simulations has been examined.

10329-59, Session 14

Error influences of the shear element in interferometry for the form characterization of optics

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The requirements for form measurement of optical elements increase with the complexity of optical imaging systems employed in industrial imaging, consumer lenses or photolithography. The optical industry took a great step forwards in manufacturing optics besides flats and spheres. Thus aspheres and freeform optics have now become indispensable. The form deviation of spheres or flats of new designs can reach up to a few millimetres. Additionally, accuracy in the nanometre range in form determination is necessary. Typical non-contact measurement systems for flatness or spherical metrology, which provide nanometre uncertainties, cannot handle the high dynamic range of the topography. Therefore special new measurement setups for the form characterization of complex optical surfaces are needed.

To overcome this drawback of the current metrology systems, we use a shearing interferometer combined with a multispot illumination based on spatial partially coherent light. Multiple light sources are arranged around the specimen until the whole area of interest is illuminated and yields a resolvable interferogram at the sensor plane. If the shear and light source distance are well adjusted, a continuous interferogram appears which can be evaluated. Hence even steep slopes and asymmetrical designs become measureable.

The core and also the crucial point of the shearing setup is the shear element. For shearing interferometry with spatial partially coherent light, a spatial light modulator (SLM) as a shear element is beneficial. A common pass configuration allows the usage of LED light. The birefringent properties of the SLM enable 50% beam splitting for 45° linear polarized light. Half of the light will just be reflected while the other half will be influenced by the modulation of the SLM. A blazed grating provides the required effect of a lateral shift at the sensor plane. The SLM itself consists of a pixel structure. Each pixel’s refractive index can be adjusted by an electric field. However, overlapping electric fields of nearby pixels influence each other, which is especially unfavourable for large differences of the refractive index, e.g. in a blaze grating. This effect is called pixel crosstalk.

We investigate and discuss influences on measurements caused by this effect. In addition, the back panel of the SLM also functions as a mirror in the setup. The corresponding surface form is important and has to be considered. To determine all these contributions of the SLM, we perform wave front measurements using a Shack-Hartmann sensor. We measure the influence of the grating, the pixel structure and also the SLM surface and discuss the influences of these errors on the form measurement.

10329-60, Session 14

Automated NDT in a production environment using Dantec dynamics’ robotic shearography

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Dantec Dynamics’ FlawExplorer is a portable, compact and robust Laser Shearography inspection system that efficiently finds flaws where other NDT methods don’t.

Shearography, an optical based Non-Destructive Testing (NDT) technique identifies internal material discontinuities or anomalies in homogenous and non-homogenous materials in an expedited manner. The FlawExplorer has the ability to inspect areas up to 2 m2 (20 ft2) in one shot, saving time and money on any given application.

The highly sensitive interferometric technique will measure microscopic surface deformations caused by internal flaws when a small stress is applied to the object. This can be done using thermal, pressure, vibration or mechanical excitation. The results are displayed live as the material responds to the excitation and are easily interpreted by the operator.

The key benefits are:

- Highly portable, easy to set-up and ready to operate within seconds

Automated NDT inspection with our robotic version

- Compact, robust design featuring Class 3R laser diodes for use on-site and in-field

- Cost-effective inspection of large areas with fast location and characterization of defects

- Intuitive evaluation of structural integrity of composite components like ply drops, bulkheads, overlaps, splicers, stringers, ribs etc.

- Enhanced live phase maps eliminate the need for time-consuming post-processing

- Advanced image filtering produces clear and unambiguous results

- User friendly software interface allows operators to locate and mark discontinuities directly on the test object surface

- Advanced, customizable reporting functionalities available

- Thermal, vacuum or vibration loading modules can be selected depending on application

According to a publication by the UK National Composites Network Best Practice Guide to the Non-Destructive Testing of Composite Materials, Shearography is a key NDT method for detecting; BVIDs (impact damage), delaminations and trans laminar cracking (fatigue cracking) for polymer matrix composites.

Shearography can be used not only as an NDI technique, but also as a developmental quality assurance process technique for composite structures design.

Dantec Dynamics' FlawExplorer inspection solution quickly detects and locates discontinuities in composites materials. The system systematically finds flaws like: Wrinkles, Disbonds, Delaminations, Cracks, Crushed core, Kissing bonds, Fluid ingress, Cracked cores, Repair defects, Voids, Foreign Objects, Impact damage (BVID's), etc.

The FlawExplorer helps expedite your complete NDT & Quality Control processes which in turn saves time and money. It can also be fully integrated with robotic systems to support automated inspection applications in production environments. This unique capability increases the throughput of a given inspection station and significantly decreases associated labor costs. Inspection processes can be optimized from R&D to production line environments. Inspection flows can be streamlined throughout the complete product lifecycle; on-site as well as in-field.

This unique capability decreases the cost of manufacturing by capturing savings in regard to direct manpower and decreased cycle times or simply the volume of test objects that can be evaluated in a production period. In comparison with other NDT techniques, the FlawExplorer requires no contact with test objects or collection of waste material and eliminates the need for health safe environments that are inherent in other NDT methods typically utilized to evaluate composites. Inspection processes can be optimized from R&D over production line environments to maintenance. Inspection flows can be streamlined throughout the complete product lifecycle. On-site as well as in-field.

During this presentation, convincing results in various composite materials will be presented as well as the capabilities and drawbacks of Shearography as a NDT method.

10329-61, Session 14

An endoscophic shearography system with radial sensitivity for inner inspection of adhesion faults between flanged joints and composite material pipes

Armando Albertazzi Gonçalves Jr., Fabiano J. Macedo, Mauro E. Benedet, Analucia V. Fantin, Daniel P. Willemann, Univ. Federal de Santa Catarina (Brazil)

This work presents the development of a special shearography system with radial sensitivity and explores its applicability for detecting adhesion flaws on internal surfaces of flanged joints of composite material pipes. The inspection is performed from the inner surface of the tube where the flange is adhered. The system uses two conical mirrors to achieve radial sensitivity. A primary 45° conical mirror is responsible for promoting the visualization, all around 360°, of the internal surface to be inspected. A special Michelson like interferometer is formed replacing one of the plane mirrors by a 1° conical mirror. The image reflected by the 1° conical mirror is shifted away from the image center in a radial way. As a consequence, a radial shear is produced on the images. The concept was developed and a prototype built and tested. First, two tubular steel specimens, internally coated with composite materials and having known artificial defects were analyzed to test the ability of the system to detect the defects. After principle validation, two flanged joints were analyzed: (a) a reference one, without any artificial defects and (b) a test one with known artificial defects, simulating adhesion failures with different dimensions and locations. In all cases thermal loading was applied through a hot air blower on the outer surface of the joint. The system presented good results on all inspected specimens, being able to detect adhesion flaws present in the flanged joints with artificially inserted defects. The results obtained experimentally in this work are promising and open a new front for inspections of inner surfaces of pipes with shearography.

10329-62, Session 14

Novel approach to determination of the third-order elastic moduli of composite materials

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Nonlinear elastic properties of materials are described based on both second- and third-order elastic moduli. The techniques for measuring second-order elastic moduli (e.g., Young's modulus and Poisson's ratio) are well developed and these moduli are measured with sufficiently high precision. The basic method applied for determination of the third-order elastic moduli of materials relies on measurements of variations of ultrasound velocity with sample compression. These variations are often quite small and measurement errors may be too high, of the order of tens of percent. The situation becomes even worse for highly nonuniform composite materials when diffraction starts affecting noticeably the ultrasonic wave propagation.

We suggest a fundamentally different approach for determination of the third-order elastic moduli of composite materials based on application of much longer waves: nonlinear strain solitary waves (solitons). Bulk strain solitons in solids, unlike any linear bulk wave, can propagate over lengthy waveguides without remarkable decay, their parameters depend on the material parameters and waves also carry information about impurities, inclusions and elasticity of material. Being recorded in three waveguides of different shape (a rod, a plate and a shell) these waves provide data allowing one to calculate values of the third-order moduli from recorded soliton parameters. The developed theory provides a system of three algebraic equations with a nondegenerate matrix for calculating the third-order elastic moduli of the material.

Optical techniques were demonstrated to be most robust in recording of long smooth disturbances as strain solitons are. In our experiments we apply digital holography with holograms reconstruction by means of an optimized algorithm operating with highly noisy holograms.

The essential limitation of the experimental approach is due to recording of wave processes in transmission configuration, and, as a result, impossibility to study opaque samples. However, in the case of strain solitons the recently developed method for their indirect „visualisation" in opaque (composite) materials allows us to overcome this constraint and makes it possible to investigate almost any material. The method is based

on the inspection of a two-layered waveguide, composed of a layer, made of an opaque material (composite), and another one made of transparent material (e.g. a pure polymer matrix), bonded together by a glass-like adhesive. In the bonded area of the layered waveguide with layers made of different materials (but both allowing soliton formation) the single generalized soliton is formed propagating in the layered structure as a unified entity. Then the soliton parameters in an opaque waveguide are determined based on the soliton parameters in a transparent layer. Measurements of soliton parameters - amplitude, full width at half maximum, velocity - provide data for determination of the dynamic elastic characteristics of the material.

The suggested methodology was tested on transparent materials with known third-order elastic moduli – polystyrene and PMMA. Further experiments were performed in laminates made of polystyrene and PMMA and composites on the base of these matrices with different inclusions.

10329-63, Session 15

Fiber Bragg grating sensors in harsh environments: considerations and industrial monitoring applications

(Invited Paper)

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Over the last few years, fiber optic sensors (FOS) have seen an increased acceptance and widespread use in industrial sensing and in structural monitoring in civil, aerospace, marine, oil & gas, composites and other applications. One of the most prevalent types in use today are fiber Bragg grating (FBG) sensors. Historically, FOS have been an attractive solution because of their EM immunity and suitability for use in harsh environments and rugged applications with extreme temperatures, radiation exposure, EM fields, high voltages, water contact, flammable atmospheres, or other hazards.

FBG sensors have demonstrated that can operate reliably in many different harsh environment applications but proper type and fabrication process are needed, along with suitable packaging and installation procedure. In this paper, we review the impact that external factors and environmental conditions play on FBG's performance and reliability, and describe the appropriate sensor types and protection requirements suitable for a variety of harsh environment applications in industrial furnaces, cryogenic coolers, nuclear plants, maritime vessels, oil & gas wells, aerospace crafts, automobiles, and others.

10329-64, Session 15

Measurement uncertainty budget of an interferometric flow velocity sensor

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Flow rate measurements are a common topic for process monitoring in chemical engineering and food industry. For example, in gas distribution networks for leakage detection. In these processes generally global measurement systems are used like ultrasound runtime measurements [1]. To achieve the requested low uncertainties of 0.1% for flow rate measurements a precise measurement of the shear layers of such a flow is necessary. The laser Doppler velocimeter (LDV) is an established method for measuring local flow velocities, where two intersecting coherent laser beams generate a single parallel fringe system. Particles which are flying thru emit an intensity modulated light signal which oscillates with the Doppler frequency, corresponding to the flow velocity. For exact estimation of the flow rate, the flow profile in the shear layer is of importance. For standard LDV the axial resolution and therefore the number of measurement points in the shear layer is defined by the length of the measurement volume. A decrease of this length accompanied by a fringe distance variation along the measurement axis which results in a growth of the measurement uncertainty for the flow velocity (uncertainty relation between spatial resolution and velocity uncertainty). As a unique advantage, the novel laser Doppler profile sensor (LDV-PS) overcomes this problem by using two fan-like fringe systems to obtain the position of the measured particles along the measurement axis and therefore achieve a high spatial resolution while it still offers a low velocity uncertainty [2]. With this technique the flow rate can be estimated with one order of magnitude lower uncertainty, down to 0.05% statistical uncertainty [3].

The problem for this technique is, in contrast to laboratory setups where the system is quite stable, that for industrial applications the sensor needs a reliable and robust traceability to the SI units, meter and second. Small deviations in the calibration can, because of the highly position depending calibration function, cause large systematic errors in the measurement result.

Therefore, a simple, stable and accurate tool is needed, that can easily be used in industrial surroundings to check or recalibrate the sensor.

In this work different calibration methods are presented and their influences to the measurement uncertainty budget of the sensor is discussed. Furthermore, an approach for a reliable calibration in media with a refractive index greater than 1 is shown, where a priori air-calibration is used to achieve low systematic deviations and an additional calibration in the media (e.g. water) is used to compensate the error caused by the refractive index. Finally, with this technique generated measurement results for different flows are presented.

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10329-65, Session 15

Laser speckle velocimetry for robot manufacturing

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In many areas of manufacturing it is desirable to replace expensive Computer Numerical Control (CNC) systems with a robotic approach providing increased flexibility and lower costs. However robots struggle to achieve high positioning accuracy and are more prone to disturbances from process forces due to the comparatively low mechanical stiffness of typical industrial robots[1]. Additionally there can be significant deviations from the desired tool-path and tool-speed due to the kinematic model used to convert joint encoder positions to Cartesian end-effector position.

The use of speckle correlation sensing for robotic manufacturing has great potential to allow rapid robot characterisation and measurement of robot trajectory and end-effector speed. The technique uses the translation of consecutive laser speckle patterns acquired and processed at high speeds (~500fps) to determine the robot end-effector translation and velocity in a horizontal plane. This can be used to characterise deviations from a desired tool speed which is of importance in many manufacturing operations, for example, in many continuous machining or processing operations the feed rate or tool speed is critical to process quality[2].

This paper reports the application of a laser speckle correlation sensors for tool speed measurements of the end-effectors of industrial robots, including the implementation of the sensor and signal processing. Results of laboratory measurements using translation stages to determine the accuracy achievable are presented, showing sensor accuracies of better than 0.01mm/s over a range of 0-50mm/s. In addition results from the practical application of the sensor for robot path characterisation in the robotic wire and arc additive manufacturing (WAAM) process developed at Cranfield[3] are presented.

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10329-66, Session 15

Noninvasive seedingless measurements of the flame transfer function using high-speed camera-based laser vibrometry

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Lean combustion by means of swirl-stabilized flames is a priority of industries development, in order to reduce pollutant emissions and to increase the efficiency of jet engines or stationary gas turbines. This combustion exhibits instabilities based on flame oscillations due to thermos-acoustic fluctuations of pressure and heat release rate [1], which potentially result in failure of the device. Therefore, the characterization of the combustion during the industrial development process is inevitable. To this aim, the flame transfer function (FTF) is measured, which is the ratio of the average heat release rate inside the flame and the average flow velocity at the combustor outlet and the temporal fluctuations of both quantities, respectively [2]. Measurements of the FTF can be obtained by a multi-microphone-method [3], but the technique allows no spatially resolved data inside the flame volume. Field measurements of the heat release rate can be achieved using chemiluminescence, but only under the condition of adiabatic flames [4], which is not fulfilled at technically premixed flames. Measurements of the flow velocity inside the flame can be realized using well known techniques such as particle image velocimetry or Doppler global velocimetry [5]. Yet, both techniques require the usage of tracer particles, which influences the thermodynamic behavior of the flow.

Simultaneous seedingless measurements of both, the heat release rate and flow velocity can be achieved using multiple laser-vibrometers and signal correlation [6]. The measurement is based on the linear relation between the heat release rate and the change of the refractive index inside flames. Such fluctuations of the refractive index can be detected integral along the laser beam of a standard pointwise laser-vibrometer. Using multiple laser-vibrometers it is furthermore possible to measure the flow velocity inside the flame due to the phase delay between two vibrometer signals and the known distance between the measurement positions. However, no simultaneous field measurements have been done and, thus, the detection of complex spatio-temporal flow behavior is not possible.

In order to overcome these limitations, a high-speed camera-based laser-vibrometer is designed for non-invasive seedingless measurements of the FTF inside swirl-stabilized technically premixed flames. The laser-vibrometer offers single pixel resolution with measurement rates up to 40 kHz at an image resolution of 128 x 64 px. Based on a comparison with a standard pointwise laser-vibrometer the new system is validated and a detailed discussion of the measurement uncertainty is presented. Spatially resolved measurements of the heat release rate and its temporal fluctuations inside a swirl stabilized flame are demonstrated for the first time. In addition, the flow velocity field inside the flame is calculated by means of signal correlation between different pixel data. Finally, the FTF is calculated by fusing both measurement data.

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10329-67, Session 15

Optical rotor-blade deformation measurements using a rotating camera system

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The knowledge of the movements and the deformation of rotor blades is of great importance for the performance and the safe operation of a rotor system, especially for blades with a high aspect ratio like on helicopter main rotors or wind turbines. To measure these parameters in the rotating system is not easy, because the number of sensors is limited due to their impact on the aerodynamics and the modification of the structure.

Measurements with strain gauges can furthermore directly be affected by the choice of the sensor location, temperature effects, etc. [1]. To avoid those problems and in addition enable direct shape measurements contactless optical methods have still been applied to rotor and propeller deformation measurements in the past [2][3][4]. These attempts have been done with measurement devices out of the rotating frame observing either only small rotors or the blade passing within the field of view. Former recordings with rotating camera devices have been performed just to visualize the flow over the blades [5] or the general blade movement.

Based on their experience from the in-flight application of a rotating camera on an aircraft propeller [6], DLR and Hardsoft developed a rotating 3D image acquisition system for helicopter rotors [7] and performed first tests on the whirltower of Airbus Helicopters in Donauwörth, Germany. The system is mounted on the hub and co-rotates with the rotor. It includes four CMOS camera sensors and a complete data acquisition system and is able to record images of the whole blade at each azimuth angle. Later, those images are processed with an IPCT software tool and deliver the continuous 3D surface shape and location of the observed blade. From the comparison of the 3D surfaces for different recordings, the bending and torsion of the blade can be obtained.

The paper will briefly describe the rotating camera system itself, the non-intrusive deformation measurement method IPCT and the measuring setup. The presentation of the recorded images, the obtained data and a discussion of the measurement results will conclude the paper.

The lessons learned from the presented campaign will be helpful for manufacturers in the design and measurement of their future rotor systems.

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10329-68, Session 15

High penetration time-of-flight digital laser distance measurements of molten metal targets in degraded visual environments

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Maintaining the control over a given material processing step would ensure that the material with the right properties is produced every time, and in the shortest possible time. Process design using feedback control methodology is one approach that can be used to win the high-stakes race for materials of the future. As feedback based, this approach is highly dependent upon the development of sensor technologies with the capability to more directly sense the product being formed and allow inferences of its quality-defining attributes. Providing immediate feedback by in-situ instrumentation can increase yield and quality, resulting thereby in substantial economic benefits. Further to this, the total energy consumption can be reduced, and eventually CO2 and other pollutant emissions to the environment as well.

However, in the case of metallurgical process control, in-situ measurements are challenged by the extreme process environment; temperatures over 1000 °C, presence of dust and smoke, variable surface properties etc. Although modern metallurgical plants can generally be considered as highly automated with a variety of data systems, the conventionally used measurement methods are mostly manual, intrusive, infrequent and human resource- and time consuming. A more efficient process control and implementation of more advanced ICT solutions are inhibited by poor quality or missing data, e.g. due to failed or faulty instruments or wrong manual inputs. Analyses of process performance are therefore executed rarely and can be unsystematic. Results are rarely incorporated into comprehensive process models and almost never implemented as operational tools. This in turn leads to poor financial gains and slow rates of process and financial improvements, characteristic of the metallurgical industry today.

In this work, we will address the case of continuous molten metal level measurement through dust and smoke. The method of choice is fiber coupled time-of-flight digital laser distance meter as an inherently non-intrusive solution suitable for continuous online measurement during furnace operation. In a single run this technology can generate multiple information about the process (surface range, orientation and reflection characteristics, atmospheric conditions). This technology is also capable of rendering the same information for multiple targets at the same time. Successful measurements are possible even in degraded visual environments (through dust and smoke). At the same time, accuracy down to ± 1 cm is readily achieved which is acceptable for the applications in mind. Advanced signal processing is performed on digitized reflections from the emitted laser pulses by high-rate sampling. Based on full wave-form analysis accurate level measurement can be possible even in case of molten metal surfaces at extreme temperatures engulfed in smoke. In this case, the signals from the smoke and the surface overlap to a large degree causing the conventional processing algorithms to fail. An additional challenge is introduced by the molten metal surface wave motion at slow or more rapid frequencies due to several physical processes (e.g. convection).

10329-69, Session 16

In-situ measurement with deflectometric acquisition of large optical surfaces DaOS using vignetting field stop VFS procedure

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The vignetting field stop procedure uses a deflectometric approach to acquire big Optical Surfaces – DaOS – and it offers the possibility to measure nearly any shape or form using a scanning routine. The basic physical measurement principle in DaOS is the vignettation of a quasi-parallel light beam emitted by an expanded light source in auto collimation arrangement with a reflecting element. Thereby nearly any curvature of the specimen, is measurable. Due to the fact, that even sign changes in the curvature can be detected, also aspheres and freeform surfaces of any size can be evaluated. The function of Vignetting Field Stop VFS Procedure in combination with Deflectometric Flatness Reference DFR will be shown and additional aspects to measure also spheres will be considered. The intensity dsistribution in the field of object will influence the linearity and zero point stability of the sensor and therefore compensation effects will be shown. The measurement uncertainty over the hole measurement process will be considered and an error budget will be shown concerning the influence of environment, adjustment and sensor unperfectness.

Actual results of test measurements with calculated absolute deviation with larger lateral dimensions on flat and spherical specimen with diameter of 300 mm are examined. These measurements are compared critically to reference results which are recorded by interferometry and Deflectometric Flatness Reference DFR-method. Even that Interferometric flatness measurements normally shows absolut flatness deviations up to 50 nm and more for dimensions of 300 - 600 mm, we do some some modal analyses to verify the resolution and accuracy of measurement accuracy on a 12 inch Quarz beam.

The DaOS-Procedure is able to be used as an in-line-measurement system, characterising flatness and absolute shape of spherical surfaces during production process in situ. With the opinion of feedback to the manufacturing process and the ability (possibility) to have a deterministic track control e.g. in an customised manufacturing lapping and polishing machine like a NLP 500, even Dwell time controlled polishing is possible up to the manufacturing of freeforms.

10329-70, Session 16

3D interferometric shape measurement technique using coherent fiber bundles

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Interference fringe system based, optical sensors enable 3-D shape measurements of fast rotating objects by simultaneous velocity and distance evaluation [1,2]. Several speckles with equal frequency but random phases and arrival times are generated on photo detectors due to rough surfaces [3]. This leads to disturbances in the power spectra, which result in systematic deviations of the estimated velocity and distance, thus, limit the achievable total shape uncertainty. For reducing the measurement uncertainty caused by speckle effect, a speckle separation method using cameras instead of photo detectors has been developed [4]. This allows a reduction of the velocity uncertainty by the order of one magnitude. However, some speckles are still not separated and only one camera cannot achieve phase difference based distance measurement. In order to realize simultaneous velocity and distance measurement two mutually tilted interference fringe patterns have to be superposed. Thus, two cameras triggered by a function generator are employed to capture the two scattered light signals at the same moment. Coherent fiber bundles are employed to realize a robust sensor head, for the first time. Meanwhile, a novel speckle tracing method is put forward for further speckles separation, thereby reducing the measurement uncertainty and enhancing the measurement efficiency and robustness. Based on a tactile internet, the sensor can be used for monitoring the cutting process in a lathe by remote control.

The velocity and distance result from the modulation frequency and phase difference between corresponding speckles. For an expected industry application, two coherent fiber bundles transmit images from the head of sensor to the cameras. Thus, a compact sensor with an applicable size is ready for the in-situ measurement in a cutting lathe. The influence of the number of independent fiber cores regarding to the achievable measurement uncertainty is investigated. The images obtained by the cameras enables phase difference evaluation of any speckle covering two corresponding pixels which have the same position coordinate in the images. This allows the distance evaluation with a linear function of distance and phase difference. The speckle tracing method recombines the camera lines in time domain, which makes the track of each speckle appear in a same image. Thereby each speckle can be separated in time and space domain simultaneously. By using a trace correction method, every speckle trace is parallel to vertical direction. Based on the Fast Fourier Transform, the modulation frequencies of the single speckles are calculated, thus, the velocity can be estimated. The numerical simulations and physical experiments demonstrate that the individual evaluation of each speckle reduces the velocity and distance uncertainty by one order of magnitude, in comparison to single pixel evaluation. As a result, the total shape uncertainty of absolute 3-D shape measurements is reduced to about 100 nm.

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10329-71, Session 16

Interferometric fibre-optic curvature sensing for structural, directional vibration measurements

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Fibre optic curvature sensing (FOCS) allows the curvature of the structure to which the fibre arrangement is attached to be tracked through space. FOCS can be used to measure directly lateral vibrations of a structure, along with the direction of vibration. The sensor could even be embedded within the structure, making measurements without the need for external access to the structure, in contrast to conventional laser vibrometry. FOCS techniques are generally based on an evaluation of the differential strain resulting from the curvature of a fibre arrangement and are employed in areas such as structural health monitoring and medical endoscope tracking. FOCS can be achieved using a variety of techniques, where interferometric approaches offer fast and highly sensitive measurements. However, practical applications are hindered by difficulties associated with multiplexing the interferometric sensors. The approach proposed in this work employs fibre segment interferometry (FSI), which allows the multiplexing of many interferometric fibre sensor segments using range-resolved interferometry (RRI). RRI is an emerging technique based on optical frequency modulation produced by modulating sinusoidally the injection current of a continuous-wave diode laser. RRI can be used in fibre-coupled or free-space applications, and is designed to exploit the potential that robust, cost-effective and highly coherent laser diodes originating in the telecoms industry offer to sensing applications.

In the optical setup used for this investigation, a sensor rod made from flexible plastic is used to support a fibre arrangement comprising of four regular single-mode fibres, where each fibre is adhered to one of the four opposing sides of the sensor rod. In each fibre four segments of length 20 cm are formed between low-reflectivity fibre Bragg gratings (FBG) which act as broadband reflectors. Signals from all four fibres are then combined and interrogated using a single distributed feedback (DFB) laser diode operating at a wavelength of 1550 nm. By evaluating the interferometric phase shifts due to differential strain in opposing fibre segments, vertical and horizontal curvature measurements can be obtained for each of the curvature sensing sections. The sensor rod is attached to the top of stainless steel cantilever test object. Vibrations of the cantilever can be introduced manually. Examples of measurements of the vibration of the cantilever tip are presented for three different vibration directions. Instantaneous tip displacement noise standard deviations are ≈4 ?m over the whole 21 kHz interferometric bandwidth and the ability to determine the two-dimensional vibration direction is demonstrated.

It is thought that the capability to measure lateral vibrations internally within structures at high bandwidths and using cost-effective and robust hardware originating from the telecom industry could be useful in many applications of structural vibration analysis, both for one-off investigations and for permanent data logging. This complements traditional laser vibrometry, which, while offering resolutions in the nanometre range and being a contactless method, requires lateral access to the structure under test and therefore might not be suitable for a considerable number of structural vibration analysis problems, for example within complex machinery.

10329-72, Session 16

Subpixel edge estimation with lens aberrations compensation based on the iterative image simulation for high-precision thermal expansion measurements of solids

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Fundamental research of thermal expansion requires most accurate, absolute and contactless methods. In the temperature range of intensive light emission (above 1500-2000K), one of the most suitable methods, satisfying these requirements, is a method of optical image acquisition and processing. By the estimation of location and distortion of the heated object's edge, the thermal expansion properties can be studied.

As the thermal expansion is a comparatively small effect in the sense of geometry changes, subpixel edge estimation methods are demanded. With the high-precision geometry estimations, the lens aberrations and spatial bandwidth should be taken into account. For the applications of thermal expansion measurements in the high-temperature range, non-constant brightness of object and background, generally variable in space and dependent on the temperature, should be also compensated.

Unlike the previously known methods, the method described in this research directly compensates for these effects by the constrained image model. The principle of the method is an iterative image simulation with subpixel accuracy until the appropriate solution is found, matching the actually acquired image. The simulated image contains the effects of the lens aberrations and spatially-variable brightness. For the method implementation, a parametric image model is presented, that consists of three parts: the edge model, the brightness distribution model, the lens aberrations model. The optimal values of model parameters are determined by means of the numerical optimization methods. Particularly, the effective application of the nonlinear conjugate gradient method is demonstrated, by means of sufficient analytical approximations for the merit function gradient.

The key feature of the method described is a freeform edge image simulation with subpixel accuracy by the direct calculation of the image Fourier spectrum. This approach significantly reduces the computational time (2-3 orders), required for the image simulation compared to the direct calculations of pixel values in spatial domain. Fast simulation is achieved by approximating the freeform edge as a set of straight lines and calculation of the image Fourier spectrum as a sum of analytically-computed Fourier spectrums, corresponding to each line. For the accurate image simulation, the overall spectrum needs to be computed only within the bandwidth, defined by the lens diffraction limit. The image of an edge with subpixel accuracy is then computed by the inverse Fourier transform.

For the computed diffraction-limited image of an edge, the brightness model is applied. The final stage of the simulation process is a convolution with the lens point-spread function (PSF). The opportunity of the defocus compensation with the actual lens aberrations is demonstrated by means of the wavefront phase-retrieval technique. The actual PSF is computed within the image simulation process as a function of the calibrated wavefront phase and a separate defocus component. The defocus value is an additional image model parameter, and can be determined in the optimization procedure. As demonstrated, the obtained defocus value can also be used for the magnification compensation.

The numerical simulations and experimental results are demonstrated. The experimental results are obtained on the optical system for the linear thermal expansion coefficient measurement within the temperature range 1000...3000K, recently developed in the Mendeleev All-Russia Institute of Metrology. Potentially achievable accuracy of edge location is within 1/100 pixel (or 100nm within 5mm field of view) in the case of spatially-variable brightness and unknown defocus value is demonstrated.

10330-1, Session 1

Simulating propagation of coherent light in random media using the Fredholm type integral equation

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Studying propagation of light in random scattering materials is important for both basic and applied research. Such studies often require usage of numerical method for simulating behavior of light beams in random media. However, if such simulations require consideration of coherence properties of light, they may become a complex numerical problems. There are well established methods for simulating multiple scattering of light (e.g. Radiative Transfer Theory and Monte Carlo methods) but they do not treat coherence properties of light directly. Some variations of these methods allows to predict behavior of coherent light but only for an averaged realization of the scattering medium. This limits their application in studying many physical phenomena connected to a specific distribution of scattering particles (e.g. laser speckle). In general, numerical simulation of coherent light propagation in a specific realization of random medium is a time- and memory-consuming problem. The goal of the presented research was to develop new efficient method for solving this problem.

The method, presented in our earlier works, is based on solving the Fredholm type integral equation, which describes multiple light scattering process. First, the Helmholtz equation for a light propagation in a nonuniform medium is transformed into the Fredholm type equation using Green function formalism. This equation can be then discretized and solved numerically using various algorithms.

We've compared three types of numerical solvers: direct solviers of the linear equations system, iterative solvers and a Monte Carlo solvers. We show that usage of iterative and Monte Carlo solvers can provide the same results as direct solvers. However, their usage is limited to problems concerning only weakly scattering media due to its limited numerical stability.

We show that the presented method provides results that are in agreement with a well-known analytical results e.g. by computing light attenuation coefficient of studying properties of the coherent back-scattering effects.

We also show the extension of the presented method for case of multiple scattering of a polarized light on a large spherical particles. This extension joins our approach with Mie theory. We've compared it with a finite-difference time domain simulation of light scattering on an ensemble of large scattering particles and we show that both method predicts the same scattering cross-section of such an ensemble.

10330-2, Session 1

Study of pure liquids using the analysis of dynamic speckle: model and natural experiments

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The dynamics of the laser-speckle pattern caused with the ground glass and layer of transparent liquid was studied. According to the percolation model H-bonded liquids are characterized with nano-sized structural heterogeneities that cause the phase ones for the light wave.

The temporary changing phase heterogeneities modulate the speckle field produced with the ground glass. The modifying of the speckle pattern provides the decrease of correlation. This causes the slow decaying of the central peak amplitude of the cross-correlation between the first images and each subsequent one. Dynamics of changes at the speckle pattern was investigated by registering with a video camera and by performing frame by frame analysis of the images.

Several large amounts of data processing algorithms have been used. For comparison, the same algorithms have been applied to analyze the dynamics of cellular matter, which formally reproduce the behavior of dynamic speckle.

When the coherent emission scatters inside the heterogeneous substances (or on the rough surfaces), we'll get the "spotted" diffractive patterns - speckle-fields. The speckle effect is caused by the interference of coherent light waves, which have the same frequency, while their phases and amplitudes are different. Adding them together, there will be got a resultant wave whose amplitude, as well as intensity, varies randomly.

The structure of speckle-fields, obviously, has the relation to the macroscopic features of the surface. And, for sure, the certain speckle particulars carry information concerned to the parameters of illuminated sample.

If we illuminate not rough surface, but volumetric object, we'll got the same features of speckle patterns. At the same time scattering the laser light inside the liquids, it's expected to observe absolutely new characteristics of speckle-structure, such as dynamics and fractal dimension. Dynamic speckle is triggered by variations in the phase of light produced by movement of the scattering centers, rotary power, etc..

According to the modern scientific views, considering the percolation model, the liquid systems tend to be heterogeneous ones. The links, connected particles inside the liquids, are rather weak, and involve percolative clusters. They're defined with nano-structured heterogeneities. Definitely these particular noticeably influences the total scatter-plane. This confirmation has been proved in some kinds of researches [1-3]. It should be mentioned, that percolative clusters can be characterized with fractal features..

To research the speckle-fields it was used device set consisted of Helium-Neon laser (2 mW); illuminated samples - such as non-transparent glass; the binary solution "water + Glycerine" (the mixture has the identified parameters of heterogeneities) and pure liquids (e.g. distillated water)

Using the web-camera registration there were dynamics speckles recognized. Furthermore it was concluded that speckle parameters likely depend on the features of researched media.

It was determined that the fading of correlation function obeys the exponential law. The time constant depends on the concentration of water-glycerol solution. The proposed research method is a variation of the dynamic spectroscopy of anelastic scattering.

The speckle dynamics appears as a result of the phase changes of light, which triggered with motion of scattering - the heterogeneities of the water system. Thus proposed method likely could be a foundation of new methods for contactless exploring structural dynamics of liquid systems.

10330-3, Session 1

Rigorous and fast simulations of light scattering from finite structures

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Methods for solving Maxwell's equations in three spatial dimensions are an integral part of many optical metrology setups in technology and science. In critical dimension metrology and pattern placement metrology, periodic metrology targets play an important role. In state-of-the-art nanometrology setups, deviations from periodicity and finite size effects of the periodic pattern increasingly impact the measurement results.

We discuss a method which allows to efficiently compute highly accurate solutions to Maxwell's equations for large, finite size scattering targets. The method is based on hp-adaptive finite-elements. Therefore, deviations from periodicity or complex shapes like corner roundings and sidewall angles can be handled without additional computation cost compared to the idealized case of geometries composed from rectangular shapes. We discuss possibilities of exploiting symmetries to further reduce computational effort.

10330-4, Session 1

Research on space object's visible scattering characteristics with irregular fold surface

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Space object's surface coating materials affected by the body structure, assembly process and space environment, not neatly wrap around the body, but show irregular folds. There are academic significance and wide application value for research on the space object's visible scattering characteristics with irregular fold surface in the areas of target detection, recognition, remote sensing, diagnosis of surface features, et al.

An experiment platform for measuring radiance of space object's surface materials was built. The solar simulator, which is similar to the solar spectrum, can simulate 0.1 solar constants. The detector using the United States ASD spectrometer, with 1 nm resolution, can measure in the range of 380-800 nm. The optical turntable is controlled by a computer, which can rotate on three dimensions with an angular accuracy of 0.05°.

The radiance of 10 pieces of gold polyester membranes with sides of 0.5 meters, usually coated on the space object, were measured. One surface was flat and the others showed different degrees of fold. By the fold, the real length of the 9 pieces of polyester membranes was larger than 0.5 meters. The incident angle was 30°and the reflection angel ranged from 0°to 80°at an interval of 1°. For ensuring the accuracy of measurement result, the radiance datum were acquired at 0.2°intervals in the reflection angle of 20° -40°. In order to describe the degree of wrinkling of surface materials, the concept of fold degree was introduced. Firstly, a ratio of fold surface's true area and the fold area was calculated. Then the difference between the ratio and 1 was defined as fold degree.

The experimental results showed that fold surface would disperse the energy in the specular reflection direction and peak value of the radiance decreased. Meanwhile half width broadened. Nevertheless, away from the direction of specular reflection, reflection energy and radiance value increased. In addition, a series of small peaks appeared and luminance glint phenomena could be observed. At the same time, it could be observed that the percentage of peak changed and fold degree of the materials showed a positive correlation.

In order to quantitatively study on the relationship between fold degree and the percentage of radiance changed, regression analysis was carried out. Resulting from a small quantity of experimental datum, traditional classical regression method had drawbacks. Since partial least squares(PLS) regression analysis integrates the advantages of principal component analysis, canonical correlation analysis and linear regression analysis in modeling, the relationship between fold degree and the rate of radiance change were analyzed and a regression model was established by using partial least squares regression. In order to investigate the accuracy of the regression model, a predictive figure was plotted. According to the predictive figure, the validity of partial least squares model was proved.

In orbit space object's surface usually covers a variety of insulation materials, thus fold phenomenon will be more obvious and complex. In this paper, gold polyester membrane is taken as research object and changes of reflection radiance with fold degree were analyzed. Related research results can provide a reference for the study on space object's visible scattering characteristics.

10330-5, Session 2

Fiber-based DUV to NIR light source: fundamental concepts and applications in optical metrology *(Invited Paper)*

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State-of-the-art semiconductor metrology or material inspection systems rely on highly stable light sources, typically emitting broadband radiation from the vacuum or deep ultraviolet (UV) to the near infrared (IR). Light source architectures are generally discharge (e.g. xenon) or laser-driven plasma lamps

[1]. A feature of these sources is their intrinsic spatial incoherence, resulting from a very high number of optical modes in the active area. As a consequence, controlling the illumination path in a subsequent optical system requires relatively complex optics that makes access of the sample difficult. In addition, focusing to a diffraction-limited spot requires spatial filtering, resulting in loss of most of the spectral power.

Here, we report recent developments of gas-filled hollow-core photonic crystal fiber (HC-PCF), pumped by a ?J-level, fs laser (system sketched in Fig. 1a&b), to generate radiation from the deep UV to the near IR (measured spectra shown in Fig. 1c). The spectral conversion is the result of nonlinear processes, in particular modulational instability (MI), soliton fission and dispersive wave generation [2,3]. Because of the all-single mode design of the HC-PCF [4], the synthesized radiation is spatially coherent (far-field is shown in the inset of Fig. 1c) allowing the beam to be focused to a diffraction limited spot, relevant in applications such as high-resolution DUV microscopy [5].

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10330-6, Session 2

Combined use of a priori data for fast system self-calibration of a nonrigid multicamera fringe projection system

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In non-rigid fringe projection 3D measurement systems, where either the camera and projector setup can change significantly between measurements or the object needs to be tracked, self-calibration has to be carried out frequently to keep the measurements accurate [1]. In fringe projection systems, it is common to use bundle adjustment methods developed initially for photogrammetry for the calibration of the camera(s) in terms of extrinsic and intrinsic parameters. However, there is also the need of an extra correspondence calibration between a pre-calibrated camera and the projector. This is usually carried out by initially performing a calibration of the camera(s) in the system by the established method of taking images of a plane inscribed with a calibration pattern at different orientations in order to register the pixels in terms of the system's global coordinates. Furthermore, the projector(s) are calibrated by performing an indirect correspondence of the projector pixels to global coordinates by taking an image of a calibration pattern produced by the projector itself. These steps are usually time consuming and require the measurement of calibrated patterns on planes, before the actual object can be measured and hence do not facilitate fast 3D measurement of objects if the experimental setup changes.

By employing and combining concepts of inverse rendering, deep learning and graphics processor unit (GPU) processing, we reduce the calibration time and simplify the procedure required for acquiring the projector's extrinsic parameters in non-rigid fringe projection systems by taking a photo of the scene and being able to predict the position and orientation of the light source. This calibration is ideally performed 'on the fly' or in some cases even after the measurement has taken place, as it can in some cases be used on the actual photos taken during the measurement cycle itself. Accurate modelling of the light source and a priori knowledge of the object to be measured can enable a fast estimation of the light source location and direction with respect to the cameras. Images rendered by two open source rendering software packages Blender and POV ray will be compared with Matlab's integrated

Gouraud lighting scheme for applicability in accurately predicting the scene and object illumination by the projector used in the system. The system will leverage the speed of a trained artificial intelligence network used for recognizing features in images (Berkley's Caffe Deep Learning network) to perform the initial guess of the projector setup and further optimisation of the scene will be performed via a fast scene rendering optimisation using a GPU. The intrinsic parameters of the projector's calibration will be measured once beforehand and used thereafter as a priori information.

With regard to accelerating the calibration of the camera(s), again a priori knowledge of the intrinsic parameters will be used by thorough prior optimisation. The identification of the extrinsic parameters will be calculated by a combination of on-board inertial sensors and an initial image of the measurement setup taken by a smart camera using photogrammetry targets to acquire the positions of the camera(s) and the projector in the setup.

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10330-7, Session 2

Metrology and quality assurance for European XFEL long flat mirrors installation

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The European XFEL is a large facility under construction in Hamburg, Germany. It will provide a transversally fully coherent X-ray radiation with outstanding characteristics: high repetition rate (up to 2700 pulses with a 0.6 milliseconds long pulse train at 10Hz), short wavelength (down to 0.05 nm), short pulse (in the femtoseconds scale) and high average brilliance (1.6E25 photons / s / mm^2 / mrad^2/ 0.1% bandwidth). Due to the very short wavelength and very high pulse energy, mirrors have to present high quality surface, to be very long, and at the same time to implement an effective cooling system. Matching these tight specifications and assessing them with high precision optical measurements is very challenging.

The mirrors go through a complicated and long process, starting from classical polishing to deterministic polishing, ending with a special coating and a final metrology assessment inside their mechanical mounts just before the installation. The installation itself is also difficult for such big mirrors and implies a special care. In this contribution we will explain how we modeled the installation process, how we used the metrology information to optimize the installation procedure and some preliminary results with the first mirrors installed in the European XFEL beam transport.

10330-8, Session 2

Fiber emulator for the performance simulation of the fiber-slit spectrograph HIRES

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The A-$Omega$ of the beam exiting the European Extremely Large Telescope (E-ELT) is too large to be directly fed into a high resolution spectrograph. As a consequence, the search of exoplanet atmospheres will be carried out with a fiber-fed spectrograph. HIRES will observe the center of the telescope focal plane by using about 60 fibers, which will be realigned to make the slit of the spectrograph. The spectrally dispersed image of each fiber will be incident on the detector. Therefore each fiber-spectrograph combination can be seen as an individual spectrograph. The relative offset and cross-talk between each fiber-spectrograph will however limit the performance of the overall system. To find a solution to overcome this limitation, an end-to-end simulator will be developed. The behaviour of fibers will be one if its central part. Here we show how we emulate the resulting intensity distribution exiting the fibers. This is done by computing the intensity distribution of Gaussian-Hermite modes. We vary the intensity between the modes randomly. Coupling intensity between the modes will be defined by rules according to the input parameters.

10330-9, Session 2

Optical design of the system for a lightship

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Nowadays, illuminating optical systems are used in various fields: optical design, manufacturing, medicine, navy, etc. So there is big need in highly specialized illumination systems with high optimization, systems there minimum amount of power provides maximum amount of illumination as far as possible.

This work describes the optical systems, which creates illumination on a long distance. Systems of this type are used for transmitting light from a buoy to a ship, as a type of lighthouse. Because of that, maximum of illumination from a light source ought to be pointed at 7.5 degrees from the horizon and must not to be focused. Superpower diode is used as a light source. Maximum power of it is needed to be less than 3 Watt. As a system which is used at navy it must provide low angel and long distance illumination, but have power of illumination low enough to make it safe for sailors to look at.

On first look, an optical indicatrix is represented by hyperboloid of revolution. For calculation of surface form by a ray reflection, which is provided by a total internal reflection for realization of this system. At the start, reflective surface was represented by aspherical surfaces of the second order, but later it was changed to more specialized surface close to the aspherical surfaces of the second order. During the work, various researches were made: selection of the material from various polymaterials, calculation of reflective surfaces shape, computer modeling of the system in, research of reflective surfaces shape and material thickness influence on reflected angle. Calculation and optimization of optical system were made in Zemax. This is possible due to the use of a freeform technology. That is method of calculation, which constructs surface point by point. This makes possible construction of complex surfaces suitable for total internal reflection of entire illumination cone of a diode. However, complex shape of reflective surfaces lays down some restriction on fabrication. This is the reason why polymaterials were selected: they make possible molding and stamping of lens with complex reflective surface. Lens stamping also makes it much cheaper and faster to manufacture lens then standard lens production cycle. Polymaterial lens production is more environment-frendly then glass lens production. For lens material polymetilmetacrilat was selected, because it has the most suitable refractive index of all polymaterials to use it with total internal reflection and it has appropriate price on the market.

Use of this system can make buoy illumination much cheaper and easier to maintain, because all illumination system is represented by one less than 3-watt power diode with one lens on it. It is simplify installation and uninstallation of such system, even in the open sea. With this, we can say that such system has a high demand and practical use.

10330-10, Session 3

Experimental light scattering by small particles: first results with a novel Mueller matrix scatterometer

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We describe a setup for measuring the full angular Mueller matrix profile of a single mm- to μm-size sample, and verify the experimental results against a theoretical model. The scatterometer is described in Maconi et al., presented at this meeting. In short, a fixed or levitating sample is illuminated with a laser beam whose full polarization state is controlled. The scattered light is detected with a wave retarder-linear polarizer-photomultiplier tube combination that is attached to a rotational stage, to allow measuring the full angular profile, with the exception of the backscattering direction.

By controlling the angle of the linear polarizers and the angle of the axis of the wave retarders before and after the scatterer we record such a combination of intensities that reconstructing the full Mueller matrix of the scatterer is possible. We have performed the first measurements of our calibration sample, a 5 mm sphere (N-BK7 glass, Edmund Optics).

We verify the first measurement results by comparing the angular scattering profile against the theoretical results computed using Mie theory. The profiles recorded using the linear polarizers only agree with the theoretical predictions in all scattering angles. With the linear polarizers, we are able to construct the upper left 2?2 submatrix of the full Mueller matrix. The constructed (1,1) and (2,2) elements of the matrix are almost identical, as they should for a sphere, as well as the (1,2) and (2,1) elements. There are some discrepancies, as expected since calibration spheres are never perfect spherical shapes with completely homogeneous internal structure.

10330-11, Session 3

B-spline parameterization of the dielectric function and information criteria: the craft of non-overfitting

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B-spline (or Basis-spline) parameterization is a popular and relatively new approach to express the dielectric function of materials in a purely mathematical way [1]. Since then, it has been proven to be very effective for multiple applications in spectroscopic ellipsometry. B-splines are constructed from piecewise polynomial functions connected at a set of points on the x-axis called “knots”. B-splines of any order can be evaluated by using simple recurrence relation. One of obvious advantages to employ B-splines is that no necessity in physical oscillator parameterization for the optical constants. Therefore, this approach is quite useful in cases where typical physics-based oscillator models cannot be easily applied. Moreover, B-splines allow the Kramers–Kronig consistent formulation and, therefore, guarantee physical validity of the line shape of the dielectric function in considered spectral range.

However, together with all advantages, B-spline parameterization possesses a serious practical problem of choosing the number and location of knots. Usually, the number of knots used in ellipsometric data analysis is determined and tuned empirically based on quite often ambiguous decisions and optimal knot number selection is an extremely complex undertaking. It is a matter of fact that if, for simplicity, we assume uniformly spaced (equidistant) knots in B-spline model of the dielectric function, then increasing the number of knots above optimal value will “overfit” the data, i.e., overfitting causes the model to fit the noise in the data and the dielectric function will contain some artificial features rather than actual behavior.

In general, splines can be considered as mathematical models and, therefore, a natural idea is to apply well-known statistical model selection techniques to optimize number of knots in B-spline parameterization of the dielectric function. In this work we use popular Akaike (AIC) and Bayesian (BIC) information criteria [2] to determine an adequate number of knots. Both criteria allow finding a compromise between under- and overfitting of experimental data. AIC and BIC penalize for increasing number of knots, i.e., increasing complexity of B-spline parameterization, and selects representation which achieves the best fit with minimal number of knots. Both these criteria are relatively easy to use since they are described by simple formulas and require only a value of residual difference between measured and calculated data which reflects the overall quality of fit. AIC and BIC selection criteria work remarkably well as we demonstrated in several practical case studies from spectroscopic ellipsometry. Thus, the use of information criteria provides more accurate B-spline parameterization of the dielectric function, - the task that has always been ambiguous for most of the practitioners. This approach formalizes the selection of the optimal knot number and may be useful in practical perspective of the dielectric function parameterization by B-splines.

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10330-12, Session 3

Optical and mechanical architecture for the E-ELT HIRES polarimeter

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Hereafter we introduce the opto-mechanical architecture of a full Stokes dual channel polarimeter for the European Extremely Large Telescope High Resolution spectrograph (E-ELT HIRES). It has been envisioned to feed the spectrograph moduli on the Nasmyth platform via two pairs of dedicated fibers: one optimized for the BVRI, the other one optimized for the JH band.

It’s intended to operate in the f/4.4 intermediate focus, representing the only rotationally symmetric focus available, i.e. below M4, in the allocated volume inside the Adaptive Optics Tower, according to the specs delivered by the ESO project office.

We illustrate the strategy of repositioning and aligning the instrument, provided that it has to withstand wind and earthquake loads, and that the PSF is varying in width and location, due to the active compensation, namely the co-phasing correction. Preliminary results of polarimetric sensitivity and accuracy are also analyzed in several configurations of M1 segments, in the context of an integration within the E2E work package.

10330-13, Session 4

Partially coherent phase retrieval with tunable phase transfer function based on the transport of intensity equation *(Invited Paper)*

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Quantitative Phase Imaging (QPI) based on single beam propagation have recently emerged as a practical tool for measuring the phase information of non-absorbing specimens [1–3] and is routinely employed over a wide range of wavelengths that go from the near infrared to the x-ray regime [4–8]. This technique only uses a stack of intensities for recovering the phase properties. In this way, the use of external agents that might harm or disturb the specimen are avoided. One of the major advantages of QPI based on a single beam propagation is that the experimental system does not require a high complexity and is robust against a mechanical and environmental perturbations. For these reasons, single beam QPI have recently gained increased interest in several fields of science and technology [7,9,10]. An important example of QPI is based on the Transport of Intensity Equation (TIE) that relates the phase of an object to the intensity distribution by a linear operator [1,2]. This TIE based technique has become a useful alternative due to its straightforward experimental [2,11] and numerical implementation [12,13]. Moreover, the flexibility to employ partially coherent illumination (PCI) in this QPI-TIE technique allows obtaining phase reconstructions with low phase noise and high accuracy. However, a mayor problem when using PCI in QPI-TIE technique is the proper calculation of the Phase Transfer Function (PTF). The analytical formula of the PTF depends strongly on the physical features of the optical system and only for a few cases an exact solution exists [14]. Thus, the calculation of the PTF for most of the practical cases relies on a heavy numerical integration [15]. For the calculation of the PTF, size of the illumination source and its corresponding degree of coherence is assumed to be constant in all the set of measurements, which might not be optimal. In order to enhance the QPI-TIE algorithm, we propose a new methodology for altering the degree of coherence for QPI-TIE systems which employs PCI in both experimental and numerical processing tools. The experimental modification consist in amplitude modulation of the field with a Spatial Light Modulator (aSLM) placed at the Fourier plane of the optical system. The aSLM will display a band pass filter that allows decreasing the energy of the zero diffraction order of the propagated field. We believe that this operation will provide the possibility to improve the coherence of the system in the case of large sources. However, in order to retrieve the phase information with the QPI-TIE algorithm from the captured intensities filtered with the aSLM, the numerical model of the new PTF will be found. Moreover, we investigate the proper optimization of the band-pass filter displayed in the aSLM that enables a proper employment of the dynamic range of the camera. Finally, we will propose band-pass filters that simplifies the calculation of the PTF, which will improve the speed of the QPI-TIE technique. It will be shown that by adding the aSLM to the original QPI experimental setup the capturing process of the intensities will be optimized. Hence, by employing the set of optimized PTFs a phase retrieval technique that can employ variable PCI will be created.

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10330-14, Session 4

Experimental measurement and numerical analysis of group velocity dispersion in cladding modes of an endlessly single-mode photonic crystal fiber

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The optical properties of the guided modes in the core of photonic crystal fibers (PCFs) can be easily manipulated by changing the air-hole structure in the cladding. Special properties can be achieved in this case such as endless single-mode operation. Endlessly single-mode fibers, which enable single-mode guidance over a wide spectral range, are indispensable in the field of fiber technology. A two-dimensional photonic crystal with a silica central core and a micrometer-spaced hexagonal array of air holes is an established method to achieve endless single-mode guidance. In addition to the guidance of light in the core, different cladding modes occur. The coupling between the core and the cladding modes can affect the endlessly single-mode guides. There are two possible ways to determine the dispersion: measurement and calculation.

We calculate the group velocity dispersion (GVD) of different cladding modes based on the measurement of the fiber structure parameters, the hole diameter and the pitch of a presumed homogeneous hexagonal array. Based on the scanning electron image, a calculation was made of the optical guiding properties of the microstructured cladding. We compare the calculation with a method to measure the wavelength-dependent time delay. We measure the time delay of defined higher order modes with a homemade supercontinuum light source in a white light interferometric setup. To measure the dispersion of cladding modes of optical fibers with high accuracy, a time-domain white-light interferometer based on a Mach-Zehnder interferometer is used. The experimental setup allows the determination of the wavelength-dependent differential group delay of light travelling through a thirty centimeter piece of test fiber in the wavelength range from VIS to NIR. The determination of the GVD using different methods enables the evaluation of the individual methods for characterizing the cladding modes of an endlessly single-mode fiber.

10330-15, Session 4

Study of the optical crosstalk in a heterodyne displacement gauge with cancelable circuit

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Laser heterodyne interferometry is a great performing technique for measuring relative and absolute distances in a wide range of applications, both in science and industry.

Pushing displacement metrology over long distances and down to nanometer and sub-nanometer accuracies demands a more elaborate layout than that of the standard heterodyne interferometer. This design, called "cancelable circuit", consists of the splitting of one of its arms in two separate parts: the reference beam (REF), which propagates straightforward to the recombination point, and the measurement beam (MRE), which travels to the fiducials defining the concerned distance and then merges back with the reference beam. Both parts recombine with the other arm at different frequency, such that two optical beatings can be extracted at the interferometer output. The phase difference gathered by MRE with respect to REF is related to their Optical Path Difference (OPD) and is equivalent to the phase offset that one can measure between the two output beats. The above described configuration shows to be insensible to any perturbance (e.g. mechanical stresses, temperature gradients,...) affecting one or both arms. Such perturbances are turned into common mode noise, which indeed acts on REF and MRE in the same manner and cancels out. This works under the fundamental assumption that after the merging point the measurement and reference beams are kept perfectly separate while travelling along the same optical path.

Therefore, one main focus of this design are the means of splitting and merging for the reference and measurement beams. The adopted methods are essentially two: polarization, with the use of polarizing beam-splitters, waveplates and properly polarized sources; and wavefront division, by taking advantage of holey mirrors and/or retro-reflectors and conveniently shaped masks.

Polarization splitting is easier to implement, but is limited by the fact that the level of isolation between REF and MRE (defined as the ratio of REF power leakage into MSE and viceversa) can hardly get lower than ?30dB.

Wavefront division was developed to overcome the limitations of the polarization approach and has already demonstrated better than -80dB isolation levels. The proper shapes and sizes of both drilled mirrors and blocking masks can be determined by studying how the laser beam propagates inside the interferometer. In particular, one must take care of the beams cross-sections after wavefront division until right before the merging point and all along the beams common path to the detectors. Diffraction at every aperture alters the propagation and can cause one beam to mix with its counterpart.

Optical mixing of REF and MSE gives birth to a systematic error called "cyclic error", which shows as a periodic offset between the detected displacement and the actual one. This error has been analyzed by previous works both in the case of zero-crossing phase detection and quadrature phase detection. Further detailed investigations have been performed on heterodyne Michelson interferometers making use of polarization splitting.

All cited works apply to experiments where the phase measurement, i.e. the OPD, is obtained between arm 1 and arm 2 of the interferometer. Therefore no cancelable circuit is considered: the sole optical beating at output is directly compared to a pure sinusoid for phase retrieval.

As previously mentioned, the introduction of a cancelable circuit deeply alters the optical layout. The interferometer acquires an additional optical beating at its output, which is used as reference for phase retrieval and substitutes the source sinusoid. Thus the observed OPD is no more measured between arm 1 and 2, but between the REF and MSE paths, as defined by the splitting and merging points inside the optical layout.

A simple derivation of the cyclic error due to optical mixing for the cancelable circuit design is proposed. Reference and measurement beatings are supposed collected by two photodiodes and conveniently converted by transimpedance amplifiers, such that the output signals are ac-coupled voltages. The detected phase can be calculated as a function of the real phase (change in OPD) in the case of zero-crossing detection. What turns out is a cyclic non-linearity which depends on the actual phase and on the amount of optical power leakage of the reference beam into the measurement channel and viceversa.

We then applied this result to the prototype of displacement gauge we are developing, which implements the cancelable circuit design with wavefront division. The splitting between reference and measurement beams is done by a double coated mirror with a central hole, tilted by 45° with respect to the surface normal. The interferometer features two removable diffraction masks, located respectively before the merging point (circular obscuration) and before the recombination point (ring obscuration).

In order to predict the extent of optical mixing between the REF and MSE, the whole layout was simulated by means of the Zemax® Physical Optics Propagation (POP) tool.

After the model of our setup was built and verified, we proceeded by calculating the amounts of optical power leakage in various configurations: with and without diffraction masks and for different sizes of both the holey mirror and the diffraction masks. The maximum displacement error due to optical mixing was then calculated for every configuration by means of the previously derived formula.

The introduction and optimization of the diffraction masks greatly improved the expected optical isolation between the reference and the measurement channels.

We plan to experimentally verify such results as soon as we'll start phase data acquisition from the prototype gauge. This will let us identify the many sources of systematic error and, among them, the expected cyclic error.

10330-16, Session 5

A Monte Carlo model of multiple scattering samples for optical feedback interferometry

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Optical feedback interferometry is a powerful and compact vibrometry technique where a fraction of the laser beam backrreflected in a target reenters the laser cavity and interferes with the standing wave. Applications include vibrometry, istance masurements, and vibrometry. When the laser light is applied to multiple scattering environments, however, it becomes difficult to know which is the origin of the backrreflected light due to the diffusion of light in the media, so the information extracted becomes undefined in its vertical dimension. There is a number of very interesting application cases, including propagation of the beam in fog or smoke, and in biological tissues, including skin or blood. Propagation in múltiple scattering conditions, however, is governed by radiometric diffusion equations, while interference in the laser cavity is in the domain of Physical Optics. A mixed model is thus required to analyze in detail the behavior of the interferòmetre. Such a model has been developed using a combination of Monte Carlo simulations and mathematical software solutions. Monte Carlo simulations estimate the distribution of energy backrreflected from a particular layer of the múltiple scattering media considered, and are performed using a commercial optical design program (TracePro®). The resolution of the nonlinear equation describing which governs the behaviour of the laser is then performed using Matlab®. Simulations on the behavior of a laser OFI velocímetre for blood flow measurement under a skin model will be presented, showng the feasibility of the approach and its potential applications.

10330-17, Session 5

Digital micromirror device as amplitude diffuser for multiple-plane phase retrieval

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Previous implementations of the phase diffuser used in the multiple-plane phase retrieval method included a diffuser glass plate with fixed optical properties or a programmable yet expensive spatial light modulator. Here a model for phase retrieval based on a digital micromirror device as amplitude diffuser is presented. The technique offers programmable, convenient and low-cost amplitude diffuser for a non-stagnating iterative phase retrieval. The technique is demonstrated in the reconstructions of smooth object wavefronts.

Introduction

Phase retrieval methods allow the recovery of the phase information which is lost during the camera detection process. In a sub-category called iterative phase retrieval methods, constraints are imposed on the calculated wavefront by forcing the calculations to conform with the values obtained from the intensity measurements, updating the phase estimate in the process [1-3]. Phase retrieval methods have the main advantage of not using a holographic reference beam, affording simpler setups and greater robustness against vibrational noise.

In an iterative phase retrieval algorithm, a change in amplitude distribution alone at an input plane will result in changing both the amplitude and phase distributions at the output plane [4]. Variation in the intensity measurements, therefore, is a critical spatial feature for a non-stagnating iterative phase retrieval of object wavefronts. In some applications involving smooth object wavefronts, such intensity variation is not observed thus hampering the performance of the iterative reconstruction algorithm. This difficulty may be alleviated by introducing a diffuser in the setup generating speckle patterns which exhibit significant intensity variation [5]. Previous works on diffuse illumination multiple-plane phase retrieval method used photolithographic diffuser glass plate with fixed optical properties [6] or a programmable spatial light modulator system which tends to be expensive [7].

Light modulation can also be achieved by using a digital micromirror device (DMD) comprised of an array of binary amplitude (i.e., ON-OFF) modulators. DMD's offer high refresh rates (~4 to 20 kHz) and fine pixels (~10 microns), all at a lower cost relative to the phase-type SLM's. DMD has been used in structured light illumination for phase retrieval techniques [8].

In this study, DMD is used as amplitude diffuser in conjunction with the multiple-plane phase retrieval method. Results of our numerical simulations based on the DMD setup for both pure-amplitude and pure-phase objects are presented.

Methods and Results

The schematic of the model starts with a plane wave incident on an array of binary amplitude modulators depicting the DMD diffuser with 10 micron-pixel pitch, and 3 mm-aperture diameter. The generated diffuse light then comprises the illumination beam of the smooth test object located 20 mm from the DMD plane. For the intensity measurements (for a total of 20 measurements), the wave intensity starting at the first plane (located 40 mm from the test object) is recorded. For the rest of the recordings, the camera is moved through the planes with a step-distance of 1 mm. For the reconstruction, the algorithm used is based on the repetitive use the Rayleigh Sommerfeld wave propagation equation as described in Refs. 5-7. Successful phase retrieval is demonstrated when the input amplitude and input phase are reconstructed using the technique.

Without the DMD amplitude diffuser, it was observed that for weakly scattering objects, the phase retrieval algorithm is unable to recover the phase information. Upon the introduction of the DMD diffuser, it was observed that although the amplitude diffuser generates diffuse light at each of the planes, the increased intensity variation paved the way for accurate phase reconstruction of the test wavefronts. This is true even for complicated amplitude-type and phase-type object distributions.

Conclusion

As a first time, a phase retrieval technique based on digital micromirror device was demonstrated. The use of DMD as amplitude diffuser was shown to be beneficial in phase retrieval in terms of achieving enhanced intensity variation. As an outcome of this study, DMD technology advances the field of phase retrieval offering programmable, convenient and inexpensive diffuser for the investigations of weakly scattering test objects.

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10330-18, Session 5

A flexible, simple telecentric three dimensional measurement system

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Fringe projection profilometry, such as Fourier transform profilometry, windowed Fourier transform profilometry, wavelet transform profilometry, S-transform, has been widely used in variety of 3-dimension measurement. Three-dimensional (3D) imaging systems based on such techniques measure the absolute phase corresponding to the 3D shape of an object surface. To obtain the shape of the measured object, the absolute phase needs to be converted into depth data. One vital step is calibration, which defines the relationship between the phase and depth data. But the inherently nonlinear and spatially variable relationship between the absolute phase of the projected fringes and the object surface depth making calibration problematic. The calibration of nontelecentric imaging system is complicated because of its nonlinear and the dependence of the relationship on the pixel position.

In this paper, a telecentric threedimensional measurement system is proposed. Due to the telecentric lens used in the system, the pixel sizes of the object will not be changed at different distance. It can obtain the transformation matrix of the camera in XY direction by calibrating on one height. The period of projection fringe on each height plane is the same, which can make the phase to height relation calibration linear and easier than that using ordinary lens. Each bright stripes of projection fringe are parallel so that it is not necessary to adjust the projection pattern and the adjustment of projection system will be easier. The phase-depth relationship and camera parameters estimation of system are derived in theory.

In this work, a novel two-step calibration method for a monocular 3D telecentric system, aiming to improve the efficiency of telecentric system in real application. The system consis of a camera with a telecentric lens and a LED light source with a telecentric lens. The LED light source with a grating inside can project a sinusoidal grating fringe on defocusing. The calibration of the camera in XY direction is using the method base on Roger Y. Tsai's approach. The calibration of Z direction mean height direction is using the phase solved by S-transform of the plane of each height to contact the corresponding height to obtain the relationship between height of object and the phase solved S-transform.

An experimental prototype has been established to verify the validity of the proposed calibration approach. Experimental results show that the phase-depth relationship of the proposed telecentric 3D measurement system is linear and the fitted lines of different pixels nearly have the same slope values. Thus, we only need calibrate one pixel to obtain the system parameters, greatly reducing the calibration complexity. Additionally, the results indicate that the standard deviation of calibration results at z coordinate is within 5 ?m, while that at x and y coordinates is within 3 ?m. Three-dimensional shape reconstruction of a coin valued ¥1 and measurement of central circle points of the calibration target further verify the validity of the proposed calibration method. It is concluded that the proposed calibration method is simple but accurate to be used in real application.

10330-19, Session 5

Optofluidic In-plane Mach-Zehnder Interferometer based on the liquid core/liquid cladding waveguides for Refractive-Index measurements

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Since the emergence of optofluidics, the fusion of optics and microfluidics, a lot of efforts has been made to miniaturize the optical systems along with increasing their performance parameters. Implementing the fluidic elements as the optical device is shown to have many advantages over the solid elements, such as smooth interfaces and tunable optical properties. Many types of optofluidic interferometers for refractive index (RI) measurements have been realized including Mach-Zehnder Interferometer, Fiber Brag gratings, Fabry-Pérot interferometers and Young interferometers.

In the last decade, the Liquid core/liquid cladding waveguides have attracted the attention of many researchers in the field of optofluidics. These waveguides can be constructed simply by injecting three streams of fluid with different refractive indices. The higher refractive index (RI) of the core stream relative to that of the cladding streams and the covering layers makes light travelling inside the waveguide through Total Internal Reflections.

In this paper, we have used the L2 waveguides in order to guide the light into two different arms constructed by the inclusion of an engineered obstacle in front of the input optical port. For RI measurements, one of the cladding liquids (the "Sensing Cladding") is considered to be connected to a micromixer fed by a T-junction. Then, water and ethylene glycol can be injected into the different inlets of the T-junction and passed through the micromixer to realize a homogenous RI for the sensing cladding (n=1.33-1.36) . The other cladding (the "Reference Cladding") and the core liquid are considered to be the DI water (n=1.33) and 5.0M $CaCl_2$ solution (n= 1.50), respectively. By using these liquids, light is able to propagate through the core liquid inside the microchannel due to the Total Internal Reflections. However, the obstacle splits the core liquid into two different arms. As a result, the light which travels inside the core liquid is coupled into these two arms experiencing different optical paths due to the asymmetric geometry of the obstacle and also the different used cladding liquids. In order to optimize the working device, we have obtained the concentration profile of the involved liquids and the corresponding RI profile by performing simulations with the "laminar flow" and the "Transport of diluted species" modules of the Comsol Multiphysics 5.2 to maximize the optical length difference between the two arms of this interferometer.

Finally, we have used the results of the previous simulations (i.e. the RI profile) to solve the wave equation using the "wave optics" module of Comsol Multiphysics 5.2 based on the frequency domain calculations. By this step, we have found the Intensity profile of the transmitted light and, consequently, the transmitted power. We have performed the simulations for different RIs of the Sensing cladding.

The simulation results indicate that this interferometry technique has a sensitivity of 91%/RIU, thus, if the accuracy of the powermeter used for the measurement is considered to be 0.01 μW and the output power is 500.0 μW, then the resolution of this interferometry device would be 10^-5 RIU. The sensing properties of this sensor can be tuned by changing either the geometry of the obstacle, the involved liquids or their flow rates.

10330-20, Session 6

Rough surface scattering for thin films and nanostructured surfaces *(Invited Paper)*

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Accurate scatterometric and ellipsometry characterization of non-perfect thin films and nanostructured surfaces is challenging. Imperfections like surface roughness make the associated modelling and inverse problem solution difficult due to the lack of knowledge about the imperfection on the surface. Combining measurement data from several instruments increases the knowledge of non-perfect surfaces. We investigate two approaches to incorporate experimentally measured surface roughness into inverse methods used in scatterometry and ellipsometry. In the first approach the surface roughness is incorporated directly into the forward Maxwell solver used in scatterometry and ellipsometry. In the second approach we decompose the non-perfect surface into two components: A perfect surface and a rough component. Each component is described by a transfer function. We explore numerically the performance of the two approaches and the validity of the transfer function description.

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10330-21, Session 6

In-line measuring method for periodical sub-wavelength nanostructures

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Periodically nano-textured surfaces are becoming increasingly important due to their various functionalities, such as light management and structural colors, hydrophobic or hydrophilic properties. The fast mass-production with high precision on large areas sharpens the demand for in-line metrology to support process development and process control. The process depending requirements regarding resolution and time exclude the use of the established microscopy techniques (interference and confocal microscopy, scanning electron or atomic force microscopy). Scattered light-based methods for surface measurements are fast, non-contact, integrating and therefore predestinated for process inspection. However, the current angular and spectroscopic scatterometry methods depend on complex mathematical models and experiments for extracting the structural information of the measurement object. For this reason, expert knowledge is necessary, which impedes the implementation of scatterometry in industrial environments in particular for in-line applications. Furthermore, a sub-wavelength resolution is difficult to achieve.

The goal of this work is to describe a simulatively designed user-friendly scatterometry approach for the in-line characterization of sub-wavelength periodical structures. The aimed structures are sinusoidal gratings with both period (pitch) and peak-to-valley heights of about 200 nm (aspect ratio around 1) printed on a transparent foil in a roll-to-roll procedure. The challenge is to determine with nm precision the dimensional parameters of the gratings from measurements of the position and intensity of the diffraction maxima. Spectroscopic scatterometers measure the variations of the specular reflection over a large range of light wavelengths. Angular scatterometers require laser wavelengths considerably smaller than the grating period in order to access the nonzero diffraction orders, which are more sensitive to changes in the grating parameters. However, in a fixed angle setup it is possible to observe the first diffraction maximum at small glancing angles for gratings with a pitch-to-wavelength ratio approaching 0.5. In order to find the best measuring configuration, scattering light simulations were performed for modelled grating structures, using an efficient rigorous algorithm, for various scattering setups and grating parameters. The scattering intensities and positions of the diffraction maxima in the reflection and the transmission region are determined simultaneously at a given laser wavelength and incidence angle.

The grating period is computed straightforward from the position of the two diffraction maxima. Determining the grating height, however, requires solving the inverse problem. The presented approach is to extract a calibration function from a set of additional simulations for gratings with different aspect ratios. In order to derive this function a polynomial fit is calculated for the scattered intensities of the diffraction maxima normalized to the incident light intensity and the grating height in units of the pitch.

The measurement uncertainty is evaluated for different instrumentation and simulation parameters, such as the detection and incidence angle, the laser wavelength as well as the input parameters of the simulation.. The investigations showed that the foil undulation, leading to local variations of the incidence angle, is an important factor influencing the measurement uncertainty for the grating height. The best results were obtained for 405 nm laser wavelength and 4° glancing angle. Calculating the incidence angle uncertainty propagation through the calibration function together with the uncertainty for the intensity measurements leads to a height uncertainty estimation slightly above 10 nm. The uncertainties of the incidence angle, the laser wavelength and the position uncertainty of the diffraction maxima result in a sub-nanometer uncertainty for the pitch.

Large area scanning measurements using the setup parameters derived from simulations were performed offline in order to characterize the variations of the grating parameters across the foil. Both diffraction maxima were simultaneously observed on a screen by a CCD camera with a kHz sampling rate. The mapping of the grating period reveals a continuous slight increase towards the middle of the foil which could be explained by the production procedure. The mapping of the grating height shows extended local fluctuations. The resulting variations in both pitch and height of the grating are significantly above the estimated uncertainty for these values.

Depending on the chosen detection system, sampling rates up to the MHz range can be achieved, meeting the requirements of in-line process control of the roll-to-roll production procedure. The observed sensitivity of the method for local variations of the spatial surface properties proofs that the combination of the simulation based calibration function with the derived measuring setup is suitable for the design of an efficient in-line measurement method.

10330-22, Session 6

Metrology of nanoscale grating structures by optical scatterometry

Matthias Wurm, Alexander Diener, Bernd Bodermann, Physikalisch-Technische Bundesanstalt (Germany)

Scatterometry is an essential metrology method to support the lithographical manufacturing of nanoelectronic devices. However, with advancing technology nodes in semiconductor industry this optical method is more and more challenged by feature sizes far below the used optical wavelength. Thus improved measurement schemes and in particular sophisticated data analysis methods are required. At PTB we have investigated the performance of a specific type of scatterometry, goniometric polarised reflectometry, for measurements of deep sub-wavelength grating structures. Here we demonstrate measurements of gratings with linewidths down to 25 nm on silicon wafers with an inspection wavelength of 266 nm. For each sample, measurements have been performed in four different configurations and the obtained data have been evaluated in parallel. As results we present the reconstruction of the complete cross-section profile. We introduce a novel geometry parameterization which overcomes some limitations of the default parameterization. A co-variance analysis of the parameters is offered to indicate the soundness of the results. A qualitative comparison with cross-section scanning electron microscope (SEM) images shows excellent agreement.

10330-23, Session 6

Advancing optical metrology to enable atom-scale technology

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As device sizes move well into the sub-10 nm regime, metrology is being pushed into the atomic measurement domain. Atomic scale resolution in three dimensions is required with measurement uncertainty in the picometer domain. Both conventional CMOS devices and a variety of prospective new structures, such as “gate all around” transistors, nanowire based devices, and tunnel field effect transistors, all require metrology that can determine atomic scale geometry and materials composition, and link these properties to electronic device and circuit characteristics. This is needed in the immediate future since there is already significant effort into the implementation of these types of devices. Beyond the development of ever smaller CMOS devices, there is investment into disruptive solutions, such as single atom transistors, spintronics, isolated electron/nuclear spins for quantum computing, or new 2D devices, based on, e.g., molybdenum disulfide (MoS2) that offer unparalleled carrier mobility. What these all have in common is the need to know the precise distribution and type of atoms, even to the extent of a single atom and its relation to an interface, because this can substantially affect device performance.

The solutions to these challenging measurements are broken into two classes of metrology challenges: 1) manufacturing metrology and 2) research and development to evaluate device concepts or material design. Different measurement methods are appropriate to the two different challenges, primarily due to the tradeoffs amongst throughput, resolution, field size, destructivity, and measurement complexity. Optics remains unique with its combination of high throughput, sensitivity and non-destructivity. However, optical methods face a few key limitations including parametric correlation in the theory to experiment fitting process and the fundamental break down of the assumptions used in the application of electromagnetic scattering theory at low dimensions. These challenges can be addressed through the use of hybridization of multiple measurements or techniques, shorter measurement wavelengths, enhanced hardware platforms e.g. interference-based methods, and the inclusion of atomistic effects in the electromagnetic scattering models.

NIST is developing atomic-scale metrology techniques to enable atom-scale device technologies using a broad spectrum of technologies such as transmission electron microscopy (TEM) techniques that offer atomic resolution imaging for layer thickness and materials composition, and atom probe tomography and its unparalleled individual atom resolution. NIST is also developing SIMS, SEM, and SAXS (small angle x-ray scattering) all of which offer high resolution measurements. In this presentation we will describe methods to incorporate high resolution measurement information into high throughput optical measurements. Extensive development has gone into developing the statistical framework that allows for the rigorous combination of supporting measurement techniques with optical methods and fitting algorithms. These hybrid methods can make efficient utilization of slower but higher resolution techniques such as SEM, TEM or SAXS.

Modeling and simulation that account for the underlying physics of signal generation are now an integral part of modern optical microscopy measurement methods. This presentation will also address from a theoretical and experimental perspective the increasing importance of including atomistic effects in the measurement of low dimensional structures, and the transition from homogeneous material assumptions to atomic-scale interfaces and quantum material variation.

10330-24, Session 6

New overlay compensation model for sub-2X BEOL Cu trench first process photolithography overlay control

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As the advanced semiconductor manufacturing technology moves into 2Xnm and beyond, the back end of line (BEOL) process turns to trench first and via last. It becomes difficult to balance and control overlay (OVL) of all critical layers. So far, conventionally, the process control of Vx, Mx+1 and Mx loop compensates the Mx+1_Mx and Vx_Mx+1 minimum, at the expense of Vx_Mx that is the key layer. Once Vx_Mx overlay is out of spec, it is needed to do rework, resulting in extra cost. Also higher Vx _Mx overlay would reduce the final yield. In this paper, we came up with a new overlay compensation model to balance overlay weight among 3 or more layers loop. It aims to improve the overlay of all key layers based

on appropriately loss of secondary layers, according to device layout. This new overlay compensation model contains pi-run procedure and correctable calculation method of the sacrificial secondary layer. The results of our study will be presented and discussed in this paper.

10330-25, Session 7

Numerical investigations of the potential for laser focus sensors in micrometrology *(Invited Paper)*

Eberhard Manske, Jörg Bischoff, Rostyslav Mastylo, Technische Univ. Ilmenau (Germany)

Laser focus sensors (LFS)1 attached to a scanning nano-positioning and measuring machine (NPMM) enable near diffraction limit resolution with very large measuring areas up to 200 x 200 mm1. Further extensions are planned to address wafer sizes of 8 inch and beyond. Thus, they are preferably suited for micro-metrology on large wafers. On the other hand, the minimum lateral features in state-of-the-art semiconductor industry are as small as a few nanometer and therefore far beyond the resolution limits of classical optics. New techniques such as OCD or ODP3 have helped to overcome these constraints considerably. However, OCD relies on regular patterns and therefore, the measurements have to be performed on special metrology tracks or boxes rather than in-die. Consequently, there is a gap between measurement and the actual structure of interest which becomes more and more an issues with shrinking feature sizes. On the other hand, near-field approaches would also allow to extent the resolution limit greatly4 but they require very challenging controls to keep the working distance small enough to stay within the near field zone.

Based on simulations of laser focus sensor scanning across simple topographies, we found that there is potential to overcome the diffraction limitations to some extent by means of vicinity interference effects caused by the optical interaction of adjacent topography features. We think that it might be well possible to reconstruct the diffracting profile by means of rigorous diffraction simulation based on a thorough model of the laser focus sensor optics in combination with topography diffraction5 in a similar way as applied in OCD. The difference lies in the kind of signal itself which is tried to be modeled. While standard OCD is based on spectra, LFS utilizes scanning signals. Simulation results are presented for different types of topographies (dense vs. sparse, regular vs. single) with lateral features near and beyond the classical resolution limit. Moreover, the influence of topography height on the detectability is investigated. To this end, several sensor principles and polarization setups are considered such as an astigmatic focus sensor as well as a dual color pin hole sensor. Finally, measurement uncertainties are derived based on perturbation simulations according to the method presented in 6. It is shown that resolution beyond the Abbe or Rayleigh limit is possible even with “classical” optical setup when combining measurements with sophisticated profile retrieval techniques and some a-priori knowledge.

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10330-26, Session 7

Measuring shape of a mirror with a moving camera

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When a moving perspective camera observes a curved mirror, its images capture the reflected (non-calibrated) environment and therefore cannot directly be used to characterise the mirror shape. However, if the environment has a sufficiently rich and detailed texture, for any small camera motion it is possible to accurately estimate the associated specular flow (SF) - a dense two-dimensional field of feature (or pixel value) displacements between the two subsequent images. The problem of estimating the SF (or, more generally, the optical flow - OF) has been studied for decades in Computer Vision, and the best existing methods achieve sub-pixel accuracy in a wide range of situations. In case the environment is located sufficiently far away from the surface and the camera, the SF in each pixel depends only on the camera position and orientation and the local mirror shape in the respective surface point. We derive a compact equation that connects the observed SF and the so-called Weingarten map of the surface (encoding the second-order shape derivatives). In particular, this result implies a very simple relation between the SF and the Gaussian curvature of the surface.

Further, we suggest a practical algorithm to reconstruct surface shapes from the observed SF fields, based on finite-element method and non-linear optimisation. We discuss the properties of the method, its the possible ambiguities, and possible ways to regularise them with external measurements. In order to verify the reconstruction, we conduct a series of synthetic and real experiments with non-trivial surfaces, and confirm the high sensitivity of the SF to the second-order derivatives of the surface (i.e. curvatures). With that, the SF-based reconstruction may complement the established optical measurement techniques based on triangulation (sensitive to the absolute point positions) and the deflectometric principle (sensitive to surface inclines), and facilitate fast (potentially even one-shot) and accurate inspection of large mirrors with compact sensors within naturally-occurring or artificial reflected environments.

10330-27, Session 7

Model-based uncertainty evaluation for absolute form metrology

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Modern optical engineering raised higher requirements for high accuracy surface form metrology. Absolute testing technique and its uncertainty evaluation are the key technology and hot topics in the surface form metrology. The quality criterion of a measurement is its uncertainty which is a measure of confidence in a measurement result. Absolute testing is the most popular method which can obtain the lowest uncertainty measurements. Most of the previous researches focused on the method of getting high accuracy result and high precision, and few concern the uncertainty of the test result, which is an important part of a complete measurement result. This paper aims to propose an alternative absolute testing method, which is a model-based method. This method is based on the idea of “Virtual Metrology” and block design. Our main work is as follows, forward modelling, inverse model solution, error propagation and uncertainty evaluation, and cross-checking of results. The results of the paper will be demonstrated to provide an alternative effective method to test absolute testing techniques.

Coordinate measuring machines (CMM) represent a key technology in industrial metrology. For a long time, measurement uncertainty evaluation was an unsolved problem for CMMs. A novel solution to this problem is the application of simulation procedures: with the so-called “Virtual Coordinate Measuring Machine”, the task-specific measurement uncertainty is calculated with the aid of a “virtual experiment” performed by a computer. Similar techniques can be applied in interferometry. Model-based interferometry was first proposed by Horst Mischo and Alexander Bai in 1998. Just like the virtual coordinate measuring machine(VCMM), then the virtual Interferometer was proposed. The

Virtual Interferometer is a tool for the systematic assessment of error-sources in interferometry,

In this paper, we proposed a model-based uncertainty evaluation approach for absolute form metrology, which is actually a virtual interferometry. Absolute testing refers to a measurement method where a complicated measurement process is modeled as a forward problem and a number of measured data are obtained by a real interferometer under different measurement configurations, and then the absolute form (measurands) are precisely and accurately reconstructed by solving the corresponding inverse problem. Thus computational metrology is essentially a model-based metrology and a typical process to solve an inverse problem.: forward modeling, reverse optimization solution and error propagation and uncertainty evaluation. The key is to finding a high efficient reverse optimization algorithm for absolute form reconstruction. A generalized reverse optimization algorithm for absolute measurement of optical surfaces is presented. It is based on iterative scheme and is effective for solving the absolute testing problems with pixel-level spatial resolution, without the usage of a fitting procedure. After evaluating measurement uncertainty of the input quantity, the final output uncertainty for the absolute form can be calculated by the absolute testing model. As an alternative, a model-based uncertainty evaluation method for absolute form metrology is proposed, which is a Monte Carlo like method. To compute the propagation of uncertainties of the random parameters through the measurement model, the most used technique is the Monte Carlo method. This technique generates several samples of the random parameters according to their distributions.

10330-28, Session 7

Evaluation of a human corneal surface with the null-screen method

Victor de Emanuel Armengol-Cruz, Manuel Campos-García, Cesar Cossio-Guerrero, Univ. Nacional Autónoma de México (Mexico)

In this work, we design a conical null-screen for testing non-symmetric corneas. We proposed a custom evaluation algorithm in order to calculate the shape of the corneal surface. This data is fitting to a custom non-symmetrical shape surface, taking into account orthogonal polynomials, in order to obtain the geometrical parameters such as the radius of curvature and conical constant. In order to proof our proposal, we perform some corneal topography measurements.

10330-29, Session 7

Evaluation of the shape of a parabolic trough solar collector with flat null-screens

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We present a method for testing the shape quality of the reflecting surface of a parabolic trough solar collector (PTSC) with flat null-screens. We develop a custom algorithm to reconstruct the surface taking into account the differences between the normal vector of the true surface and the reference one. Also, we perform a numerical simulation to analyze the accuracy of the method by introducing controlled systematic errors such as misalignments of the null-screen or the CCD plane.

10330-30, Session 8

Simulation of the influence of line edge roughness on the performance of deep ultraviolet wire grid polarizers *(Invited Paper)*

Thomas Siefke, Carol B. Rojas Hurtado, Johannes Dickmann, Physikalisch-Technische Bundesanstalt (Germany); Martin Heusinger, Institute of Applied Physics (Germany); Stefanie Kroker, Physikalisch-Technische Bundesanstalt (Germany) and Technische Univ. Braunschweig (Germany)

Controlling the polarization of light is crucial in numerous applications for optical metrology such as spectroscopy, ellipsometry as well as for industrial vision. The polarization control can be realized by wire grid polarizers (WGPs), which are large-aspect-ratio, zero order gratings that offer an anisotropic transmittance depending on the polarization direction of incident light. WGPs' high attractiveness originates from their large free aperture, while simultaneously being extremely thin. Furthermore, these elements can be integrated into other nano-optical devices. Recently, such elements were successfully developed for applications down to the deep ultra violet spectral range. However, for shorter wavelengths the influence of roughness of the structures poses a severe limitation on the feasible optical performance. To tackle this problem, we numerically simulated the impact of line edge roughness on the polarization properties of WPGs.

For that purpose we generate edge position data of rough grating lines by the Thorsos method. The grid spacing along the ridges is determined to reduce the influence of statistical bias. The optical response is then calculated by finite difference time domain (FTDT) method from that. For the FTDT 11 ridges with 512 sampling points are simulated. The grid size orthogonal to the ridges was 0.45 nm, along the ridges ? of the optimal spacing and parallel to the incident light, the grid size was chosen as 10 nm. With this procedure the influence of standard deviation, correlation length, Hurst exponents are investigated at a wavelength of 248 nm. Additionally, the influence of the wavelength was investigated at fixed roughness parameters. We find that for standard deviations of 2.5 nm and 5 nm the polarization contrast is reduced by a factor of 3 and 7, respectively. In relation to the wavelength of the incident light, Hurst exponent and correlation length determine the optically effective spatial frequency range of the roughness. Small correlation lengths lead to a roughness with periods much shorter than the wavelength of incident light and can thus be interpreted as reduction of the effective complex refractive index. Here, the polarization contrast is less impaired. Large correlation lengths lead to a roughness with periods well above the wavelength of the incident light. Thus, they can be interpreted as macroscopic disturbances which, as well, have a less detrimental effect on the polarization contrast. In contrast, for intermediate correlation lengths the polarization contrast shows a minimum. Our theoretical findings correlate well with experimental results we retrieved with measured roughness parameters in fabricated elements. Our investigations lay the foundation for future improvement of fabrication technology which is expected to substantially enhance the optical performance of WGPs at short wavelengths.

10330-31, Session 8

Structural information and performance prediction of nano-optical wire grid polarizers based on guided mode resonances

Carol B. Rojas Hurtado, Physikalisch-Technische Bundesanstalt (Germany); Thomas Siefke, Physikalisch-Technische Bundesanstalt (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Johannes Dickmann, Stefanie Kroker, Physikalisch-Technische Bundesanstalt (Germany)

The performance of nano-optical elements is subject to limitations set by the fabrication process accuracy. This is of special importance for structures aiming at short wavelength applications, because here necessary feature sizes approach the magnitude of achievable fabrication process deviations. For the fabrication of nanostructures with periods down to a few ten nanometers the self-aligned double patterning process is an efficient and well-established method. Hereby, the initial period of a template grating is halved by using its sidewalls to define the positions of two ridges by coating deposition. Virtues of this method

are a smaller lithographic writing time compared to direct writing the final structure period and access to small features sizes with less complex fabrication procedures. For example, double patterning, is a common technique in the fabrication of nano-optical wire grid polarizers for wavelengths down to the far ultraviolet spectral range. However, the experimentally achieved performance usually differs up to several orders of magnitude from the simulations. This disagreement is mainly caused by structural asymmetries introduced by the fabrication process. The asymmetries lead to guided mode resonances at wavelengths of about three times the polarizer period. In this contribution we introduce an optical characterization method, exploiting these resonances as a sensitive probe to retrieve reliable information about ridge geometry, asymmetric displacement and tilt. We derive an analytical model based on perturbed waveguides to describe the relationship between structural features and the resonance properties. Furthermore, we realize nano-optical wire grid polarizers made of titania with different degrees of structural asymmetry. Therefore, we vary the distance of the two ridges generated by the double patterning process. This is achieved by changing the template line width. The samples are then characterized using a commercial Perkin Elmer Lambda 950 spectrophotometer. From the spectral positions and the depths of the resonance we derive, for example, that the ridges exhibit a tilt. This may be the result of stress in the ridge material. With the additional structural information we extract from the investigation of the resonances, we are able to substantially reduce the discrepancy between simulation and experimental results in the extinction ratio of the wire grid polarizers in the far ultraviolet spectral region. The residual difference can be attributed to scattered light and will be subject to further investigations. Furthermore, our investigations show, that employing measurements at variable angle of incidence in both linear polarizations, transverse electric and transverse magnetic, the transmittance measurements in the near ultraviolet spectral range yield structural information with a precision of a few nanometers. Data on this scale are hardly accessible with conventional tools for dimensional metrology, such as e.g. scanning electron microscopy. Consequently, the proposed method is a promising tool for in-situ process control and structure optimization covering structures with one dimensional and two dimensional periodicity (e.g. nanorings) made of dielectric and hybrid materials (e.g. resist structures on metal) and may be extended to even shorter wavelengths down in the XUV range. The method allows for a closed loop feedback within the fabrication process chain and can be considered as a crucial step for future improvement of the optical performance of such elements.

10330-32, Session 8

Fingerprinting the type of line edge roughness

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??Lamellar gratings are used as diffractive optical elements as well as structural elements in state-of-the art integrated electronic circuits. Roughness is a non-desirable characteristic of such structures. The shrinking dimensions of the nanostructures challenge the metrology methods and the impact of the roughness on the total performance has even increased in importance. A rapid non-destructive method is needed for the control of the lithographic manufacturing process. Several reports on the determination of the geometric parameters of the nanostructures by scatterometry have indicated that the identification of the roughness contributions is essential for their unequivocal characterization. EUV scatterometry is very sensitive to the imperfections on the structures, which makes it suitable for roughness analysis. For lamellar gratings the roughness is understood as the unevenness of the line edges which is usually classified into two types of edge roughness: line edge roughness (LER) or line width roughness (LWR). The impact of the roughness assuming this distinction has been already analytically studied but so far only for lamellar gratings with periodic pseudo-roughness distributions. However real samples deviate from this periodic assumption.

?Our study aims at a better understanding of the scattering caused by line roughness of gratings. We designed a set of nine lamellar Si-gratings to be studied by EUV scatterometry at the PTB. It consists of one reference grating where no aritifical roughness was added, four gratings with a periodic roughness distribution, and four gratings with a stochastic roughness distribution, two with LER and two with LWR, respectively. From our studies we conclude that the type of line roughness has a strong correlation on the diffuse scatter angular distribution. These distinct scatter distributions allow for new approaches for the characterization of nanostructures by EUV scatterometry.

10330-37, Session PS2

Modeling of luminous stream in photovoltaic systems

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The paper presents a new algorithm which allows for the analysis of the distribution of luminous stream in the solar concentrator system for photovoltaic panels. The use of the concentrator increases the intensity of incident radiation on the photovoltaic surface. An essential element of the presented system is tracking system which tracks apparent position of the Sun on celestial sphere (so-called tracking system), which provides a perpendicular angle incidence of solar radiation on photovoltaic surface. The presented system belongs to LCPV solution (Low Cost Photovoltaic System). The concentrator consists of two flat mirrors which direct the reflected solar radiation on photovoltaic surface. The primary factor influencing the efficiency of the presented system is the material from which the solar concentrator is made and the correlation between the step resolution of tracking system and the angle inclination of the mirror to the photovoltaic surface.

Complex software which allows for the simulations and analysis of luminous stream in the solar concentrator has been developed. The software is based on the authorial algorithm, which uses a combination of two models of BRDF function (Bidirectional Reflectance Distribution Function). This function includes full information about the properties of the reflective flat surfaces. The presented model utilizes the empirical Torrance-Sparrow model and physical HTSG model. Empirical models are quick, easy to implement but they are inaccurate in the estimated parameters. In contrast, physical models allow for an estimation of the surface parameters in much greater detail but they require three or four times higher computational cost as compared to the empirical models.

The action of the authorial algorithm is divided into several stages, which accelerates the execution of mathematical operations. The algorithm uses the Monte-Carlo method for generating the radiation incidence of the most likely direction of incidence. Then, it determines parameters of incident luminous stream, which illuminates the test point. In the next stage, basing on the Gaussian distribution the amount of light reaching to these point is calculated. Then, the local lighting, which corresponds to the reflected stream, is simulated. In the next stage the transformation of incident light to reflected light is calculated. The analysis of the distribution specular, directional and diffuse component in the reflected stream allows to determine the light properties of the mirror surface and to determine the distribution of radiation and the phenomena (shading and masking) occurring in it.

The purpose of the analysis of luminous stream is to select the best materials for mirrors of the solar concentrator system and to minimize the resolution step of tracking system. The simulation of the distribution of directional (dfs) and diffuse (drc) component in reflected stream for different surfaces of solar concentrator, depending on the incidence angle has been performed. In the simulation were used surfaces made of steel polished electrochemically, mechanically polished steel and silver-plated steel for incidence angle in range of 0°-90°. A separate analysis of specular component was not performed because there is a negligible share in the reflected stream.

The simulation results revealed that the stream reflected from a mirror made of polished electrochemically steel has the largest share of the directional component for incidence angle close to 45°. In case of the silver-plated steel, the share of directional component is lower by 7% as compared to the previous surface. On the other hand, the best value of incidence angle was shifted by about 4,56°. The smallest share of directional component has been characterized by a mirror made of mechanically polished steel, which is confirmed by the simulation. The share of the diffuse component in reflected stream is the largest for mechanically polished steel. Clearly, it can be assumed that the steel polished electrochemically has the smallest surface roughness.

Knowing the surface parameters of solar concentrator the simulation of light stream intensity depending on the angle between mirror and photovoltaic surface and resolution step of tracking system in range of 1°-90° for geographic coordinates equal to 51.1079N and 17.0385E were made. The greatest value of intensity radiation was obtained for the angle between 40°-50°, while maintaining resolution step of tracking system equal 24°-27°. In other range there is a significant decrease in the share of directional components while compared to the diffuse component, which reduces the value of luminance. For selected geographic coordinates, the recommended resolution step of tracing system is equal to 15°. The use of higher resolution step of tracking system for photovoltaic system will reduce the power consumption required for the rotation for the entire equipment - changing the incidence angle of solar radiation on the photovoltaic surface. Calculations showed that for such a step resolution the energy needed for the rotation of photovoltaic panels can be reduced by nearly 28%, which is 16.4W increase in the power output of the entire system. In order to verify the accuracy of simulations results the measurement of voltage, current and power output of monocrystalline photovoltaic panels, placed in V-trough solar concentrator system made of steel polished electrochemically was performed. The measurement results showed that the use of 25° step resolution of tracking system increases the power output by 15.3W as compared to the step resolution equal 15°. The measurements has confirmed the correctness of the simulation at the level of 92.7%.

10330-38, Session PS2

Simulation and considering in the experimental data of polarization effects in optical measuring instruments

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Optical elements, both anisotropic and isotropic, are able to affect the polarization state of polarized light, which they are interacting with. The reasons for this in case of anisotropic elements are obvious. In the case of anisotropic it occurs, when orientation ofelement plane relative to optical axis differs from normal. This fact and is explained by the change of amplitude transmittance and refraction indices if element material according to Fresnel conditions. In most applications this effect is almost imperceptible and can be neglected. However, in specific areas, especially in high-precision measuring instruments, it can significantly affect final result of measurements. These areas are, for example, monitoring of food or other biomaterials with polarization methods, in particular the method of Stokes-polarimetry.

Any optical element, such as a plane-parallel plate or a spherical lens, can affect the final polarization state. This effect is the most significant by matrix photodetector. It has a complicated multilayer structure and contains non-flat elements (spherical microlens on each pixel). If the plane of detector is oriented at an angle to the optical axis, then the distribution of polarization parameters on the sensitive area becomes non-uniform, since the incidence angles are different for each pixel. Under certain conditions the measurement result may be significantly distorted by this effect.

For increasing the accuracy of measurements and obtaining a reliable result, the effect of optical path elements on the polarization state must be numerically evaluated. The modeling method of polarization sensitivity based on Jones matrix formalism was proposed previously. Polarization effects manifested in the change of azimuth of source polarized light, which occurs when the detector is illuminated with parallel beam of linearly polarized light, was calculated by different incidence angles.

In this paper we show the simulation results of polarization effects in non-parallel (divergent and convergent) beam, excluding the effect of the lens. Furthermore, the method of calculating the effect of spherical lenses with given geometric parameters on the polarization state is proposed.

Moreover, we show the method of considering the polarization effects of the optical path elements. Using this method it is possible to obtain pure experimental data containing only the influence of measured object on the polarization state. In this way the measurement result becomes independent on the experimental conditions and on the used optical elements. This makes it possible to perform high-precision measurements in polarized light, in particular with Stokes polarimeter with conventional commercial matrix photodetectors.

10330-39, Session PS2

Two-mirror device for laser scanning systems: multiparameter analysis

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We study a simple and low-cost optical configuration with two plane mirrors set at an adjustable angle. The multiple reflections of a laser beam on the mirrors are considered, the number of images produced is deduced, and the total optical path is obtained – everything for a set-up which includes this two-mirror device between a laser scanner with oscillatory or rotating mirrors and its objective lens. We apply the device to increase the optical path of the laser beam between the scanning mirror and the lens in a compact construct. One of the possible purposes for optical metrology is to linearize the scanning function, while reducing the total size of the system. A multi-parameter analysis is carried out with regard to the characteristics of the system. Selected References:
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10330-40, Session PS2

Measuring polarization-dependent dispersion of nonpolarizing beam splitter cubes with spectrally resolved white light interferometry

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Spectrally resolved white light interferometry has proved to be a simple and high precision technique for measuring the phase dispersion of various optical elements. The experimental set-up is based on a Michelson or a Mach-Zehnder interferometer which may contain cube beamsplitters dividing the light beam into two parts. One beam propagates in the reference arm, while the other beam goes through the optical element inserted in the sample arm. Before inserting the optical element it is necessary to measure the residual dispersion of the empty interferometer, as it has been shown that beam splitter cubes introduce a small dispersion between the two arms of the interferometer. The residual dispersion must be substracted from the dispersion value obtained with the optical element. The origin of the residual dispersion has been explained by the small shift between the two parts of the cube. Therefore the geometrical path lengths of the two light beams in the beam splitter cube are not equal. It has been stated that the beam splitter cube can be considered as a combination of an ideal beam splitter and a very thin glass plate inserted in one arm of the interferometer.

In this work we investigate the residual dispersion of an empty interferometer for p- and s-polarized light beams applying various non-polarizing beam splitter cubes. Our experimental set-up was a Michelson interferometer illuminated by a broad-band, tungsten halogen lamp. Polarized light was produced using a broad-band linear polarizer. The

direction of polarization was adjusted to 45° respect to the horizontal plane. The mirrors of the interferometer were simple plane metallic mirrors. At the output of the interferometer another polarizer was placed that could change the polarization direction of the output beam between the s- and p-polarization. Two beam splitter cubes were tested. The interference pattern appearing at the output of the interferometer was resolved with two spectrometers (700-900 nm and 500-900 nm). It was found that the measured residual dispersion of the empty interferometer was different at the s- and p-polarization directions in case of both beam splitter cubes, and the magnitude was also different. It means that the previous explanation for the beam splitter cube dispersion is not entirely correct. Assuming the beam splitter layer is a multilayer structure, the spectral phase shift caused by the reflection on the beam splitter layer depends on the polarization direction of the incident light beam.

These results show that to reach high precision linearly polarized white light beam should be used. In the case of unpolarized light the different dispersion values result in the shift of the spectral fringes decreasing the fringe visibility and the precision of the measurement.

10330-41, Session PS2

Numerical solution of deformation of circular membrane of liquid lens under uniform hydrostatic pressure

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Many optical systems face the requirement for a continuous change of parameters of optical imaging. In past years, such a problem was usually solved by moving some of the key optical elements in the system, which caused the desired modification of image. Soliciting examples are zoom systems in photography, hunting riflescopes, or metrological systems. However, the mentioned mechanical movements of components have many disadvantages and may lead to unwanted distortions of image quality. Moreover, such an optical system could contain many optical and mechanical parts, which causes other complications connected with design, assembly, and mechanical construction. Especially optical systems with an excellent imaging quality then become very heavy and expensive devices.

During last decades, active optical elements have become one of the centres of focus in optics. They are one of options for easy modification of optical imaging without any difficult mechanical movement. Moreover, one can define changes in the image in a desired way, and image quality can be adaptively controlled and rectified.

The key components for such a manipulation with optical imaging are, for example, spatial light modulators, deformable mirrors, or active lenses. The active optical parts are usually quite expensive devices. However, active lenses are much less expensive than the others mentioned, and they can be used in many applications. There are three main construction types usually used in practice – electro-wetting lenses, acoustic-optical lenses, and membrane liquid filled lenses. Each of them has some advantages and disadvantages. Due to their construction simplicity, membrane liquid lenses promise fast spreading in the close future.

This paper is focused on a theoretical general description of membrane deformation in membrane liquid lenses, which is based on the theory of large deformations of thin plates under uniform hydrostatic loading. To the authors' best knowledge such a formulation for membrane lenses has not been published or presented yet.

The general formulas are derived, leading to a system of differential equations that describe the shape of a deformed membrane. Since an analytical solution cannot be found, numerical methods are applied and the membrane shape is calculated for given practical examples. Further, the dependency of maximal deflection of the membrane on the applied hydrostatic pressure is analysed. For a better understanding and possibility of modelling the membrane shape in an optical design software, the shape is depicted as an aspherical too, and a dependency between environmental conditions and aspherical coefficients is discussed as well. Finally, the theoretical simulations are compared with experimental results for a given membrane and applied loadings.

It is clearly seen that the shape of the membrane does not correspond to a sphere even under a small applied loading. Therefore, the presented analysis could bring significant impact in the optical design. Using the results of the paper and numerical examples, one can easily model many cases of membrane liquid lenses and exploit the results of the simulation for precise description of optical systems with active components. It is obvious that without similar detailed analysis it would be difficult to get correct results.

10330-42, Session PS2

Development of graphene process control by industrial optical spectroscopy setup

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The successful integration of graphene into microelectronic devices depends strongly on the availability of a full wafer deposition process, which can provide uniform and high quality graphene on arbitrary substrates. Fast and nondestructive characterization methods are essential to analyse graphene grown by CVD on large diameter production wafers [1-3] which are of interest to the semiconductor industry. Here, a high-throughput optical metrology method for measuring the thickness and uniformity of large-area graphene sheets is demonstrated. The method is based on the combination of spectroscopic ellipsometry and normal incidence reflectometry in UV-Vis wavelength range (200-800 nm) with small light spots (~ 30 μm2), realized in wafer optical metrology tool. This study is based on investigation of graphene layers transferred on SiO2/Si substrate in order to determine the optical constants of graphene by the combination of multi-angle ellipsometry and reflectometry. The graphene layer quality was monitored by Raman spectroscopy. Atomic force microscopy measurements were performed for evaluating the micro topography. Then these data were used for the development of a process control recipe of CVD graphene on 200 mm Ge(100)/Si(100) wafers. A robust recipe for unambiguous thickness monitoring of all components of a multilayer film stack, including graphene, surface residuals or interface layer underneath graphene and surface roughness is developed. Optical monitoring of graphene thickness uniformity over a wafer has shown an excellent long term stability (?=0.004 nm) independent on growth of interfacial GeO2 and surface roughness. The sensitivity of the optical identification of graphene during microelectronic processing was evaluated.

This optical metrology technique with combined data collection exhibit a fast and highly precise method allowing one an unambiguous detection of graphene after transferring as well as after the CVD deposition process on a Ge/Si wafer. This approach is well suited for many industrial applications due to its repeatability and flexibility.

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10330-43, Session PS2

Contact angle measurement by means of a confocal device

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This work presents the results obtained in the validation study of an

innovative technique to calculate the contact angle of a solid surface by means of a confocal device, which confirms the reliability and the accuracy of the presented method.

The bibliography presents a correlation between the microstructure of a surface and the contact angle of a drop placed on it [1, 2], meaning that the surface energy of a rough material shouldn't be calculated directly from the contact angle measurements [3]. Unfortunately, no commercial device is currently available to perform both topography and contact angle measurements. The use of two different devices leads to a sample positioning uncertainty, implying that no assurance can be given that both measurements are performed on the same area on the sample and that the resulting surface energy calculation is correct.

In order to solve this problem, a measurement technique has been developed and validated to measure the contact angle with of a confocal device. This technique allows the measurement of both topography and contact angle with a single device, therefore avoiding any shift in the sample positioning between the two measurements and ensuring the proper location of both measurements in the same area of the sample. Specifically, this technique uses the confocal device to measure some parameters of the drop in a top-view configuration. These parameters are the height (h) and the apparent diameter (L) of the liquid drop. The drop volume is already known and small enough to discard gravity effects, so the shape of the drop can be approximated by a truncated sphere [4]. Several purely geometric calculations are available to calculate the radius de of the drop and subsequently, the contact angle.

This work reports the validation study of this technique and the several mathematical calculations employed to extract the contact angle value. The measurements were performed for different solid samples with different roughness and different measurement liquids, ensuring repeatability to the technique for a large range of conditions. Furthermore, the contact angles of these samples were also measured by a commercial contact angle meter in side-view configuration, with the same liquids and drop dimensions, in order to verify the validity and the accuracy of the presented techniques.

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10330-44, Session PS2

A tunable fiber-optic LED illumination system for noninvasive measurements of the characteristics of a transparent fiber

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An optical characterization of single and transparent particles (e.g. water droplets, glass fibers used in composite materials, optical fibers, etc.) or multiphase systems containing droplets, bubbles or particulates, can be made using rainbow refractometry technique. An inverse problem, which is investigated to predict the values of parameters of the scattering particle or system of particles, consists in using scattering data from the vicinity of a rainbow phenomenon. The physical properties of the scattered optical field depend not only on the characteristics of the scattering particle, but also on measurement conditions, including temporal and spatial features of the incident beam of light that acts as a non-invasive diagnostic tool. The scattering far field pattern typically consists of numerous interference fringes and other nonlinear features resulting from reflections, refractions, extinctions, and absorptions of light. These effects often prevent an unambiguous detection of the characteristics of the scattering object of interest. They can be especially complicated when the incident beam is quasi-monochromatic, as with lasers. However, by using an incident beam having low degree of temporal coherence (emitted by e.g. light-emitting or superluminescent diodes) some interference effects will be weaken if the optical paths taken by the interfering scattered waves differ by more than the coherence length of the light. Such incident beam implementation choices can be considered as a kind of regularization technique for the ill-posed inverse problem and can lead to an inverse solution that is stable under small perturbations of the scattering object characteristics. The stability and reliability of measurement results, in turn, is critical in industrial process control.

This investigation reports an application of a fiber-optic LED-based illumination system to solve the inverse problem in optical measurements of the diameter and refractive index of a single-mode fiber. The illumination system has the advantages of low temporal coherence, high-intensity, collimation, and thermal stability of the emission spectrum. The inverse analysis applies to the far field scattering pattern in the vicinity of a polychromatic rainbow. As the inversion possibility depends considerably on the properties of the incident radiation, a detailed discussion is provided on both the specification of the illumination system as well as preliminary characteristics of the produced radiation. The illumination system uses a direct coupling between a thermally-stabilized LED junction and a plastic optical fiber, which transmits light to an optical collimator. A particular attention has been devoted to a numerical study of fiber-to-LED coupling efficiency with lateral and longitudinal misalignments. In addition, a brief characterization of the optical layout used to perform rainbow measurements has been provided. Finally, the feasibility of the illumination system for optical measurements of the diameter and refractive index of a single-mode optical fiber is discussed on the basis of sample rainbow fringe patterns.

10330-45, Session PS2

Hybrid model of arm for analysis of regional blood oxygenation in noninvasive optical diagnostics

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Non-invasive determination of mixed venous oxygen saturation (SvO2) by occlusion method has been known for several years, but its sensitivity on external factors and influence on micro- and macroscopic circulation still remains the subject of an intensive research. The aim of this paper is to present a new comprehensive approach to modeling and analysis of processes occurring during the blood flow in the arm's small vessels as well as non-invasive measurement method of mixed venous oxygen saturation.

The central part of this work is a discussion on a novel hybrid model of the forearm vascular tree, based on a meta-analysis of available physiological data. Its structure results from both nonlinear hydro-electric analogy as well as analysis of light-tissue interaction.

The electrical analog model of the vascular tree that includes vascular resistance, inductance and capacitance parameters was obtained by analyzing a number of MRA (Magnetic Resonance Angiography) images, which revealed several geometries. Due to the complex nature of an arm and a palm, the vascular network was simplified for the purposes of further analysis; internal branches and smaller vessels were consolidated into corresponding analogues of all same-type vessels characterized by common geometric dimensions located in the considered area. The values of the model parameters take into account real physical and mechanical properties of blood and vessel walls, such as viscosity, density, wall vulnerability etc.

The optical interaction between light and tissue was modelled using a modified Lambert-Beer equation, as in pulse oximetry. In this case, the absorbance registered by detector is related to changes in the effective optical path through the investigated area and depends on the blood oxygenation level. Light scattering effects on boundaries (emitter-air-skin) were neglected in the present study.

The manuscript also offers a description of a nonlinear equation for oxygen distribution in arteriole, capillary and venule vessels. Its coefficients were estimated using both anatomical data available in literature as well as some experimental results. All necessary approximations were made using Levenberg-Marquardt optimization algorithm. The model was validated by comparing its output results (a synthetic plethysmogram obtained by excitation of a brachial artery

with a flow wave) with the response of a real system (Doppler flowmetry results recorded in a brachial artery and plethysmograms recorded from the index finger of left hand).

The proposed hybrid model of the forearm vascular tree enables us to predict the forearm blood flow, taking into account the effect of cuff and vessel wall mechanics on the recorded photo plethysmographic signals. In particular, it is possible to analyze the influence of certain anatomical effects in small vessels and microcirculation caused by occlusive maneuver on the blood flow. Our preliminary studies show that an inappropriate selection of occlusion maneuver parameters (e.g. occlusion time, cuff pressure, etc.) can cause turbulence of blood flow in the venous section of the vascular tree.

In conclusion, the mathematical model of the forearm vascular tree proposed in this manuscript can be used for the purposes of analysis of regional blood oxygenation in non-invasive optical diagnostics. By using easily measurable clinical parameters e.g. Doppler flow results and photoplethysmograms, it enables us to test new diagnostic techniques and estimate some clinically relevant diagnostic parameters.

10330-46, Session PS2

Modelling of influence of spherical aberration coefficients on depth of focus of optical systems

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The depth of focus of an optical system is an important parameter of the optical system. It characterizes a part of an image space, where a diameter of a circle of confusion is the same or smaller than a given value. The diameter of circle of confusion characterizes a diameter of area, where a point of the object will be imaged and which can be accepted as an “image point” (size of spot is smaller than a given tolerance acceptable by some image quality metric used to characterize the imaging system). In the case we permit a certain limit value of the diameter of the circle of confusion, then there can exist a specific part of the image space, where the diameter of the circle of confusion is smaller or equal to a given limit value. This part of the image space is called the depth of focus of the optical system. It is well known that an image of a point is not a point, but a specific spatial distribution of light energy - point spread function, which is affected by diffraction of light and aberrations of the optical system. In the case of a real optical system with aberrations the diameter of the circle of confusion depends on spherical aberration of this system. It is possible to affect the diameter of circle of confusion by an appropriate choice of spherical aberration of the optical system according to its distance from the paraxial image plane. In some applications it is advantageous to have an extended depth of focus of an optical system. One can affect the depth of focus of an optical system in case of axial point imaging by a proper choice of spherical aberration or longitudinal chromatic aberration functions. Other methods, which affect the depth of focus, consist either in insertion of an optical element, for example behind the optical system, which will change an amplitude, phase and polarization of the transmitted wave field, or in the use of lens with specially designed aspheric surfaces, or in the use of tunable focus lenses. Many optical systems with the specially designed depth of focus can be used in various applications in practice in different optical imaging applications, optical metrology systems, biomedical diagnostics, biometrics, correction lenses in ophthalmology and optometry, and industrial optical systems in the field of laser cutting, drilling, annealing engraving, etc.

It is very important to understand how the optical systems may affect the depth of focus and how to design such an optical system with the required depth of focus and the size of circle of confusion. Thus, the aim of our work is to model the influence of spherical aberration coefficients of an optical system on the depth of focus in the case of axial point imaging of the rotationally symmetrical optical system. It is shown how to calculate aberration coefficients of the third and fifth order of the transverse spherical aberration of the optical system for given values of the diameter of geometric-optical circle of confusion and the depth of focus. Analytical formulas for the calculation of beam’s caustics are derived. The conditions for aberration coefficients are derived if the Strehl definition should be the same in two symmetrically placed planes with respect to the paraxial image plane. One can calculate the maximum depth of focus and the minimum diameter of the circle of confusion of the optical system corresponding to chosen conditions. Our work helps to understand how spherical aberration affects the depth of focus and how spherical aberration coefficients must be chosen in order to achieve the required depth of focus defined by the limiting size of the circle of confusion. One can perform computer modelling and design of the optical system and its spherical aberration in order to achieve the required depth of focus.

10330-47, Session PS2

Satellite attitude identification based on nonresolved spectrometric brightness measurements

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As an important part of space situational awareness, the identification of satellite attitude is helpful to perceive running states of satellites, especially for non-cooperative satellites. The technology of non-cooperative satellite attitude identification based on non-resolved spectrometric brightness measurements is studied by means of simulation and experimental measurements. The identification problem is decomposed into three aspects, i.e., attitude control pattern identification, attitude change rate identification and specific attitude identification of satellite components.

In the numerical simulation part, five key problems in attitude identification based on numerical simulation of non-resolved satellite spectroscopy are studied. 1) the spectral BRDFs(bi-directional reflectance distribution functions) model of the material commonly used on satellite surface is established to ensure the reliability of material scattering properties; 2) the orientations of the sun and the detector in satellite coordinates are simulated using the STK software to ensure the correctness of observation geometry; 3) the satellite is modeled using 3ds Max software to ensure that the target model is consistent with the real satellite; 4) the facets which are both visible to the optical detector and the sun are selected based on OpenGL picking-up technology to ensure the real-time and accurate character; 5) the satellite’s spectral radiance is calculated based on facets spectral radiance which are calculated one-by-one using the information obtained in previous steps.

In experimental measurements part, the spectral irradiance of the STSS-Demo1 satellite is obtained by using Space Objects Spectroscopic Measurement System which has already been built-up. The system includes four parts, i.e., the solar simulator using high-power xenon lamp, the three-axle table and its control system, the scaled STSS-Demo1 model and ASD spectrometer to probe optical measurements.

Different types of attitude data are extracted by using different methods for simulating and measuring spectral radiance data. The satellite attitude control mode is identified by spectral analysis method and the rotation speed of satellite attitude is identified by cross-residual method. In order to identify specific attitude of the satellite, the attitudes of a variety of satellite surface components using different materials are identified. Those materials include the triple-junction GaAs solar cell used in satellite panels, the white paint used in satellite antennas and so on. Because such whole-body measurements represent a summation of contributions from many reflecting surfaces, an “un-mixing” or inversion process is employed to determine the materials covering each of the satellite’s individual sub-components.

Finally, the methods proposed above are validated using simulation data and measurements. The validity of the identification method and its constraint are analyzed. The results indicate that, the attitude recognition method is effective for spin-stabilized satellites and three-axis stabilized satellites, but for the failure satellites with some precession motion, there are some limitations on the application of the methods. For the satellite rotates with precessional velocity, when the precessional angle is less than 25 degree, the attitude speed identification method is effective. When the attitude changing ratios of three or more components can be identified, the orientation of the satellite spindles can be determined effectively.

10330-48, Session PS2

Stress evolution during microstructure formation at laser sintering of powders using phase field method

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Laser powder sintering is a well-established manufacturing process for rapid prototyping of fully dense metal components. It involves the supply of powders into a laser-heated spot where the powder is melted and forms a melt pool, which quickly crystallizes. During the laser sintering (LS), several complex non-stationary phenomena occur as the laser beam interacts with both incoming powders and the substrate. These phenomena include thermal transport, fluid flow, mass transport, and fast crystallization, as well as others. Many researchers [1] have studied the macroscopic temperature, concentration and fluid velocity fields during the LS. However, the modeling of microstructure evolution of the solidification (mesoscale process) has received a little attention. Mechanical properties of fabricated materials strongly depend on their microstructure. The prediction and control of microstructure formation play crucial roles in high-intensity laser additive manufacturing. The existence of mechanical stresses, which are generated during the LS, is also of great importance. Most of the defects (macrosegragation, nanopores), formed in materials are a result of residual stresses in the solid-liquid mushy zone. Therefore, useful methods for modelling stress evolution during microstructure formation have been required.

The phase field modeling [2] is one of the most powerful approach to modeling and predicting mesoscale morphological and microstructure evolution in materials. The author previously used a simplified phase field model in which only elastic behavior was included to show stress/strain evolution during binary alloy solidification [3].

In this contribution, the elastic-plasticity constitutive relation is assumed to study the stress evolution during microstructure formation at the process of LS of metal and alloy powders. Fundamental equations accounting for the coupling effects among phase variable, concentration, thermal and stress/strain fields have been derived based on the principle of entropy production positiveness, in which thermal and concentration expansions, anisotropy effects, transformation dilatation, and stress dependency on phase transformation are considered. From the analysis of the system of simplified equations, the physical meaning of the parameters in the evolutionary equations is identified. The possibility to describe the process of structure formation at the interface during the melt crystallization is discussed. The analysis of the linearized stability problem makes it possible to find a spectrum of wave numbers of unstable perturbations. It is shown, that, in addition to the thermal and mass transfer processes, the elastic field generated by the stresses is another important factor that controls the instability mode. An increase in stress values increases the maximally wavelength of the unstable perturbations. Disturbances growing with the greatest speed determine the characteristic size of the structure at the solidification front.

The obtained results can be also useful for the development of modern methods of nondestructive detecting and characterization of synthesized materials by LS, including the detection of defect concentration regions in them and the coating quality testing.

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10330-49, Session PS2

Analysis of instrumental effects on polarization of the polarimetric unit in the high-spectral resolution spectrograph with fiber input for the 6m SAO RAS telescope

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According to the objectives of the spectrograph the polarimetric unit should allow to measure the polarization of the incoming radiation. Polarization measurements in the traditional concept can be carried out through the phase-shifting plate's ?/4 and ?/2 together with a linear polarizer that divides a beam of light into two orthogonally polarized beams (ordinary and extraordinary rays). Then beams of light, passing through a forming optical system are recorded on the CCD. By rotating phase-shifting plate around its axis at a certain angle, at a constant position of the polarizer, it is possible to determine all the Stokes parameters of the incoming radiation. The "half-wave plate– polarizer" combination corresponds to the mode of observations of linear polarized light. The "quarter-wave plate– polarizer" combination is used in observations of circular polarization. Using the known relations, widely presented in the technical literature, it is possible to find all parameters of polarization of light from the Stokes parameters. In this paper we consider only the polarimetric unit of the spectrograph, the light flux after the optical system of the polarimetric unit, lands on the respective input ends of the optical fiber. Fiber channel transfers the light flux to the entrance slit of the stationary part of the spectrograph where it is decomposed into a spectrum and then recorded onto the CCD.

A polarimetric unit of the mounted part of the spectrograph converts the polarization of the incoming radiation in the output radiation of different intensity. All the information about the polarization state of the incoming radiation, therefore, is determined only by the difference of the intensities of outgoing radiation. To describe the polarization state of the incoming radiation the Stokes vector is used. The Stokes vector of the incoming radiation S = [I, Q, U, V] and the outgoing radiation S´= [I´, Q´, U´, V´] completely describes the state of polarization of the light and allows to estimate all the parameters of polarization of light, such as its full intensity I, the azimuthal angle ?, ellipticity ? and degree of polarization P. To find the Stokes vector of the emerging radiation Mueller matrices method is used. The formalism of the Mueller matrix allows us to assess the impact of each component mounted part of the spectrograph on the polarization of the incoming radiation, by finding the Mueller matrix for each component. Also the main advantage of this method is that it allows you to work with non-monochromatic and partially polarized radiation. To analyze the instrumental polarization it is necessary to find the Mueller matrix of each optical element. Each optical element previous to the polarizer affects the state of polarization of the incoming radiation. With the aim of improving the measurement accuracy of polarization should account for this effect. The main components that change the state of polarization of the incoming radiation are: the primary mirror of the telescope, the lenses and the phase plate ?/4 and ?/2. Since the polarimetric unit will be placed directly in the primary focus of the first mirror, it is possible not to take into account the instrumental polarization introduced by the second mirror and the other components of the telescope. The Mueller matrix of the primary mirror is determined by finding the Jones matrix of the reflective coating of the mirror. It is also intended to assess the impact of the main mirror of the telescope on the state of polarization of the incident beam for different coverage's. The influence of individual lenses on the state of polarization of the input beam of light caused by the presence of residual stresses in the glass, resulting in birefringence manifests itself. Birefringence can also be caused by the lenses mounts and most often appears at the edges of working surfaces of details. After finding the Mueller matrices of the main mirror BTA and matching optics of polarimetric unit, it is possible to estimate the instrumental polarization of these components. The main effects in the phase-shifting plates, which introduce the largest error in the measurement of polarization, are crosstalk effect and depolarization due to the chromatism of their polarization properties. Crosstalk F(V) in this case is measured as the share held through the system of light

converted into circular polarization from linearly-polarized light fed to the input. Similarly, you can evaluate the amount of "pumping" in determining the Stokes parameters Q and U in the measurement mode of linear polarization. Taking into account the results of the assessment of instrumental polarization the accuracy of the tool can be significantly improved. A computer model of the optical system of the polarization unit allows us to analyze the errors introduced by the optical elements of the telescope and the polarization module, at the measurement of the Stokes parameters.

10330-50, Session PS2

Characterization of a conical null-screen corneal topographer

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In this work, we perform the characterization of a conical null-screen corneal topographer. For this we design custom null-screens for testing a reference spherical surface with a curvature radius of 7.8 mm and 12 mm in diameter, and for an aspherical surface with a curvature radius of 7.77 mm and 12.5 mm in diameter. We designed five different target distributions with the same target size to evaluate the shape of the reference surfaces. The shape of each surface was recovered by fitting the experimental data to a custom shape using the least square methods with an iterative algorithm. The target distributions were then modified too, by changing the number of targets and its size in order to obtain a more accuracy measurement.

10330-51, Session PS2

Assessment of yearly lidar ratio values in Penang, Malaysia

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Lidar ratio (LR) is an important parameter to invert the lidar equation to subsequently get information from the lidar signals. Therefore, it is the objective of this study to assess the LR values for each day to implement into the inversion method. An algorithm has been generated to estimate the lidar ratios in Penang for the Raymetrics ground-based lidar. Daily average humidity and visibility parameters was obtained and the lidar ratios for each day in year 2014 and year 2015 were assessed. It is found that the LR values in the year 2014 and 2015 generally lie in the range from 55 sr to 85 sr. Maximum LR values in year 2014 and 2015 is 141 sr and 177 sr respectively. Both years has the same minimum LR value of 46 sr. Extreme values are found in both years during the haze events that occurred in Penang. The LR values estimated are valuable as they represent the atmospheric conditions in Penang and plays an utmost important role in the lidar inversion method.

10330-52, Session PS2

Out-of-squareness measurement on ultraprecision machine based on the error separation

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Traditional methods of measuring out-of-squareness of ultra-precision motion stage have many limitations, especially the errors caused by inaccuracy of standard specimens, such as bare L-square and optical pentaprism. And generally, the accurate of out-of-squareness measurement is lower than the accurate of interior angles of standard specimens. Based on the error separation, this paper presents a novel method of out-of-squareness measurement with a polygon artifact. The angles bounded with the guideways and the edges of polygon artifact are measured, and the out-of-squareness distraction is achieved by the principle that the sum of internal the angles of a convex polygon artifact is (n-2)ϖ. A out-of-squareness metrical experiment is carried out on the profilometer by using an optical square brick with the out-of-squareness of interior angles at 0.3°. The results show that the repeated measurement of out-of-squareness between the X axis and Y axis of the profilometer is 0.22 arcsec. The accurate measurement is much higher than the accurate of the interior angles of brick.

10330-53, Session PS2

Active marks structure optimization for optical-electronic systems of spatial position control of industrial objects

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To increase automation level, efficiency, and reliability of the monitoring processes on potentially dangerous constructions, building, foundations of the bases and other stretched infrastructure facilities, monitoring of their spatial position the optical-electronic systems constructed based on the active reference marks widely found application.

Control over movement is based on analysis of space provision of the reference marks which are established in critical (nodal) points of a controlled construction. The reference marks represent set of light-emitting diode that oriented in space. Application of the active reference marks (unlike passive marks) solves a problem of energy efficiency of use of optical emitting at realization of system for monitoring of the large-size stretched objects or objects located at larger distances. However in such systems one of the important procedures is a reliable detection of the reference marks on a random gradient background with a noise and hindrances during the whole time of operation with the changing external conditions (existence of a background glare from various natural and man-made sources of light, change of a air path condition, etc.).

The purpose of this work is the research of probabilistic characteristics of detection and error estimation of their spatial position definition for optimization structures of the active reference marks on a random gradient background with a noise and hindrances at influence of various influencing factors. In this work structures of the marks performed in the form of a point (one LED), a line (two LED), an equilateral and rectangular triangle (three LED), a square (four LED) are considered.

The probability of an error detection depends not only on the signal/noise ratio, but also on intensity of a background radiation, brightness of the emitting diodes, the size of the image, its structure, and on interrelation of these parameters among themselves. By means of computer model operation probabilistic characteristics of detection and an error of mark's spatial position definition depending on these parameters were studies.

The analysis of the results of model operation shows that the probability of the exact detection for structure of a marks in the form of diodes of the equilateral and rectangular triangles located in tops carries higher values. The probability of false alarm is not exceeded by 8% and 25% respectively. For a mark with structure in the form of a square the probability of the exact detection is also rather high, however at the same time the probability of false alarm is slightly higher, than at structures in the form of triangles.

Also the research of influence of a ratio of the sizes of an arrangement of LED on a mark which showed what at increase in the admission at length of base (distance between LED) allows to increase value of probability of the exact detection while the probability of false alarm has poorly expressed dependence on this parameter was conducted. The error estimation of measurement of coordinates of marks for various structures of an arrangement of LED was carried out.

The developed computer model and results of a research allow to estimate probabilistic characteristics of detection of the composite structured marks on a random gradient background with a noise, and determination of its spatial position gives error estimation. In total results of a research allow to increase measurement accuracy of spatial position of an object. Based on results of research, recommendations about the choice of parameters of optimum structure of an active marks for use in optical-electronic control systems of spatial position of elements of large-size constructions are made.

10330-54, Session PS2

Fatigue strength calculation of the fused silica protective window for aviation-related applications

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The protective windows of optoelectronic devices made of fused silica have several advantages. High transmittance in a wide range from 200 nm to 2 microns allows you to combine a set of UV, visible and NIR spectrum sensors in a single device. Fused silica has a very high temperature resistance and a high mechanical strength over a wide temperature range. Commercial availability of fused silica makes possible to use it in the civil instrument making, particularly, commercial aviation.

Fatigue strength calculation of the protective window is an important task of optoelectronic devices designing. Lifetime calculation of the protective window allows you to select an optimal thickness while preserving mean time between failures. Special strength properties of brittle materials, such as fused silica, require taking into account the factors related to a wide range of operating altitudes and aircraft flight modes. Results of the presented calculation were shown a strong dependence of the fused silica fatigue strength one ambient temperature and the lack of erosion phenomena impact at low speeds of the aircraft.

In this paper results of crack extension velocity calculations on the uniformly-loaded protective window surface, based on Wiederhorn's model, were presented. To account for the difference in the strength characteristics of the samples used in the model description and the subjects of this research the assumptions of Ritter and Charles model were used, as well as the formula for stress intensity factor on the criterion of Griffith. The results were underlain the theoretical basis for the adequate choice of the used samples of protective windows. Further research will take into account the influence of various factors on the strength characteristics of brittle optical materials more accurately.

10330-55, Session PS2

Dielectric function parameterization by penalized splines

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Modern semiconductor device manufacturing consists of multiple process steps such as implantation, deposition, etching, polishing, cleaning, etc. and those steps need to be controlled and verified routinely to achieve required production yield in semiconductor fabrication facilities. At present, well-established and informative optical metrology techniques, such as spectroscopic or angular ellipsometry, polarimetry, reflectometry (polarized or unpolarized) and scatterometry, are widely used for in-line characterization of 2D and 3D micro- and nanoelectronic structures. However, those methods have an indirect nature and require appropriate modeling of material dielectric functions to interpret optical measurements and extract useful information. For this purpose numerous analytical models have been developed (see, for instance, Ref. [1]) and used to describe various types of materials – amorphous and crystalline semiconductors, dielectrics, metals, etc.

Nowadays, an alternative approach to express the dielectric function became quite popular among ellipsometric community, namely, the use of various types of spline functions. One of the most successfully applied in spectroscopic ellipsometry types of splines is so-called Basis-splines (or B-splines) [2]. This is a purely mathematical way of parameterization which also allows the Kramers–Kronig consistent formulation. However, the B-spline approach still requires special efforts for optimizing the number and positions of knots in order to avoid a wiggly overfitting of the data which easily occurs if too many knots were selected.

There are different approaches to avoid data overfitting by B-spline parameterization. One approach is to consider B-splines with different number of knots as a set of mathematical models and apply some model selection strategies, like popular Akaike (AIC) and Bayesian (BIC) information criteria [3], for choosing optimal knot number. Another way is to introduce a penalty to restrict flexibility of dielectric function parameterization by B-splines and prevent the overfitting. It is achieved by putting some constrains on the B-spline coefficients. In this kind of penalized splines, known as P-splines [4], the penalty degree is easily controlled by a certain smoothing parameter. Due to the penalty P-splines possess very interesting the "power of the penalty" property: "The number of B-splines can be (much) larger than the number of observations. The penalty makes the fitting procedure well-conditioned. This should be taken literally: even a thousand splines will fit ten observations without problems."[5]. In fact, use of P-splines replaces the problem of knot selection by a task of choosing the smoothing parameter using various approaches. The practical application of this method is demonstrated by examples of P-spline parameterizations with real ellipsometric data.

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10330-56, Session PS2

Evaluation of thermal behavior during laser aided metal deposition with powder injection using optical pyrometry and numerical simulation

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Simulation of the processes in the technology of laser aided metal deposition with powder injection requires knowledge of the proportion of laser energy absorbed by the material. Flows of the absorbed energy in the material form the thermal field and affect the microstructure formation in solidification process [1-2]. Possibility of numerical evaluation of the thermal behavior in process is limited to a number of factors which are difficult to control. These include, among others, the proportion of reflected radiation; the amount of energy introduced by powder particles; inaccuracy of the numerical values of the material parameters used and its temperature dependence [3]. At the same time, it is also not possible to accurately recreate the internal heat field, using only the experimental data of the temperature dynamics in one or more areas of the synthesized surface due to the specifics of the thermal field in the objects of a particular geometry and the influence of fluid dynamics on the heat transfer.

We propose a method of estimating the proportion of the laser radiation energy absorbed in the laser aided metal deposition with powder injection. For this purpose, a comparison and the mutual supplementation performed of the results obtained by optical pyrometry and numerical simulation. Numerical simulation is used to recreate the structure of thermal field and heat flows in the material. The final structure is obtained based on the formation of deposited bead and heat transfer features in it, as well as taking into account the formation of the molten pool and convective heat transfer. According to the optical pyrometry data the binding of calculated 3D temperature field is performed, as well as its correction using the experimental data of the temperature dynamics in a number of spatial regions.

Numerical simulation performed using the finite volumes method on unstructured hexahedral mesh. The numerical model takes into account a scanning exposure to laser radiation and the injection of metal powder. It describes the effects of surface capillary forces, thermocapillary convection, molecular and convective heat and solute transfer, melting-solidification phase transition. We also measured experimentally the dynamics of the local thermal emission of the melt and solidified metal during the exposure to focused laser radiation of 1.8 kW CO2 laser in the process of the laser aided metal deposition with gas-powder jet. The temperature was measured in five areas of the surface of the deposited bead from its center to the boundary with the substrate using the multichannel pyrometer of spectral ratio. The dependences of the temperature variations on the scanning velocity, the laser power and powder flow rate are obtained. The possibility of the surface temperature monitoring over the metal powder jet using a spectral ratio pyrometer is shown. The results of adaptation of calculated thermal field using experimental measurements are shown.

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10330-57, Session PS2

Detection of nanoparticle changes in nanocomposite active sample using random laser emission

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Multiple-scattering of light in disordered medium is a very common phenomenon in some optical experiments. But, in many applications, multiple-scattering is often an undesirable effect. However, in the past decade, nanophotonics shows that multiple-scattering in disordered nanocomposite can enable new functionalities, including the unexpected property of random lasing or light localization. In random lasers resonant cavities are self-formed due to multiple scattering, while, conventional lasers consist of optical cavity for the system to lase. In other words, a random laser is a multiple-scattering-induced laser which does not use any optical resonant cavities [1]. Also, disorder-induced scattering can provide intensity feedback or amplitude feedback, depending on the nanostructures size, which range from a few nanometers to several hundreds of nanometers. In the recent years, different disordered nanostructures such as laser dye in colloidal systems, photonic crystals, polymeric matrices, rare earth doped nano powders, quantum dots, semiconductors, and biological tissues have been reported as high-performance random lasers [1, 2].

In other hand, since spectral property of random laser emission is unique, it can be detectably altered when introducing nanoscale changes to a nanocomposite. In other words, random lasing process amplifies the perturbations to easily detectable spectral change in multiple emission peaks. Also, straightforward and large-area detection, ultra-sensitivity and simple spectroscopy setup are the advantages of using random laser principle for change detection [2].

In this work, a simple method is introduced for estimating the number of the nanoparticles in an active sample based on random laser theory. The sample includes nanoparticles which are distributed randomly. Random laser action can occurs when the sample is pumped optically because of multiple scattering. Here, one-dimensional random laser system is considered and the sample changes are added to the system by changing the number of layer or size of layer. The spectral emission of the sample is calculated by transfer matrix method [3]. In the next, the statistical behavior of output emission spectrum is achieved by calculation the averaged spectrum from many random realizations [3]. The results of simulation shows that change in the number of nanoparticles (or in the averaged size) can be estimated from the statistical random laser output emission and averaged lasing wavelength. This proposed method is fast, non-contact, and needs to a simple setup. Also, it can be used for biological and chemical medium for analysis of different parameters which effect on the spectral random emission.

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10330-58, Session PS2

Modeling of nondestructive method for doped semiconductor layer diagnostics

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The goal of the work is modeling and development of nondestructive method for the doped semiconductor layer diagnostics and measurment of the impurity levels depth relatively to the conduction band. To carry out diagnostics for materials with a high linear absorption there is required a method allows to measure material characteristics on the surface layer. To solve this problem was chosen reflected degenerate four-wave mixing technique. Nonlinear response increases dramatically in the case of the resonant excitation of electron-hole transition of semiconductor. Reflected degenerate four-wave mixing has been discovered in the case of one-photon resonant excitation of the excitons (electron – hole transitions) in the model atomic-like model – quantum dots (QDs) CdSe/ZnS (highly absorbing colloidal solution) by powerful beams of mode-locked laser with picosecond pulse duration. Formation of the beams in forward direction can be explained both self-diffraction of the input beams on the induced one-dimensional photonic crystal (induced diffraction grating) and by degenerate four-wave mixing. Backward direction beams formation can be explained only by degenerate four-wave mixing.

Along with two beams at the output of the cell with colloidal QDs, which retained the propagation directions of the two input beams I0 crossed in the cell at an angle ?, we discovered beams with intensity I±1 in forward direction and I±2 in backward direction for one-photon resonant excitation of the fundamental exciton transition in CdSe/ZnS QDs (Fig.1).

The self-diffraction of the beams I0 occurs on induced dynamic photon crystal (transient diffraction grating), whose period is , (?=35°). The beams I±2 are formed due to four-wave mixing in backward direction [1].

The angles in forward direction (I±1) and backward direction (I±2) beams were calculated (?1=?2=?3=?4≈64°).

Passed through the highly absorbing colloidal solution of QDs CdSe/ZnS (Fig. 1) laser beams holding the direction of their propagation created typically for Fresnel diffraction at a circular aperture the diffraction rings. The observed diffraction rings can be explained by self-diffraction of laser pulses from their induced transparency channels [2].

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10330-59, Session PS2

Theoretical investigation on multilayer nanocomposite-based fiber optic SPR sensor

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In the past decades, huge investigations were done on various sensing techniques, which employed for real-time and accurate measurement of physical, chemical and biochemical parameters. Among different techniques, Surface Plasmon Resonance (SPR) is a very sensitive technique for determining refractive index variations at the interface between a metallic layer and a dielectric medium. Since, the SPR effect has been widely used as a detection principle for many sensors in different applications, such as bio and chemical sensing [1].

Also, fiber-optic sensors have been utilized in different fields for detecting very small amounts of chemical, gas and biological material. Using optical-fiber as sensor presents many well-known advantages such as reduces the cost and size, and increased the sensitivity for both labeled and label-free methods [2].

By using SPR sensor principle in optical fiber, plasmonic optical fiber sensor was introduced. In this kind of SPR sensor, bulky prisms and microscope systems are replaced by optical fiber with metallic coating to probe SPR. This allows remote and real-time sensing and has the potential for measurement in wide variety environments [3].

In this work, a multilayer nanocomposite based fiber optic SPR sensor is considered and especially designed for CO2 gas detection. This proposed fiber sensor consists of fiber core, gold-silver alloy and the absorber layers. The investigation is based on the evaluation of the transmitted-power derived under the transfer matrix method and the multiple-reflection in the sensing area. In terms of sensitivity, the sensor performance is studied theoretically under various conditions related to the metal layer and its gold and silver nanoparticles to form a single alloy film. Effect of additional parameters such as the ratio of the alloy composition and the thickness of the alloy film on the performance of the SPR sensor is studied, as well. Finally, a four-layer structure is introduced to detect carbon dioxide gas. It contains core fiber, gold-silver alloy layer, an absorbent layer of carbon dioxide gas (KOH) and measurement environment. Lower price and size are the main advantages of using such a sensor in compare with commercial (NDIR) gas sensor. Theoretical results shows by increasing the metal layer thickness the sensitivity of sensor is increased, and by increasing the ratio of the gold in alloy the sensitivity is decreased.

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10330-60, Session PS2

Application of the graphics processor unit to simulate a near field diffraction

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For many years, computer modeling program used for lecture demonstrations. Most of the existing commercial software, such as Virtual Lab, LightTrans GmbH company are quite expensive and have a surplus for educational tasks capabilities. The complexity of the diffraction demonstrations in the near zone, due to the large amount of calculations required to obtain the two-dimensional distribution of the amplitude and phase. To date, there are no demonstrations, allowing to show the resulting distribution of amplitude and phase without much time delay. Even when using Fast Fourier Transform (FFT) algorithms diffraction calculation speed in the near zone for the input complex amplitude distributions with size more than 2000 ? 2000 pixels is tens of seconds. One of the ways of increasing the speed of the FFT calculations is using the graphics processing unit (GPU) instead of CPU. The FFT algorithm, is implemented on an NVIDIA GPU using their general-purpose computing platform called the Compute Unified Device Architecture (CUDA). To solve the problem significantly reduce calculation speed we have developed a set of software modules that use different algorithms for calculating diffraction in the near field. Our program selects the appropriate propagation operator from a prescribed set of operators including Spectrum of Plane Waves propagation, Rayleigh-Sommerfeld propagation (using convolution) and Fresnel propagation. The selection is based on estimating both, the deviation of the propagation operator and its numerical effort. The selection is based on finding a compromise between numerical accuracy and numerical effort required for computing the propagated field. The primary criterion for selecting the operator is that the deviation must not exceed a certain fraction of the total energy of the field. After implementation we made a comparison between the speed of phase retrieval process of series of images made on GPU and CPU, showing that using GPU for calculations diffraction pattern in near zone does increase the overall speed of algorithm for an image of size 2048?2048 sampling points and more. The calculations demonstrated 2D amplitude and phase distribution. Further demonstrates the color pattern of intensity, the color of which is determined by the wavelength.

The modules are implemented as separate dynamic-link libraries and can be used for lecture demonstrations, seminars, self-study of students and in solving various problems such as the phase retrieval task.

10330-61, Session PS2

Comparison of interpolation and approximation methods for optical freeform synthesis

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Nowadays freeform optical surfaces are becoming dramatically popular for both imaging and illumination applications. Complex shapes of these surfaces provide a number of benefits, e.g. energy consumption reduce in the lighting systems, weight reduction of a device, field of view increase, improvement of rendering performance, decrease of optical aberrations. This paper presents a comparison of the mathematical techniques of interpolation and approximation used for the synthesis of optical freeform surfaces. The following methods for the synthesis of the freeform surface were used: spline interpolation of different orders, cubic spline interpolation based on the surface normals calculated with the SMS-method, Lagrange polynomial interpolation, Newton polynomial interpolation, approximation with algebraic polynomials of a given degree, two-parameter splines.

The advantages and disadvantages of each method are considered. Possibilities to apply the reached results in the optical design commercial software, e.g. Zemax, are shown.

In order to simplify the study of applicability of each method a special program tool has been developed. This program is purposed to obtain an information suitable for the studied method analysis such as calculation accuracy and visual representation of results. In general this information is subjective to each method.

In the case of cubic spline interpolation the result of the program is to calculate the coefficients of the third order polynomial for each segment. To give a visual assessment of how the polynomials describe an optical surface all polynomials are displayed on the same graph. After analyzing the cubic spline interpolation with different input data, it was concluded that the splines are of limited accuracy and usefulness in high precision optical design. However, cubic splines can be used for mathematical description of non-standard surfaces that do not require high precision manufacturing, and used mainly in nonimaging optics. To obtain a higher order of continuity it is possible to use the polynomials of higher orders with fewer segments. The advantage of two other ways to describe freeform surfaces - Lagrange polynomial interpolation and Newton polynomial interpolation - is the presence of a single equation that describes all of the given points.

However, due to the fact that with large input samples the smoothness of the functions is also great, studied polynomials give high interpolation error, especially near the extreme values of the input sample of points. That is unacceptable in the optical design. Cubic spline interpolation based on the surface normals calculated with the SMS-method is applicable due to the fact that additionaly to coordinates of points on the surface the angles of normals to the wavefront are also used as input data. Therefore, the challenge is in the spline synthesis, which is besides connection of all points would be perpendicular to the normals at these points.The results of the program is to calculate the coefficients of the third order polynomials which are perpendicular to the wavefront at the appropriate points.

For visual evaluation of the spline interpolation results and the normals are displayed graphically.

To solve the approximation issue an algorithm was implemented, which aims to find a polynomial that approximates best the original data. The criterion according to which there is a selection of the most suitable polynomial is an average approximation error.

In order to evaluate the results graphically, the construction of the three polynomials occurs with the lowest average approximation error. The approximation errors are also obtained as the output data.

For the synthesis of the optical freeform surfaces the bi-splines can be used. In this paper the most popular bilinear, biquadratic and bicubic splines are considered.

The result of the program is the the 3D graph construction. This interpoilation type is the most interesting, since the result is a freeform surface.

10330-62, Session PS2

Active mark image modelling in distributed optical measuring systems

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Active marks are widely used in measuring systems for univocal identifying the objects of interest from the background and object coordinate estimating in the difficult observation conditions. In distributed opto-electronic measuring systems active marks mounted on the sensor housing can be used as an anchor points in coordinate transformation from the local coordinate system of a single sensor to global coordinate system. Metrological quality of coordinate estimation strongly depends on the proper selection of the active mark geometry parameters and the characteristics of its radiating elements. At the same time, determination the optimal active marks parameters cannot be performed without optical sensitivity calculations.

This paper presents the techniques of modeling the active mark image through the optical system of the camera. Results of comprehensive study of the influence of various optical system aberrations on the resulting active mark coordinate estimation error. The influence of the mark radiating elements parameters in various viewing conditions to the signal-to-noise ratio are shown. The spatial coordinates errors, depending on the relative position of the active mark and measuring sensor are calculated.

Research described in this paper was done as a part of research and development of swarming visual sensor network for multiple object tracking. This article may be useful in the development of distributed optical-electronic systems, photodetectors characteristics determining, as well as object coordinate estimation algorithms development.

10330-63, Session PS2

Graphene-based multimode interference coupler as an optical sensor based on nonlinear modal propagation analysis

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The objective of this study is to propose and introduce nonlinear modal propagation analysis (NMPA) method being a viable way to study the application of graphene based multimode interference (MMI) coupler as an optical sensor. The purpose of using graphene in this study is because of its high conductivity and transparency as well as having a small bandgap due to its thin layer. The graphene based sensor can be tuned for highest sensitivity in wavelength and refractive index to detect and determine the optical properties such as the refractive index of the sample. Graphene will act as the core of the sensor which will be placed on top of the sample. The input waveguide will pass through the sensor and the output will react accordingly to the sample refractive index. The refractive index value can be obtained by observing and analyzing the change in the output facet of the sensor. The result also shows that the sensor has high sensitivity due to the usage of graphene and nonlinear region.

10330-64, Session PS2

Modeling on guide star beacon generated by bessel beam for wavefront sensing

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Bessel beam is the important member of the family of non-diffracting beams and has the advantages of reducing scattering artefacts and increasing the quality of the image and penetration. This paper proposed to generate a guide star by Bessel beam, and use the beacon with special spot structure to measure the atmosphere turbulence aberrations. But the energy of Bessel beam generated by tranditional methods is not enough high for long distance propagation, especially in application of laser guide star. Using optical engineering technologies of phase locking and coherent combining, a method of generating high energy Bessel beam is proposed. The Bessel beam of Na wavelength laser was transmitted through atmosphere to generate a ring spot in sodium layer as an artificial guide star. The wavefront sensor use the echo wave from this beacon to measure the atmospheric turbulence aberrations. With the matching algorithm of measured characteristic spot in each subaperture, the detection accuracy of Hartmann wavefront sensor can be improved.

Based on wave optics theory, the modeling of Bessel beam guide star sytem and wavefront sensing system were built. An annular array of 20 Gaussian beams with discontinuous piston phases as a whole vortex phase forming a second-order Bessel-Gaussian beam were simulated by source model. The coherence beam array was propagated through 10 atmosphere turbulence phase screens in simulation system. The spot intensity generated by this Bessel beam in sodium layer was determined by the distribution of sodium concentration. The profile of sodium distribution was according to Gaussian in the model. The echo wave from spot was measured by Hartmann wavefront sensor. The spot in each subaperture of Hartmann wavefront sensor remained the structure characters of Bessel beam guide star. By using the matching spot structure algorithm of centriod calculation, the detection error of Hartmann vavefront sensor can be reduced. Compared with the results measured by echo wave from Gaussian beam generated guide star beacon in the same simulation system, this novel method showed an advantage of high detection accuracy of Hartmann wavefront sensor even with different noises been considered.

10330-65, Session PS2

Phase retrieval technology within a single shot using multifocal lengths chromatic aberration system

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Full-aperture non-interference phase retrieval system, namely one single shot, can overcome the impact of low Signal-to-Noise ratio in the condition of weak illumination by extended beacon. Contributing to its robustness and practicability, the technology has been widely applied in industrial inspections. However, this technology is limited by the operational speed and the accuracy of the phase retrieval algorithm in most situations. In this paper, we proposed a new fast phase retrieval method by capturing three high resolution images of the beacon within a single shot, utilizing resolution algorithm to solve the problem mentioned above. The system consists of a specially designed chromatic aberration lens, whose focal length is distributed over three spikes in the wavelength, and a 3CCD camera, in which three CCDs have been precisely tuned to fully conjugate by a specially designed dispersion prism whose coating ensures that the spectra received by each CCD do not overlap each other. In this way, we can get three full-frame images with various focal lengths by only once photographing of the extended beacon in uniform illumination conditions. The phase resolution algorithm used is derived from phase space optics. In the four-dimensional phase space formed by spatial-spatial frequency, the phase of the quasi-coherent light field from small view field extended beacon is equal to the convolution of the partial differential of the difference value of the three intensities with respect to the rotation angle of the phase space and the sign function, the detailed proof process is given in the third part of the paper. The numerical simulation results show that the method can accurately recover the aberration of more than 20 orders, with the RMS value below 0.4 wavelengths. At the end of the paper, the details of the experimental results are introduced, and meanwhile the error sources and the further improvement measures are discussed at length.

10330-66, Session PS2

Experimental study of diffraction fields from fractal amplitude-phase objects

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This paper deals with experimental study of diffraction fields from amplitude-phase fractal objects. Study of diffraction fields from fractal objects is a subject of great interest from two points of view. First, some information on the physical properties of fractal objects may be extracted from diffraction distributions, such as fractal dimension and scaling factor. Second, the diffraction on fractal objects may create new wave front types which may lead to development of new optical elements with enhanced characteristics. It is well known that diffractals differ essentially from wavefronts diffracted from simple geometrical objects. The principal one is that the optical fields derived from fractal exhibit self-similarity properties as same as initial objects. The majority of papers is devoted to modelling of diffractals in connection with difficulties in experimental set. In our previous works we presented the modelling results of diffraction from fractal objects. It was shown that diffraction spectrum of amplitude-phase type fractal screens possess prevailing power of high frequencies in comparison with spectra of fractal structures with binary transmittance and phase shift. We also propose the method of fractal dimension estimation by diffraction distribution processing. In this method for the calculated diffraction pattern was determined the dependence of the intensity of the distance to the center of the diffraction pattern. Average intensity for each radius was calculated as the sum of the intensities of the pixels located within a ring and normalized to the area of this ring. The thickness of the rings in the limit minimized, which allowed us to obtain one-dimensional radial function of intensity I(r). Next, a graph of the average intensity of the coordinates plotted in the double logarithmic scale. The slope approximated I(r) determine the fractal dimension of the original structure.

In this work we present the experimental results of far field diffraction from amplitude-phase fractal objects. Amplitude-phase fractal objects based on well-known fractals, possessing managed amplitude transmittance and phase shift, were realized by means of two spatial light modulators (SLMs). It is shown that the averaging scattering indicatrices, obtained from modelling and experimental results are in a good agreement and amplitude-phase objects possess prevailing power of high frequencies in comparison with spectra of separate phase or amplitude fractal.

The method of fractal dimension estimation is experimentally verified in examples of Serpiensky carpet, Vischek fractal and Koch snowflake. It is shown that measurement accuracy heavily depends on intensity registration format. Fractal diffraction patterns are characterized by a large range of intensities, therefore, in experiment the digital camera with dynamic range in 16384 intensity units was used, and result patterns was saved in RAW file format. For error reduction the procedure of processing RAW images is described. Obtained in experiment results allow to use this method in estimation of fractal dimension of real object, for example, thin transparent films.

It is well known that majority of natural objects demonstrate fractal properties. Polyolefin films – such as polypropylene (PP) are the very promising commercial polymers due to their wide-spreading and easy manufacturing. Owing to high chemical resistance to various media, they are widely used as membrane materials in medical, chemical, and food industries. Preliminary studies of the films structure using electron and optical microscopy lead to the assumption of the existence of different-scale self-similar elements. For testing of this hypothesis diffraction spectra from polyolefin films were investigated. Using a developed technique the fractal dimension of the porous film of polypropylene was estimated.

10330-67, Session PS2

Improvement of the method of optical testing of fast aspherical surfaces with null-screens

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We extend the principles of the null-screen method for testing fast aspheric surfaces with polynomial expansion. We present the formulae to design the null-screen in such a way that the image on the CCD is a perfect array circular points; the departures of the surface from a perfect shape are observed as deformations of the array in the image. For the testing of fast aspherics with polynomial expansion, we propose some geometrical configurations. In addition, we perform an analysis of the deformations of the image of the null-screen reflected by the testing surface due to the slop defects of the surface. Experimental results for the testing fast aspherics are shown. The main advantages and the limitations of the method will be discussed

10330-68, Session PS2

Increase in the measurement of the normal vectors of an aspherical surface used in deflectometry

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In order to know the profile of an aspherical surface, we propose to use the method of optical deflectometry that uses the normal vectors to each point of the surface. These normal vectors are determined using the vectors associated with the refracted rays by the plano-convex aspherical lens. In order to increase the precision of measurement of the normal

vectors associated with the refracted rays, we propose implement a ray selector placed in different planes along the optical axis after the exit pupil of the lens under test and a CCD camera with A=2048 x 1536 ppx of 3.2 μm,located at a fixed distance after the focal point of the lens. The only restriction is do not making measurements in the caustic zone. In the proposal test used a spherical reference wavefront, also is considered on the flat side of the aspherical lens. The ray selector is a LCD with A= 1024 x 768 ppx of 36μm each pixel, where the transmittance of the liquid crystal display changes for each pixel, and thus the refracted rays are selected. With the processing of the obtained images, we have the initial position of the refracted ray and the position that reaches the detector, and thus we can find the slope associated with the refracted ray. The increase in accuracy of the test will be analyzed when we having 2,3 and 5 LCD measurements positions. The preliminary qualitative and quantitative results are presented with advantages and disadvantages of the method.

10330-69, Session PS2

Interband and intraband optical light absorption in quantum dash systems

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The electronic structure and optical properties of the semiconductor quantum dots (QD) have been in the spotlight of researchers in recent years thanks to the rapid development of fabrication technology. QDs are thought to have vast potential for future technological applications in fields of quantum computing and information as a possible application in many areas of quantum dot based optoelectronic devices of the new generation.

Modern precise technologies allow growing spherical, cylindrical, lens-shaped, ellipsoidal and ring-shaped QDs, etc. QDs with highly elongated truncated prism geometry (so-called quantum dashes) have been obtained recently. The change in the geometry of the InSb Nano islands from a quantum dot to a quantum dash was observed depending on the growth conditions. Thus, the authors reported on the implementation of the InSb quantum dashes by metal-organic vapor phase epitaxy. At the same time, the narrow emission bands associated with the formation of electron-hole pairs in a single quantum dash were discovered. The problem of describing the charge carriers behavior in such system was discussed in, where the authors investigated optical properties based on the proposed theoretical model of the quantum dash and showed a fortunate coincidence of theoretical calculations with the experimental results. It is noteworthy that the quantum dashes were approximated by strongly flattened truncated prisms and the effects induced by mechanical strain were not taken into account. On the other hand, recent experiments of the fabrication of the quantum dashes were presented in. Here it has been shown the possibility to fabricate vertically disposed quantum dashes with a small width. The length of one side of quantum dash is much smaller than the two other sides. Optical properties of prism-shaped quantum dashes ensemble have been studied in the framework of the adiabatic approximation. The analytical expression for the electron energy and wave function in all three regimes: strong intermediate and week of size quantization in prism-shaped quantum dash have been obtained. The selection rules for quantum transition have been revealed. The dependence of interband and intraband light absorption coefficient on the incident photon energy for different values of mean quantum dash height has been investigated. The size dispersion of quantum dash ensemble has been taken into account.

Therefore, in this paper, we will concentrate on the investigation of interband and intraband optical absorption of prism-shaped quantum dash ensemble all three (strong, intermediate and week) size quantization regimes.

We will consider an ensemble of quantum dashes and dispersion of their sizes. Note, that this dispersion will lead to broadening of spectral lines. The main effect on broadening will be caused by dispersion of the height of the quantum dash. As it is known, the process of formation of quantum nanostructures is associated with the recondensation process. During the growing process of QD's ensemble, depending on the technological parameters of the growth, symmetrical or asymmetrical distribution of the QD geometric parameters may occur. In this paper we will use Lifshits–Slezov distribution, where distribution variable is the ratio of dispersion parameters to their average values. As the effect of the size dispersion of the quantum dash height is dominant, than the effect of the size dispersion of the other geometrical parameters will be neglected.

10330-70, Session PS2

Design optimization of a refractive index sensor based on optical micro-ring resonators

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Optical ring resonators are interesting optical devices with a plethora of applications especially in optical switching [1-4], routing [4-7], and sensing [8-10]. An optical ring resonator usually consists of a straight waveguide coupled to a circular one, or two straight waveguides coupled through a circular one.

It can be shown that, in both cases, the relative change in the resonant wavelength is equal to the relative change in the effective refractive index. Consequently, the sensitivity of the system as a refractive index sensor is proportional to the quantity which describes the dependence of the effective refractive index of the system on the refractive index of the environment.

In this work we provide design guidelines in order to maximize the sensitivity of the system. In more detail, based on a result of waveguide perturbation theory stating that the change in the effective refractive index of the propagating mode due to a refractive index change in some part of the waveguide is proportional to the fraction of the mode power in this specific part of the waveguide, we calculate the optimum dimensions of the waveguide maximizing the sensitivity of the system as refractive index sensor. It is found that, when optimally designed, the system can detect relative refractive index changes of the order of , assuming that the experimental setup is able to resolve relative wavelength shifts of the order of . The performance of the systems as bio-sensor has also been examined. It is found that, when optimally designed, the system can detect refractive index changes of the order of for a layer thickness of , and changes in the layer thickness of the order of , for a refractive index change of .

10330-71, Session PS2

Errors in the estimation method for the rejection of vibrations in adaptive optics systems

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In recent years the problem of impact of mechanical vibrations in adaptive optics (AO) systems has been renewed. These signals are damped sinusoidal signals and have deleterious effect on the system. One of software solutions to reject the vibrations is an adaptive method called AVC (Adaptive Vibration Cancellation) where the procedure has three steps: online estimation of perturbation parameters (amplitude, frequency and phase), online estimation of the frequency response of the plant, update the reference signal to cancel or minimalize the vibration. In the first step a very important problem is the estimation method.

A very accurate and fast estimation method of these three parameters has been presented in several publications in recent years. The method is very universal because it can be used to estimate multifrequency signals (the sum of many sinusoidal signals). The method was developed for a photovoltaic system connected to the grid where there is also a problem to estimate a signal (grid signal) distorted by harmonics and noise in short time (below 10 ms). In this paper the estimation method is used in the AVC method (in the first step) to increase the system performance.

The estimation method is based on using the FFT (Fast Fourier Procedure), the 3-point spectrum interpolation and Maximum Sidelobe Decay time windows. There are several parameters that influence the accuracy of obtained results: CiR (Cycle in Range) – the number of signal periods in a measurement window, N – the number of samples in the FFT procedure, H – the time window order, SNR (Signal to Noise Ratio), THD

(Total Harmonic Distortion), b – the number of A/D converter bits in a real time system, ? – the damping ratio of the tested signal, ? – the phase of the tested signal. Systematic errors increase when N, CiR, H decrease and when ? increase. Random errors decrease when SNR, b increase and when H, ? decrease. The value for systematic error is approximately 10^-7 Hz/Hz for N = 64, CiR = 1.5 and H = 2. The value of the eMSE (empirical Mean Squared Error) of the frequency estimator is approximately 10^-4 Hz for SNR = 80 dB, H = 2, N = 256 and CiR = 1.8. The value of systematic error for ? = 0.1%, CiR = 1.1, N = 32 and H = 3 is approximately 10^-4 Hz/Hz. This paper focuses on systematic errors. It presents equations that can used to estimate maximum errors for given values of H, CiR and N of amplitude, frequency and phase estimators before the start of the estimation process. It is very useful from a practical point of view.

This paper presents the fast and accurate method to estimate frequency, amplitude and phase of vibrations in AO systems. The method in not computationally complex and can be used in the cancellation method to improve its performance.

10330-72, Session PS2

Removing damped sinusoidal vibrations in adaptive optics systems using a DFT-based estimation method

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The problem of a vibrations rejection in adaptive optics (AO) systems is still present in many publications. These undesirable signals emerge because of shaking the system structure, the tracking process, etc., and they usually are damped sinusoidal signals. There are some mechanical solutions to reduce the signals but they are not very effective. One of software solutions are very popular adaptive methods. An AVC (Adaptive Vibration Cancellation) method has been presented and developed in recent years. The method is based on the estimation of three vibrations parameters and values of frequency, amplitude and phase are essential to produce and adjust a proper signal to reduce or eliminate vibrations signals.

A novel estimation method of multifrequency signals has been presented in recent years. It was developed for a control process in photovoltaic systems but it can be also used in many other fields of science and technology. The method was tested for the grid signal, which is the special case of a multifrequency signal distorted by harmonics and noise. The method is very accurate and fast (the estimation time can be even below 10 ms) and can be used in the AVC method to increase the AO system performance.

The parameters are estimated in the frequency domain and the method is based on using the fast Fourier transform procedure, the spectrum interpolation, and I class Rife-Vincent time windows. The method accuracy depends on several parameters: CiR (Cycle in Range) – the number of signal periods in a measurement window, N – the number of samples in the FFT procedure, H – the time window order, SNR (Signal to Noise Ratio), THD (Total Harmonic Distortion), b – the number of A/D converter bits in a real time system, ? – the damping ratio of the tested signal, ? – the phase of the tested signal. Systematic errors increase when N, CiR, H decrease and when ? increase. Random errors decrease when SNR, b increase and when H, ? decrease. The value for systematic error is approximately 10^-13 V/V for N = 32, CiR = 1.5 and H = 7. The value of the eMSE (empirical Mean Squared Error) of the frequency estimator is approximately 10^-5 Hz for SNR = 90 dB, H = 2, N = 256 and CiR = 1.7. The value of systematic error for ? = 0.1%, CiR = 0.5, N = 32 and H = 3 is approximately 10^-3 rad. Using additional digital band-pass filters improves the estimation accuracy. This paper focuses on the signal phase impact on the results and the impact of the damping ratio for various values of measurement parameters.

This paper presents the fast (the method is not computationally complex) and accurate method to estimate frequency, amplitude and phase of damped sinusoidal vibrations, that can be found in optics systems. The method in not computationally complex and can be used in the AVC method to improve its performance.

10330-33, Session 9

Role of coherence in microsphere assisted nanoscopy *(Invited Paper)*

Stéphane Perrin, Audrey Leong-Hoi, Sylvain Lecler, Paul Montgomery, ICube (France)

In optical microscopy, the diffraction of electromagnetic waves limits the resolving power. The optical aberrations generated by the components also play a crucial role in the ability to separate two adjacent objects. Assuming a coherent light source and a circular pupil, the lateral resolution of an optical microscope can thus be quantified by the cut-off frequency of the amplitude transfer function or coherent frequency transfer function. This ability for an optical system to reproduce the image of a continuous sinusoidal object at a specific frequency is defined as the ratio between the wavelength and the numerical aperture of the microscope objective. Hence, in air, the lateral resolution cannot be smaller than lambda. For example, at a wavelength of 500 nm and with a NA of 0.55, the imaging system can resolve objects down to a size of 900 nm, but no smaller.

Several far-field methods, based on stimulated-emission-depletion or the use of a negative refractive index lens, have been developed in order to overcome this limitation. Nevertheless, these methods cannot be applied to the full-field imaging. In 2004, a new potential far-field microscopy technique at sub-wavelength resolution using a microsphere was proposed. Six years later, the first experimental results of this microsphere-assisted super-resolution technique were reported opening new possibilities for high resolution characterization in nano-structures. When a microsphere is placed on top of a sample, a magnified and virtual image of the object occurs under the plane of the object. Using white light illumination, this full-field imaging technique achieved a lateral resolution of 50 nm. Several hypotheses exist to explain this imaging process including the photonic jet phenomenon. When an incident wave interacts with a dielectric microsphere, the light is scattered in the far-field. Whereas in the near field, the same light may be highly concentrated at low distance of the microsphere i.e. less than the wavelength. Depending on the geometry and the material of the microsphere, the wavelength of the illumination, and the immersion media, the radiated power density can be concentrated more than 200 times with a low divergence. Furthermore, the beam emerges from the microsphere with the particularity of having a sub-wavelength width. Hence, reciprocally, a microsphere should image a sample with a sub-wavelength resolution.

In the present work, we have numerically analyzed the phenomena of super-resolution through a 2D model with a finite element method. The virtual image of two-point light sources placed under a glass microsphere were simulated and the magnification, the axial position of the imaging plane and the lateral resolution were determined according to geometrical and optical parameters. For a wavelength of 600 nm, a refractive index contrast of 1.42 and a microsphere diameter of 4 μm, the magnification is 4.5 and the lateral resolution is 100 nm, i.e. lambda / 6. Moreover, the results of this numerical analysis show that it should be possible to attain a lateral resolution of 70 nm by combining a microsphere with a diameter of 5 μm and a refractive index of 1.9, with a water immersion objective. This result has been obtained by simulating a coherent light source with a wavelength of 400 nm, leading to a lateral resolution of lambda / 6. In addition we also investigated the impact of the coherence on the imaging quality. The results show that two out-of-phase point sources, spaced laterally 300 nm apart, yield two diffraction patterns which can be clearly distinguished, whereas two in-phase point sources are not observable. Furthermore, we demonstrate that the phase could concurrently be exploited to quantify the third dimension.

10330-34, Session 9

Optimizing image-based patterned defect inspection through FDTD simulations at multiple ultraviolet wavelengths *(Invited Paper)*

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Accurate inspection of pattering defects is critical to the semiconductor manufacturing process. Challenges arise as the “critical dimensions” (CDs) of the device structures decreases with improved photolithographic approaches. At the current 14 nm manufacturing node and below, the reductions in CD and also in the pitch between pattered features are allowing previously unimportant patterning imperfections to have direct impacts upon the viability of devices. As state-of-the-art devices are manufactured on 300 mm diameter Si wafers, only optics provides the relatively low-cost, non-destructive, and high-throughput solutions required for defect inspection. Specifically, optical methods are used to pinpoint the location of a defect, while scanning electron microscopy can then be used for defect review.

However, it is well-understood in the industry, as shown in the literature [1], that with decreased dimensions, these “killer” pattered defects will scatter far less light thus complicating inspection. Comparisons have been made in the literature between the scattering off deep-subwavelength-sized defects and the scattering off spheres, the latter of which can be analytically solved using Mie’s Theory. This theory reduces to the Rayleigh approximation, for a particle with diameter d << ?, the inspection wavelength. For the Rayleigh approximation the scattered intensity I scales as I ? d^6*?^(-4). Defect scattering is not directly analogous to the scattering from spheres as the intended patterning and substrate also scatter and reflect light as well. However, using this approximation, simple reductions of wavelength hold promise for increases in detectability and state-of the art techniques now use wavelengths as short as ? = 190 nm.

Therefore, in this work, a series of simulation studies is presented that explores the role of wavelength in optimizing defect detectability. In addition, as with our prior work [2-3], the roles of incident angle and polarization are also explored as well as wafer noise arising from line-edge roughness. Publically disclosed information regarding modern device fabrication has been integrated into an intentional defect array previously defined by SEMATECH. Optical constants as functions of wavelength were determined from the literature. Dimensions were decreased to allow for arrays of 8 nm CD Si fins with additional conformal coating. Simulations were performed with and without line-edge roughness to realistically assess “wafer noise” due to the roughness as functions of wavelength, incident angle, and polarization.

Images were simulated for the no-defect case and following the nomenclature from SEMATECH, for orthogonal bridge directions (“Bx”,”By”). “Bx” joins two fins end-to-end while “By” joins two parallel lines with a perpendicularly oriented bridge. Differential images are formed by subtracting an image with a defect from an image without a defect. These differential images are analyzed to assess defect detectability. Our most preliminary data includes differential images with no wafer noise from LER from two VUV wavelengths (122 nm, 157 nm) as well as ? = 193 nm as a benchmark. In the absence of any noise, all three wavelengths show scattering due to the defect. From qualitative observation, the data demonstrate an increase in defect detectability as the wavelength decreases.

This work explores how further reductions in wavelength affect the detectability with the inclusion of LER, using quantitative defect metrics designed to maximize the distinction between the noise and the defect signal. These defect metrics harness increases in the scattered intensities while accounting for the reduction in scattering area with wavelength. Factors affecting the rates of false positives and false negatives are discussed. Optimizations in linear polarization, and incident angle for defect inspection are to be considered for each wavelength. Strategies for optimizing defect metrics at reduced wavelengths are discussed as well as the fundamental requirements for realizing effective defect metrology in the VUV.

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10330-35, Session 9

Optical vortex scanning microscope with the simple phase object: theoretical model and its experimental verification

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Resolution in classical optical microscopy is diffraction limited and it is roughly defined by the formula ?/2NA, where ? is a wavelength and NA is a numerical aperture of the microscopic objective. For modern nanotechnology, cell science and medicine this resolution is far too low. For this reason a number of non-classical imaging systems, both optical and non-optical, have been promoted over the last three decades. Despite remarkable success of nonclassical superresolution imaging systems, there still is room for new solutions overcoming the drawbacks of the presently used systems. In a vortex microscope the investigated sample interacts with the illuminating beam that contains an optical vortex. Thus it can be considered as the new microscopic system working with structured illuminati on. We present an analytical model of an optical vortex microscope in which a simple phase sample inserted into the illuminating beam. It has been shown that the beam at the detection plane can be separated into two parts: a non-disturbed vortex part and object beam one. The intensity of the non-disturbed part spreads out over the center, hence the small disturbance introduced by the object can be detected at the image center. Variations in the internal structure of the beam caused by scanning with the sample were analyzed and the procedure for recovering the information about the object from this set-up was proposed. The theory has been successfully verified by the experiment. The measurements were performed in the interferometer setup. In the object arm the conventional gaussian beam passed through the spiral phase plate and was focused on the sample plane, where it interacted with the investigated object. The sample plane was imaged into the CCD camera. The interferometer’s reference arm enabled detection of the interference fringes, from which the internal structure of the object beam was recovered. The interferograms were demodulated following the theoretical considerations allowing to recover size and position of the sample properly.

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10330-36, Session 9

First nanofabrication results of a novel cascaded plasmonic superlens

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With the growing development of nanoscience and technology, the requirement for imaging with improved lateral resolution becomes more and more desired. Conventional microscopy is limited by Abbe diffraction, which is about half of the incident wavelength. As a result, intensive efforts have been devoted to obtaining subwavelength images using specific methods such as structured illumination microscopy, stimulated emission depletion etc. [1-2]. However, most of the well-developed methods need post processing, which leads to increased consuming time to obtain a single image.

To realize an imaging system with a subwavelength resolution without scanning or post-processing, plasmonic superlenses for far-field imaging were suggested [3-4]. Recently, we have designed and demonstrated numerically a subwavelength imaging system of a cascaded plasmonic superlens [5]. The cascaded superlens is composed of two parts: a double layer meander cavity structure (DLMC) used for coupling and supporting the propagation of evanescent waves and a planar plasmonic lens (PPL) used for transferring waves into free space with magnification.

In this paper, we will demonstrate experimentally the imaging property of the cascaded plasmonic superlens, which was fabricated using a focused ion beam (FIB) milling system (FEI Helios NanoLab 600). Before fabricating the whole lens, each part of the cascaded structure was fabricated separately to optimize the fabrication parameters. Optical properties of each part were also characterized to ensure that each behaves as designed. A double-slit structure was used as a nano-object, which was first fabricated on a glass substrate. Then the cascaded lens was fabricated on the top of the nano-object by using a precise alignment procedure of the FIB machine. Challenges concerning the nano-fabrication will be discussed in the paper.

The superlens was characterized using an aerial laser scanning microscope with NA = 1.3, which enables us to measure field intensity distributions in 3D with a position control of several nanometers. An image with a magnification factor of two of a double-slit structure with a distance of 800 nm behind the superlens structure was obtained in the far-field at the wavelength of 640 nm. A very good agreement between the measured and calculated fields was obtained due to the well-controlled nano-fabrication procedure. These results pave the way for further demonstrating the resolving capability of the superlens below the diffraction limit.

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10331-1, Session 1

A novel macroscanner imaging system for collection of multimodal hyperspectral image cubes of Old Master paintings

(Invited Paper)

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A multi-modal imaging scanner able to cover an area up to 1.5 by 1.5 m has been designed and constructed to provide high spatial and spectral resolution image cubes of Old Master paintings. The scanner has linear encoders providing micrometer positional information and can move the artwork across an array of imaging sensors in three different collection modes: raster scan, line scan, and step/stare. The three imaging modalities include optical reflectance imaging spectroscopy from the visible to near infrared (400 nm to 2500nm, few nm sampling), fluorescence imaging spectroscopy in the visible to near infrared using variable excitation light sources, and X-ray fluorescence imaging spectroscopy. The first two imaging modalities provide molecular information and the third elemental information of the materials. Such information provides insight into how the paints were constructed as well as reveals changes made by the artists including the reuse recycling of early paintings. A systems engineering level description of the scanning system will be presented along with findings from examination of paintings by Rembrandt, Van Gogh, and Giovanni Bellini's Feast of the Gods in the collection of the National Gallery of Art, DC.

10331-2, Session 1

Nonintrusive tools to detect salts contamination in masonry: the case study of Fontaine-Chaalis church

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Such developments come from conservation experts in the community of cultural heritage - encompassing artworks, museum artifacts or historical monuments – for less intrusive and non-destructive tools to gain information about the subject. Increasingly the demand is for information regarding internal structures and indications of life histories and behaviours of an object.

As it is well known, the deterioration due to the capillary rise of water through the walls is a very widespread problem. In this paper, a study of Stimulated Infrared thermography and Evanescent-Field Dielectrometry was applied to a non-destructive mapping, in situ, and in a semi-quantitative way the distribution of water, salt and the structural deterioration induced in an wall of the 13th century of the abbey's church of Chaalis. The chapel, located in an ancient Cistercian Abbey in the North of Paris, was built in the 13th century, and has 16th century mural paintings by Primaticcio. Since the 16th century, several interventions (including reconstruction and restoration of the paintings) have been carried out in the chapel and on the mural paintings. A large campaign of restoration work had been implemented by the end of 2005 The complementary of the both techniques will be underlined.

The Stimulated Infra-Red Thermography (SIRT) is a contact free technique and allows the detection of plaster layers delamination of a masonry. First, the analyzed zone is excited with a flux of photons that produce an increase of the temperature of the area. The variation of temperature leads to a variation of the infrared radiation that is visualized through an infrared thermography camera. The photo-thermal signal can be correlated with the following characteristics of the object: aspects of the surface, presence of delamination, presence of cracks, internal structure of the material, progress of a physical and chemical transformation, drying and sedimentation. This technique gives an overview at large scale (metric).

Evanescent-Field Dielectrometry (EFD) is a recent diagnostic method based on dielectric spectroscopy at microwave frequency. The measuring instrument is a portable resonant microwave device for mapping the water content and salinity on flat surface up to a depth of 2–3 cm in real time, in a non-destructive way,. The method detects the water content and salt concentration in frescoes and walls by estimating the dielectric properties of a tested porous materials that is viewed as a "binary" dielectric mixture consisting of bulk material and water, by the contrast between the dielectric constant ? of a dry material (e.g. ? < 4 for mortar, plaster, brick, stone) and water (? approximately 80).

According to the resolution of the optics, the SIRT has a less lateral resolution and more limited in depth, but it is easy to implement and can be used on-site, like in scaffolding conditions. Moreover, this technique gives an overview at a larger scale (metric) than EFD (centimetric).

10331-3, Session 1

Optical characterization of natural protective varnishes and their influences on perception of painted samples

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This research is about optical properties of works of arts materials related to visual appearance: gloss and colour. The definitions and description of both quantities, as well the measurement methodologies were developed by metrologist for reference materials (ceramic tiles for colour and dark glass specimen for gloss) that are not representative of works of art, nor of the condition of observation during exhibition. The prediction of material appearance is of recognized importance in for Cultural Heritage (CH) exhibition, unfortunately literature shows that the measurements of visual properties are not always in fully agreement with subjective assessment of the corresponding perceived quality. This research investigates, for coloured samples representative of painted CH (natural protective varnishes i.e. mastic, dammar gum and wax), gloss and saturation (measured quantities), glossiness and saturation (perceived qualities) and their crossed influences (how gloss/glossiness influences the saturation).

Three different coloured (red, green, blue) scales with seven gloss levels have been realized and fully characterized for gloss (with a glossmeter) and for the spectral BRDF (Bidirectional Reflection Distribution Function) at INRIM. Measured values provided a ranking on G.U. (Gloss Unit) and on C* (CIE parameter for colour saturation) that was compared with the local subjective ranking of sixty people, not visually impaired during a subjective experiment under controlled visual conditions: level of adaptation and geometrical conditions of observation (i.e. direction of lighting and of observation) representative of measurement conditions (incidence 45° and 20° and 30° of observation) and of CH exhibition set-up (incidence 45° and free condition of observation). The experiment was done under two different lighting sources of the same CCT (Correlated Colour Temperature) but different Spectral Distribution (i.e. a Compact Fluorescent lamp and a LED source). The approach followed is based on soft metrology principles.

Results highlighted interdependence between colour and gloss, a well known concept by artists, but not considered in quantities measurement

methods and definitions. Only the geometrical condition at 60° of the three suggested in references (20°, 60°, 85°) for gloss measurement assures the highest uniformity between quantity and quality local ranking, the expected higher sensitivity of the other two conditions to discriminate samples with similar low (or high) gloss is not confirmed, measured G.U. and subjective results suggest influences of sample colour (Gloss definition relies on the specular reflection of a given glass specimen at a given wavelength). For saturation the measured quantity C* is useless for assessing the ranking of perceived saturation when, on the same coloured sample, different gloss levels are considered. Results showed no particular influences of Lighting Spectrum (LED or Fluorescent), proof that available measurement methods take it correctly in account.

To improve the uniformity of measurement values with the perception judgements and accuracy on material visual appearance predictions, metrology must provide a better definitions and measurement methods for gloss as well for saturation. The paper provides some suggestions on how to consider gloss in CH coloured samples as well some criteria for protective varnish selection. Actually protective varnishes are selected based on general criteria related to chemical and mechanical properties and especially reversibility. The results can provide some useful indications to select the protective varnish considering appearance influences as supplementary parameter useful to know.

10331-4, Session 1

Methodology proposal and case studies for diagnostics in cultural heritage by integration of terahertz, HMI, fluorescence, Raman, FT-IR and X-ray, noninvasive analysis

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Analysis in the Cultural Heritage requires increasing demand for information and data about pieces of art.

Particular attention is due to conservation, where a non - invasive approach is preferred. Techniques have been developed to this aim, but none of them is able to cover all aspects of the subject under investigation.

However, the integration of data from different techniques makes it possible to reach a very high level of knowledge. In this study, run by an international team of experts, we propose an integrated multi-analytic approach where a number of techniques have been used in the investigation of artwork case studies. With the Hypercolorimetric Multispectral Imaging (HMI) we analyze the spectral reflectance ranging from 300 nm (UV) to 1000 nm (IR) and we acquire the Fluorescence for each pixel of the surface of the artwork; using these radiometric imaging data, and applying advanced clustering methodologies, each cluster of the image is better characterized with Raman and FT-IR analysis to establish reliable association between spectral response and chemical components of the pigments or inks on the surface. The use of Terahertz analysis, with frequency-wavelet domain deconvolution processing, allowes us to scan both the surface morphology and the substrate structure. The resulting stratigraphy is able to reveal key information about painting layers, substrate morphology and in case of manuscript to try to read writings on hidden faces of not detachable pages, not accessible in any other way. Finally with Xray we identify the global thickness and density. In the study we demonstrate how the use of Terahertz can play similar role of X-Ray for the thickness and can also give equivalent information of raking light. We show as well how spectral and fluorescence analysis and local Raman and RT-IR analysis can be integrated through clustering techniques to obtain highly reliable imaging pigment mapping of the painting. As a result, we demonstrate how integrating techniques that are not only non-invasive but also not dangerous for the health of the operators, it is possible to achieve a complete characterization of the piece of art under investigation. The aim of this work is to propose a methodology and practice that integrates a number of consolidated and emerging noninvasive techniques. Part of this work is also the development of calibration samples and methodologies for each techniques to assure that every obtained measure is reliable and repeatable. All collected imaging data are aligned and registered under a dedicated software tool to integrate them and to allow advanced analysis and correlations and to integrate a dedicated multi-spectral and multi-data database. Along with the methodological description in the work are presented a number of specific case studies focusing on paintings and manuscripts analysis.

10331-30, Session PS2

The hybrid thermography approach applied to architectural structures

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This work contains an overview of infrared thermography (IRT) method and its applications relating to the investigation of architectural structures. IRT is classified among the non-destructive testing methods that can be widely used due to the outstanding advantages that it offers in a number of applications and, specifically, in the assessment of structural materials.

The method has been divided for a long time into passive and active approaches. The first one is usually used in civil engineering, since it provides a panoramic view of the thermal anomalies to be interpreted also thanks to the use of photographs focused on the region of interest (ROI). The second one, is more suitable for laboratory or indoor inspections, as well as for objects having a small size. The external stress to be applied is thermal, coming from non-natural apparatus such as lamps or hot / cold air jets. In addition, the latter permits to obtain quantitative information related to defects not detectable to the naked eyes. Very recently, the hybrid thermography approach has been introduced to the attention of the scientific panorama. It can be applied when the radiation coming from the sun directly arrives (i.e., possibly without the shadow cast effect) on a surface exposed to the air. A large number of thermograms must be collected and a post-processing analysis is applied on via advanced algorithms. Firstly, the thermographic signal reconstruction (TSR) technique is used because with the application of a low-order polynomial function, it approximates the temperature evolution cooling profiles obtained from the raw thermograms. One of the most important features of TSR is that it can be used to obtain time-derivative images, which offer important advantages when compared to raw data. In fact, their use increases the detection sensitivity and reduces, in the mean time, both the effects of non-uniform heating and unwanted reflections. Secondly, the quantitative approach of pulsed phase thermography (PPT) technique based on the fch of the maximum phase-contrast between sound and defects areas, or linked to fb (i.e., the blind frequency) is also applied. Real and imaginary parts of the Discrete Fourier Transform (DFT) can be used to calculate the amplitude and the phase delay of the transform and to reconstruct 3D matrices. It is important to underline that from a sequence of N thermograms, there are N/2 useful frequency components; the other half of the spectra only provides redundant information. Therefore, an appraisal of the defect depth can be obtained passing through the calculation of the combined thermal diffusivity of the materials above the defect. The approach is validated herein by working, in a first stage, on a mosaic sample having known defects while, in a second stage, on a Church built in L'Aquila (Italy) and covered with a particular masonry structure called apparecchio aquilano. In particular, both a lateral side and a part of the rear side of the fa?ade of Santa Maria di Collemaggio Church were investigated. Data were firstly analyzed using the ThermaCAM researcher computer program by FLIR, and subsequently treated in Matlab® environment. In the first case (i.e., the mosaic) the defects are fabricated, while in the second case (i.e., the Church) the defects are natural. In both cases, the results obtained appear promising and reasonable if the rules of manufacture of the time are kept in mind.

10331-31, Session PS2

Study of cement setting by dynamic speckle pattern and digital holographic interferometry

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The Portland cement is used as a binding material, due to its adhesive properties which permits an unlimited number of applications (Civil Engineering, Architecture, Arts and Reconstruction of Architectural Heritage), converting it into one of the basic materials in this field.

For this material there are a number of regulations which permit to distinguish, know or confirm the characteristics of the cement. In addition to setting requirements, they have a set of rules that establish test techniques for determining the parameters you want to know.

In the IRAM norm 1619:2003 (Regulations in Argentina) describes the test procedure to determine the beginning and ending time of the setting. This can also be obtained by observing the insertion of the needle and the cement paste with normal consistence allocated in the frustum mold. Must be considered as the beginning time of setting to the lapsed time since the cement became in contact with water (zero instant), until it gets registered a new insertion which leaves a distance of 4±1 mm between the needle point and the base of the mold. In the same way, the setting ending time is the time that lapsed between the zero instant until the needle stops marking the sample for the first time.

As an alternative method, it is proposed an application of the dynamic micro-speckle pattern and digital holographic interferometry. The first method is applied to determine the setting time and the second one is used to detect the dynamic behavior of the surface and quantify the dimensional changes ((x, z) coordinates) in the surface during the setting time.

In this work is presented the study in the behavior of cement samples through the application of the dynamic speckle method in long duration tests. The analysis is realized by two different algorithms and an alternative optical scheme in which is used as capturing system an stereoscopic microscope with a CMOS integrated camera, so the speckle pattern is analyzed through a magnified image.

With digital holographic interferometry (DHI), the objective is to determine the presence of displacement over the surface due to the chemical reaction which occurs during the setting period. By this method, it is possible to localize the evolution of bubbles from the inside to the surface, lateral displacement of the material and all dynamic processes which involve movement due to the formation of crystals. Which are formed due to the chemical reaction between water and Tricalcium Silicate -C3S-, Dicalcium Silicate or Belite -C2S-, Tricalcium Aluminate -C3A- and Tetracalcium Alumino-Ferrite -C4AF-.

The results obtained indicate the feasibility of the application of the methods to define the evolving phases in the process of the setting of the CPC40 type of cement.

10331-32, Session PS2

Power estimation of martial arts movement with different physical, mood and behavior using motion capture camera

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In Malay world, there is a spirit traditional ritual where they use it as healing practices or for normal life. Malay martial arts (Silat) also is not exceptional where some branch of silat have spirit traditional ritual where they said can help them in combat. In this paper, we will not use any ritual, instead we will use some medicinal and environment change when they are performing. There will be 2 performers (fighter) selected, one of them have an experience in martial arts training and another performer does not have experience. Motion Capture (MOCAP) camera will help observe and analyze this move. 8 cameras have been placed in the MOCAP room 2 on each side of the wall facing toward the center of the room from every angle. This will help prevent the loss detection of a marker that been stamped on the limb of a performer. Passive marker has been used where it will reflect the infrared to the camera sensor. Infrared is generated by the source around the camera lens. A 60 kg punching bag was hung on the iron bar function as the target for the performer when throws a punch. Markers also have been stamped on the punching bag so we can detect the movement how far can it swing when hit by the performer. 2 performers will perform 2 moves each with the same position and posture. For every 2 moves, we have made the environment change without the performer notice about it. The first 2 punch with normal environment, second part we have played a positive music to change the performer's mood and third part we have put a medicine (cream/oil) on the skin of the performer. This medicine will make the skin feel a little bit hot. This process repeated to another performer with no experience. The position of this marker analyzed by the Cortex Motion Analysis software where from this data, we can estimate the kinetics and kinematics of the performer. It shows that the increase of kinetics for every part because of the change in the environment, and different result for the 2 performers.

10331-33, Session PS2

RTI studies of conservation works on palaeolithic art at Kapova Cave (Russia)

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No Abstract Available

10331-5, Session 2

Bridging research with innovative products: a compact hyperspectral camera for investigating artworks. A feasibility study *(Invited Paper)*

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For more than a decade, a number of studies and research projects have been devoted to customize and readapt hyperspectral imaging techniques and instrumentations to the specific needs of conservation applications in the museum context. This has led to the birth of a new, though well-grounded, research area focussed on the development and testing of hyperspectral devices tailored for applications on artworks (e.g. paintings, illuminated manuscripts, etc.). A growing scientific literature definitely demonstrated the effectiveness of reflectance hyperspectral imaging in providing both analytical spectral information and high-quality documentation of valuable 2D artworks, by non-invasively acquiring a unique data-set, called hyperspectral image-cube, which include both spatial and spectral information on the imaged area. Additional studies have been dedicated to the problems of hyperspectral data processing and analysis, with a focus on the development of algorithms and software platforms optimised for visualisation and exploitation of hyperspectral big-data sets acquired on paintings. This scenario proves that, also in the field of Cultural Heritage (CH), reflectance hyperspectral imaging has nowadays reached the stage of mature technology, and is ready for the transition from the R&D phase to the large-scale applications.

In view of that, a novel concept of hyperspectral camera - featuring compactness, lightness and good usability - has been recently developed by Specim, a leader company in manufacturing products for hyperspectral imaging. The camera is proposed as new tool for novel applications in the field of Cultural Heritage. The novelty of this device relies in its reduced dimensions, weight, and in its user-friendly interface, which make this camera much more manageable and affordable than conventional hyperspectral instrumentation. The camera uses a 2D detector operating

in the 400-1000nm spectral range. It can be mounted on a tripod and its optical module allows imaging of different size areas, by varying the working distance from short-distance (tens of cm) to long distances (tens of meters) with different spatial resolutions. These technical features extend the possibility of applications to several typologies of artworks, both indoor and outdoor, including large-size wall paintings, ceilings, decorative elements and inscriptions, as well as inspection small details of interest selected on the surface of quasi-flat objects.

The first release of the prototype underwent a preliminary in-depth experimentation at the IFAC-CNR laboratories in order to assess its performances and basic functionality, as well as its advantages and limitations with respect to other hyperspectral imagers commonly used for artworks investigations.

This paper illustrates the feasibility study carried out on the new Specim hyperspectral camera, before its official launch on the market. The device was tested under different conditions with the specific aim of defining its potentialities, strengths and weaknesses in the applications to the study of different types of artworks. The main results of laboratory tests and measurements carried out on specific targets, as well as on real artworks (case studies), will be presented and critically discussed.

10331-6, Session 2

Dating of bricks by optically stimulated luminescence (OSL) with modified protocol sheds new light on the chronology of medieval church

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The main idea of luminescence dating method comes from dosimetry where luminescence signal is used as a measure of absorbed dose. The information on the age of an object can be derived from luminescence emitted by mineral grains, mainly quartz, extracted from the sample. Intensity of natural luminescence is proportional to the palaeodose originating from natural ionizing radiation and accumulated in the sample since its beginning. Therefore: the older sample the higher natural luminescence signal. Absolute age can be determined after luminescence sensitivity of the sample is estimated.

In the middle of 20th century thermoluminescence (TL) method was elaborated for dating ancient ceramics. Shortly after archaeometry this method was applied for dating geological deposits as well. However disadvantage of TL dating in case of sediments was relatively high signal of residual TL resulting in possible age overestimation. Newer method of Optically Stimulated Luminescence (OSL) partially solved this problem. What even more it enabled to develop Single Aliquot Regenerative (SAR) protocol for measuring palaedoses for single aliquots or even single grains of mineral. This made it possible to improve precision of age estimates and now SAR OSL is the most common procedure of luminescence dating. However SAR protocol was developed for geological sediments but not heated samples. Because of that it is interesting to check if given form of SAR procedure is suitable for ceramic samples, so well as it serves in dating of sediments .

The archaeological excavations of foundations of gothic St. James church in Torun, Poland provided 20 bricks for OSL dating. Such amount of samples ranks this building as the most intensively studied in the light of luminescence dating monument in Poland. This gave opportunity to test if SAR OSL protocol can really be modified in order to better adjust it for dating of fired materials. As a matter of fact it was found that scatter of results can be reduced if temperature of OSL readout is kept lower than temperature applied in standard SAR procedure. It confirms earlier predictions based on numerical simulations. Till now only preliminary partial results obtained for barely 5 samples were reported [Chru?ci?ska et al., 2014].

In order to interpret OSL ages, the results obtained for all 20 individual bricks were compared and statistical analysis was applied enabling to distinguish two stages in chronology of the building. A few bricks dating back to beginning of 14 century are consistent with current historical theory, which indicates that the church was constructed c.a. AD 1309 at sight as one unit. However some bricks revealed age originating from half of 13 century. These samples can be connected with unknown earlier form of the church. This finding refreshes old theory, up to now regarded to be obsolete. It tries to explain some irregularities in the construction of the walls as consequences of rebuilding original first church after several dozens of years with a new concept and by another master in 1309.

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10331-7, Session 2

Quantitative assessment in thermal image segmentation for artistic objects

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The use of thermal imagery into the cultural heritage field grows year by year, since the idea of limiting possible impairments is nowadays of paramount of interest. Here, the problems caused by the earthquake of 2009 which partially destroyed the city of L'Aquila (Italy) and its surroundings is investigated in two works of art. The first one is a fresco which was preserved in the Church of S. Peter Apostle – Onna (L'Aquila, Italy), while the second one is a polychromatic wooden statue representing a Madonna with his Child coming from a village in the province of L'Aquila. In both cases, the thermographic campaigns were conducted in the Museo di Paludi di Celano (L'Aquila, Italy) where the objects were transported after the quake for a first aid. The thermographic inspections were focused on the detection of sub-superficial cracks, inclusions of heterogeneous materials and splitting. During the inspections, a restorer indicated the main region of interest (ROI) to be recorded. The radiation source consisted of lamps (no flashes) which provided long thermal stimuli, while in each experimental campaign a ThermaCAM S65 HS by Flir collected the infrared thermography (IRT) data. The latter were subsequently analyzed in Matlab® environment.

There are well-known approaches such as Principal Component Thermography (PCT) among many others, which have been previously used in the scientific literature for the inspection of artistic objects.

Non-Negative Matrix factorization (NMF) is an approach which having the similar decomposition but non-negative values as compare to PCT. Two NMF approaches called standard Non-Negative Matrix Factorization (NMF) optimized by gradient-descent-based multiplicative rules (SNMF1) and standard NMF optimized by Non-negative least squares (NNLS) active-set algorithm (SNMF2) are used as preprocessing stage. These two methods are shown considerable performance in terms of magnifying the impaired regions in works of art. This magnification presented a considerable role as a preprocessing step before segmentation and increases the ability of the segmentation on these regions. For segmentation, an unsupervised approach –HSV based PCA kernelled clustering– was used along with the analysis of computational complexity for each approach. NMF techniques make easier the segmentation process and their results indicate promising performance and demonstrated a confirmation for the outlined properties.

To the best of our knowledge, the above mentioned techniques have been used in this context for the first time herein. These methods provided substantial benefits also in terms of reduction of the computational cost, as well as the obtaining of quantitative results concerning the defects detected, by limiting in the same time the emissivity variation which is naturally present in both cases. Regarding the latter point, the main reasons were: a) the pigments applied by the art masters on the upper layers, and b) the thermal stimuli induced by lamps useful to generate a 3D thermal transient.

10331-8, Session 2

Nondestructive evaluation of protective coatings for the conservation of industrial monuments

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For the conservation of cultural monuments standard anti-corrosion coatings are not applicable because the historical character of the objects would be concealed. Therefore the Deutsches Bergbau-Museum Bochum develops techniques to non-destructively monitor the functionality of alternative transparent coatings and to detect defects in an early stage. These techniques are intended for in-field maintenance done by unskilled personal with a portable analytical instrument. Electrochemical impedance spectroscopy (EIS) can meet these requirements. With EIS in principle it is possible to predict the protection efficiency of coating layers and obtain information about the progress of underlying corrosion. But this information has to be derived indirectly out of Bode and Nyquist plots that have to be fitted against suitable models (equivalent electrical circuits). In order to get valid models and easy to use metrics for the in-field monitoring the actual state of the coatings and the underlying corrosion must be known. Moreover there is no possibility to determine the actual layer thickness with underlying corrosion. With a magnetive inductictive measurement technique the layer thicknesses of non-corroded metal can be determined.

Here Optical Coherence Tomography (OCT) could be used as a comparison tool to provide both desired information, i.e. differentiation between corrosion and metal and the actual layer thickness. OCT yields depth information that can be used to calculate the actual coating layer thickness and with its lateral resolution in the µm scale small, early corrosion areas could be detected. The capability of OCT for the non-destructive inspection of anti-corrosive protective coatings has already been demonstrated in a qualitative manner by others. Based on these findings we have developed post-processing algorithms to automatically determine the coating layer thickness.

For our measurements we used a commercially available SD-OCT-System (Thorlabs Ganymede) with a center wavelength of 930 nm, an axial resolution of 6µm in air and a lateral resolution of 8µm. First we examined clean metal samples covered with Paraloid B48N in different layer thicknesses having a refractive index of 1,89. To verify our results the layer thicknesses were determined with a Fischer® Dualscope® FMP40. The OCT A-scans were post-processed in order to determine the thickness of the coating layer and compared with the results from the Dualscope® FMP40 measurements. The coating layer thicknesses could be determined with an accuracy lying within the axial resolution of the OCT system.

Our preliminary studies showed that OCT can be used for evaluating the protection efficiency of transparent anti-corrosion coatings by determining its thickness and we are confident that it can be applied to corroded samples as well. Thus OCT can be used as a comparative technique for developing a monitoring tool based on EIS for non-destructive investigations on cultural monuments. Especially if portable OCT systems will become available it could even be used for the in-field monitoring itself. In the future we will build a phantom sample that consists of pre-corroded metal with and without coating as well as pure metal with and without coating to validate our results and to determine the coating layer thickness with underlying corrosion.

10331-9, Session 2

A versatile optical profilometer based on conoscopic holography sensors for multiscale acquisition of specular and diffusive surfaces in artworks

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The acquisition of the surface at micron and sub-micron scales is routinely used for materials inspection in the engineering field, e.g. high precision tasks in quality control as the measurement of roughness and the gauging of the 3D topology of machined surfaces, but it is still experimental in Cultural Heritage (CH) due to the main facts that surface metrology of artworks requires the design of suitable devices for in-situ non-destructive measurement together with reliable tools for an effective analysis of such non-engineered, i.e. complex and unknown, materials. The extension of the standard surface metrology toolboxes to CH applications is not straightforward, due to shape irregularity and composite materials in artworks. Moreover, measurement performance, reliability, and effectiveness of surface data analysis depend on characteristics of the target object as texture and response of materials to the probes.

Optical profilometry based on laser-stylus systems has demonstrated its potential in pilot CH applications (from hi-res 3D survey for general documentation to micro-structure diagnosis for monitoring surface decay and treatments or supporting restoration), certainly leading to a growing interest towards this advanced tool, as well as underscoring the potential for further work in the field. Among the challenges, there are the scanning of multi-scale surfaces, the acquisition of surfaces with both specular and diffusive materials, and the profilometry-based feature extraction for modelling artwork surfaces.

Currently, no ready-to-use set-up is available on the market to perform the above tasks and, despite it mentioned potentiality, 3D profilometry is not being used within museum laboratories due such lack of tailored acquisition and processing platform.

This work deals mainly with the first instrumental aspect. To advance the state-of-the-art, we have implemented a versatile and multi-scale optical micro-profilometry, taking advantage of the adaptability of the conoscopic holography interferometric technique in order to operate with irregular shapes, composite materials (diffusive and specular) and polychromy of artworks. The scanning technique is then used to obtain wide field and high spatially resolved areal profilometry. Common-path interferometric techniques as conoscopic holography represent a solution also for applications in hostile environments. Thanks to this aspect, the device will be integrated in a multi-sensor platform supported by a robotic arm that is going to be developed in the framework of the European Scan4Reco (2015-2018) project.

The scanning prototype has a modular scheme and is based on a set of triggered conoscopic sensors, by extending the typical design based on a raster scanning stage and a single probe, thus allowing to collect simultaneously information over materials with different optical response. Each component has been characterized and the performance of the system has been optimized on different CH materials. A processing tool with texture and roughness computation tailored to CH has been implemented starting from the ISO standard descriptors, with the aim of characterizing local material morphology and extracting the significant small-scale features for CH applications, e.g. documentation of the conservation status, decay monitoring, treatments controlling. In this presentation we discuss the device's capability through some applications - measurements and surface data processing - on painting and metallic objects, included specular silver, in different conditions of treatment or forced aging.

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10331-10, Session 3

Nonlinear optical microscopy reveals the degradation of historic parchments *(Invited Paper)*

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Parchment was the main writing material in the Middle Ages in Western Europe. It is made from an untanned animal skin, which is preserved by liming, scraping and drying under tension. Parchment is very sensitive to water, which causes in extreme case the denaturation of collagen, its main constituent, to gelatin. This work aims to characterize this degradation mechanism by use of complementary techniques at different scales, and to demonstrate a new tool for in situ mapping of collagen conservation state in a non-invasive way and possibly in a remote configuration. Application to historical artefacts is also demonstrated.

Nonlinear optical (NLO) microscopy provides non-invasive three-dimensional imaging with micrometer-scale resolution. A key advantage is its multimodal capability based on different modes of contrast that are directly linked to the structural or chemical nature of the materials. 2PEF signals are emitted by a wide range of materials in historical artifacts with specific absorption and emission fluorescence spectra [1]. SHG signals are specific for non-centrosymmetric structures, with no counterpart in usual (linear) optical techniques. In particular, it reveals fibrillar collagen as widely used in biomedical imaging.

In this study [2], we show that SHG microscopy provides structural information about the 3D organization of the fibrillar collagen within parchments. We investigate historical parchments at different states of degradation (well-preserved to gelatinized), and show that SHG signals decrease in degraded parchments, while 2PEF signals increase. To further characterize the molecular and/or macromolecular processes involved in this process, we use infrared nanoscopy. Since the analysis have to be performed at the fibers (~1-5 ?m) or fibrils (~100 nm) scale, we couple AFM imaging with IR illumination to collect IR spectra with nanometer scale resolution (nanoIR) [3]. The correlation of NLO microscopy and nanoIR data provides unique morphological and chemical information about collagen degradation at different length scales. Most importantly, it validates that SHG signals are specific to well-preserved collagen, and 2PEF signals to gelatinized collagen in altered parchments [3].

Considering that a remote configuration is required to widen the application of this new tool, we present NLO images recorded from a fiber-based setup, which was previously developed for biomedical imaging [4].

Finally, NLO imaging is used to investigate the conservation state of an historic parchment, the Mappa Mundi of Albi (8th century, France). It is one of the first representation of the occidental world, recently recorded in the UNESCO Memory of the World Register. In situ NLO images of this parchment confirm that it is well preserved, and further demonstrate that NLO imaging is a safe characterization technique for historical parchments.

NLO microscopy therefore appears as a powerful tool to reveal collagen degradation in a non-invasive way. It should provide a relevant method to assess in situ the condition of collagen-based materials in museum and archival collections.

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10331-11, Session 3

Mapping the opacity of paint layers in coloured grounds paintings using optical coherence tomography

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Optical diagnostics techniques are becoming important for technical art history (TAH) as well as for heritage conservation. In recent years, optical coherence tomography (OCT) has been increasingly used as a novel technique for artwork inspection. OCT is a contactless and non-destructive technique for microstructural imaging of turbid media. It has shown that OCT is an effective tool for vanish layer inspection. However current OCT instruments have difficulty in paint layer inspection due to the opacity of most pigments. This paper explores the potential of OCT for the investigation of coloured grounds paintings. Coloured grounds was a technique that originated in the later 15th century in Italy and spread to Northern Europe by 1550. Semi-transparent paint layers were painted over a coloured, brown or grey, ground layer to give increased visual depth, changing dramatically the visual characteristics of the finished painting. In this work, we have developed two OCT systems working at the longer optical wavelengths of 1550 nm and 2000 nm. Due to less light scattering, longer wavelength OCT gives a better depth penetration in the painting. Secondly we processed the depth scans and calculated the penetration depth based on 1/e light attenuation. The variation in paint opacity was mapped based on the microstructural images and 3D penetration depth profiles was calculated and related back to the construction of the artwork. The performance of the two OCT systems was also compared and discussed.

10331-12, Session 3

High-resolution mobile optical 3D scanner with color mapping

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Optical 3D measurements using structured light projection technique getting more and more fields of application. Whereas industrial quality management, rapid prototyping, and architecture are established application areas, digital storage of artifacts and museum inventory or 3D acquisition of crime scenes (forensics) are growing application domains.

A new mobile handheld scanning device with a measurement volume of approximately 320 mm x 200 mm x 100mm with a lateral resolution of 150 µm was developed at our institute. This mobile scanner can be optionally used with a common SLR camera in order to obtain color representation of the 3D measurement data. Main fields of application of the new device are forensics and digital 3D storage of artifacts.

The scanner has a size of about 250 mm x 200 mm x 150 mm and its weight is 3.6 kg without and 4.4 kg with optional color SLR camera. The cameras have a sensor size of 2048 x 1280 pixels. The PC for measurement control and point calculation is included inside the housing and power supply is realized by batteries. Possible operation time is between 30 and 60 minutes. The object distance is between 400 and 500 mm, the scan time for one 3D shot may vary between 0.1 and 0.5 seconds and the complete 3D result is obtained a few seconds after starting the scan. Measurement objects larger than the measurement volume must be acquired partly. The different resulting datasets must be merged using a suitable software module.

Calibration can be performed like a classical photogrammetric stereo scanner. The optional SLR camera is calibrated simultaneously. Hence color images can be immediately mapped onto the 3D representation.

The forensic use of the scanner is mainly for capturing traces of shoes or tyre tracks at crime scenes, which take more than 20% of traces at scenes of crime. Here the scanner significantly improves the classical preservation of evidence by plaster impressions. Some advantages are: the trace won't be destroyed and can be kept, the process is much faster than before, and the data can be quickly sent elsewhere. Some examples of shoe traces and tyre tracks are shown and the results of reference tests using different subsoils as sand, clay, soil, and mortar powder.

The digitization of art objects in museums or the digital cultural heritage preservation is a growing application field of optical 3D scanning technique using structured light projection based mobile scanning devices. Digital models can help the "non-invasive" analysis of the valuable objects. Archives of museums possess many historical earth and celestial globes which would provide, if digitized in 3D models, a virtual and free access to the contemporary knowledge of our world to interested people. In our institute high resolution and color 3D digitization of a valuable historical relief globe was performed using the presented 3D scanner. Several reconstruction examples of this globe are shown.

Future work will be addressed to the improvement of the measurement stability of handheld measurements by code reduction without loss of completeness and accuracy and the automatic detection and compensation of measurement disturbances by user movements or vibrations.

10331-13, Session 3

Quantitative assessment of parchment degradation by polarization-resolved second harmonic microscopy

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Non-invasive investigation techniques are strongly needed to avoid sampling during the examination of cultural heritage artefacts. This study aims at developing a non-destructive method for investigating the degradation state of parchments, which are mainly composed of dermal fibrillar collagen. To that end, we implement polarization-resolved Second Harmonic Generation microscopy (P-SHG) and demonstrate that this new method allows probing the early stages of collagen degradation within parchments in a non-invasive way.

Nonlinear microscopy is an emerging and promising optical technique for the investigation of artworks. It provides non-invasive three-dimensional (3D) imaging with micrometer-scale resolution based on intrinsic optical sectioning. Second harmonic generation (SHG) signals are specific for non-centrosymmetric structures, with no counterpart in usual (linear) optical techniques. A well-preserved parchment exhibits strong SHG signals originating from fibrillar collagen. On the contrary, in case of strong degradation, SHG signals vanish because fibrillar collagen is transformed into gelatin, which exhibits a centrosymmetric structure [1].

In this study, we further implement P-SHG by the use of a rotating linearly polarized excitation. SHG intensity is then recorded as a function of the orientation of the linear excitation for each pixel of the image. P-SHG microscopy provides two quantitative information at different scales [2]. The first parameter is the mean orientation of the collagen fibrils within the focal volume, which provides orientation mapping in the field of view of the SHG image (typically 500 x 500 μm?) or in larger areas by tiling several images. The second parameter is the SHG anisotropy parameter, which measures the square root of the ratio of the SHG signals for fibrils parallel versus perpendicular to the exciting polarization. It is related to the organization of the fibrils within the focal volume and provides the degree of orientation disorder at a submicrometer scale.

Model samples exhibiting different levels of degradation were prepared. Modern parchments were artificially degraded by exposure to dry heat at 100 °C for increasing duration (reference, 2, 4, 16, 40, 80 and 122 days). The level of degradation was assessed by measurement of the shrinkage temperature, using differential scanning calorimetry (DSC), on a micro-sample. This measurement of the resistance of a wet material to heat, is commonly used in cultural heritage field to assess the degradation state of collagen-based materials.

These model samples were then investigated by P-SHG. At high levels of degradation, SHG signals decreased as expected. In the early stage of degradation, the SHG intensity level was preserved but the SHG anisotropy parameter increased, which revealed a disorganisation at the fibrillary scale.

In conclusion, P-SHG microscopy gives a better insight into the collagen modifications during degradation process, especially in the early degradation stage. Compared to DSC measurements, P-SHG microscopy requires no sampling and therefore provides a new promising tool for assessing in a non-invasive way the conservation state of historical parchments in museum collections.

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10331-14, Session 3

Spectral-domain optical coherence tomography technology for diagnoses and detection of Chinese mural and pottery

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Optical coherence tomography (OCT) is a non-contact, non-invasive imaging technique which has proved valuable in the area of art history, conservation, archaeology and heritage, it has been successfully applied to the imaging of painted objects due to its function to visualize the subsurface microstructure recent years. In this paper, we demonstrate a spectral-domain OCT (SD-OCT) system based on optical fiber Michelson interferometer for Chinese cultural heritage research. The theoretical axial resolution and maximum imaging depth of the proposed system in air are 7?m and 8mm. The test results demonstrate that the OCT images of Chinese pigments, mural, pottery figurine and jadeite samples can provide a lot of valuable subsurface microstructure information for the cultural heritage research and identification works.

10331-15, Session 4

Lock-in-shearography for the detection of transport-induced damages on artwork *(Invited Paper)*

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Cultural heritage is a testimony of time and therefore it is necessary to ensure its preservation. But on the other hand it should be accessible for many people that makes the transportation of the artwork unavoidable. Although specialized companies are deployed to carry out this transports, environmental changes and vibrations can lead to non-reversible distortions. In the worst case the artwork is damaged and has to be restored. To decide if this is necessary an efficient detection of all occurring defects has to be provided. While some of the defects can easily be identified with the naked eye or magnifying systems like a microscope, others arise under the surface and are therefore invisible for a conservator. Many techniques for the detection use radiation, which can penetrate inside the object like X-ray, OCT or thermography. Besides these approaches it is also possible to load the object and observe the change of the surface. The obtained surface information allows conclusions about the defects. This can for instance be achieved using shearography. The potential of this method in the field of cultural heritage could successfully be proven in the past [1-2]. Advantages of this techniques are the simple and robust setup, the high sensitivity and the good lateral resolution. A main problem however is the whole-body-deformation. Especially if the loading is introduced via thermal heating, the deformation of the entire sample can be much higher than the local deformation, which is induced by the defects. This leads to a reduced detection efficiency. Furthermore the phase maps of a shearographic measurements do not contain any depth information of the defects. To overcome the problems the so called lock-in-technique can be used. Similar to lock-in thermography the loading is modulated sinusoidally and an evaluation in the Fourier-domain is performed. Very recently the lock-in shearography was successfully tested for the use on PMMA-plates [3], but was not yet applied on paintings. In general, paintings are complex multi-layer structures with different thermal properties (heat conductivity, heat capacity). Especially the penetration depth of the thermal wave and the warming process during the thermal heating depends strongly on the material.

We investigate the application of lock-in shearography in the field of conservation of artwork. Self-manufactured samples are used to compare the results of lock-in shearography with conventional shearography with respect to detection efficiency, signal-to-noise-ratio and depth information. Besides the loading with thermal waves, we furthermore investigate the possibility of applying a mechanical loading using a pressure chamber. Earlier measurements have shown that even for conventional shearography a change of pressure does not entail a whole-body-deformation [4]. So a sinusoidal change of the pressure should not improve the detection efficiency, but increases the signal-to-noise ratio. Although no thermal wave, which penetrates inside the object, is produced it is likewise possible to retrieve depth relevant information. This concept is supported by the fact that the response of the surface to the modulation takes longer for deeper defects.

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10331-16, Session 4

Method for dating old handwritten manuscripts based on spectral photometry of ink in near infrared range

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Dating of old manuscripts is often important to evaluate accurate date of a document appearance. There exist several attributes allowing to provide dating like peculiarities of paper material and properties of ink. Properties of paper material relate to corresponding epoch, but accurate dating is problematic in this way. More accurate date estimate can be based on comparison of documents with known dates with the ones that have to be dated. To achieve this, it is possible to use the fact that ink chemical composition was essentially variable in the past due to handicraft manufacturing process with variable properties. Assuming that both the dated and evaluated documents had been written using an ink from the same batch, it is possible to find their time correspondence. The problem consists in how to characterize ink chemical composition accurately. Additional difficulty consists in that often not allowed to damage a heritage subject, and non-destructive methods only are applicable. Optical methods present such a possibility.

The considered approach had been suggested [1] to date more accurate the handwritten manuscripts by famous Russian writer F.M. Dostoevsky. There are known a few post letters written and accurately dated by the writer, but other handwritten documents were not dated. It is important to compare that documents with the letters to evaluate accurate dates of the former documents. For this purpose, spectral photometry method has been applied [1, 2]. The handwritten documents were illuminated by light in near infrared range at a few different wavelengths where spectral properties of ink are more noticeable, and reflected light recorded by high resolving photo camera.

There have been found several problems of spectral photometry analysis of handwritten documents: combined reflection from the both ink and paper material impregnated by ink, the need in compensation of the rest illumination spatial non-uniformity with small light intensity, flexibility and instability of paper sheets (any mechanical contact like cover glass is not allowed) when switching light wavelengths. It is why the images acquired at different wavelengths were spatially matched using special computer software and then regions of interests, i.e. ink lines were extracted. Then reflection spectra obtained at all pixels were composed in vector representation and comparison of the vectors was conducted. As a result, there have been evaluated probabilities of correspondence between different fragments of text that allowed to enhance dating of several fragments related to the famous book "Crime and punishment" written by F.M. Dostoevsky (1866).

In the paper, the optical set-up and its calibration procedures are considered in detail as well as results of image processing, matching, segmentation and spectral photometry evaluation of ink. Results of different text fragments matching and probabilities of their correspondence are presented and discussed.

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10331-17, Session 4

Deciphering innovative metallurgical processes though the study of the oldest lost-wax cast object using dynamics-photoluminescence imaging

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Photoluminescence spectroscopy is a well-established technique in semiconductors science to characterize crystals defects. However, in the field of ancient materials, if the pioneering work in the early 20th century established UV photoluminescence photography as an important tool to visualize contrast of materials on works of arts of museum artefacts, very scarce have been undertaken to impart luminescence-based technique capabilities to retrieve quantitative information on the composition or structural specificities of materials.

Novel synchrotron luminescence approach based on a full-field configuration has been developed by IPANEMA laboratory at the DISCO beamline of SOLEIL synchrotron to provide new probes to characterize ancient materials, using tunable excitation from the deep ultraviolet offers up to the visible range. The configuration developed offers and flexible approach to study and map the luminescence properties of a variety of heterogeneous samples at the micron scale, from organic varnishes applied on historical musical instrument to minerals such as semiconducting pigments and corrosion products.

Latest developments have conducted to enhance critical parameters to tackle the multi-scalar heterogeneity of ancient materials: particular efforts have been undertaken to increase the spatial dynamics and the spectral dynamics in emission and excitation to collect low-signal emission at the sub-microscale. These parameters have been optimised on a selection of metal based archaeological artefacts originating from the Indus valley. In particular, a 6,000-year-old amulet from Mehrgarh (Baluchistan, Pakistan) identified as the oldest known artefact made by lost-wax casting was thoroughly studied (ref Nat.Comm.?).

The study of the object, started in early 2000, had demonstrated that the amulet is totally corroded. However contradictory results showed that all the corrosion products were copper-based species, without any relevant concentration of other alloying elements such as Pb, As or Sn, even if a remnant dendritic microstructure linked to alloy formation was observed. Only cuprite (cuprous oxide) was identified in the interdendritic spaces.

Using the luminescence full-field imaging technique, we can access to spatial distribution of crystal defect fluctuations in the cuprite-based areas at the crystallite level across centimetre-wide fields of view, owing to sub-microscale lateral resolution in the 850–1020 nm range.

Luminescence imaging offered unprecedented information on the object manufacturing process: at the macro scale, the continuity of the spatial distribution and orientation of the remnant dendritic structure all across the equatorial section, confirmed that the object had been cast in one piece. At the microscale, an unexpected hidden microstructure was revealed in the interdendritic space, resulting to the coexistence of two hitherto indistinguishable non-stoichiometric cuprous oxide phases: an eutectic pattern with a rod-type structure. Cu_2O is a semiconductor whose luminescence properties is sensitive to the nature of the crystal defects. Although uniquely consisting today of Cu_2O, luminescence imaging allowed a direct visualisation of an original rod-type Cu–Cu_2O eutectic morphology, within the interdendritic phase and distinct from the corrosion. The different nature of crystal defects results from the two different formation processes of the Cu_2O phases: the original Cu_2O directly linked to metallurgical casting and the other related to the corrosion of the Cu metallic phase. The rod-type pattern of the original cuprite phase, exhibits a stronger emission yield in the near infrared than the one of the corrosion resulting cuprite. Such difference is due to a variation of the content of copper vacancies within cuprous oxide phase. The results allowed inferring that the Chalcolithic metal workers used very pure, and possibly native, copper. Although, the use of high-purity copper turned out to be a dead end, since it did not improve the casting properties of the melt but caused unfamiliar problems to the founder. This nevertheless reveals the innovative metallurgical process accompanying the elaboration of the new casting technique. Such discovery highlights the early step of the highest precision metal forming technique that is still in use today

Owing to its ability to reveal spatially stoichiometric contrast within semiconductor structure at sub-micron resolution and over centime-size field of view, development of high-spatial dynamics photoluminescence full-field imaging opens new way to decipher critical information of semiconductors crystal defects heterogeneity. In this context, the study of nano- and polycrystalline materials for applications within a variety of fields, ranging from quality control in semiconductor solid-state physics to geophysics, archaeology, cultural heritage and environmental sciences, could strongly benefit from the exceptional potential of high spatial dynamics-photoluminescence.

10331-18, Session 4

LIBS, Raman spectroscopy and optical microscopy analyses of superficial encrustations on ancient tesserae in Lebanon

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The aim of research was determination of composition and nature of superficial deposits, cumulated at the selected mosaic's tesserae from Lebanon. Selected were three series of objects from different locations, namely from the seaside and mountain archaeological sites as well as from the mosaics exposed in the city center. Analyzed were stone and ceramic tesserae. The selection of objects was dictated by wide diversification of factors influencing the state of preservation and composition of deposits in given location.

Investigations were performed including LIBS, Raman spectroscopy and optical 3D microscopy. LIBS spectra with resolution on the level of ?/??~20000 in the range of 200-835 nm were recorded by illumination of samples with radiation of Nd:YAG laser (12 mJ, 4 ns, 1064 nm). Raman microscopical analyses were performed using four different excitation sources (?1= 532 nm , ?2= 633nm , ?3= 785 nm and ?4= 1064 nm). Optical analyses were supported by digital 3D microscope Hirox KH 8700.

The experimental results included composition and kind of deposit at the tesserae surfaces, and composition of tesserae itself. Compounds in the superficial deposits were identified. Confirmed was occurrence of different encrustations in dependence on geographic localization of a given sample. The interpretation of results was supported by multidimensional statistical techniques, especially by the factor analysis.

The reported results confirm high usefulness of applied methods in the complex analysis of superficial deposits. They will serve as a basis to create the individual conservation programs, aimed at development of appropriate conservation and preventive activities for preservation of the original matter of antiques. Performed analyses constitute the pioneer realization in terms of determination of deposits composition at the surface of mosaics from the Lebanon territory.

10331-19, Session 5

3D internal reconstruction by the use of terahertz time domain imaging (THz-TDI) on stucco reliefs from 15th century

(Invited Paper)

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In the field of Cultural Heritage and conservation science the development of non-invasive tools to retrieve information on artworks and historical artifacts remains one of the most important and increasing demands.

In this work a focus was made on the capability of THz imaging to investigate the internal structure of objects made of superposed plaster layers. In particular, gypsum based plaster used for stucco reliefs were investigated.

A selected number of 15th century painted stucco reliefs were studied by means of THz-TDI in the framework of the ESPRIT project, promoted by the Louvre Museum. The objectives were to assess the presence

of internal layers and to locate them: all of these in order to both confirm and give useful information about the supposed manufacturing techniques.

As well as many dielectric materials plasters are opaque or highly scattering at optical wavelengths but they are transparent at THz frequencies. This feature allows to provide depth information from tens of micrometers to approximately one centimeter in most of the non-polar, non-metallic media, making THz imaging complementary or alternative to X-rays imaging techniques. Moreover THz radiations other than non-destructive are also low-damaging because of their non-ionizing low photon energy and low energy heating. These techniques could provide a range of information: spectroscopy provides material characterization; time-of-flight analysis gives information on radiation penetration which is correlated to the stratigraphy. Some examples of the usefulness of this approach will be shown in this contribution. Using a Picometrix T-Ray 4000® THz-TDS system, multi-layer mock-up samples were measured to test the capability of the system in the detection of the different plaster mix used. Once validated the protocol and optimized the data treatment, the same approach was applied on a real case and selected areas were scanned on representative artworks. THz tomography, so called B-scans along x and y axis, allows to obtain information on the stratigraphy of the object while internal layers can be visualized through 3D reconstruction.

10331-20, Session 5

Surface and subsurface layers characterization in artworks using conoscopic laser holography and acoustic microscopy

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The characterization of the surface profile and the material layers is a pivotal step in several stages of the conservation process of an artwork. Generally, an optimal characterization of the surface and sub-surface cannot be achieved using a single technique and is not always possible to find techniques that can be coupled in an effective way.

Acoustic microscopy is a technique with tomographic capabilities that is able to acquire the thickness and the profile of surface and internal layers with sub-micrometre accuracy. The technique is widely used in industry but represents a novel application in the Cultural Heritage field. The correct analysis of the surface profile retrieved using acoustic microscopy is not straightforward, hence, in order to validate and clarify the results is very useful to compare the collected data with data coming from others techniques that produce surface 3D maps to be used as ground-truth. Laser conoscopic holography is a technique from the routine of surface metrology that provides accurate distance measurements in a contact-less way, that is, without any preparatory treatment of the sample. In this study, a conoscopic probe has been coupled with two micrometric stages for allowing the acquisition of surface maps with micrometric lateral resolutions over areas up to 900 cm-2. The conoscopic holography sensor operates on a different physical principle respect to acoustic microscopy, thus providing profile data that are not affected by the same artifacts; in addition, it can achieve comparable resolution allowing an effective comparison of the two techniques. Furthermore, the use of multiple sensors and lenses in the conoscopic set-up allows the user to control effectively the working range of the measurement and to adapt the set-up for measuring both specular and diffusive materials thus allowing the analysis of a broad range of materials.

Acoustic microscopy and conoscopic holography have been used over the same set of samples and the surface profiles measured have been compared morphologically and using the computed areal parameters from ISO25178 standard. In order to compare the multimodal measurements more effectively, we performed a registration of the two scans acquired with the two different instruments over the same area of the sample. Once registered in a single stack, the scans can be compared. Further processing, such as sub-sampling for homogenizing the resolution may be applied. The final dataset gives us a more complete surface and subsurface modelling, allowing the characterization of the layers in depth. The results obtained from the quantitative comparison are discussed highlighting the main pros and cons of the two techniques as well as how these two techniques can be possibly fused for an integrated approach. In this way besides having an insight on the effectiveness and on the performance of the instrument it is also possible to overcome many uncertainties linked with the measurement and to fuse the two scans in a single more accurate representation of the surface for its multi-layered digitization.

The presented work is part of the EU project Scan4Reco (2015-2018), aimed at developing a multi-sensor scanning platform for the acquisition of artworks. In this framework, the above characterized acoustic microscopy and conoscopic holography, once integrated in the portable device, will respectively serve the roles of monitoring the artwork materials in terms of their sub-surface and surface behavior.

- References

www.scan4reco.eu, EU Project SCAN4RECO (2015-2018) “Multimodal Scanning of Cultural Heritage Assets for their multi-layered digitization and preventive conservation via spatiotemporal 4D Reconstruction and 3D Printing”

10331-21, Session 5

In-depth analyses of paleolithic pigments in cave climatic conditions

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Prehistoric caves are in constant exchange and in equilibrium with their surrounding environment. Their preservation needs multidisciplinary studies carried out within owners, conservation scientists, archaeologists and curators. The actions set up must follow national and European ethics and treaties (i.e.: Venice Charter, heritage monument protection, etc.) and be as less disruptive as possible to preserve the integrity of the site. In these conditions, materials and analytical tools used to study prehistoric colorants and pigments in caves should meet these expectations. In the same time they also must take into account on-field conditions such as high rate of humidity, material portability, reduced or non-existent access to electricity and no release of heat. Therefore, non-invasive analyses should be preferred (i.e.: XRF, Raman, etc.). However, their limits restrict the field of application and they cannot meet more complex situations where sampling and laboratory analyses must be used to answer the problematic. It is especially true when the pigments are covered by calcite produced during a long period of time. Accessing its composition requires stratigraphic analyses. For this purpose, the Laser Induced Breakdown Spectroscopy (LIBS) whose application is spreading to analyze wall paintings in France has been here assessed to meet the requirement of painted cave problematic.

The objective of this study is to carry out in-depth profile with the LIBS instrument on laboratory samples with conditions close to the ones meet in the original sites. This work has been carried out in an artificial cave with a temperature of 13°C and a humidity of 87%. Six samples have been prepared on a calcareous substrate using three pigments: red ocher, manganese black and carbon black. Three samples have been made by adding water to the pigments and the other three by adding saliva. All six samples have then been covered with calcite: a solution of Calosil® had been dropped on top of the samples several months prior to the analyses. Four set of measurements have then been done using the LIBS instrument:

Set A: 1 measure

Set B: 5 successive measures

Set C: 10 successive measures

Set D: 20 successive measures

The in-depth profiles were obtained with a mathematical treatment: the Standard Normal Variate (SNV) normalization. This treatment notably reduces the influence of laser energy variation within the spectra. For all the samples, the pigment layer has been identified in the second or third measure, the calcite layer being quite thin. The results were especially promising with the carbon black pigment as the carbon element presents a higher concentration rate in the pigment layer , this element being generally quite difficult to quantify with traditional portable methods. The samples were then observed under a 3D-microscope were multi-focus treatments can be done to assess the depth of measures.

LIBS measures coupled with normalization treatments proved to be a good combination to access in-depth profiles in cave conditions and light element identification. Limits of the instrument still need to be enhanced such as access to electricity and energy stability and the next step will be experiments carried on samples with thicker calcite covering layer.

10331-22, Session 6

LIBS-LIF-Raman, a new tool for the future E-RIHS

Vincent Detalle, Ctr. de Recherche et de Restauration des Musées de France (France)

France is one the countries involved in the future E-RIHS - European Research Infrastructure for Heritage Science -. The research infrastructure dedicated to the study of materials of cultural and natural heritage will provide transnational access to state-of-the-art technologies (synchrotron, ion beams, lasers, portable methods, etc.) and scientific archives. E-RIHS addresses the experimental problems of knowledge and conservation of heritage materials (collections of art and natural museums, monuments, archaeological sites, archives, libraries, etc.). The cultural artefacts are characterized by complementary methods at multi-scales. The variety and the hybrid are specific of these artefacts and induce complex problems that are not expected in traditional Natural Science: paints, ceramics and glasses, metals, palaeontological specimens, lithic materials, graphic documents, etc. E-RIHS develops in that purpose transnational access to distributed platforms in many European countries. Five complementary accesses are in this way available: FIXLAB (access to fixed platforms for synchrotron, neutrons, ion beams, lasers, etc.), MOLAB (access to mobile examination and analytical methods to study the works in situ), ARCHLAB (access to scientific archives kept in the cultural institutions), DIGILAB (access to a digital infrastructure for the processing of quantitative data, implementing a policy on (re)use of data, choice of data formats, etc.) and finally EXPERTLAB (panels of experts for the implementation of collaborative and multidisciplinary projects for the study, the analysis and the conservation of heritage works).Thus E-RIHS is specifically involved in complex studies for the development of advanced high-resolution analytical and imaging tools. The privileged field of intervention of the infrastructure is that of the study of large corpora, collections and architectural ensembles.

Based on previous I3 European program, and especially IPERION-CH program that support the creation of new mobile instrumentation, the French institutions are involved in the development of LIBS/LIBS/RAMAN portable instrumentation. After a presentation of the challenge and the multiple advantages in building the European Infrastructure and of the French E-RIHS hub, the major interests of associating the three laser based analytical methods for a more global and precise characterization of the heritage objects taking into account their precious character and their specific constraints. Lastly some preliminary results will be presented in order to give a first idea of the power of this analytical tool.

10331-23, Session 6

Nonlinear optical microscopy imaging for nondestructive analysis of paintings

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State-of-the-art technologies based on non-invasive nonlinear optical microscopy (NLOM) techniques are being investigated for obtaining three-dimensional (3D) multimodal imaging of scattering samples and objects of cultural heritage with superficial and depth resolution in the micrometre scale [1-3]. NLOM relies in infrared, ultrafast laser excitation (pulses in the femtosecond range) to exploit nonlinear optical effects, namely multiphoton excitation fluorescence (MPEF) and second and third harmonic generation (SHG, THG). MPEF signals, upon absorption of 2 or 3 femtosecond laser photons, provide information related to the chemical composition of layered substrates. In turn, SHG signals identify the presence of non?centrosymmetric structures, while THG signals are capable of image interfaces between different layers of transparent samples. Application of these methods to a broad range of substrates and materials with different structures and composition will support implementation of these advanced microscopies to study artworks and heritage objects and boost the development of user-friendly instruments based on these advanced microscopies.

In this study we concentrate on a set of test samples, consisting of multi-layered paints that simulate real paintings, based on three traditional pigments, Egyptian blue, cadmium yellow and red lead. We perform NLOM measurements, applying the above mentioned modalities of MPEF and THG, using different nonlinear microscopes with diverse characteristics and based on excitation with pulsed femtosecond laser sources emitting at selected wavelengths in the 750-1030 nm spectral range.

To support and complement the NLOM measurements we characterize the relevant morphological and chemical properties of the samples in a multi-analytical approach which involves the use of a broad range of spectroscopies. In particular, we have applied colorimetry, Fibre Optics Reflectance Spectroscopy (FORS), scanning multispectral Vis-NIR reflectography, UV-Vis-NIR reflection and fluorescence emission spectroscopy, micro-Raman spectroscopy and laser-induced fluorescence spectroscopy. 3D information was also collected from the samples for a comparison with NLOM results via UV-Vis cross-section images of micro-samples and through techniques able to generate cross-sectional views of 3D objects, such as Optical Coherence Tomography (OCT) and acoustic microscopy.

The results of this interlaboratory, comprehensive study provide valuable information about the use of non-destructive NLOM for the analysis of layered substrates, particularly paintings and painted objects, and for development of mobile NLOM imaging workstations.

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10331-24, Session 7

Analytical robustness of quantitative NIR chemical imaging for Islamic paper characterization

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Recently, Spectral imaging techniques such as Multispectral (MSI) and Hyperspectral imaging (HSI) have gained importance in the field of heritage conservation. Such techniques have widened the possibilities of imaging and material characterization by expanding spectroscopy to examination of an entire surface of an object which consequently improved the knowledge of distribution of material properties.

Most of the applications of hyperspectral imaging in the field of cultural heritage have focussed on qualitative investigation due to the complexity of the objects and lack of standard materials for calibration. Similar to any other technique, calibration is crucial for the performance of hyperspectral imaging systems before and after collecting the spectral and spatial data to ensure its reliability and accuracy. Calibration significantly influences the analytical outcome as well as the stability of calibrations over time.

This paper will explore the analytical robustness of quantitative chemical imaging for Islamic paper characterization (distribution of sizing, acidity, and cellulose DP) by focussing on studying the effect of different measurement and processing parameters i.e. acquisition conditions and calibrations on the accuracy of the collected spectral data. This will provide a better understanding of the technique which then will provide a measure of change in collections through imaging.

For the quantitative model, special calibration target was devised using 105 samples from the well-characterized reference Islamic paper collection of UCL Institute for Sustainable Heritage. Three material properties of Islamic paper were of interest: starch sizing, acidity and degree of polymerization (DP). Multivariate data analysis methods were used to develop discrimination and regression models which were used as an evaluation methodology for the metrology of quantitative NIR chemical imaging. All data processing was performed using Matlab with the aid of the PLS - Toolbox library from Eigenvector.

Spectral data were collected using a pushbroom HSI scanner (Gilden Photonics Ltd) in the 1000-2500 nm range with a spectral resolution of 6.3 nm using a mirror scanning setup. The scanner is based on a line-spectrograph (Specim, ImSpector N25E) with a 30-?m slit connected to a Mercury Cadmium Telluride (MCT) camera with a spatial resolution of ~0.8 px/mm. The object is illuminated by a line of halogen lamps (500 W) at approx. 30° angle and ~18 cm distance. Data were acquired at different measurement conditions and acquisition parameters.

Preliminary results showed the potential of the evaluation methodology showing that measurement parameters such as the use of different lenses and different backgrounds may not have a great influence on the quantitative results. Moreover, the evaluation methodology allowed for the selection of the best pre-treatment method to be applied to the data.

10331-25, Session 7

Remote hyperspectral imaging with simultaneous 3D texture mapping

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PRISMS (Portable Remote Imaging System for Multispectral Scanning) has previously been developed for simultaneous high resolution and 3D topographical imaging of wall paintings and other large surfaces. It is the first imaging device capable of both 3D mapping and spectral imaging simultaneously without additional distance measuring devices. The distance was determined as a by-product of the image focusing mechanism (depth from focus). It allows fully automated high spatial resolution imaging from a remote distance of tens of meters at a stationary position, making imaging difficult-to-reach areas significantly easier. Material identification can be obtained from the spectral reflectance collected using an appropriate spectral reference library of known materials.

The original PRISMS device was designed for rapid remote scanning of large areas of wall paintings, thus a trade-off was made to use 10 interferences filters in the 400-900 nm with a relatively low spectral resolution of 50 nm and the 3D position acquired for only the centre of each field of view. By redesigning PRISMS to use a grating based spectrograph for simultaneous spectral measurement along one spatial line rather than sequential 2D spectral imaging using bandpass filters, the spectral resolution has been significantly increased to allow certain pigments to be identified with greater certainty. The 3D mapping has also been refined to 3D measurements per pixel. In this paper, we will show the results through imaging a polychromic 3D object.

10331-26, Session 7

Interferometry and thermography for cultural heritage structural diagnostic

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The simulated infrared thermography (SIRT) and digital holographic speckle pattern interferometry (DHSPI) are techniques realised in portable systems to be used on artworks and historical monuments non-destructive testing. Interference fringe formation and thermal diffusion reveal the invisible structural characteristics of a variety of materials and structural combinations. Fringe patterns are formed due to structural displacement and trace in quantitative and qualitative mode the reaction of materials to a specific load while the thermography reveals the distinct thermal gradient of the materials and the structure. The application of both techniques on artworks and monuments confirms the effectiveness of both techniques in the structural diagnostics field. The deformation of defects has not been up to now correlated to specific temperature gradient that can pave the path to development of new diagnostic technique and a new insight to the mechanisms of deterioration. In this research it is explored the enhancement of the data provided if it is combined and the future aim is to introduce a combined method for simultaneous application in artwork conservation and preservation research and practice.

10331-27, Session 7

Contribution of computed tomography to the investigation of early La Tene culture iron artefacts

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The X-ray tomographic study was realized in addition to the standard X-ray radiography for the purpose of the new conservation work upon the La Tene culture iron artifacts (swords and clips in this work) from the collections of the National Museum in Prague. These artifacts are heavily damaged by the corrosion, so their exploration is not possible to be done visually. The work shows that shallow details (compared to the artifact thickness), which are not detectable in standard radiographic images, can be made visible tomografically. The tomographic data acquisition was performed utilizing the unique TORATOM (Twinned Orthogonal Adjustable Tomograph) device. The device comprises of two independent pairs X-ray source – detector, precise rotational stage and computer-controlled axes that allow full geometrical adjustment of the positions of X-ray sources, detectors and the rotational stage with high precision (units of micrometers). Unlike in medical tomographs, where the investigated object is laid horizontally and the X-ray source and detector rotate around the object in a ring cover, in TORATOM the X-ray source and detector are fixed during the measurement and the object rotates around the vertical axis. The device can be adjusted in order to get the maximum possible magnification (from 1.2x to 100x as a standard) and thus the best possible spatial resolution for the particular investigated objects. Since the X-ray sources and detectors are shiftable even in the vertical direction, it is possible to make partial tomographies of elongated objects in several steps and tile together the resulting virtual models. In this way, objects longer than 1 m can be investigated. The maximum weight of the object is 40 kg and its maximum diameter in a standard measurement is 35 cm. The twinned configuration enables comfortable dual-energy measurements. The X-ray tube potential is adjustable from 20 kV to 240 kV in one X-ray tube and to 160 kV in the second X-ray tube. The installed power allows investigation of iron objects up to the thickness of 2 cm in a standard measurement with the duration of several tens of minutes. Tomography of highly attenuating materials, such as lead, requires even units of hours. The used beam energy influences the achievable contrast in the image, so it has to be chosen carefully. As the investigated artifacts consist mainly of iron and iron oxides (rust), relatively high X-ray tube

potential had to be used for the beam to penetrate through the objects (230 kV for swords and 100 kV for clips). Large area X-ray detector equipped with Gadox scintillator with 2048 x 2048 pixels and pixel pitch of 200 micrometers was employed for radiograms acquisition. There were 1200 angle steps per one rotation, resulting in 1200 projections of each object, made with 1 s exposition time. With respect to the size of the investigated objects, the magnification was set between 1.6 to 3.3, resulting in the voxel size between 125 and 61 micrometers. Advanced method for beam-hardening effects correction was used, employing a set of filters of different thicknesses to acquire appropriate sets of correction images. The tomographic reconstruction revealed insufficiencies in the earlier conservation processes of the swords, as well as so-far unknown details, such as the details of the sword shape and its decoration. These new findings allowed classifying of one sword as an artifact belonging to the early La Tene culture, akin to the swords reported recently in Germany and eastern France. In case of another sword, the tomography yielded detailed information of the decorative disks on the chape-end of the so-far unknown shape. Tomography also allowed to visualize the details of the iron clips that are completely hidden under the rust, making thus the technology of the clip formation very clearly observable. With this work, it has been proven that tomography can bear a lot of new information compared to the standard X-ray radiography in the investigation of iron archeological artifacts.

10331-28, Session 7

Micro-XRF complemented by X-radiography and digital microscopy imaging for the study of hidden paintings

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The present study describes a novel approach to the study of underpaintings by combined use of non-invasive micro-X-Ray Fluorescence spectroscopy (Artax-200, Bruker), X-radiography (digital, transmission mode) and digital microscopy (Hirox KH8700). The case study analysed is a portrait of a male figure discovered under the painting of Ecce Homo, attributed to Titian's studio with an estimated date in the 1550s. The examination of X-radiography images exposed the details of the underpainting, which appeared to be a nearly finished portrait of a standing man, overpainted by the current composition of Ecce Homo at a 180° angle. The application of digital microscopy on the upper painting's cracks and flaked areas enabled the identification of the entire painting's stratigraphy, starting from the canvas up to its uppermost layer (i.e. the visible painting). This test also allowed studying the colour appearance and pigment particles of the underlayers. The subsequent pigment analysis was performed by micro-XRF. Since the described XRF analysis was performed not in scanner mode, the correct selection of the measurement spots for the micro analysis and separation between pigments of the lower and the upper painting was of paramount importance. The described approach for spot selection for micro-XRF was based on the results of the preceding X-radiography and digital microscopy tests. First, contours and compositional elements of the underpainting were delineated by the analysis of X-radiography image. It was followed by the identification of areas of interest on the underpainting focusing on color and pigment composition. The third step concerned the creation of a map of spots for point analysis by micro-XRF taking into consideration compositional elements of both the upper and the lower paintings. The selected spots were mapped on the X-radiography image and transferred onto the visible image in order to facilitate navigation, when performing micro-XRF analysis. Elemental distributions of Pb, Hg, Cu, Fe and Mn indicative of lead white, vermilion, copper green/blue and ochre/umber were obtained for the documentation of pigments present in the underlying portrait. The described investigation method proved to be useful in the correct identification of the pigments of the underlying painting and consequently assisted in the tentative reconstruction of its colour palette. Moreover, the undertaken approach enabled a comparison between the sets of pigments and thus revealed important information about the underpainting and its relation to the upper one. Additionally, the undertaken approach allowed discovering the potential of micro-XRF technique in the study of hidden compositions.

10331-29, Session 7

Combined use of optical coherence tomography and macro-XRF imaging for noninvasive evaluation of artworks

Piotr Targowski, Magdalena A. Iwanicka, Marcin Sylwestrzak, Nicolaus Copernicus Univ. (Poland)

Optical Coherence Tomography (OCT) and relatively novel large scale XRF scanning (MA-XRF) are both non-invasive imaging techniques that provide a complementary information on subsurface structure of some artworks. The limitation comes from the fact that OCT as an optical sectioning technique is able of imaging only the structures accessible to infrared light. Additionally, not all elements are detectable with XRF technique, especially if examination is conducted through air. Nevertheless, there are many structures, like varnish and glaze layers of easel paintings, glazes on ceramics, inscriptions and illuminations on parchment which can be effectively examined with both techniques.

It the contribution, the overview of results obtained with such an approach will be given. For the study, the laboratory-built portable OCT instrument constructed around an ultra-broadband superluminescence source (770 – 970 nm spectral span) was utilized. The instrument is characterized by 0.8 mW power of the probing beam and 2 ?m axial resolution (in varnish of refractive index equal to 1.5) and 12 ?m lateral resolution. As the complemental instrument, the transportable M6 JetStream scanning system from Bruker Nano GmbH was used. It enables extended surface scans (up to 70 cm x 55 cm) during a single examination, with lateral resolution up to 50 ?m. The instrument comprises a X-ray lamp working at 50 kV/600 ?A conditions with Rh anode and a poly-capillary optics. An open-air system permits imaging elements of atomic numbers not lower than 16 (S).

This approach has been successfully used for authentication of easel paintings by precise determination of location of structures containing dating pigments both at given depth (by OCT) and/or at given areas (by MA-XRF). Another application concerns the monitoring and evaluation of some restoration treatments. Specifically, OCT can be used to monitor varnish and/or overpaint removal in terms of decrease of the unwanted layer's thickness. The comparison of MA-XRF scans of the cleaned area prior to and after the treatment, helps assessing both whether the primary layers are left intact and whether the secondary layers are sufficiently removed. In case of objects on parchment both techniques are used independently to investigate different phenomena, contributing to the knowledge of the object.

10332-1, Session 1

Development of a high accuracy multisensor, multitarget coordinate metrology system using frequency scanning interferometry *(Invited Paper)*

Ben Hughes, National Physical Lab. (United Kingdom)

No Abstract Available

10332-2, Session 1

A multimodal imaging device for skin cancer diagnosis and prognosis

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Skin cancer, and melanoma in particular, is a deadly disease which is becoming more and more prevalent due to depletion of the ozone layer combined with incorrect sun exposure practices.A large amount of surgical procedures for suspicious lesions are practiced onto simple nevocytic lesions, yielding to huge unnecessary costs in public health services. Biophotonics techniques have been recalled to improve the precision of the diagnosis, as far as lesions are present near the surface of the skin, where photonics-based techniques can extract very useful information. Within the Diagnoptics project, funded by the EU CIP-PSP Programme, two identical multimodal prototypes have been built, tested and implemented in two different hospitals in order to check the usefulness of combining three different photonic-based technologies for the diagnosis of skin cancer. A single in vivo platform has been implemented which includes a handheld prototype for multispectral imaging of lesions for the measurement of different radiometric quantities, a movable 3D fringe projection unit for 3D profiling of the lesions quantifying their shape, and the measurement of blood flow below the skin for the local detection of angiogenesis through the self-mixing technique, plus a commercial confocal microscope for direct imaging of the first layers of the skin.

The multispectral unit consists of a CCD camera and a set of light-emitting diodes (LEDs) enabling the sequential acquisition of the lesion under analysis through several spectral bands (from 400 nm to 1000 nm). From the images taken, the reflectance images are computed and several parameters such as those based on color are computed for the lesions as well as for the surrounding skin. The 3D unit projects a set of fringes over the skin lesion. These fringes are distorted due to the lesion shape and the images are acquired by two cameras. The distortion of the fringes allows then for the accurate retrieval of the 3D topography of the lesion by triangulation. Finally, the self-mixing imaging unit exploits the optical feedback interferometry phenomenon which produces an interference inside the laser cavity which translates into power emission changes when a small percentage of the light aimed to the patient's skin is backscattered from the blood vessels, enabling to extract Doppler flow information from the signal.

The full system has been integrated onto a clinical grade cart, and each subunit was built according to medical standards, and set to work at two different hospitals to check about its performance and its ergonomics. In this paper we will review the complete process of construction of each of the subunits, and their final integration into a commercial instrument usable in a clinical environment which has been incorporated in two pilot lines which have analyzed over 600 lesions as of today.

10332-3, Session 1

Rigorous accuracy assessment for 3D reconstruction using time-series dual fluoroscopy (DF) image pairs

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Biplanar videoradiography (BPVR), or clinically referred to as dual fluoroscopy (DF) imaging systems, are being increasingly used for skeletal kinematics analysis. Typically, a DF system comprises two X-ray sources, two image intensifiers and two high-speed video cameras. The combination of these elements allows stereoscopic view of joint bones and permits bony rotation and translation measurement in 3D at high temporal resolution (e.g., 120-250 Hz). Recently, the accuracy of 3D measurements derived from DF imaging has been the subject of many research efforts.

Many reported accuracy assessment procedures do not exploit the benefits of robust photogrammetric tools for the calibration of the DF system parameters. For instance, direct linear transformation (DLT), or modified DLT, are usually used for the estimation of the system orientation parameters. The DLT-based approaches can result in low-quality orientation estimates, which introduce errors to the final accuracy estimates. In addition, traditional accuracy assessment procedures utilize reference 3D models measured with computed tomography (CT) or magnetic resonance imaging (MRI). The CT and MRI models are limited by low spatial resolution (e.g., 0.3 to 0.6 mm for clinical CT), which also introduces errors in the output accuracy measures. A recent study, which involved 3D positioning of a rolling sphere using a DF system, has reported a maximum of 0.15 mm error in the sphere position estimates. The value of 0.15 mm error in position might be optimistic when neglecting the errors associated with system orientation estimates and the low resolution inherent to the used reference model.

This paper presents a novel and simple accuracy assessment procedure that is based on using bundle adjustment with self-calibration for the estimation of the system parameters and is independent from utilizing CT or MRI reference models. A photogrammetric intersection of time-series image pairs is used for the motion reconstruction of a rotating planar object. The accuracy of 3D measurements from DF imaging is evaluated based on a comparison between 3D coordinates from ray intersection and independently surveyed coordinates. Specifically, the accuracy assessment procedure involves capturing a time-series image pairs of a rotating planar object with implanted radio-opaque beads. Some of these images are used to run a bundle adjustment with self-calibration for the estimation of the system relative-orientation and interior-orientation parameters (ROPs and IOPs, respectively), as well as the reference 3D coordinates of the radio-opaque beads. The bundle adjustment with self-calibration provides a precise estimation of the system parameters and the bead coordinates through utilizing ROP stability constraints, free-network adjustment constraints, and adequate optical and X-ray-imaging distortion models. The remaining images are corrected from distortion artifacts and used to perform the photogrammetric intersection for the reconstruction of the bead coordinates at different time epochs. For an image pair at a given time-epoch, the image intersection output is the 3D coordinates of the beads that appear in both images. A point-based registration method is used to combine the 3D coordinates from images intersection and the bundle adjustment-based coordinates. The final accuracy measure is reported as the differences between

the 3D coordinates from image intersection and bundle adjustment. A preliminary experiment of using the rotating planar object, has reported an average positional error of 0.3 ± 0.09 mm in the reconstruction of the bead coordinates. Further analysis will be applied to investigate the 3D reconstruction accuracy of different DF imaging configurations. Also, we will evaluate the accuracy of motion parameters (i.e., translations and rotations) derived from time-series DF images.

10332-4, Session 1

Accurate hole detection by fringe projection profilometry in the presence of discontinuity-induced measurement artefacts

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Locating holes and hole geometries in machined parts is often required in quality control and automated assembly. The current industry standard is to use coordinate measuring machines (CMM). As an alternative, fringe projection profilometry (FPP) techniques can scan part(s) in a single scan to generate a dense 3D point cloud of the measured part(s). In this paper, we investigate the ability of FPP to replace the costly and time consuming process of a CMM.

We measured a flat aluminium plate with arrays of circular holes ranging from 30 mm diameter down to 1 mm diameter with a mechanical CMM with a tip, by touching the holes along the perimeter at multiple points. The measurement accuracy of the holes using the CMM was 0.025 mm and the measurement process took more than 2 hours even having known the placement of the holes beforehand.

The same plate was measured by a Phase Vision Quartz 1200 FPP scanner. Using edge detection, cluster grouping and circle detection on the texture image, and subsequently fitting a circle to the X, Y,Z points on the perimeter, we were able to identify and characterise all holes except the smallest 1mm diameter holes. The root mean squared (RMS) error of the circle centres was in the range 0.099 mm - 0.03 mm. The radii estimated from FPP was consistently larger and the rms error (0.22 mm - 0.46 mm) was 11 times larger the measurement accuracy of the CMM.

In FPP, measurement artefacts occur at intensity and depth discontinuities. These symmetric artefacts overestimate the radii consistently, and these occur due to the finite point spread function (PSF) of the camera in the FPP scanner. Pixels on or in the neighbourhood (5 pixels in this case) of edges, average collected light emitted from both the surface and the hole, underestimating the intensity and the depth near the edge. This gives rise to a raised and lowered unwrapped phase and a subsequently distorted 3D edge.

In order to overcome this discontinuity induced measurement artefact (DMA) errors, we used a compensation technique by extrapolating from regions just outside the PSF zone after detecting the hole edge from the texture image to sub-pixel accuracy.

The RMS error of the estimated radii was reduced by 4-11 times in the range 0.02 mm (30 mm hole) to 0.36 mm (2 mm hole), while the centre location error was slightly improved and was in the range 0.06 mm (30 mm hole) to 0.04 (2 mm hole). Therefore, we concluded that the DMA error compensation method could be used with FPP to successfully measure holes larger than 4 mm diameter for the given scanner, with a radii rms errors less than 90 um (smaller for larger holes) and centre location errors less than 70 um (larger for larger holes).

10332-5, Session 2

Optical aberrations in underwater photogrammetry with flat and hemispherical dome ports

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The paper analyses differences between flat and dome port housings during underwater photogrammetric projects. First a short review of theory behind flat and dome port geometry is reported then experimental tests using a specifically designed photogrammetric modular testfield in a swimming pool and in sea water are described. The experiments are carried out using a Nikon D750 24 Mpx SRL camera with a 24 mm f2.8 AF/D lens coupled with a NIMAR NI3D750ZM housing, equipped first with a flat and successively with a dome port. The outcomes of self-calibrating bundle adjustment calibrations are shown and commented. Optical phenomena like field curvature as well as chromatic aberration and astigmatism are analysed and their implications on the degradation of image quality is taken into account through a different weighting of 2D image observations in the bundle adjustment.

10332-6, Session 2

Determining the beam directions for the laser illumination calibration

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In the modern world optical sensor systems have a vast number of applications. In many cases these systems are used to estimate the distances to the objects of the observed scenes. Therefore it is possible to obtain information about locations of the objects in the 3D space. Often the complex systems based on the both active and passive sensing technologies are utilized for such purposes. In this research work the system composed of the two cameras and the laser illumination with the 49 lasers is considered. All the system elements are fastened rigidly with each other. However their precise locations in the space relative to each other aren't known a priori because of the inaccuracies when manufacturing the system. In the previous research work we proposed the general calibration technique for the stereo camera system with the laser illumination. It was shown that the most complicated subtask in this technique is determining the beam directions for the laser illumination calibration because it couldn't be solved using the known algorithms. But finding the solution is necessary as far as these laser beam directions differ from the ideal directions considerably. This research is devoted to the development and the experimental approval of the algorithms to determine precisely the laser beam directions for the considered system. These algorithms can be used within the previously proposed calibration framework.

To perform the calibration of the laser illumination along with the cameras according to the proposed technique the classical calibration object in the form of the asymmetric chessboard can be used. The main stages which are required to execute for determining the beam directions for the laser illumination are the following: 1) tracking of the laser illumination points in the image sequence of the calibration object; 2) calculation of the coordinates in space for the found laser illumination points; 3) constructing the laser beams in space passing close as much as possible to the found points. There are many well-known algorithms to implement the mentioned stages. However not all of them appeared applicable for the calibration of the specific laser illumination. That is why we decided to develop the missing algorithms and also to adapt the existing algorithms to the given conditions.

To track the laser illumination points we need the algorithms for solving the following problems: 1) detection of the laser illumination points in the image of the calibration object; 2) extraction of the feature descriptors for the detected points; 3) matching of the extracted descriptors to find tentative correspondences; 4) exclusion of the false correspondences. To solve the first indicated problem we developed extra algorithms. The selection of the particular algorithm in this case is determined by type of the lasers utilized in the laser illumination. The form and the brightness of the laser spot depend on their type. So it was required to develop specific filters to detect such spots from the available lasers. In so doing we used the fact that the desired areas in the image have in average substantially higher intensity than the average intensity of the surrounding background. This fact is the distinguishing feature for detecting the laser spot. The center of the detected spot is assumed as the laser illumination point. The rest of the problems to track the laser illumination points are

easy to solve using the well-known algorithms.

The calculation of the coordinates in space for the found laser illumination points from the coordinates of the centers of the laser spots can be done in two ways. This stage can be performed based on the known solutions of the triangulation problem using the two cameras or the back-projection problem using each camera separately with averaging the result coordinates.

Much attention in this work is devoted to the stage of constructing the laser beams in space passing close as much as possible to the found points. Mathematically the assigned problem of determining the laser beam direction can be formulated as follows. The origin of the laser beam is known since it coincides with the known location of the laser on the laser illumination. Besides approximate coordinates in space for the points through which the laser beam passes are found in the previous stages. These coordinates can be a little distant from the real position of the laser beam path in space because of the inaccuracies in measurements. Thus the problem is to find the ray passing through the origin and the least divergent in mean square from the found set of points. To solve this problem we developed two algorithms. The idea of the first algorithm consists in the finding of two mutually perpendicular planes passing through the origin of the desired ray and the least divergent from the found set of points. The laser beam will be located at the intersection of these planes. The idea of the second algorithm consists in the finding of the parametric ray formula directly on the basis of the given criterion of optimality. This criterion is the minimization of the sum of the distances from the ray to the points from the found set. Consequently the beam directions in space can be determined for each laser of the illumination. These determined directions can be used as the subset of the calibration parameters for the whole system.

Within the scope of the research carried out, the main stages for determining the beam directions for the laser illumination are considered. The algorithms for performing each stage are suggested. Particularly, we developed our own algorithms taking into consideration specifics of the available system with the laser illumination, viz. the algorithms for detecting the laser illumination points, the algorithms for constructing the laser beam from the found set of points. The utilization of the known and developed algorithms makes it possible to determine the laser beam directions as the calibration parameters. These parameters are necessary to obtain for the implementation of the general calibration technique for the stereo camera system with the laser illumination.

10332-7, Session 2

Out of lab calibration of a rotating 2D scanner for 3D mapping

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Mapping is an essential task in mobile robotics. To fulfil advanced navigation and manipulation tasks a 3D representation of the environment is required. Applying stereo cameras or Time-of-flight cameras (TOF cameras) are one way to archive this requirement. Unfortunately, stereo cameras have drawbacks when scanning low textured areas or have insufficient lightning. In contrast TOF cameras have a low measurement range and suffer from strong light influences, e.g., sunlight. Therefore, costly 3D laser scanners are used. An inexpensive way to build a 3D representation is to use a 2D laser scanner and rotate it around an additional axis.

A 3D pointcloud acquired with such a custom device consists of multiple 2D line scans. The pose of each line scan need to be determined to generate a 3D pointcloud. The pose consists of the encoder feedback as well as parameters resulting from a calibration. Using external sensor systems are a common method to determine these calibration parameters. This is costly and difficult when the robot needs to be calibrated outside the lab.

Thus, this work presents a calibration method applied on a rotating 2D laser scanner. It uses a hardware setup to determine the required parameters for calibration. This hardware setup is light, small, and easy to transport.

Hence, an out-of-lab calibration is possible.

The hardware components of the 3D scanner system are an HOKUYO UTM-30LX-EW 2D laser scanner, a dynamixel servo-motor, and a control unit. The scanner uses a laser source (? = 905 nm) to scan a 270 ? semicircular field. A dynamixel controller regulates the rotation speed by receiving speed commands via USB.

When rotating the scanner, it supplies scans via ethernet with a frequency of 25 Hz.

The calibration system consists of a hemisphere, cf. Figure 1a. In the inner of the hemisphere is a circular plate mounted, cf. Figure 1b. The 3D scanner has to be positioned roughly in the center of the hemisphere, such that the motor axis is close to the axis of the hemisphere.

The scanner software as well as the calibration algorithm are implemented as ROS-nodes which are available at: (Link supported after review.).

The algorithm needs to be provided with a dataset of a single rotation from the laser scanner, cf. Figure 1c.

To minimize the impact of measurement errors, the same scan is performed multiple times and averaged. To achieve a proper calibration result the scanner needs to be located in the middle of the hemisphere. If the offset is too big, the individual calculations are not assignable. The aim of the calibration system, cf. Figure 2, is to register the angular deviation (? and ?), the position deviation of the 3D scanner (in X- and Y -direction), and its scan length deviation (R of f). Therefore following parameters are required: diameters of the plate (d plate) and hemisphere (d hemisphere).

By means of geometric formulas the algorithms determine the individual deviations of the placed laser scanner.

In order to minimize errors, the algorithm combines the above mentioned formulas in an iterative process.

To verify the algorithm the laser scanner was mounted differently, the scanner position and the rotation axis was modified. In doing so, every deviation, was compared with the algorithm results. Several measurement settings were tested repeatedly. Additionally, the length deviation of the laser scanner is determined as there is an increased influence on the deviations during the measurement.

10332-8, Session 2

Compensating over-/underexposure in optical targets pose determination

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Optical coded targets consist in distinctive visual patterns designed to be automatically detected and measured in camera images. The a-priori knowledge of the position and/or the dimension of specific features, such as corners, lines or other shapes, is used to determine the target relative position and orientation from its projection on the image plane. Several target designs and detection algorithms have been proposed in the literature, such as ARToolKit (Wagner et Al, 2008), AprilTags (Olson, 2011) and arUco (Garrido-Jurado et Al, 2014) yet the field is still fertile for research due to the countless number of applications such as camera calibration, photogrammetry, robotics, augmented reality and in machine vision techniques in general.

One factor that influences the accuracy of target relative pose determination is the image exposure time. Indeed, the most critical step in target ranging algorithms is the accurate measurement of specific features, such as lines and circles, on the image plane. However, the amount of light entering the imaging systems influences their apparent position. This effect is ultimately caused by the lenses not being ideal, and the light coming from a specific direction affecting also neighboring pixels. In Figure 1 we compare two images of the same scene, taken with different exposure times. A ranging algorithm for such a target (Cucci, 2016) based on the size of the two main concentric circles would estimate different target poses for these images, even tough they depict the same scene. It is possible to show that the same happens with other state-of-the-art algorithms, such as arUco.

In many optical targets applications, such as in photogrammetry, autonomous navigation and robotics, it is difficult to automatically achieve optimal image exposure because of unpredictable light conditions, variable scene illumination as a function of time and space, and reflection on the target surface. Automatic exposure algorithms are implemented at acquisition level and tipically optimize the overall scene exposure, which does not guarantee optimal target exposure.

In this work we show how an exposure invariant target ranging algorithm can be designed based on the specific target design. The reference target design, depicted in Figure 1 is based on two concentric circles and on a code given by the position of the white dots in the outer black ring. The same patter repeats in a fractal fashion to allow for multi-scale detection (e.g., from very far, or very near). In brighter images the light from white regions is captured also at pixels which correspond to black regions in the darker images, de facto affecting the apparent positions of edges. In particular, the inner circle appears to have a bigger diameter, whereas the outer a smaller one. We note that this effect on the circles size is orthogonal to the one obtained changing the target distance from the camera, in which case both circles would appear smaller or larger. We are thus able to design an algorithm that exploits this effect to estimate the circle contour shift due to over/under exposure, called ?, and thus achieve illumination invariant target ranging.

We performed scrupulous experimental evaluation of the algorithm in controlled laboratory conditions, in which the target position have been measured to millimeter precision with teodolites and several images were captured with different exposure times. The results were a very accurate target position accuracy, with a mean error of 0.2% with respect to the actual target distance, and invariant to illumination changes. In Figure 2 we show the illumination invariance property of the novel algorithm, for a single target position, plotting the target distance estimated by the algorithm in (Cucci, 2016) and the illumination invariant one. Finally, we observe that the ? parameter is substantially uncorrelated (< 5%) with respect to the target position parameters.

10332-9, Session 2

Appearance-based video change detection using slanted viewing from repeat-pass UAV missions

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There has been an increased use of unmanned aerial vehicles (UAV) during the last years. In particular, for video reconnaissance and surveillance, UAVs have been proven to be a flexible and useful platform. An important application in this context is change detection in UAV video data. Here we address short-term change detection, in which the time between observations ranges from several minutes to a few hours. We distinguish this task from video motion detection (shorter time scale) and from long-term change detection based on time series of still images taken between several days, weeks, or even years. Each observation (previous and current) is a short video sequence acquired by UAV. Relevant changes are, e.g., recently parked or moved vehicles or displaced objects. Examples for non-relevant changes are parallaxes caused by 3D structures of the scene, shadow and illumination changes, and compression or transmission artifacts. We addressed this task already in (Saur & Krüger 2016a) in the case of Nadir viewing geometry thus assuming a 2D task and considering the 3D effects as noise.

In this paper, we study UAV video change detection using slanted viewing onto a 3D scene. In this case, the effects of varying appearance and shading of the scene objects, of varying visibility of the object faces and of parallaxes of scene objects w.r.t. the background are much more prominent compared to using Nadir view. The main challenge of our task consists in transferring the detection performance of the 2D case to this 3D case. Possible approaches may consist in modelling the 3D effects by structure from motion methods or by bundle block adjustment and detecting changes in the 3D domain.

In our paper however, we suggest an approach which is based on repeat pass UAV missions. The flight paths and the video footprints of the UAV missions are configured to be repeated identically. By the investigations it turned out, that when using a commercial of the shelf UAV (DJI Phantom 3), the sensor positions in a continuous flight (not only for isolated single way points) are visited and reproduced with an accuracy that is sufficient for applying our 2D change detection methods. Not too unfavorable weather conditions (wind, humidity) are assumed, of course.

The paper describes the following aspects of the task:

1. Processing chain: Selecting corresponding video frames (see Fig. 1 right), registering the images to each other (Saur & Krüger 2016b), applying 2D change detection (see Fig. 2), temporal filtering of detection results, elimination of moving objects.

2. Analysis of the expected and observed errors caused by the sensor displacements depending on the flight path and viewing geometry. Especially the case of small 3D structures is considered where 3D methods are expected to provide only a limited benefit.

3. Illustrated example applications for several UAV flights (see Fig. 1 left for circular flight path near a parking site) and viewing geometries (fixing one single point or fixed viewing angles relative to the platform).

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10332-10, Session 3

A new angular and positioning sensor-system with vignetting field stop procedure allows 6 DoF per axis

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Using a reflector with a plane mirror combined with a double triple reflector it is possible to measure and monitor six degrees of freedom in one moving axis.

For this purpose, the Vignetting Field Stop method according to Dr. Hofbauer is used in which, with the aid of an extended light source, the aperture stop acts via a reflecting element as a field stop forming the vignetted SPOT (so called V-SPOT) as a blurry stop in the field of image.

The position of the V-SPOT varies according to the angle of device under test and is evaluated with digital image processing with a reproducibility of up to 0,03 Pixel depending on size of V-SPOT and effective binarisation.

First, with the mostly centered mirror, the angle of DUT is directly imaged on the sensor. Second, with one or two triple prism the autoreflection process starts and the reflected light will change according to the lateral position of the triple prism.

Third with the aid of two well-known distanced triple prism we can do a simple triangulation procedure and calculating the distance between reflector and sensor, measuring the actual angle of the two spots and knowing the distance of the triple prism.

The intensity Distribution in the field of object will influence the linearity and zero point stability of the sensor and therefore compensation effects will be done. The Talk will show some compensation procedures to optimise the uniformity of luminance in object field and illuminance in the image plane to compensate errors of illumination. Linearity in dependence to angle and also varying distance will be considered and compensated.

The highest accuracy is reached by the angular measurements in two perpendicular directions. The measurement reproducibility is smaller than 0,0001 deg (0,3 arcsec) and the linearity smaller than 0,02% over a measurement range of +/- 3 degree and distances from 300 mm to 2400 mm. This is actually limited only by a wide-angular-measurement system in our research project WiPoVi.

The lateral positioning accuracy is about < (1 µm + 2 µm/m*lengh). The distance measurement sensitivity is dependent on absolute distance and reaches up to 0,003% (33 ppm; about 150 µm at distance of 5 m). The roll angle is the last of the six degrees of freedom. The reproducibility reaches up to 0,002 degree (6,8 arcsec).

The measurement uncertainty over the whole measurement process will be considered and an error budget will be shown concerning the influence of environment, adjustment and sensor unperfectness.

10332-11, Session 3

Novel short-pulse laser diode source for high-resolution 3D flash LIDAR

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Imaging based on laser illumination is present in various fields such as medicine, security, defense, civil engineering and automotive sector. In this last domain, research and development to bring autonomous vehicles on the roads has been intensified these years and various technologies for geolocation, object detection and recognition are under strong developments to increase detection reliability, which also includes combination of different sensors and data fusion for the highest automation levels. In particular, interest in automotive lidars is fast-growing due to their obvious accuracy to detect a wide range of objects at distances up to a few hundreds of meters in various weather conditions. First commercialized devices for ADAS (Advanced Driver Assistance System) were laser scanners. However, main hurdles for their wide introduction to the general public are their high cost and poor robustness due to a high number of complex mechanical parts required for integration of a rotating mirror or prism needed to achieve a 360° mapping. This is the reason why new architectures have recently appeared such as solid-state lidar and flash lidar. Flash lidars, as other ranging techniques, are based on time-of-flight measurements, with the particularity that they do not require beam scanners because only one short laser pulse with a large divergence is used to enlighten the whole scene. Depth of encountered objects can then be recovered from measurement of echoed light at once, thus enabling real-time 3D mapping of the environment. These new generation sensors provide major improvements in compactness, robustness and affordability for automotive ADAS, but also for high-resolution 3D measurements of buildings or area monitoring.

The best candidate for flash lidar light source is certainly laser diodes. They can offer highly divergent beams in a compact package at a low cost and with a high electrical-to-optical efficiency due to their inherent properties, without having to compromise on performances of final systems, because laser diodes can provide short pulses at a kilohertz repetition rate. A recent breakthrough in laser diode and diode driver technology made by Quantel (France) now allows laser emission higher than 1 mJ with pulses as short as 12 ns in a footprint of 4x5 cm2 (including both the laser diode and driver), leading to peak powers in the range of 100 kW. Their electrical-to-optical conversion efficiency is higher than 30%, making them suitable for integration in environments in which compactness and power consumption are a priority. Their emission in the range of 800-1000 nm is considered to be eye safe when taking into account the high divergence of the output beam.

An overview of architecture of these state-of-the-art pulsed laser diode sources will be given in which highly efficient diode bars and a dedicated pulse generator were integrated. Experimental results of such illuminators integrated in 3D mapping systems will be discussed together with future work leads for miniaturization of the laser diode and drastic cost reduction.

10332-12, Session 3

Methods for linear radial motion estimation in time-of-flight range imaging

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Time-of-flight (ToF) range imaging is the multiframe method of acquiring full field distance measurements [1]. The distance images from a ToF camera provides the means to analyse shape at full frame rates. Unlike some other forms of distance imaging, ToF range imaging has low computational burden, where instead the burden is placed on the specialised lidar imaging camera to encode distance across a small number of raw frames. During the capture of the raw frames, the scene under observations is assumed static. Herein lies the problem of motion in ToF imaging, namely that if objects move then the static scene assumption is broken and the range measurements subsequently corrupted.

ToF range imaging is an active imaging technique. The range imaging process proceeds by active light modulation over time, typically in the tens to low hundreds of Megahertz. The travel time, or ToF, induces a phase shift in the light modulation envelope, which in turn is directly dependent on the distance that the light travels. The light return is demodulated at the sensor by the sensor shutter operating in homodyne with the light source, typically by transistor switching on pixel in CMOS. Integration by the sensor acts as a low pass filter, leaving only the direct current part of the demodulated signal.

At each integration there are at three unknown variables, the brightness and phase of the modulated light return, and the background light intensity. Therefore, at least three measurements, viz. raw frames, are required to solve for the phase shift and compute the range image. An extra programmable electronic phase shift is added to the light source for each raw frame, and this phase shift is stepped in sequence between the capture of the raw frames. The sequence of measurements at each pixel over the raw frames is a correlation wavefunction between the light return and sensor modulation wavefunctions, and the phase of the correlation wavefunction is the phase shift due to the ToF of the light.

The phase stepping process is designed to encode distance and amplitude in an efficient manner. Radial motion introduces a fourth variable in addition to the three listed above. The phase stepping also encodes this fourth radial motion variable in the form of a pseudo-Doppler shift. That is, the correlation wavefunction is stretched (compressed) when objects move towards (away) the camera. Electronic bandwidth limitations and the large number of pixels in ToF cameras necessitates a small number of samples of the correlation waveform, typically over one period. Therefore estimating radial motion is challenging and we must devise new signal processing and statistical analysis methods.

Classical signal processing provides the means to estimate radial motion from raw ToF camera data. In this work we will consider methods to obtain pseudo-quadrature measurements to compute radial velocity at low speeds. Making the assumption that the motion is undetectable in each set of raw phase steps frames, we construct the quadrature estimate of the correlation waveform. The quadrature estimate is analysed within and between sets to find the radial velocity and an uncorrupted range measurement.

Stochastic calculus [2] is the analysis of noisy time series data, bringing a consistent theory of integration and differentiation to continuous and discrete signal that are corrupted by random noise. Stochastic calculus enhances classical signal processing by providing the tools to analyse noisy data, and seek statistical means to estimate desired parameters, such as radial motion in raw ToF data. Invoking stochastic calculus, we will supplement the signal processing for low radial velocity measurement by analysing the correlation waveform to extract and estimate radial motion. Discrete stochastic differentiation and integration will expose the radial velocity in the rate of change of the correlation waveform in time. Using Pearson's correlation coefficient, analysing the difference between the derivative and the indefinite integral of the correlation waveform with respect to the phase steps we statistically infer the radial velocity.

The work will yield a suite of radial velocity measurement methods using a single ToF range imaging camera. These methods will be compared with each other and evaluated in simulation and by measurement using a ToF camera. The anticipated results will lead to recommendations on the suitability of radial velocity measurement methods in applications, and extension to more general forms of motion.

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10332-13, Session 3

Unsynchronized scanning with a low-cost laser range finder for real-time range imaging

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Range imaging plays an essential role in many fields: 3D modeling, robotics, heritage, agriculture, forestry, reverse engineering. One of the most popular range-measuring technologies is laser scanner due to its several advantages: longer range, highly precise and real-time measurement capabilities, no lighting condition dependency, and less computational power requirement. However, laser scanners are very costly. Their high cost limit their usage in applications with low-cost limitation, especially for static environments like heritage sites. Thanks to the latest developments in electronics, optics, computer vision, computational processing power, now, we have begun seeing low-cost, reliable, faster, and light-weight 1D laser range finders (LRF), which are also called point laser range finders. A low-cost 1D LRF with a scanning mechanism, providing the ability of laser beam steering for additional dimensions, enables us to capture a depth map. On the other hand, some obvious limitations of these low-cost LRFs needed to be addressed; for example, the ever-changing sampling frequency of the LRF causing longer scanning period in synchronized scanning, larger laser pulse diameter preventing the use of rotating mirror systems. In this work, first some reliability tests have been done on the chosen sensor. As a result of these experiments, the sensor is reliable for different colored surfaces, but it malfunctions on rough shiny surfaces. Moreover, one important characteristic of the chosen sensor is that the acquisition time increases when the distance between the sensor and the target surface increases: this causes fluctioations in sampling frequancy which is the reason for uneven sampling intervals in unsynchronized scanning. In this work, we present an unsynchronized scanning with a low-cost LRF to decrease scanning period and reduce vibrations caused by "scan-stop" in synchronized scanning. Moreover, we developed an algorithm for alignment of unsynchronized raw data and proposed range image post-processing framework. The algorithm is composed of six main processes: position feedback alignment in bidirectional scanning, noise cancellation, line alignment and scaling, interpolation of uneven sampling intervals, deinterlacing, and anisotropic filtering. The proposed technique enables to have a range imaging system for a fraction of the price of its counterparts. The results prove that the proposed method can fulfill the need for a low-cost laser scanning for range imaging for static environments because the most significant limitation of the method is the scanning period which is about 2 minutes for 55,000 range points (resolution of 250x220 image). In contrast, scanning the same image takes around 4 minutes in synchronized scanning. Once there are faster LRFs available, the scanning period will respectively shorten.

10332-14, Session 4

Optical sensors for robotics and automotive applications: an industrial perspective *(Invited Paper)*

Max Ruffo, Terabee (France)

No Abstract Available

10332-15, Session 4

Comparison of calibration strategies for optical 3D scanners based on structured light projection using a new evaluation methodology

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Applications in industrial quality management, rapid prototyping, archaeology and paleontology, architecture, arts and cultural heritage preservation, medicine, and forensics are increasingly using 3D sensors based on structured light projection technique. Measurement accuracy is one of the most important features for certain applications, especially in industrial quality management. However, not only the physical properties of the hardware components and their arrangement in the sensor are essential for the measurement precision. The quality of system is one crucial element for the measurement accuracy.

In this work two different calibration strategies for structured light based stereo scanners are compared concerning handling, personal effort, level auf automation and the achievable precision of the subsequent 3D measurements. The first calibration strategy follows the common principle of bundle adjustment. The commercially available software package BINGO was used. The second strategy used the well-known OpenCV-calibration procedure using views of a planar chessboard pattern. Additionally, two short-calibration methods were involved into the comparison.

Several 3D scanning devices developed at our institute were calibrated using both strategies and measurements of certain reference specimen were performed in order to evaluate the calibrations.

BINGO-calibration was performed using different calibration bodies. First was the same chessboard pattern as in the OpenCV-calibration. The second was a similar plane showing a squared grid pattern. This pattern is more suitable for involvement of projection device in the calibration procedure which is usual in structured light profilometry. Third calibration body was a frustum of a pyramid placed on arbitrary ground which was used for self-calibration.

The evaluation of the calibration quality was performed using a new methodology for evaluation of the current state of an optical 3D scanner based on structured light projection technique. This new methodology will be described in detail. It determines mean and maximal random and systematic measurement deviations. Evaluation measurements of certain specimen and analysis procedures have to be performed and analyzed. The used characteristic parameters for the evaluation complement the parameters from the known VDI/VDE guidelines for optical 3D measurement systems based on area scanning.

The results of the comparison show the big influence of the intrinsic camera parameters including distortion correction operators for the quality of the complete calibration. Here, the BINGO package provides more selectable distortion functions leading to a better calibration quality. However, a remaining problem is the high correlation between certain calibration parameters, especially intrinsic parameters and certain distortion coefficients. This leads to a manual intervention of the user at certain moments of the calibration procedure and requires a high level of experience. Additionally, complete automation of the calibration process is not always possible to obtain.

BINGO-calibration showed a high quality, well balanced calibration result and a better calibration quality than using OpenCV, because OpenCV-calibration was more sensitive for errors if the extrinsic conditions were not optimal. Especially deviations from radial and decentering distortion cannot be handled with the OpenCV-software.

Future work will be addressed to the automation of calibration procedures and the involvement of more scanning devices into the comparisons. Additionally, calibration conditions should be set to certain describable levels, and the calibration quality should be analyzed depending on these levels.

10332-16, Session 4

A photogrammetric technique for generation of an accurate multispectral optical flow dataset

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Optical flow based methods proved to be a robust solution for visual odometry problems in such fields as an autonomous driving or mobile robotics. In recent years deep learning based algorithms have shown the best results in optical flow estimation. However for a successful learning of such algorithms a large dataset with ground truth optical flow is required. The generation of such dataset is challenging as no reliable devices for optical flow measurement are developed to date. This paper presents a novel photogrammetric technique for generation of an accurate ground truth optical flow. We introduce Zero Endpoint error optical Flow dataset with InfraRed Uniform motion Sequences (ZEFIRUS) that was created using the developed technique. In contrast with most modern optical flow datasets the ZEFIRUS dataset contains long image sequences captured in visual and infrared wavelengths with an accurate and uniform ground truth optical flow.

The developed technique is based on two different methods that are common in optical flow dataset generation: synthetic motion flow generation and camera motion estimation. The main drawback of a synthetic optical flow is that it is generated for synthetic images. If optical flow estimation algorithm is trained only on synthetic images it will provide poor performance when applied to real images. The developed technique overcomes this drawback by providing an accurate synthetic optical flow for real image sequences. It is achieved by an accurate tracking of a calibrated camera using high-speed motion capture system. A custom developed motion capture system was used for the measurement of an optical flow. The motion capture system includes up to 4 high speed cameras capable of recording sequences with frame rate up to 100 frames per second. The captured trajectory is loaded into 3D-modeling software that generates a synthetic optical flow using a 3D-model of a real scene. The open source 3D-modeling software Blender was used for generation of a synthetic optical flow. A custom software was written for conversation of the Blender internal optical flow format to the .FLO format used in the Middlebury optical flow dataset.

To produce accurate 3D-models of the environment captured in real image sequences an industrial laser scanner was used. A dense point cloud was produced by the laser scanner. The point cloud was triangulated and separated to 3D-models. A number of targets were used for transformation of the recorded data to a common coordinate system.

The ZEFIRUS optical flow dataset was created using the developed technique. The dataset is focused on scenarios related to mobile robotics and autonomous driving such as obstacle avoidance, wheel slip avoidance and parking in a garage. A custom developed mobile robot equipped with infrared and visual cameras was used to record image sequences. The robot is based on a skid-steering mobile platform. Raspberry PI computer with a WiFi adapter was used to control the robot. To record infrared image sequences the FLIR ONE thermal imaging camera was used. The camera was connected to a smartphone that was mounted on a mobile robot. The synchronisation of the mobile robot, the motion capture system and the FLIR ONE was provided by WiFi network.

The problem of synchronisation of robot's cameras and motion capture system is discussed. The dataset includes images captured under various challenging conditions such as low light and complex ground textures. The design of LED markers for a reliable performance of the motion capture system under low-light conditions is presented. A number of integrity checks were used to provide a nearly zero endpoint error of the ground truth optical flow. As well as the ground truth optical flow the dataset includes accurate 3D-trajectories of the camera that could be used to assess wheel slip avoidance algorithms.

Visual and infrared image sequences of the ZEFIRUS dataset were used to evaluate optical flow algorithms. The benefits and challenging aspects of the modification of optical flow algorithms for multiple channel image sequences are discussed. The evaluation of optical flow algorithms on the developed dataset proved that fusion of visual and infrared data provides a significant improvement in an accuracy of an optical flow algorithm under low light conditions.

10332-17, Session 4

Localisation accuracy of semidense monocular SLAM

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In many applications SLAM (Simultaneous Localisation and Mapping) technology is used to generate scaled metric maps. Other SLAM approaches function exclusively in image space and is not the focus of this paper. In this paper, the ability of a semi-dense monocular SLAM approach to generate accurately scaled maps, or the localisation accuracy, is evaluated. Semi-dense approaches dispense with feature extraction in order to generate a dense map of the environment. It is also claimed that semi-dense approaches are computationally faster than feature-based approaches. Monocular SLAM is attractive in many applications due to the low cost of the sensor and rich data obtained from it. It can also function in GPS denied environments. Accurate metric information is vital if the SLAM feedback is to be fused with other sensor data, e.g. GPS, or if it is to be related to existing maps. In previous work by the authors, the error propagation of monocular SLAM was modelled. It was found that after an initial phase, the error grows linearly. The growth rate and error magnitude strongly depends on the sensor and vehicle kinematics. Existing literature report some results for localisation accuracy of feature-based monocular SLAM approaches, but no results are available for semi-dense monocular SLAM.

In this paper, experimental results are reported that verify the modelled results. Outdoor test runs were repeated 16 times over a distance of one hundred meters. In each test run, a straight line was followed, therefore loop-closure is not considered. Monocular SLAM can only obtain metric data up to scale, therefore the results were scaled by using a reference point after a short distance (5 m, 10 m and 15 m from the start were tested). The LSD-SLAM algorithm developed at the Technical University of Munich is used as representative of a semi-dense monocular SLAM approach. The SLAM output of each run is compared to odometry data from the test run. It is verified that the odometry data are more than an order of magnitude more accurate than the SLAM results. The experimental results confirm the trend predicted by the modelled results, but the magnitude of the localisation error is much bigger than predicted by the model. After 100 m the experimental localisation error was up to 80 m! It is also much bigger than comparable studies done with feature-based methods as reported in literature. The closest comparable study of a feature-based approach found a 3.5 m error after covering a distance of 205 m.

The results are useful in that it confirms the trend predicted by the model, however further refinement of the model is needed in order to predict the error magnitude accurately. Possible reasons for the deviation is that the model do not take mismatched image points into account, some random image distortions from the webcam used in the experiments were also found and finally the model is based on an Extended Kalman Filter. A more accurate filter, e.g. a particle filter, may give better results. The results also seem to indicate that semi-dense monocular SLAM, used in isolation, may not give adequate results.

10332-18, Session 5

Investigation of indoor and outdoor performance of two portable mobile mapping systems

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The aim of the paper is to investigate the performances of the non-traditional handheld ZEB-REVO and the backpack solution Leica Pegasus. Both systems are evaluated in indoor (Figure 2) and outdoor (Figure 3) environments. In the indoor test, two-floors of a building are surveyed with the two portable MMS and reference measurements are taken using a ToF (time-of-flight) phase-shift laser scanner (Leica HDS7000). The indoor scene, characterized by smooth and homogenous surfaces, as well as constructive elements like columns, is also used to derive meaningful information about noise on horizontal and vertical planes, along with fitting of geometric primitives for the two systems. On the other hand, the outdoor experiment is carried out in an open square where the two portable MMS are compared against a classical MMS mounted on a car, the RIEGL VMX-450. A robust statistical analysis is performed to evaluate the portable MMSs geometric performance outdoor.

The full paper will present the results of both tests and discuss the critical issues related to the systems under investigation.

10332-19, Session 5

Construction of a vehicle for recording basic data of roads

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We have developed sensor units and additionally installed them on an existing measuring vehicle in order to be able to record various road parameters. These parameters mainly include the inclination of the road, both parallel and perpendicular to the travel movement, the width of the road, the detection and location of road markings and the detection of weather-related road damage. These values can be used to calculate the maximum speed, the shock absorber settings or optimize the driving comfort of vehicles.

The roll-angle-module, in conjunction with the additional values given by the measuring vehicle itself, provides the transverse inclination of the road. For this purpose, the distances obtained from two IR modules located on the outside of the vehicle are recorded in real time and the resulting angle of the vehicle with respect to the road is determined with a suitable function. This is necessary since the measured value changes of the two modules based on the rotation-related movement and the radiation characteristics of the IR modules do not have the same magnitude. Thus, without mathematical adjustment, the ascertained value of the inclination would be greater than the actual angle of vehicle to the road. This value is again calculated with the angle from the vehicle to the center of the earth, which is output directly from the vehicle, and the angle of the road is obtained.

The angle in the direction of travel is calculated purely on the GPS data. A mesh of the road topography can be created by the superposition of the angular values at all measurement coordinates.

The width module, which consists of a camera and two line lasers, provides the width of the roadway in a post-processing step. Furthermore, road markings are detected and provided with the corresponding time stamp of the video and grouped on the basis of various criteria. The lasers used here serves as a width standard for calibration. A schematic diagram of the measuring vehicle is shown in Figure 1.

The post processing is done by means of Python code, which stores the individual frames of the recorded video one by one. By means of this routine, colors are detected, a recalibration of the width over the created “green” image is executed and then the “white” image is examined on objects with specific parameters and divided into groups, such as “pedestrian crossings”.

The bluish-colored cameras shown in Figure 1 are used for the stereoscopic recording of the road and the subsequent processing and recognition of road signs, traffic lights and roadside borders. The output can be done as a text document or as a collection in the graphical user interface.

Furthermore, a laser module is used to generate a structured light pattern in order to detect weather-induced influences on the road, such as potholes. For this purpose a routine was developed and adapted, which can determine the dimensions of the road defects based on the position of the imaged points and the known geometric parameters.

10332-20, Session 5

Range resolution analysis of stereo triangulation of forward-facing vehicle-mounted monocular and binocular cameras for augmented reality applications

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In this paper, we analyse the triangulation of objects in front of a forward-moving monocular or binocolar camera, in particular with respect to automotive Augmented reality applications. Triangulation proceeds by capturing a series of images along the vehicle trajectory. I.e. the stereo baseline is given by the vehicle movement and, for binocular setups, by the camera baseline. Note that apart from triangulation of object positions, no parameters are estimated. In particular, it is assumed that the camera calibration and vehicle trajectory are known with sufficient precision, e.g. from a-priori calibration or vehicle odometry.

Augmented reality applications are the motivation of the present analysis. For these, knowledge of the geometry of the enviromnent is a crucial requirement for exact and environment-aware augmentations. Furthermore, we have the special situation that one the one hand, viewing distances can be quite large in traffic situations (often several hundreds of meters, sometimes more than one kilometer), but on the other hand, the presence of the street in front of the vehicle means that usually, there is (apart from moving vehicles, which are already detected by specialized driver assistance packages in many modern cars) a large open space directly in front of the camera. We argue and later show in detail that this open space in front of the vehicle mitigates the fact that for the monocular setup, there is a singularity along the line of movement, on which triangulation is not possible.

The analyis of this singularity, of the behavior near the singularity and of the difference between monocular and stereo setups in this region forms the main body of the paper. In particular, we focus on the derivation of explicit formulas or approximations for the relevant variables in order to obtain a detailed and geometric understanding of this singularity.

In order to obtain explicit formulas, we assume as a simplification that the vehicle travels with constant speed in a perfectly straight line. This approximates a common case since a large fraction of roads are either straight or bend with large curve radii.

Furthermore, it is well-known that this is actually the worst case since the singularity along the line of movement is only present for one-dimensional trajectories.

From the map $k:p->m$, which maps object positions to vectors of (noise-free) measurements, we obtain its Jacobian J, whose singular values (in particular the inverse of its smallest singular value) are crucial in order to understand the achievable precision of the object triangulation. We access the singular values of J via its symmetrization $J^T J$. Examination of $J^T J$ shows that the direction of the baseline of the stereo setup is actually irrelevant for triangulation. This allows us to eliminate one degree of freedom and to split off one of the three singular values of J. We obtain an explicit formula as well as asymptotic approximations for the smaller one nu_min of the remaining singular values, which is the overall smallest singular value.

Next, we plot the inverse of nu_min for monocular and stereo setups for a typical situation, which clearly shows the singularity in the monocular setup. However, examination of the behaviour surrounding the singularity shows that already quite close to the singularity, the behaviour of monocular and binocular setup is quite similar and for positions distant from the singularity, the main advantage of the binocular setup is due to it capturing twice as many frames as the monocular setup. We examine this behaviour in detail as follows.

We use integral approximation to transform the sums in $J^T J$ caused by aggregation of multiple frames first into integrals and then into explicit formulas. This way, we can show that if one compensates for the different number of captured frames, the difference between monocular and stereo setup can be described using only the following variables

- the ratio of lateral distance to longitudal distance of the triangulated object (i.e. the distance of its image position to the image centre)

- the ratio of the baseline of the stereo baseline to the distance travelled by the vehicle while observing the object

In particular, positions at which the ratio of performances of monocular and stereo setup has a given value lie on the surface of a cone around the axis of movement, with the tip of the cone given by the vehicle position. Inside the cone, the binocular setup performs much better, outside the cone, the performances become more similar.

In particular, this is used to show that for most objects encountered in vehicular Augmented reality applications, the advantage of automotive-grade stereo setups over monocular setups is mainly caused by the larger number of frames captured.

In the last section of the paper, we perform a Monte-Carlo simulation of triangulation performance by performing least-squares fitting to synthetically generated noisy measurements. This way, a rough bias analysis is provided and the analysis of the covariance estimation using the inverse of smallest singular value nu_min of the Jacobian J is verified.

10332-21, Session 5

Real-time localization of mobile device by filtering method for sensor fusion

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Recently, development of high performance CPU, cameras and other sensors on mobile devices have been used for wide variety of applications. Most of the applications require self-localization of the mobile device. GPS have been widely used for the self-localization in outdoor environment. On the other hand, the GPS cannot be used in indoor environment, the positions of mobile devices are estimated autonomously by using IMU including gyro sensor, acceleration meter and magnetic field sensor. Since the self-localization is based on IMU of low accuracy, and then the self-localization in indoor environment is still challenging. The self-localization method using images have been developed, and the accuracy of the method is increasing. This paper develops the self-localization method without GPS in indoor environment by integrating sensors, such as IMU and cameras, on mobile devices simultaneously. Since real-time localization is required for many applications, the method is developed as real-time localization method.

The key concept is that the localization problem is equal to stochastic process modeling. A data assimilation technique, widely used in many fields of geosciences, is employed as the stochastic process modeling. Also as the huge volumes of data is processed for the localization, sequential process is suitable as real-time method. According to the concept, the proposed method can be described in a form of state space model. The flow of the proposed method is depicted in Figure 1. The proposed method can integrate the data from IMU and camera. Since the data from IMU has various noises, denoising processes are applied in advance. For the localization by using images, various feature points extraction and tracking methods are compared.

The data assimilation technique consists of observations, forecasting and filtering. In the self-localization, observations correspond to observation data from IMU and camera, forecasting to mobile device moving model (system model) and filtering to tracking method by inertial surveying and photogrammetry (observation model). The self-localization process is modeled as follows. Positions of a mobile device (state vectors) being tracked are estimated by system model (forecasting step). Then estimated positions are optimized referring to the new observation data based on likelihood (filtering step). The optimization at filtering step corresponds to estimation of the maximum a posterior probability. Kalman filter and particle filter are utilized for the calculation through forecasting and filtering steps.

As before mentioned, the data assimilation system can be described in a form of state space model. For state space model, a state vector is defined as position and velocity of the mobile device. An observation vector is also defined as observations from IMU and camera. Then a system model which describes dynamics of the state vectors is formulated by using linearly moving model. Observation models are also formulated for the filtering step. The observation models consist of likelihoods with regard to data from IMU and camera. The likelihood of data from IMU is model based on linear equation according to inertial surveying. The likelihood of data from camera is calculated by integrating coplanarity condition and inverse depth model (Figure 2), which are nonlinear equations. By using the state vector, the observation vector, the system model, and the observation models, sequential Bayesian filtering is applied to estimate the positions of the mobile device. For the linear model, namely observation model for IMU, Kalman filter is applied. For nonlinear model, namely observation model for camera, particle filter is applied. The particle filter is extended to Rao-Blackwellized particle filter to make estimation stable. The positions can be estimated at every time of data acquisition, real-time localization is accomplished.

The proposed method is applied to two kinds of data acquired by mobile devices in indoor environment. The total lengths of the pathways are 7.5 m in a room, and 31 m in a corridor. The results are 40 cm and 3.7 m as root mean squared errors, respectively. Through the experiments, the high performance of the method is confirmed. As a result, the method will contribute developments of services with mobile devices, and then will be expected to contribute convenient interface between real and virtual space.

10332-26, Session PS1

A generic point error model for TLS-derived point clouds

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My abstract includes some equations and figures. Because of this reason, I uploaded my abstract as a supplemental file in PDF format. For review process please see the supplemental file in PDF format.

10332-27, Session PS1

Depth image super-resolution via semi self-taught learning framework

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Depth images have recently attracted much attention in computer vision and high-quality 3D content for 3DTV and 3D movies. The emerging consumer depth cameras, such as Microsoft Kinect and Intel RealSense, can capture 3D range data at frame-rate as a per-pixel depth. However, the resolution of depth image provided in these low-cost cameras is generally very limited. A brute-force upscaling of obtained resolution depth will blur sharp boundaries, which cannot be applied in practice.

The mainstream techniques of depth image upscaling use the aligned RGB color image as a guidance cue. It has a general assumption that depth maps and the corresponding color or intensity images are two descriptions of the same scene from different perspectives, thus presenting strong structural correlations. Unfortunately, the corresponding color and depth image pair do not always appear as a companion in many practical situations. Meanwhile, in 3D image hardware, the calibration error of pairing color image and depth image is nearly inevitable. Furthermore, color texture and depth discontinuities are always uncorrelated, which causes texture copying artifacts in many methods.

In this paper, we present a new semi self-taught learning (SSTL) application framework for enhancing resolution of depth maps without making use of ancillary color image data at the target resolution, or multiple aligned depth maps. Our framework consists of cascade random forests reaching from coarse to fine results. We learn the surface information and structure transformations from both small high-quality depth exemplars and the input depth map itself across different scales. Considering that edge plays an important role in depth map quality, we optimize an effective regularized objective that calculates on output image space and input edge space in random forests. We use modified random forests to classify the depth image space into numerous patch subspaces and learn a linear regression model for each subspace. In stage one we train the forest model in high-quality dataset to obtain initial regression representation as features for regression, while in stage two we gain finer upscaling results. Our method can be regarded as a combination of example-based super resolution methods and classical multi-image super resolution methods.

We evaluate the performance of our method through various experiments with synthetic clean Middlebury benchmark dataset and real-world laser scan dataset. Our quantitative and qualitative results are both shown together with some latest method results. We obtain the state-of-the-art performance on real-world laser scan dataset and exceed SRCNN for most test samples from Middlebury benchmark dataset. Average RMSE error of the proposed method with upscaling factor of four is 0.0098 on real-world laser scan dataset. We avoid the problem that textures in color image would be over-transferred to depth image on homogeneous regions. Our SSTL preserves clear lawyer information of depth image together with some detailed geometries.

10332-28, Session PS1

Reliable stereo camera calibration with a 3D pattern defined by a laser tracker

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Computer vision techniques provide reliable measurement in wide range of applications. The measuring accuracy is mostly limited by the definition and calibration of the vision system parameters. One of the most reliable and widespread techniques for obtaining such parameters is a camera calibration. The technique usually involve 2D and/or 3D calibration patterns, which are observed by the measuring system from various viewing directions. This commonly used approach requires calculation of 6m parameters (3 angles and 3 translations for each of m points of view) additionally to the camera parameters. This core problem is originated from the fact that spatial dimensions of the calibration pattern usually are strictly limited by required rigidity of the pattern. The rigidity should be high enough in order to eliminate sufficient errors in prediction of 3D pattern points' position. As a possible solution we proposed to use one continuous well-defined 3D pattern with sufficient number of points distributed all over the working volume of the camera-based system. In this case a number of calibrated parameters is decreased to just 15+k, where 9 parameters define intrinsic camera parameters, k coefficients of distortion (in practice, 4 or 5) and rest 6 parameters define relative position of the camera and the calibration pattern). This approach provides linear equations to find reliable results as the traditional one, but the number of unknowns is significantly smaller. The decrease of the unknowns leads to a possibility of a more accurate calibration solution and reduction of the measuring error. As a practical solution, the 3D calibration target can be defined by a 3D scanning stage and controlled by a laser tracker.

Laser tracker is an instrument which determines object position by measuring the location of a retroreflective target mounted on the object. The tracker traces the target's position and measures it with accuracy no larger than 50 micrometres over a distance of 5m in a unified coordinate system. Therefore calibration process can be easily automated by using the laser tracker, set of motorized stages and a test-target.

The proposed approach was tested on simulated linear model when the influence of different errors with certain distribution introduced in coordinates of each point of the calibration pattern was estimated. Linear simulation was performed in order to identify the requirements for nodes location and stability of the 3D pattern.

Sequential movement of a test-pattern within measuring range was also numerically simulated using Zemax. Obtained results showed reliability of the proposed approach in the presence of nonlinear deformation of images and revealed the optimal path for test-pattern movement in order to achieve better convergence of the algorithm. Then, a second camera was added to the simulation and the same procedure was performed with the previously defined calibration target nodes in 3D. This multiple-view registration gave enough data to implement stereo calibration algorithm and clarify both intrinsic parameters of the cameras and their relative position.

The proposed approach was experimentally verified with a developed setup based on a stereo camera and a laser tracker. The setup was mounted on a 6 m long bench for target distancing and two motorized stages were used for orthogonal target positioning. The setup included two Basler acA1600-20gm cameras with 25 mm lenses divided by 400 mm distance and the activemark with 4 LEDs. A working volume of the stereo system was defined by an industry partner (5 meters deep, 500 mm high and 120 mm wide). For the experimental verification we compared the proposed calibration approach and a well-known checkerboard calibration technique. The proposed resulted in maximum of 1 mm error at distances from 1 up to 5 m instead of 4 mm error provided by the traditional calibration technique.

In addition, a possibility of use of the proposed approach for calibration of a multiple view computer vision system (with more than 2 cameras) was also investigated.

The paper also includes a lessons learned section with a discussion on better convergence of the calibration algorithm and practical recommendations on how to obtain reliable calibration results.

10332-29, Session PS1

A decomposition algorithm of airborne laser waveforms integrating with neighborhood waveform information

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Airborne laser scanning (ALS) is a powerful remote sensing technique providing direct range measurements between the laser scanner and the Earth's topography. Such distance measurements are mapped into 3D point clouds.

How to extract high quality point cloud from waveform sampling data is a key problem in lidar data process, and various studies have focused on it. However, there are several defeats in the present algorithm: first, the noise threshold is difficult to determine. At present, in order to eliminate the influence of signal noise, most algorithms assign it to be the higher value empirically. Second, weak signals are difficult to reliably detect. When preprocessing the waveform data with a higher threshold, some weak pulse signals would not be taken into account in the later process, as the signal's strength is not enough to detect them. This phenomenon is particularly serious in the dense vegetation areas for extracting the ground information under the vegetation cover.

Aim to this problem, this paper proposes a decomposition algorithm of airborne laser waveforms integrating with neighbor waveform information. The main idea is that by applying two thresholds with high and low value to detect the significant and candidate pulse peaks in the waveforms, decomposing the significant pulse peaks first, which are dynamically updated, and take advantage of the context information of them to guide the decomposition of candidate pulse peaks, realizing the robust weak pulse signal extraction.

In order to achieve the above object, the following measures are used:

1) Firstly, using the one-dimensional Gaussian filter to smooth the waveform data, reducing the noise level, and based on the plane coordinates of the waveform establish the k-d tree index for query.

2) Secondly, by calculating the first derivative zero cross point of the waveform the initial position of the center of the pulse peak is determined, and by applying high and low threshold, the significant and candidate pulse peaks are determined and the pseudo pulse peaks are removed.

3) Thirdly, for the significant pulse peaks, the generalized Gaussian model and the Levenburg-Marquardt algorithm are used to fit the waveform data, and the fitting error are calculated.

4) Fourthly, for the waveform data containing the candidate pulse peaks, search for the adjacent waveforms within a certain radius by the k-d tree index, and the candidate pulse peaks in the waveform are judged by using the height information provided by the significant pulse peaks of these adjacent waveforms. If the candidate pulse peak has an elevation

approximately similar to that of the adjacent waveform significant pulse peak, it is considered to be compatible with the surrounding environment and re-identified as a significant pulse peak. When existing the candidate pulse peak identified as significant pulse peak, it will be extracted by using the generalized Gaussian model mentioned in the last step, and the waveform with successful extraction of new significant pulse peak is added to the list of updated waveforms.

5) Fifthly, for the updated waveforms, search the adjacent waveforms within a certain radius, and add the waveform to the list of waveforms to be analyzed if the adjacent waveforms contain candidate pulse peaks. When the list of waveforms to be analyzed is not null, the candidate pulse peak is analyzed and extracted using the method mention in the previous step taking into account the adjacent waveform. Loop the iteration until there is no more waveform to be analyzed.

6) Finally, when the loop iteration is aborted, the information extraction of all the waveform data is completed, and the point cloud is generated.

The experimental results show that the method can extract the more ground point effectively compared with the point cloud generated by the relevant commercial software. It can especially improve the ground information underneath the dense vegetation cover.

10332-30, Session PS1

Work modeling of the scanning type laser radar in real-time

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Laser radars are used in mobile robot's technical vision systems. The most of devices has round mechanical circular unfolding on horizontal field of view. The vertical viewing angle is provided by several independent laser beams tilted in a vertical plane. The maximum distance measured by these devices usually does not exceed 100m. Huge cloud of points is calculated by movement of the carrier with a range finder for some time.

Not the circular viewing but directed is preferred for some classes of technical vision systems. The maximum required distance for obstruction detection can be up to 2000 m. Such sensors are supposed to be used as an addition to the optical and thermal sensors in multispectral machine vision systems. As an example, the HELLAS-sensor allows to detect 10 mm wires at a distance of 500 m. The complexity of design and construction of such devices, the uniqueness of the individual components requires pre-simulation of such sensors in a variety of weather conditions, taking into account various terrain and obstacles in different ways reflecting radiation rangefinder. Modeling is necessary to confirm the specific parameters of the developed device and getting the sensor work results before making of model sample. For certain tasks, a computer emulator of the sensor is needed that can model its work in real-time. In the paper the method of mathematical modeling of transceiver path of one of such devices in real-time with OpenCL technology is discussed.

As a simulation object transmitting channel laser radar is selected. It consists of a solid state diode pumped laser with a frequency converter and a parameter of wavelength 1570 nm output, wide-aperture acousto-optic deflector and prismatic telescope. Wide-aperture acousto-optic deflector performs high-speed angular scanning of the laser beam. Prism telescope provides increasing in the scan angle at the output of acousto-optic deflector to a value of 40 degrees in the horizontal plane. Scan is performed on the second axis mechanically. The model has the following characteristics: a point cloud size 300x300 pixels with a frequency of results obtaining in the range of 4 Hz and sensor angles of view of 40° x 30°. Simulation is carried out by tracing laser radiation inside the virtual scene with a highly detailed 3D model of the terrain and obstacles. The paper presents a mathematical model that takes into account the physical principles of light propagation in the atmosphere with different conditions of the meteorological visibility. The model takes into account the reflection angle of the laser beams on obstacles, the material properties and the movement in space of the laser radar. High speed simulation is achieved through the approach to the formation of a grid of triangles from which surface of terrain model and obstacles is formed, as well as a method for selecting triangles with laser beam tracing.

Parallelization process of laser beam tracing is done using OpenCL technology. The model takes into account the ability of real sensors to record two different distances for each laser beam. The value of the second distance to object is fixed by receive path if the first part of its aperture gets to edge of obstacles, and the second part of laser beam aperture is reflected from the surface of another distant object.

Laser rangefinder emulator testing shows the possibility of using it in the real-time mode on cheap graphics cards which support OpenCL 2.0. Emulator testing with the terrain model which contains approximately 4*105 triangles on the graphics card AMD HD-6670 shows the result of the calculation of the raw lidar data at a speed of 20Hz that more than 5 time higher than speed of the physical sample work.

After the analysis of the simulation results we can quickly make the decision about choosing the particular instance of the laser transmitter and the receiving diodes or the matrix with the required characteristics of sensitivity.

10332-31, Session PS1

Detecting imperceptible movements in structures by means of video magnification

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The naked eye is not able to perceive very slow movements such as those that occurs in certain structures under external forces. This might be the case of metallic or concrete bridges, tower cranes or steel beams. However, sometimes we are interested in viewing such movements, since they can provide useful information regarding the mechanical state of those structures. In this work, we analyze the utility of video magnification to detect imperceptible movements in several type of structures. Two video magnification techniques were tested: one is based on estimating color changes over time through linearization of the signal, while the other relies on calculating the phase variations obtained by means of a localized Fourier decomposition.

The results obtained after applying both methods to the structures under study allow us to conclude that video magnification is indeed a promising low-cost technique for structure health monitoring. In addition, we conclude that the phase-based technique, although slower, is preferable to the linear method, since it permits a larger amplification without disturbing excessively the original video.

10332-22, Session 6

Stereo vision for fully automatic volumetric flow measurement in urban drainage structures

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Overflows in urban drainage structures, or sewers, must be prevented on time to avoid their undesirable consequences. An effective monitoring system able to measure volumetric flow in sewers is needed. Existing state-of-the-art technologies are not robust against harsh sewer conditions and, therefore, cause high maintenance expenses. An alternative non-intrusive solution was proposed by Nguyen et al.: a system able to track volumetric flows in sewers with the help of video-cameras by combining image-based approaches of water level measurement and surface velocity estimation with the help of particle tracking velocimetry was described. Despite the high accuracy claimed by the authors, there is a major inconvenience in the technique proposed relying on the detection of the water borderline in the images: the described scenario requires calibration relative to the world.

For that calibration, special rulers need to be placed into the scene, and correspondences need to be chosen manually by experts. This complicates initial setup in the field and originates a source of error.

Having the goal of automatic, robust and non-contact volumetric flow measurement in sewers, we came up with an original and innovative idea of a vision-based system for volumetric flow measurement. Introducing a second camera to the setup, we exploit stereo vision to achieve automatic calibration to the real world. Depth of the flow is estimated as the difference between distances from the camera setup to the water surface and to the canal's bottom. The latter is measured upon installation and recorded into the system. The process of depth estimation runs as follows: (i) images are undistorted and rectified; (ii) image contrast is equalised; (iii) a dense disparity map is calculated for the given left-right image pair; (iv) the disparity map is reprojected to a point cloud; (v) the points belonging to canal walls are removed from the model based on a preset region of interest; (vi) the parametric water surface plane is approximated using the maximum likelihood estimation sample consensus (MLESAC) algorithm. Surface velocity is calculated using cross-correlation template matching. Individual natural particles in the flow are detected and tracked throughout the sequence of images recorded over a fixed time interval. Prior to applying this method, images are undistorted and preprocessed in order to enhance the particles of interest, remove noise, and reduce the negative impact of light reflections and raindrops. Having the water level and the surface velocity estimated and knowing the geometry of the canal, we calculate the volumetric water discharge.

The preliminary evaluation conducted on 60 image sequences recorded on 6 different dates has shown that the average error of depth computation was 3 cm, while the average error of surface velocity resulted in 5 cm/s. Due to the experimental design, these errors are rough estimates: at each acquisition session the reference depth value was measured only once, although the variation in volumetric flow and the gradual transitions between the automatically detected values indicated that the actual depth level has varied. We will address this issue in the next experimental session. The outcomes of our preliminary evaluation are comparable to the results achieved by Nguyen et al.

10332-23, Session 6

Exact rigid-body motion compensation for dynamic holography

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High quality digital holographic screens may become technically feasible in the near future, allowing multiple viewers to have a continuous full-parallax experience without glasses. Signal processing and transmission for holographic screens is challenging because a dynamic holographic video can require up to billions of pixels per frame for containing all information over a large field of view. Moreover, holograms contain high frequency interference patterns and each pixel contains partial information from the whole scene. We can therefore not apply readily standard motion compensation from classical video coding techniques.

There is a need for an accurate motion compensation model predicting how hologram content changes with respect to 3D rigid-body motion that arises in natural scenes. This paper aims at deriving a fast and accurate motion prediction algorithm from known rigid-body trajectories.

Using diffraction theory, we derive tractable closed form expressions for transforming a 2D complex-valued hologram frame given 3D motion vectors in scene space. We decompose the rigid-body motion into its translational and rotational components for computing sequentially their respective effects in Fourier and spatial domains. The effects of subpixel-accurate in-plane translations are computed in the Fourier domain along with depth translations that are computed using the angular spectrum method. The effects of in-plane rotations use image resampling with a standard image interpolation filter while axial rotations are approximated with a frequency shift in Fourier domain. This approximation is valid for small rotational increments.

Our experiments use videos of computed generated holograms with known ground truth motion. We first confirm the validity of our motion prediction model then evaluate qualitatively the potential compression gain over classical block-matching motion estimation. We quantify the accuracy of motion compensation in terms of PSNR in both the source hologram and 2D view projections. Results demonstrate exact prediction of translations while in plane rotations are limited by the accuracy of resampling in holographic plane. Axial rotations are well predicted for sufficiently small rotation angles. The validity range depends on the relative ratio between the spatial extent of the object and the distance to the detector.

The presented compensation method will allow subsequent inclusion in a holographic video coding chain. The compensation approach is valid as long the relative motion from subsequent frames is small enough. This work demonstrates the feasibility of designing motion compensation for digital holographic video.

10332-24, Session 6

Lidar-based individual tree species classification using convolutional neural network

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Background & Purpose

Terrestrial lidar is commonly used for detailed documentation in the field of forest inventory investigation. Recent improvements of point cloud processing techniques enabled efficient and precise computation of an individual tree parameters, such as breast-height diameter, height, and volume. However, tree species are manually specified by investigators to date.

Previous works for automatic tree species classification focused on aerial or satellite images, and few works have been reported for classification techniques using ground-based sensor data. There exist several candidate sensors for classification, such as RGB or multi/hyper spectral cameras. Above all candidates, we use terrestrial lidar because it can obtain high resolution point cloud in the dark forest. We selected bark texture for the classification criteria, since they clearly represent unique characteristics of each tree and do not change their appearance due to seasonable variation and aged deterioration.

In this paper, we propose a new method for automatic individual tree species classification based on terrestrial lidar by Convolutional Neural Network(CNN) using depth images created from point cloud. We focus on Japanese cedar and cypress which cover the most part of domestic forest. We used FARO Focus3D scanner. The laser angular pitch was set to 0.018deg for both horizontal and vertical directions.

Proposed method

Our proposed method consists of the following four steps.

Step1: Bark patch extraction

Given a point cloud of an individual tree, the first step extracts a patch which is a point subset corresponding to a tree trunk. For this, point cloud is stored in a 2D array by cylindrical expansion, and point subset in 256?256 pixels area at nearly breast height is extracted.

Step2: Trunk points identification by RANSAC-based circle fitting

The second step projects a patch onto the xy plane and then the trunk points excluding branches and leaves are identified by RANSAC-based circle fitting.

Step3: Depth image creation by bi-cubic polynomial fitting

The third step fits a bi-cubic polynomial surface for the trunk points extracted by the previous step. Then the depth is computed at each point as the distance to the surface, and the depth image is created.

Step4: Species classification using Convolutional Neural Network

Finally, tree species of the input individual tree is classified using the depth image for CNN classifier.

Experimental results

In this section, experimental results by the proposed method are described. We prepared 17,473 and 18,901 scans for Japanese cedar and cypress. We used 768 scans respectively as the test data for CNN. These scans are restricted within 15 meters from the scanning position since a certain image resolution is required for our method. We manually excluded approximately 10% scans with heavy occlusions. As for the classification results, we achieved 89.3% accuracy as a whole. Classification accuracy was larger than 90% for scans from 3 to 12 meters from the scanning position. As for those within 3 meters, accuracy was about 85% since the number of scans was only a few hundreds and sufficient training could not be done in the CNN. For scans farther than 12 meters, the accuracy was approximately 86% since the image resolution were not enough to capture bark texture in detail.

10332-25, Session 6

Accuracy evaluation of SFM 3D surface reconstruction

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Structure from motion approach became a powerful mean for scene 3D reconstruction using only a sequence of images from moving camera as initial data. Such a technique has a significant potential for unmanned aerial or unmanned ground vehicles for navigation in unknown environments. Different techniques are used for estimation the 3D structure of a scene such as optical flow approach, feature detection and matching in the set of images, features tracking through a sequence of images. Robustness and accuracy of scene 3D coordinates measurements are the important characteristics of structure from motion algorithms which has to provide the reliability of the navigation.

The technique for scene 3D reconstruction from a set of the sequential images is developed based on preliminary features detection and matching in a stereo pair with appropriate basis which allows reaching reasonable accuracy of 3D measurements. After that for this stereo pair relative orientation of these images is estimated using identified corresponding points and then 3D coordinates of these reference points are calculated. These 3D points are used for exterior orientation of the neighbor images in the sequence and new points in the new neighbor images are used for expanding the set of 3D points of the surface. Then the exterior orientation procedure and adding new points procedure are repeated. At every step of including new images in the processing set the correction of surface 3D coordinates is performed: for each 3D point its 3D coordinates are calculated using all images which contains it using all images containing this point. Such approach allows avoiding bundle adjustment procedure instead of which repeated process of exterior orientation is carried out. After processing all images in the sequence a set of reference 3D points is calculated that is later used for dense surface 3D model generation.

For dense surface 3D model reconstruction least square matching technique is used. It applied for a set of stereo pairs formed under the conditions of appropriate basis and high degree of image overlapping. After the stereo pairs processing a set of 3D surface fragments (patches) are generated. These surface fragments are obtained in common system of coordinates because all images are oriented using the common set of reference 3D points.

Evaluation of 3D surface reconstruction accuracy is performed using scaled terrain model. The scaled terrain model is produced by 3D printer and has dimensions of approximately 600 mm by 300 mm. To obtain the reference surface with high accuracy an original photogrammetric 3D scanning system is used. The photogrammetric 3D scanning system includes two Basler a641f cameras and structured light projector. The accuracy of the produced surface 3D models is provided by original calibration technique. For concerned scaled terrain model the accuracy of 3D reconstruction is at the level of 0.1 mm.

First stage of evaluation is to estimate the accuracy of reference 3D points set calculation. For this purpose the coordinates of the reference points are found in the reference surface 3D model by back projection from corresponding images. Then both sets of the reference points (produced by the developed algorithm and obtained by back projecting) are compared using least squares technique. At the second stage evaluation of 3D surface reconstruction accuracy is performed. The 3D surface produced by image sequence processing is compared with reference 3D surface using iterative closest point algorithm.

The results of accuracy evaluation for two variants of surface 3D reconstruction from image sequence are presented and discussed: for the case of un-calibrated images and for images with known interior orientation. The ways for improving the accuracy of the developed 3D reconstruction technique is proposed.

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10333-1, Session 1

Investigation on microfluidic particles manipulation by holographic 3D tracking strategies

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Particle and bio-particles manipulation in microfluidic environment is a topic of growing relevance in the scientific community, in response to the rapid development of biochips, miniaturized analysis systems or lab-on-a-chip (LOC) devices. Indeed, successful chemical, biological and biomedical analysis in these systems requires the ability to perform some fundamental operations such as trapping, separation, filtering, concentration detection, sorting, counting or washing. To this end, different techniques have been proposed for particles manipulation in microfluidic systems. They exploit the channel geometry and exert forces based on a variety of physical phenomena (i.e. optical tweezers, acousto-phoresis, electrophoresis and dielectrophoresis forces or magnetic forces). For any application, it is paramount to control the particles' position in the microchannel to validate the manipulation effectiveness and stability.

Standard tracking techniques are based on quantitative analysis of video microscopy images and are commonly employed for motion parallel to the microscope's focal plane. On the other side, multi-particle axial tracking is based on the interpretation of diffraction rings and can be obtained only after extensive calibration or at the expenses of reduced spatial-temporal resolution or z-range. Thus, observing three-dimensional (3D) trajectories of particles is in general a challenging task in classical microscopy, which represents a serious drawback for the analysis of time-lapse microscopy image data.

Those limitations can be surmounted employing digital holography (DH) in microscopy. This full-field and label- free imaging technique is able to provide quantitative phase-contrast information by single-shot image acquisition [1]. It is proven a powerful tool for the imaging of micro-objects contained in a 3D volume, moreover allowing to investigate dynamic processes and to track cells and particles migration [2-3]. In particular, it allows the accurate retrieval of the spatial coordinates of multiple targets performing 3D particle tracking in the entire imaged field of view (FOV).

We employ a 3D holographic tracking method to investigate particles motion while inducing their migration through microfluidic manipulation. The employed methodology is articulated in steps. Firstly, particle in the FOV are detected and identified, labelling the elements that stand out from the background by suitable image segmentation approaches. Then the displacement along the optical axis are assessed by numerical refocusing criteria [2]. In particular, an automatic refocusing method to recover the particles axial position is implemented employing a contrast-based refocusing criterion. Lastly, the transverse position of the in-focus object is evaluated through quantitative phase map segmentation methods and centroid-based 2D tracking strategy [2].

The introduction of DH is thus suggested as a powerful approach for validation of particles and biological samples manipulation efficacy, as well as a possible aid to precise design and implementation of advanced LOC microfluidic devices.

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10333-2, Session 1

Characterization of the mechanical behavior and pathophysiological state of abdominal aortic aneurysms based on 4D ultrasound strain imaging *(Invited Paper)*

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Abdominal aortic aneurysms (AAA) are permanent local dilations of the aorta that go along with changes in the microstructural composition of the fibre reinforced composite constituting the healthy aortic wall: degradation of elastin, reorganisation of the collagen network, necrosis of the medial layer, and local calcifications result in the disappearance of the 3-layered structure of the wall, a substantial increase in stiffness and local variations of wall thickness, microstructural composition, and elastic properties. Eventually, these changes result in the weakening of the walls structural integrity. The main risk of this mostly asymptomatic disease is the rupture of the aneurysmal wall, with an associated mortality rate of up to 85%. Currently, the clinical indications for surgical treatment are an AAA diameter larger than 5 cm in women and 5.5 cm in men or a growth rate of more than 1 cm per annum. However, up to 13% of small AAA (d < 5 cm) rupture and 54% of untreated large AAA with diameters between 7.1 and 10 cm remain stable. Thus, the need for additional patient-individual biomarkers for AAA rupture risk is widely acknowledged.

In order to develop new approaches to biomechanical characterization of the individual human aneurysmal wall, a non-invasive in vivo method for full field displacement and strain measurement of the wall was established using a customized commercial real-time 3D echocardiographic device (Artida, Toshiba Medical Systems) that is equipped with a speckle tracking algorithm (ACP, Toshiba Medical Systems). Statistical indices of the obtained systolic strain fields (Figure 1) are proposed as biomarkers for the pathological state of the AAA wall. The pathophysiological rationale behind this approach are the known changes in microstructural composition of the aortic wall with progression of AAA development. Such changes in microstructure – that cannot be measured directly in vivo - will result in a decrease of the spatially averaged strain amplitude (mean), and an increase of the heterogeneity of the strain field, that may be measured as increased coefficient of variation, and an increased value of the ratio of the local peak and the mean. Local peak strains may indicate sites that are prone to rupture. In a clinical study, the proposed biomarkers proved to be able to distinguish significantly aortic wall kinematics of a group of young volunteers without known cardiovascular disease, a group of aged atherosclerotic patients with normal aortic diameter, and a group of AAA patients. Additionally, the in vivo strain fields are used in an inverse Finite Element Model Updating approach to identify the orthotropic and hyperelastic constititive behaviour of the individual aneurysmal wall. Taking into account the heterogeneity of the full field data, constitutive parameter identification in vivo is possible even though only two load cases (systoli and diastolic blood pressure) are accessible. This is a step to overcome the well-known problem in Finite Element analyses of AAA wall stresses that the constitutive behavior of the wall usually is unknown in a clinical setting.

10333-3, Session 1

Optical control of functional nanocontainers for force sensing

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A current demand in single cell analysis is to deposit biochemicals on targeted locations without affecting the whole population. A novel approach addresses this issue by applying functionalized nanocontainers able to carry biomolecules, yet these nanocontainers require of an adequate transportation mechanism. Optical tweezers (OT) allow the manipulation of microscopic objects in living organisms. Beyond the simple control on the location of the objects (grab and hold), OT can also be used to exert or measure forces in the piconewton range [1]. Consequently, investigations of biomechanical properties of cells like elasticity have been enabled through the optical control of standard spherical probes. More complexly shaped and versatile probes have current limitations in their applicability as force sensors. Recently, Zeolite-L crystals have emerged as versatile cylindrical nanocontainers capable to deliver drugs into living cells [2]. The dynamical manipulation and assembly of nanocontainers with OT broadens the variety of their uses, including the generation of optical sensors and waveguides [3]. In this work, we investigate the possibility to increase the biological functionality of such cylindrical nanoprobes beyond transportation, using them also for force sensing.

Force sensing with OT is based on force being related to a position displacement between trapped object and optical trap via a factor called trap stiffness, ?. One of the most common and reliable calibration method to obtain ? is based on the power spectrum of the Brownian motion of the object in the trap [4]. The ? value can be then derived from the corner frequency, f_c, of the power spectrum. We show that, although Zeolite-L crystals and silica spheres have on average a different corner frequency, the shape of their power spectra remains similar; both exhibit a plateau for low frequencies and a decay proportional to 1/f? at high frequencies. Having such common spectral features satisfies a first necessary condition for force measurements with nanocontainers [4]. Still, to obtain the ? value of the Zeolite-L crystals some assumptions on the hydrodynamic interactions due to their cylindrical shape need to be made.

Here, we apply the power spectrum analysis to cylindrical nanoprobes to discuss the trapping efficiency, the validity of the hydrodynamic assumptions and study their behavior in the optical trap. The influence of polarization and the output power of the laser on the trap stiffness is investigated and compared with spherical silica particles. The results will shed light into the utilization of the Zeolite-L crystals for biomedical applications as multitasked nanoprobes acting as containers and probes for force sensing all-in-one.

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10333-4, Session 1

Inspection of arterial-induced skin vibration by Moiré fringe with two-dimensional continuous wavelet transform

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A non-contact arterial-induced skin vibration inspection system is implemented. This system is based on a fringe analysis algorithm developed by the Two-dimensional Wavelet Transform (2D-CWT) retrieving height-correlated phase information from Moiré fringe patterns. Using a commercial video camera or a CMOS image sensor, this system could monitor the skin-vibration induced by the cyclic deformation of inner layered artery. The cross-sectional variation and the rhythm of heart cycle could be continuously measured for health monitoring purposes.

The average vibration amplitude of the artery at the wrist ranges between 30 ?m and 60 ?m, which is quite subtle comparing with the skin surface structure. Having the non-stationary motion of human body, the traditional phase shifting (PS) technique can be very unstable due to the requirement of several frames of images, especially for case that artery is continuously pumping. To bypass this fundamental issue, the Moiré technique is introduced to enhance the surface deformation characteristic. The shadow Moiré and tattoo Moiré are applied to measure the out-of-plane and in-plane deformations.

Due to the need to use multiple intensity maps to calculate phase information, PS technique is not applicable for this application. It is suggested to draw phase information from spectral domain in this study. The instantaneous surface morphology can be reconstructed with a single shot of fringe pattern. 2D-CWT method possesses the ability to construct a characteristic mother wavelet of good time and frequency localization according to different fringes conditions. Comparing with the powerful time-frequency analysis method, Short Time Fourier Transform (STFT), 2D-CWT method not only has more appropriate signal description but also performs a faster computation process for its better time-frequency window accumulation efficiency. During phase retrieval process, the wavelet ridge detection method is adopted to determine the correct phase.

The close fringe, whose phase does not change monotonically as that of the carrier fringe, is often observed under the shadow Moiré setup and is not resolvable with ordinary fringe analysis algorithms. The rotational factor of 2D-CWT is capable for determining directional information. The phase correction is therefore performable during the phase retrieval process, accomplishing the powerful 2D-CWT fringe analysis algorithm for both carrier fringe and close fringe. For phase unwrapping, the Poisson’s equation with Neumann boundary condition on the assumption of continuous surface is solved by fast Fourier Transform (FFT) providing the least computation time as possible.

In this paper, we have set up a Moiré metrology system with a powerful 2D-CWT algorithm. And the proposed system is capable of reconstructing the surface morphology at every moment. No matter the corresponding input frame is a carrier fringe or close fringe. Hence, the artery vibration profile can be acquired from the frame sequences according to the appropriate interval configuration with a period of time. The comparative results between different mother wavelets will be carefully demonstrated numerically and experimentally. The measurement results from ultrasonic reflectoscope will be used as the reference for the validity of health monitoring potential of the proposed system.

10333-5, Session 2

Imaging cell clusters and tissue using learning tomography *(Keynote Presentation)*

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Over the past decade, optical tomography has attracted attention due to the promise for three-dimensional imaging of biological processes at the cell level. The working principle of the technique is exposed in the seminal paper by Emil Wolf that proposes a direct formula to calculate the refractive index distribution of the object from measurements of the scattered field. This formula, which we refer to as the Wolf transform, is based on the first Born approximation and is a linear map from the refractive index to the scattered field. The corollary is that the Wolf transform only accounts for single scattering and is thus restricted to objects having weak refractive index contrast. Significant improvement in image quality can be obtained by using the Rytov approximation in conjunction with the Wolf transform. However, this approximation solution is still based on a linearized scattering equation and is also a single scattering model. The Rytov and Born approximations yield satisfactory results for objects that are small and with moderate refractive index contrast such as a single cell or small group of cells. For thicker object, multiple scattering can no longer be neglected.

In recent publications, we proposed Learning Tomography (LT) as a new tomography technique, based on machine learning concepts and a propagation model, namely the beam propagation method (BPM) that accounts for multiple scattering. Here, we present recent experimental results that compare the performances of LT against conventional diffraction tomography (DT) based on Born and Rytov approximations.

The experiments were carried out on a three-dimensional arrangement of yeast cells in an agarose gel. We used an interferometric imaging system to measure the complex optical field scattered from the sample, which was illuminated with plane wave at different incidence angles.

The DT reconstruction was performed according to the Born and Rytov approximation from a collection of measurements taken at 160 illuminations angles arranged in a circle in k-space. The LT reconstruction was performed from the same measurements, but randomly selecting only eight views at every iteration of the LT algorithm. There were 50 iterations in total. In order to converge, the LT algorithm needs to be regularized. We globally impose a total variation (TV) regularization that forces solutions to be piecewise constant. We also enforce the non-negativity of the refractive index contrast, the cells having a larger index than the surrounding medium (essentially water). In order to display a fair comparison between LT and DT, we applied the same regularization and positivity constraint to the DT reconstruction. For that, we devised an iterative linear algorithm that is similar to LT except that the nonlinear propagation (the BPM) is replaced by the linear Wolf transform.

The Born approximation largely underestimates the refractive inside the cells and only the edges are visible. Rytov approximation solves that issue, but the reconstruction becomes blurred as the distance from the imaging plane (plane in which the measurements are recorded) increases. In the case of Learning Tomography, the refractive index is estimated correctly, and the cells have sharp edges even away from the imaging plane.

10333-6, Session 2

Biophysical monitoring of cell cultures for quality assessment utilizing digital holographic microscopy

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Quality and reproducibility of cell-based assays strongly depend on the quality of the underlying cell culture which is influenced by various parameters like nutrient and growth factor availability, buffer conditions, subculture routines and optimal cell concentrations. However, cell culture quality assurance is usually performed by microscopic inspection that depends on the investigator's expertise and experience with the appropriate cell line. Thus, methods for accurate assessment of objective cell parameters that characterize a specific cell line and detect global changes in cell culture are highly desirable. Biophysical cell properties such as cell volume and mass, reflecting intra cellular protein content or the concentration of the intracellular solutes, are suitable quantities. Established state of the art flow cytometry methods provide high throughput acquisition of label-free information related to cell size, intracellular density and internal structures from suspended single cells, for example, optically by analysis of forward and sideward light scattering, or by impedance measurements. However, due to the underlying measurement principles sophisticated and sometimes extensive calibration procedures, e.g. with artificial test standards and reference materials, are required and accurate access to absolute data is limited.

We demonstrate the utilization of quantitative phase imaging with digital holographic microscopy [1] for quantification of the impact of cell culture condition alterations for the example of a pancreatic tumor cell model. Label-free QPI imaging of detached cells in suspension is performed by utilizing digital holographic microscopy (DHM) based on a Michelson interferometer approach [2]. The retrieved quantitative DHM phase contrast images of the cells are analyzed for refractive index, volume, and dry mass [3,4] in response to changes of external parameters. Firstly, we validate our approach by determination of suitable cell numbers that are adequate for reliable statistics and quantify the influence of osmolality changes of the cell culture medium on cell volume, refractive index and dry mass. Then we demonstrate that quantitative phase imaging based on DHM is capable to quantify cell morphology changes in response to different confluence states.

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10333-7, Session 2

Peripheral blood mononuclear cells analysis in microfluidic flow by coherent imaging tools

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Our blood stream is composed of different cell types, which can be divided in so called white blood cells (WBCs) and red blood cells (RBCs). In general, WBC are responsible for the maintenance of the general body health and ensure immunity against pathogens, while RBC deliver oxygen to the body tissue. However, WBCs are a heterogeneous and widespread group of cells divided in several subclasses according to their different morphological properties. Two main classes of WBCs are recognizable in the human blood stream, i.e. granulocyte cells and A-granulocyte cells. Neutrophils, basophils and eosinophils belong to the granulocyte cell class, while A-granulocyte cells can be divided into two lymphocytes and monocytes. Structurally, WBC differ in their general size, nucleus shape and size as well as in their overall complexity. RBC are assumed to have a biconcave disk shape enclosed by a thin, elastic, lipidic bi-layer. A mature RBC is a soft, flexible and elastic cell, which has neither nucleus nor substantial internal elements.

Intrinsic physical properties of blood stream cells -that reflect underlying molecular structures- are indicators of their own cellular state and furthermore of the overall human body state. All along, nuclear and cytoplasmic cell structure or morphology have been used for histological detection and classification, making the investigation of intrinsic physical properties of cells of great relevance for fast and reliable diagnostic approaches. Essential in diagnosing the presence of possible pathological conditions of the human body, is the absolute number of each single kind of WBCs, which usually significantly change in such cases. Moreover, structural modifications can occur to WBC sub-populations during malignant events. Therefore, a fast and cost-effective structural characterization of a cell is a desired goal for pathologists to better understand the meaning of the transformations occurring at the cell level of an unhealthy body. Thus, the accurate comprehension of the physiological structure of WBCs is fundamental to recognize diseases.

Here we show the possibility to simple and straightforward characterize mononuclear WBC as well as RBC in their physiological conditions (label-free) using a microfluidic-based measurement system. Therefore, a non-Newtonian polymer solution is used to ensure precise viscoelastic induced individual cell alignment in-flow for different applied cell velocities. We founded for both kinds of cells, that higher cell velocities lead to enhanced cell alignment and smaller variations from the centerline. In our study, an investigation of physical cell properties of each aligned cell has been performed using a wide angle light scattering apparatus. Moreover, a quantitative phase imaging holographic system was employed to check the transversal and optical axes positions in flow of individual cells using a holographic 3D cell tracking method; and to estimate their 3D morphometric features, such as their refractive index.

We analyzed more than 200 WBCs and 100 RBCs from three different probands. Light scattering results showed distinct cell populations according to their measured dimensions and shape, which can be associated to the presence of RBC, lymphocytes classes as well as monocytes. The presented measurement approach did not require chemical and/or fluorescent cell labelling and moreover allowed further investigation of analyzed cells. A Trypan blue test was performed to ensure adequate cell survival rates after our measurement procedures. Results obtained from both measurement approaches have been compared with literature values, showing good agreement and confirm the possibility to obtain detailed physical cell properties in microfluidic flow, avoiding chemical staining or fluorescent labelling. We believe this study could open-up a new route for the label-free detection, of single cells in medical applications, especially in the diagnosis and follow up of blood diseases.

10333-8, Session 2

Skin melanoma characterization with optical nondestructive techniques *(Invited Paper)*

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The skin is the largest and most extended organ in the human body. Its weight goes up to 1/6 of the total body and has many functions including protecting the body against infections and the electromagnetic radiation. According to the World Health Organization the skin cancer is growing rapidly around the world, ethnic dependent, occupying among cancers the first place in men and third in women. There are three main types of skin cancer: basal cell carcinoma, squamous cell carcinoma and melanoma. The first one is the most common and likely to be cured while the second is less frequent but more aggressive; the third one is by far the most aggressive of the three and therefore the cause of more fatalities.

Today, skin diseases are diagnosed by physicians primarily qualitatively by a visual inspection and palpation, a procedure that needs quite a bit of practice and expertise from the specialists. Modern diagnosis techniques include dermatoscopy, confocal reflectance microscopy, optical coherence tomography, high frequency echography, magnetic resonance and spectrophotometry. Most of these techniques render images with acceptable resolution that allow the specialist to interpret them and give a treatment to the particular skin condition, but they all are still qualitative. It is therefore important to have alternative techniques that may offer quantitative data that can be related to more reliable parameters that can identify the type of skin disease being observed.

The study of the skin's visco-elastic properties using optical non-invasive means provide important physical parameters of this organ that aid to understand different pathologies that may arise due to external factors such as UV radiation. The correct assessment of this tissue parameters will serve to early diagnose and help to treat skin cancer disease, since it is known that a large portion of the skin related pathologies modify its properties such as elasticity, thickness, color, etc. The skin cancer diagnostic is commonly associated to a change in the skin rigidity with respect to its surrounding area, this is done through palpation. This rigidity change is expressed by a change in the skin's Young's modulus of the affected area, a feature that can be retrieved with optical nondestructive techniques.

In this Invited Paper, we are presenting in-vitro results obtained with digital holographic interferometry and optical coherence tomography to characterize the skin melanomas. This research study was done with a batch of melanomas at different stages, all the samples were deformed statically and dynamically to create a data bank with the aim to identify the particular stage of the tissue. The data gathered is quantitative in nature and may provide a reliable and alternative source to evaluate skin cancer.

10333-9, Session 3

Adaptive optics and biomedical imaging: improved characterization of thick tissue *(Invited Paper)*

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No Abstract Available.

10333-10, Session 3

Adaptive optics in visual science

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Imperfections of the optics of the eye introduce aberrations to the imaging beam which degrades the resolution in retinal images. In order to compensate for these aberrations, adaptive optics (AO), a technique known from astronomy, can be used. This lecture presents basic principles of AO for visual science and provides an overview over different instrumentations that can be combined with this technique. Image results are presented that were recorded with AO fundus photography, AO scanning laser opththalmoscopy and AO optical coherence tomography. Finally, latest developments in the field are outlined and discussed.

10333-11, Session 3

Hybrid computational and physical adaptive optics for fluorescence microscopy

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Adaptive optics can be used in microscopy to compensate for sample induced wavefront aberrations. This is usually done through an adaptive optical element (e.g. deformable mirror, spatial light modulator) with multiple actuators in a sensorless configuration, performing optimization of an image based metric as a function of the actuators' inputs. This can be a lengthy procedure, and, moreover, the price and complexity of adaptive optics devices increases dramatically with the number of actuators, so that high order aberrations can only be partially corrected.

It must be noted that a low order only correction, while not being able to restore the diffraction limited performances of the system, can dramatically increase the signal to noise ratio in the images.

In the absence of an adaptive optical device, multiframe blind deconvolution algorithms can be used, acquiring multiple images with artificial unknown high order aberrations in the system (e.g. with spinning ground glass surface). The algorithm processes the dataset, assuming all images are from the same object, convolved with different PSFs, and extracts the most probable shape of the object. While blind multiframe deconvolution algorithm can theoretically restore the diffraction limited image of the system, their performance is strongly impaired in the presence of high stochastic noise, as is the case in strongly aberrated microscopy images.

In this contribution, we will present the combination of two image correction methods recently developed in our group, one for fast sensorless adaptive optics (Rejected Light based Seonsorless Optimization. RLSO), and one for robust blind multiframe deconvolution (Tangential Iterative Projections, TIP). In this hybrid correction technique, a fast correction of low order aberrations is performed through RLSO, in order to maximize signal to noise ratio through the correction of low order modes in the aberration, and TIP is used for correction of the remaining high order modes.

RLSO is a wavefront sensorless adaptive optics method for laser scanning confocal microscopy based on the use of a reflective surface for the confocal aperture. The out of focus light rejected by the pinhole is therefore reflected on a secondary optical path, and an image of its spatial distribution is acquired on a camera. Adaptive optics correction is performed through a model based procedure, requiring 2N+1 iterations for correction. Since the frame rate of the camera is much higher than the frame rate of the scanning microscope, full correction can be achieved in a fraction of the frame time of the microscope.

TIP is a modification to thestandard framework of recursive blindmultiframe deconvolution algorithms is proposed, based upon a change to the projection operation between the sets. This modification allows the algorithm to remove the effect of the perpendicular noise component in the images and therefore, produce a solution that minimizes the object's correlation with noise. As a result, it produces a better deconvolution output with respect to increasing noise corruption than alternative algorithms. The mathematical basis for this change alongside comparison with other algorithms is shown on simulated and experimental fluorescence microscopy images.

We demonstrate that the use of TIP on images obtained after RLSO optimization have higher quality that images obtained through standard adaptive optics, and through strandard blind multiframe deconvolution aswell.

10333-12, Session 3

Digital wavefront sensing and aberration correction for in-vivo retinal imaging

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Cellular resolution for retinal in-vivo imaging is becoming increasingly important with the advent of novel therapies acting on the cellular and sub cellular level. Unfortunately the poor quality of the natural optics of the eye leads to significant aberrations, especially when aiming for high lateral resolution and related high numerical apertures. Adaptive optics helps to correct for aberrations but comes at increased system complexity and price. Recently introduced digital wavefront sensing and aberration correction leads to significant reduction in hardware effort, and can be combined with optical coherence topography to provide high isotropic resolution in 3D. The principle of digital wavefront sensing is making use of the complex signal available in OCT being an interferometric technique. It employs a scene based wavefront reconstruction method using pupil splitting, and determining the wavefront slope for each sub-pupil. The wavefront is then estimated from the local slopes in each sub-pupil, and can be seen as analoge to a Hartman Shack wavefront sensor. Aberration is then corrected by digital phase conjugation across the pupil plane. We demonstrate the principle of digital wavefront sensing for in-vivo visualization of retinal photoreceptors and micro capillary structures in-vivo.

10333-13, Session 3

Scanless nonlinear optical microscope for image reconstruction and space-time correlation analysis

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Optical Microscopy has been applied to life science from its birth and reached widespread application due to its major advantages: limited perturbation of the biological tissue and the easy accessibility of the light sources. However, as the spatial and time resolution requirements and the time stability of the microscopes increase, researchers are struggling against some of its limitations: limited transparency and the refractivity of the living tissue to light and the field perturbations induced by the path in the tissue. We have developed a compact stand-alone, completely scan-less, optical setup that allows to acquire non-linear excitation images and to measure the sample dynamics simultaneously on an ensemble of arbitrary chosen regions of interests.

The image is obtained by shining a square array of spots on the sample obtained by a spatial light modulator and by shifting it (10 ms refresh time) on the sample. The final image is computed from the superposition of (100-1000) images. Filtering procedures can be applied to the raw images of the excitation array before building the image. We discuss results that show how this setup can be used for the correction of wave front aberrations induced by turbid samples (such as living tissues) and for the computation of space-time cross-correlations in complex networks.

10333-14, Session 3

Adaptive optics for in-vivo exploration of human retinal structures *(Invited Paper)*

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Adaptive optics (AO) is an optoelectronic technique that compensates optical aberrations by the mean of a deformable mirror. AO imaging was first developed in astronomy and has been applied to the exploration of the retina since 1997. AO improves the lateral resolution of fundus images, which can reach the micrometric scale and hence not only improve the precision of measures of structures but also reveals others that are otherwise not detectable such as individual photoreceptor cells and vessel walls. The makes the retina the only human tissue in which subcellular structures may be routinely observed in vivo. High resolution imaging therefore holds promises for cellular-scale diagnosis and guidance of therapy of retinal diseases, and also of diseases for which the retina is a surrogate of other organs such as the brain and vessels. An increasing number of clinical applications are identified for AO imaging, progressively translating from the lab to the clinics. At such small scale the information brought by optical imaging may be complex because the optical properties of normal and pathological structures may differ considerably. Therefore, the integration of information from AO into medical decisions is still far from optimal. Integration of AO images in the diagnostic process has not been as straightforward as for optical coherence tomography. Among the factors that currently impair medical applications are the level of pigmentation of the fundus, the transparency of the retina, the presence of other sources of light reflection in diseased retina, the spatial and temporal variability of photoreceptor reflectance, and the variable orientation of photoreceptor outer segments. Nevertheless, quantitative biomarkers may be extracted from currently commercially available systems, the most reliable being the thickness of the arteriolar wall. Photoreceptors counts may vary according to factors such as their physical orientation (the Stiles-Crawford effect) and this is the subject of considerable research. Longitudinal observation of the fundus at high magnification is helpful to detect progression in slowly evolving diseases. In the future, other biomarkers of interest for various sectors of medicine may be validated, such as those related to vasomotricity, to the function of neuronal structures and to inflammation.

10333-15, Session 4

High-speed single-pixel digital holography

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The complete phase and amplitude information of near-transparent biological specimens can be easily determined by phase-shifting digital holography, without the need of exogenous imaging contrast agents such as fluorescence dyes. Spatial light modulators (SLMs) based on liquid crystal technology have been employed in digital holography for phase-shifting and for active compensation of the wavefront aberrations induced by the optical system. However, these phase modulator devices have a stringent frame-rate limitation, usually around 60 Hz. In contrast, digital micro-mirror devices (DMDs) can reach frame rates up to 22 kHz. Several techniques, such as the method to design computer generated holograms (CGHs) proposed by W. H. Lee, permit the use of such binary amplitude modulators as phase-modulation devices.

Single-pixel imaging techniques record images by using a simple photodetector, instead of a conventional camera, by sampling the object with a sequence of microstructured light patterns. This approach can be convenient for cases with low light intensity or with light spectral bands for which high resolution detectors are not easily accessible. Besides, single-pixel techniques allow imaging through turbid media under certain conditions. The combination of single-pixel imaging techniques and digital holography using a liquid-crystal spatial light modulator has also been reported.

In this communication, a high-speed single-pixel phase-shifting digital holography system with phase-encoded illumination is presented. It is based on a Mach-Zehnder interferometer, with a DMD acting as the modulator for projecting the sampling patterns on the object. These patterns are phase-encoded Hadamard patterns generated through a Lee hologram approach. The modulator is also used for phase-shifting. The detection system consists of a simple photodiode and a digitizing acquisition card recording the integrated irradiance of the interference pattern between the light diffracted by the object and the reference light beam.

Our holographic technique benefits from the advantages of single-pixel imaging approaches. The complex amplitude distribution of an object can be recorded at high speed and reconstructed in just a few seconds because of the high frame rates of the DMD. Besides, the optical setup is a true adaptive system, since it is able to measure the aberration induced by the optical system in the absence of a sample object, and to compensate the wavefront in the phase-modulation stage. It is worth to note that we employ a single amplitude SLM for modulating three different types of phase information: the sampling patterns, the phase shifts to perform on-axis digital holography, and the compensation of the wavefront distortion induced by the aberrations of the optical system.

Preliminary experiments confirm the validity of our approach. Firstly, we have shown the ability of DMDs to act simultaneously as a phase-shifting device and a wavefront compensating device in a phase-shifting digital holographic system with a conventional camera. Then, we have extended the holographic system to high-speed single-pixel detection with phase-encoded illumination. Our experimental results include images of different objects: amplitude-only, phase-only and general complex-amplitude objects. Images of a complex-valued object have also been obtained with a 25° holographic diffuser placed more than one centimeter before the photodiode.

10333-16, Session 4

Real-time 3D optical sectioning by differential interference contrast microscope using pixelated polarization camera

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In the field of biology, it is important to analyze structure of a bio-sample. A differential interference contrast (DIC) microscope is useful to observe small structure without staining work. It cannot judge high or low of sample height. To overcome these problems, a phase information of sample can be integrated from several differential images which are changed phase of incidental light by deconvolution analysis. We propose a real-time integrating analysis of DIC microscope using a pixelated polarization camera whose micro polarizer array consists 4 different azimuthal angles attaches on CCD sensor. This system can measure phase information related sample stricture in single shot. The 3D optical sectioning of the born, blood vessel and bristle of Medaka egg can be show by changing focus plane.

10333-17, Session 4

Simultaneous shape and deformation measurements in a blood vessel model by two wavelength interferometry

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The shape measurements of large rough surfaces with non-destructive and contactless techniques, as Digital Holography, can be interesting for some mechanical, biomedical or artwork applications.

In this paper, the feasibility of applying holographic techniques to measure deformation and shape almost simultaneously will be investigated. Although many techniques have been used for shape measurements we will focus on the two wavelength method using Digital Speckle Pattern Interferometry (DSPI). Spatial Phase Shifting techniques (SPS) are used for the simultaneous and multiplexed recording of the two holograms. Temporal series of these holographic images are taken in order to obtain information on the deformation.

In our two wavelength Digital Holographic setup, all beams are guided by fiber optics. The illumination beams are combined by a Fused Fiber Optics coupler to ensure the directions for the two beams are identical. The fiber output tips of the reference beams have an appropriate position for introducing a different carrier fringes for each wavelength, which allow the correct multiplexing. Thus, in the Fourier plane the image of the aperture for each wavelength is located in a different quarter which allows separating each contribution and retrieving the complex object amplitude for each wavelength. From this information the phase difference can be calculated giving a wrapped phase map corresponding to a depth difference, being each fringe related to the synthetic wavelength. Depending on the position selected aperture center a finite referential could appear on the phase difference map. To eliminate this contribution a plane surface parallel to the camera sensor is taken as a reference plane and its corresponding phase map is taken as a reference background.

The recording of the several two wavelength holographic images at different time instants allows retrieving the temporal evolution of the complex object wave for any wavelength. The comparison of these object waves for any wavelength gives a phase difference map with information, in this case, of the object deformation along the sensitivity vector, related to the recording geometry. In our case, an off-axis hologram is recorded with very small angle between illumination and observation direction and both almost perpendicular to the camera sensor. Thus, the sensitivity vector is almost perpendicular to the camera too.

The two wavelength interferometry will be applied to measure in a blood vessel model and in a sheep artery. In these cases, the radial deformation

is more interesting than the deformation in the sensitivity vector direction. The first approach will be done with a silicone tube. Considering the tube a cylinder, the analysis of the shape information allows to retrieve the tube radius and axis. With this information and knowing the recording geometry parameters the radial deformation can be determined. Then, the behavior of the silicone tube as blood vessel model and the biological real tissue will be compared.

10333-18, Session 4

Multiplexed two in-line holographic recordings for flow characterization in a flexible vessel

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Previous work [1] has shown that an in-line Digital Image Holography (DIH) configuration, with a shifted aperture at the focal plane of the imaging lens, can produce holograms where the real and virtual images are completely separated. In this paper two holograms are recorded simultaneously using one camera and retaining the simplicity of the in-line configuration and the advantage of the shifted-aperture strategy.

A small square aperture is used for the simultaneous recording. Two collimated beams illuminate the object from two slightly different angles; so that they are focused at two different corners of the aperture (bottom left and bottom right corners). In this way the frequency information of each multiplexed hologram can be separated at the Fourier spectrum of the composite recording.

As in typical stereoscopy, the advantage of this configuration is limited by the angle between the two illuminating beams, and therefore the aperture size. The aperture can be sized up to a quarter of the spectrum recorded by the CCD to separate each contribution at the Fourier spectrum. Thus it is limited by the camera pixel size and the chosen magnification. However some improvement on the out-of-plane resolution can be envisaged, in particular if different wavelengths are used for each hologram.

The capabilities of this two-illumination DIH as a fluid velocimetry technique are evaluated with a test object made of 10 ?m latex particles attached to a standard microscope slide. The test object can be rotated around the vertical axis, parallel to the camera-image plane. Several multiplexed holograms have been recorded of the particles with in-plane and out-of-plane controlled displacements. Two collimated illuminations from a 515nm DPSS laser are used. Polarizing plates are placed with different orientation so the interference between both beams is minimized

The capabilities of this configuration for characterizing the flow in a flexible and transparent model of a carotid bifurcation are also investigated. The bifurcation vessels are excavated inside a thick silicone layer. This kind of model, which allows reproducing realistic and patient-specific bifurcation vessels, introduces some difficulties for holographic velocimetry technique: the inner walls have some roughness that can obscure the seeding particle scattering. The fluid refractive index needs to be matched to the silicone refractive index with a higher than usual accuracy. Besides, the subsequent hologram analysis has to take into account that part of the scattered beam comes from the vessel itself and not only from the seeding particles.

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10333-19, Session 5

Increasing the frame rate of superresolution structured illumination microscopy by means of 2-pattern illumination

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Breaking the diffraction limit (superresolution) is an important challenge for the modern optical microscopy. Over the last years, due to the advances in spatial light modulator (SLM) technologies, structured illumination microscopy (SIM) has become an attractive superresolution technique. SIM is based on the projection of spatially-modulated light beam onto a sample with a set of strictly defined patterns. The superresolution image is calculated by digital processing of an acquired set of images, each corresponding to a different pattern. If the sample is illuminated through the same aperture as the image is formed, the resolution of the resulting superresolution image could be increased up to 2 times. A drawback of the method is the need of acquiring many images to generate a single superresolution image. This leads to a reduced output frame rate. Besides that, the sample object must be still for the whole data acquisition time, otherwise noise will be introduced in the output image. To increase the method efficiency for dynamic events observations, minimizing the data acquisition time is required.

The conventional SIM pattern set consists of many parallel lines in a periodical grid. To achieve a superrresolution effect in one spatial direction a set of 4 patterns, shifted by 1/4 of lines period, should be projected onto the sample. This should be repeated for different spatial directions. A set of 8 images should be acquired in the practically useful case of two orthogonal spatial directions. It is known that this image set can be reduced up to 6 images by switching to 3 patterns for each direction.

The method described in the presented research needs only 2 patterns shifted by half a period. When applied to several spatial directions, the image set can be further reduced to a single pattern for each spatial direction, complemented by a single non-modulated image for all the directions. By utilizing this method for the case of two spatial directions, the total image set is reduced to 3 images. This provides with up to 2 times improvement in data acquisition time compared to the conventional 3-pattern method.

The key difference of the method described is that the optical transfer function (OTF) must be known to calculate the superresolution image. For the diffraction-limited systems the OTF can be computed analytically, while for the real systems with aberrations it can be estimated from the point source images.

As for the conventional method, the superresolution image is calculated be means of digital processing the acquired set of images. Particularly, the high-frequency component lost due to the diffraction is estimated. The calculation procedure is based on the decomposition of the structured-illuminated image into the low-frequency and high-frequency components. The low-frequency components are estimated with the knowledge of OTF, and the resulting high-frequency component is combined with the low-frequency component to generate a superresolution image. The calculation procedure operating in a Fourier domain is presented in this work.

It is shown, that for the hypothetically ideal conditions – unlimited signal-to-noise ratio (SNR) and precisely known OTF – the resolution can be enhanced up to by a factor of 2, as for the conventional SIM. The real conditions and corresponding resolution improvements are discussed.

Besides the frame rate improvement, the method can be used to simplify the illuminating scheme. For the raster-based SLMs (like DMD or LC), the field of view can be increased with the same number of raster elements.

The numerical simulations and experimental results are presented. The experimental results are obtained on a SIM setup, recently developed by the authors, with the SLM based on a 1920x1080 digital micromirror device DLP6500.

10333-20, Session 5

In-focal-plane characterization of excitation distribution for quantitative fluorescence microscopy applications

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The applications of fluorescence microscopy span medical diagnostics, bioengineering and biomaterial analytics. Full exploitation of the potential that fluorescent microscopy could offer is hampered by imperfections in most available systems in illumination, detection and filtering. Most important errors stem from inhomogeneity of these optical components, and they can be addressed most effectively through consistent and accurate calibration. For many such applications, the minimum requirement for achieving meaningful results is homogenous relative fluorescence sensitivity over the entire imaging area. We present a method to quantitatively characterize novel reference materials as a calibration reference for biomaterials analytics.

The reference materials under investigation comprise thin layers of fluorophores embedded in polymer matrices. These layers are highly homogeneous in their fluorescence response, where the sum of all variations does not exceed 1% of the fluorescence response over the field of view (1.5 x 1.1 mm). In order to reliably characterize this very stringent requirement, an automated and reproducible measurement methodology was developed, enabling sufficient correction for measurement artefacts and thus identification of undesired effects within the film under test. This methodology is presented in Figures 1-8.

96 measurements of the fluorescent films allow an initial evaluation of each sample, through which films with large inhomogeneity or other deviations from the specifications can be discarded. The measurement setup is equipped with an autofocus system. This ensures that the measured film quality is not artificially increased by images that are slightly out of focus, since only images that are precisely focused on the film surface will depict defects affecting the suitability of the sample as a calibration reference.

The 96 images are used to calculate a mean image and the deviation of each image to the mean is calculated. The standard deviation of the images on each sample allow the qualification of the layer homogeneity in a comparative way. This method is then further developed to allow calculation and compensation of systemic errors due to the measurement setup such as variations in illumination and detection units, as well as dirt or defects on filters. A comparison of images before and after correction are depicted in Figure 3 and Figure 7 respectively.

The quantitative characterization method is suitable for analysis of modified biomaterials, especially through patterned protein decoration. The imaging method presented here can be used to characterize protein patterns/gradients generated through e.g. micro contact printing in order to statistically analyze such materials, thereby increasing both precision and throughput. Further, the method can be developed to include a reference emitter and detector pair on the image surface of the reference object, in order to provide traceability of the measurements on each sample under investigation.

10333-21, Session 5

Easy and versatile adaptive optics setup with deformable lens for high-resolution microscopy

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Images acquired with high performance optical microscopy systems can be severely affected by the presence of phase aberrations introduced by the sample, or by defects and misalignments of the optical system itself. Correction of phase aberrations has been proven possible through the use of active optical devices, such as deformable mirrors or spatial light modulators.

While the results presented in literature show how implementation of adaptive optics could provide significant advantages for the end users, the complexity of implementation of adaptive optics in an existing microscopy setup prevents the widespread adoption of the technique. In particular, the implementation of adaptive optics through a reflective optical element (i.e. a deformable mirror) requires significant modification to both the hardware and software of the microscopy system, which requires time and effort for a custom made setup, and is in general simply impossible in a commercial setup.

In this paper, we present a technique to easily implement adaptive optics on any optical microscopy system through the addition of a refractive adaptive element at the back of the microscope objective, and a standalone control software which performs wavefront optimization based on images acquired from the computer screen.

The refractive adaptive element is a deformable lens composed of two thin glass windows, upon each of which is mounted a piezoelectric actuator ring. The space in between the windows is filled with a transparent liquid, mineral oil. The first window is used to generate defocus and astigmatism while the second one generates coma and secondary astigmatism. Both rings are divided into 8 sectors that can be actuated independently. The piezo rings are glued to the windows and act as a bimorph actuator, such that the application of a voltage generates a bending of the glass window. The actuators are controlled by a 16 channel high voltage driver. The 8 actuators on the top and bottom windows generate different effects because the top window is attached to the actuator by an elastomer foam that is free to move. Due to the possibility of attaching the refractive element, with a total thickness of 1 cm, to the back of any microscope objective, any microscope can be easily converted to an adaptive system, by simply changing the distance between the objective and the sample.

Optimization of the image quality is performed by grabbing images directly to the computer screen, in order to make the system compatible with any commercial microscope, even if the software is closed source. A variety of image based metrics (e.g. Total intensity, Fourier content, contrast) is employed for different kind of microscopy methods. Optimization is performed through the internally developed DONE algorithm, providing fast convergence even in the presence of significant measurement noise, and under small dynamic variations of the aberration.

We prove the validity and versatility of the technique by implementing it on a variety of different microscopy systems: in particular a commercial confocal microscope, a generic epifluorescence microscope, a lightsheet microscope, and a multiphoton microscope used for in-vivo functional imaging.

10333-22, Session 5

An all-holographic interferometer for phase contrast imaging

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Modern holographic photopolymers such as the Bayfol HX are cost-efficient, easy to handle and can achieve diffraction efficiencies beyond 90%. We show that the angular readout-sensitivity can be substantially increased by stacking multiple foils and demonstrate the recording of a self-adjusted, highly sensitive interferometer.

We show how a setup of two, respectively three, holograms can be used for microscopic phase contrast imaging.

10333-23, Session 5

Label-free imaging of single microtubule dynamics using spatial light interference microscopy *(Keynote Presentation)*

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Due to their diameter, of only 24 nanometers, single microtubules are extremely challenging to image without the use of extrinsic contrast agents. As a result, fluorescence tagging is the common method to visualize their motility. However, such investigation is limited by photobleaching and phototoxicity. We experimentally demonstrate the capability of combining label-free spatial light interference microscopy (SLIM) with numerical processing for imaging single microtubules in a gliding assay. SLIM combines four different intensity images to obtain the optical pathlength map associated with the sample. Because of the use of broadband fields, the sensitivity to pathlength is better than 1 nm without (temporal) averaging and better than 0.1 nm upon averaging. Our results indicate that SLIM can image the dynamics of microtubules in a full field of view, of 200 X 200 ?m2, over many hours. Modeling the microtubule transport via the diffusion-advection equation, we found that the dispersion relation yields the standard deviation of the velocity distribution, without the need for tracking individual tubes. Interestingly, during a two-hour window, the microtubules begin to decelerate, at 100 pm/s2 over a 20-minute period. Thus, SLIM is likely to serve as a useful tool for understanding molecular motor activity, especially over large time scales, where fluorescence methods are of limited utility.

10333-24, Session 6

Digital holographic microscopy as a technique to monitor macrophages infected by leishmania

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Macrophages are cells of the immune system that are located in the tissues and are the procedures of mature monocytes that introduce into a developed tissue the phagosytic capacity, that means that they surround with their cytoplasmic membrane solid particles and introduces them into the cellular interior. As a result of this process, they drastically change their size and increase the number of their organelles. Their function is to phagocyte antigens, changing their physiology and secreting different types of substances. Macrophages are activated by stimuli due to the immune response, antigen phagocytosis serves as a stimulus but this process is accompanied by changes in their density and morphology which depends on the type of pathogen and levels of infection. A type of bacteria that directly affects macrophages is the leishmania. This parasite is a disease that is usually found in jungle areas or tropical forests and is transmitted by the bite of a hematophagous insect. The parasite enters the blood in the form of promastigotes, when it is in contact with the macrophages it is phagocytosed and the macrophage becomes a host cell; changing its spherical shape, size and density. The characteristics of this cell make macrophages play a central role in the human immune system and their study is of vital importance in interpreting and fighting diseases.

The leshmania has several categories and these depend on the location in which they are located, either cutaneous or visceral, its diagnosis is based on epidemiological history of the area, symptoms and examination of the lesions, but what is sought for definitive diagnoses is the presence of Promastigotes through cultures of the affected material by optical microscopy, eventought this technique is very limited to obtain detailed information about size and individual infection status of each cell. Research has been undertaken of the changes undergone by macrophages before and after phagocytosis has been performed using fluorescent marker techniques as described below. Samples of J744.A1 cells (control, exposed to latex or infected particles) adhered to glass flakes were collected for 24 hours on two different fluorescent anion probes. The Zeiss IM-35 inverted optical microscope was used and the images were recorded with a CCD sensor (Charge Coupled Device) model IC-100 coupled under the microscope and with the AIW 2.2 program. The cells were exposed to the yellow lucifer probe (521 da), which absorbed at 427 nm and emitted at 535 nm at a concentration of 0.5 mg / ml, plus 5 mM ATP and 5 ?M pluronic acid in RPMI for 5 minutes. The cells were also exposed to Calcein / AM (995 da) probe, which absorbs at 494 nm and emits at 517 nm (Molecular probes, Eugene, Oregon), at a concentration of 25-40?M in RPMI for 5 minutes. Fluorescent labeling was detected using a set of 480 nm / 520 nm filters. Through this technique changes in shape and density could be monitored inside the cells under study.

As an alternative technique for this study, the interferometric technique of Digital Holographic Microscopy (DHM) technique was implemented as a non-invasive and no-marker optical technique to study mouse peritoneal macrophages (J774. A1) in different states: healthy, Having phagocytosed latex microspheres or being infected by leshmania. For this purpose an optical setup of a modified Mach Zehnder interferometer was set up in transmission, in order to perform the digital recording of the holograms. The interference pattern produced between the optical field diffracted by the samples under study and an optical reference field with a CMOS (Complementary Metal-oxide-Semiconductor) solid state sensor was acquired. In order to reconstruct the complex optical field transmitted through the object, the integral diffraction of the field must be calculated using numerical methods. For this, the angular spectrum approximation is used, obtaining the diffracted complex optical field and from it the amplitude maps and phase difference maps. The amplitude allows to determine both the size and the morphological changes that the macrophages undergo in the presence of pathogens. Additionally, with the phase variations, information of the integral refractive index associated with variations in sample density has been obtained and as a consequence it is possible to determine the infection status of an infected macrophage. The records are made with living cells in an environment similar to natural, a prerequisite for visualizing biological processes. The results offered by DHM for the study of leshmania show significant phase changes between healthy and infected macrophages implying variations in the integral refractive index, providing the possibility to quantify significant changes in size and to estimate levels of infection.

With the use of this technique it was observed that the study of macrophages reveals significant phase changes between healthy macrophages, those that phagocytosed latex beads and those that were infected by the leshmania bacterium, which implies variations in the integral refractive index which depends significantly on what the cell phagocytes. In addition to this technique, it was possible to observe the infection in two conditions 24h and 48h after infection, which makes it possible to estimate the infection status of a culture or sample without any dye or damage to the sample. It was possible to quantify significant size changes depending on the state of the macrophage.

10333-25, Session 6

On-axis programmable microscope using liquid crystal spatial light modulator

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Spatial light modulators (SLM) are currently used in many applications in optical microscopy and imaging. One of the most promising methods is the use of liquid crystal displays (LCD) as programmable phase diffractive optical elements (DOE) placed in the Fourier plane giving access to the spatial frequencies which can be phased shifted individually, allowing to emulate a wealth of contrast enhancing methods for both amplitude and phase samples. We use phase and polarization modulation of LCD to implement an on-axis microscope optical system. The LCD used are Hamamatsu liquid crystal on silicon (LCOS) SLM free of flicker, thus showing a full profit of the SLM space bandwidth, as opposed to optical systems in the literature forced to work off-axis due to the strong zero-order component. Taking benefits of the phase modulation of the LCOS we have implemented different microscopic imaging operation as high pass and low pass filtering in parallel using programmable blazed gratings. Moreover, we are able to control polarization modulation to display two orthogonal linear state of polarization images than can be subtracted or added by changing the period of the blazed grating. In that sense, Differential Interference Contrast (DIC) microscopy can be easily done by generating two images exploiting the polarization splitting properties when a blazed grating is displayed in the SLM. Biological microscopy samples are also used.

10333-26, Session 6

A pocket device for high-throughput optofluidic holographic microscopy

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The study of biological specimens onboard compact Lab-on-a-Chip (LoC) platforms with embedded label-free, quantitative, 3D imaging functionalities is highly demanded. Among the existing imaging methods, Digital Holography microscopy is preferred to achieve full field imaging of samples flowing in a liquid volume with a single-shot recording. Recently, handy holographic imaging platforms have been introduced, mainly relying on lensless Digital in Line Holography (DILH) setups. In order to obtain the phase information of the samples and to overcome the resolution limitations imposed by the finite pixel size, iterative algorithms need to be used, whose convergence to a global solution is not always guaranteed. In general, a trade-off exists in microscopy between sample magnification and the maximum available Field-of-View (FoV). Here we introduce a lens-based imaging modality, named Space-Time Digital Holography (STDH), which exploits the samples motion inside microfluidic channels to obtain a synthetic hologram, mapped in a hybrid space-time domain, and with intrinsic useful features [1]. Indeed, a single Linear Sensor Array (LSA) is sufficient to build up a synthetic representation of the entire experiment (i.e. the STDH) with unlimited Field of View (FoV) along the scanning direction and reduced noise, independently from the magnification factor. Out-of-focus recordings are performed using a LSA and polymeric micro-lenses embedded onboard chip [2], in order to synthesize a STDH carrying full field, 3D information of flowing biological specimens. We discuss the method and prove that a STDH still maintains all the advantageous capabilities of DH microscopy. The throughput of the imaging system is dramatically increased as STDH provides unlimited FoV, refocusable imaging of samples inside the liquid volume with no need for hologram stitching [1]. We then afford the issue of integrating the holographic interferometer onboard chip. Instead of adopting a DILH approach with iterative reconstruction algorithms, we use an off-axis DH configuration and closed form solutions to the diffraction integral to reconstruct the STDH [3]. At this scope, a polymer grating is written onto the channel to extract a reference wave from the object wave impinging the LoC. A portion of the beam reaches the samples, carrying their information content to the LSA, while one of the diffraction orders from the grating acts as an off-axis reference wave. Thus, all the required optical components are embedded onboard a pocket device, and fast, non-iterative, reconstruction algorithms can be used [3]. To test our embedded STDH microscopy module, we counted, imaged and tracked in 3D with high-throughput red blood cells moving inside the channel volume under unideal flow conditions. The robustness of STDH against unwanted velocity distributions will be demonstrated, thus validating the method.

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10333-27, Session 6

Label-free investigation of the effects of lithium niobate polarization on cell adhesion

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The interfacial effects influencing cell adhesion and morphology and the temporary formation of adhesion contacts between cells and substrate is of considerable interest in the study of cell motility, mechano-transduction and biocompatibility1. In particular, the importance of surface charges on cell behavior at the biomaterial interface was demonstrated concluding that surface charges have a profound effect on biological responses. The surface charges affect the adsorption of proteins onto the material surface and subsequently influence the cell morphology and migration2,3. Here, we use for the first time Holographic Total Internal Reflection Microscopy (HoloTIRM) to study the NIH-3T3 cell behavior on c-cut Lithium Niobate (LN) crystals, focusing our attention on the effects of the polarization sign of the crystal on the cytoskeleton and focal adhesion organization that, in turn, regulates a wide variety of cell functions such as cell migration and fate4. The selective illumination of a very thin region directly above the substrate, achieved by Total Internal Reflection, provides high-contrast images of the contact regions. Holographic recording, on the other hand, allows for label-free quantitative phase imaging of the contact areas between cells and LN. Phase signal is more sensitive in the first 100nm and, thus more reliable in order to locate focal contacts. This work shows that cells adhering on negatively polarized LN present a significant increase of the contact area in comparison with cells adhering on the positively polarized LN substrate, as well as an intensification of contact vicinity. This confirms the potential of LN as a platform for investigating the role of charges on cellular processes. The similarity of cell adhesion behaviour on negatively polarized LN and glass control also confirms the possibility to use LN as an active substrate without impairing cell behaviour.

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10333-28, Session 6

Multimodal nanoscale microscopy *(Invited Paper)*

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Today, the unique possibility of inspecting, characterizing and imaging biological systems by means of far-field optical microscopy both under fixed and living conditions down at the nanoscale allows a more commensurate correlation with high resolution methods like the ones used in scanning probe microscopy, i.e. STM, AFM and SNOM. Phase contrast, confocal and multiphoton microscopy were a prelude for the super resolved approaches. Today, in the era of super resolution, we have a continuous growth of variations on the theme including multimodal and correlative approaches. Optimized exploitation of microscopy data, from lifetime to polarization signatures, and new approaches for extending the knowledge about living systems can be integrated in a new paradigm for the microscope. A multimodal microscope tunable on the scientific question and posing scientific questions about light-matter interactions. As well, correlative microscopy coupling optical, scanning force and electron microscopy methods enhances the capabilities of the modern microscope. Super resolved approaches, Mueller matrix signature, multi photon and light-sheet microscopy will be discussed in the framework of multimodal and correlative microscopy in 4D biological applications.

10333-29, Session 6

Applications of holographic on-chip microscopy *(Keynote Presentation)*

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My research focuses on the use of computation/algorithms to create new optical microscopy, sensing, and diagnostic techniques, significantly improving existing tools for probing micro- and nano-objects while also simplifying the designs of these analysis tools. In this presentation, I will introduce a set of computational microscopes which uses lens-free on-chip imaging to replace traditional lenses with holographic reconstruction algorithms. Basically, 3D images of specimens are reconstructed from their "shadows" providing considerably improved field-of-view (FOV) and depth-of-field, thus enabling large sample volumes to be rapidly imaged, even at nanoscale. These new computational microscopes routinely generate >1–2 billion pixels (giga-pixels), where even single viruses can be detected with a FOV that is >100 fold wider than other techniques. At the heart of this leapfrog performance lie self-assembled liquid nano-lenses that are computationally imaged on a chip. These self-assembled nano-lenses are stable for >1 hour at room temperature, and are composed of a biocompatible buffer that prevents nano-particle aggregation while also acting as a spatial "phase mask." The field-of-view of these computational microscopes is equal to the active-area of the sensor-array, easily reaching, for example, >20 mm2 or >10 cm2 by employing state-of-the-art CMOS or CCD imaging chips, respectively.

In addition to this remarkable increase in throughput, another major benefit of this technology is that it lends itself to field-portable and cost-effective designs which easily integrate with smartphones to conduct giga-pixel tele-pathology and microscopy even in resource-poor and remote settings where traditional techniques are difficult to implement and sustain. Some other examples of these smartphone-based biomedical tools that I will describe include imaging flow cytometers, immunochromatographic diagnostic test readers, bacteria/pathogen sensors, blood analyzers for complete blood count, and allergen detectors. Through the development of similar computational imagers, I will also report the discovery of new 3D swimming patterns observed in human and animal sperm. One of this newly discovered and extremely rare motion is in the form of "chiral ribbons" where the planar swings of the sperm head occur on an osculating plane creating in some cases a helical ribbon and in some others a twisted ribbon. Shedding light onto the statistics and biophysics of various micro-swimmers' 3D motion, these results provide an important example of how biomedical imaging significantly benefits from emerging computational algorithms/theories, revolutionizing existing tools for observing various micro- and nano-scale phenomena in innovative, high-throughput, and yet cost-effective ways.

10333-30, Session 7

Stereo microscope 3D digital image correlation system for micromechanical characterization of biomaterials

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Scientists and engineers in biomaterials research rely on measurements to make breakthroughs in applied research, technology development, and quality assurance. There are many challenges in biomaterials research. One of them is that many specimens are very small and sensitive - therefore it is extremely difficult to measure their deformation and strain. In order to overcome this limitation we have recently developed stereoscopic microscope 3D digital image correlation (DIC) system capable of the measurement of the sub-micrometer deformation of different types of biomaterials and biological tissues. The method is based on a pattern recognition on the specimen to be observed, the so-called "speckles". Two cameras in a stereoscopic setup connected to a stereoscopic microscope create an opportunity to perform 3D deformation and strain measurement of micro specimens. Single camera provides just a 2D view. Software forms a 3D image through a correlation algorithm based on two camera images taken from different angles. Specimens have to be marked by applying a stochastic pattern (speckles) on their surface. This pattern is created by using white matte paint as a background and later black speckles are created by spraying the surface with black matte (no reflective) paint. For some materials it is recommended to apply dry paints for example powdered titanium oxide (white) and carbon or magnesium powder (black). For best results it is recommended to use particles of different size in order to create an optimal speckle size. In some materials, it is possible to use a natural speckle pattern (for example, grains of metals or cell lumen and cell walls in wood). Pattern adhesion is an important factor of DIC accuracy. However, the currently available choice and quality of paints ensures sufficient pattern adhesion. In delicate materials for speckle pattern generation, we can use water-based chalk spray or dry pigments which can be applied by an airbrush. Dry pigments which do not contain any "aggressive" solvents are recommended for materials which could chemically interact with surface. This could change mechanical properties of tested material. Stereoscopic perspective is used by correlation algorithm to identify the same object points (homolog points). The gray value pattern on the surface (a stochastic structure) enables the correlation algorithm to calculate 3D coordinates. A digital image of the surface can be reconstructed with knowledge of the imaging setup like camera distance from the measured object, angle and distance of the cameras and also optical distortions caused by objectives. The first step of analysis is the recognition of shape and reconstruction of the 3D surface. Second step is measurement of deformation. Measurement of the deformation begins with comparison of the reference image with the image acquired after deformation of the specimen. The correlation algorithm analyzes small areas, sub-frames, or facets composed of 10–30 pixels in length. The algorithm needs a unique and recognizable pattern in each facet. In order to accurately calculate 3D deformation in units of length image from two cameras has to be calibrated. The calibration process enables the algorithm to correct errors generated by a distortion of an image during passage of the light path through optical system. During calibration a certified "checkboard" plate is rotated in 3D space under different perspective views. The calibration process calculates such parameters like focal length, radial distortion, tangential distortions, principle point which are influenced by focal lens, focal distance, and aperture. After calibration and measurement, it is possible to calculate 3D displacements, different strains and when force generating strain is known it is possible also to calculate values like Young's Modulus. The data are represented in the many different forms like false color map where different values of strain and displacement are shown in a color scale, object contour, mesh deformation, arrows etc. Stereo Microscope 3D Digital Image Correlation System enables true full-field, non-contact and three-dimensional analysis of displacements, strains and stress on biomedical materials and components in microscale. It can be used for many tests including tension, compression, torsion, bending and combined loading, peel, creep, relaxation and many others on a wide range of biomaterials. It can be used in the field of research for micromechanical characteristics of ultra-small and sensitive materials. High measurement sensitivity and accuracy enables to measure deformation induced not only by direct mechanical loading but also by thermal loading, changes of humidity and by physiological factors. Micro DIC system was successfully used in tensile test of micro specimen made of titanium used for hip implant after fatigue lifetime test. Results included 3D map of displacement and strain, Modulus, Poisson Ratio and many other results. We present also successful measurement of trabecular bone (Lat. substantia spongiosa ossium) structure during compression test. The experiment was performed in order to obtain strain values of individual trabeculae to calculate their Young's Modulus and improve FEM model of bone. This microscale measurements are used to correctly predict macro-scale interaction between bone and implant. We have also performed shear test of polyurethane with special coating used for producing artificial heart valve. The values of strain measured by Micro DIC were similar as tested by in situ SEM (scanning electron microscope) micro shear test and calculated by FEM (Finite Element Method) model for the same values of load and displacement. System was also used for strain measurement of micro-stents. Another application was measurement of the dogwood stems (Cornus alba L) cross sections strains under influence of humidity. Development of new types of biomaterials, prostheses and implants requires full mechanical characteristics of this new materials. This materials have to fulfill certain mechanical requirements – they have to match mechanical properties of materials that they substitute. Therefore there is a need for information

of mechanical properties of existing tissues and of materials that are used to replace them. The purpose of this presentation is to present different examples of micromechanical measurements performed on 3D stereomicroscope DIC proving successful application of this system for biomedical research.

10333-32, Session 7

Correlation plenoptic imaging *(Invited Paper)*

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The unavoidable trade-off between resolution and depth of focus (DOF) limits traditional optical imaging. High numerical apertures (NA) enable to increase the resolution, but the associated large angular uncertainty results in a limited range of depths that can be put in sharp focus.

Plenoptic imaging was introduced a few years ago to improve the DOF of imaging devices. To this end, plenoptic imaging reconstructs the path of light rays from the lens to the sensor [1]. This is practically achieved by inserting a microlens array in the conjugate plane of the object (as created by the main lens), and moving the sensor in the conjugate plane of the main lens (as created by each microlens). The microlens array also enables the single-shot acquisition of multiple-perspective images.

The working principle of plenoptic imaging is currently employed in the most diverse applications, from stereoscopy to microscopy, particle image velocimetry, particle tracking and sizing, wavefront sensing, as well as photography, where it currently enables digital cameras with refocusing capabilities [2]. In particular, the capability of PI to simultaneously acquire multiple-perspective 2D images puts it among the fastest and most promising methods for 3D imaging with the available technologies (e.g. [3]).

However, the improvement offered by standard plenoptic imaging is practical rather than fundamental: the increased DOF leads to a proportional reduction of the resolution well above the diffraction limit imposed by the lens NA. Also, the change of perspective is effectively strongly limited by the small field of view of the microlenses [1].

We demonstrate that this fundamental limitation can be overcome by taking advantage of the second-order correlation properties of light: Correlation Plenoptic Imaging (CPI) exploits the spatio-temporal correlation of specific light sources to push plenoptic imaging to its fundamental limits of both resolution and DOF [4,5]. In the scheme employed for the theoretical and experimental demonstration of CPI, light from a chaotic source is divided in two optical paths by a beam splitter. Reflected light directly impinges on the high-resolution sensor Sa, while transmitted light first passes through the object and then through a lens, which focuses the source on the high-resolution sensor Sb. By measuring intensity correlations between the two sensors, multiple images of the object can be retrieved on Sa, which are focused if the optical distance between the source and Sa is equal to the distance between the source and the object. Each image corresponds to a different pixel of Sb, hence to light emitted by a different point of the source. Information encoded in the intensity correlation function can be used to effectively refocus largely out-of-focus images. The intensity correlation function thus possesses plenoptic imaging properties, namely, it encodes both the spatial and the directional information enabling its key refocusing capability. We will also present the first experimental demonstration of diffraction-limited imaging with a DOF increased by a factor of three with respect to standard imaging.

Our results represent the theoretical and experimental basis for the effective development of the promising applications of plenoptic imaging. The plenoptic application is the first situation in which the counterintuitive properties of correlated systems are effectively used to beat intrinsic limits of state-of-the-art imaging systems.

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10333-33, Session 7

Spatial coherence engineering of lasers for speckle-free and multimodality imaging *(Invited Paper)*

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1. Introduction.

Spatial coherence is a defining characteristic of laser emission. High spatial coherence allows focusing electromagnetic energy to a small spot or collimation of an optical beam over a long distance. However, spatial coherence can also introduce coherent artifacts such as speckle, since any uncontrolled scattering in the imaging system can cause multi-path interference. These artifacts have limited the use of lasers in full-field imaging applications ranging from traditional wide-field microscopes to laser projectors, holography, and photolithography systems. Instead, traditional low spatial coherence sources such as thermal light sources and LEDs are still used for illumination in most full-field imaging applications, despite having lower power per mode, poor collection efficiency, and less spectral control than lasers. These limitations are particularly pronounced in applications requiring high-speed imaging, or imaging in absorbing or scattering media, prompting the use of raster-scanning for laser imaging.

For parallel imaging and projection applications, the ideal illumination source would combine the high power per mode of a laser with the low spatial coherence of an LED. The common approach to achieve this combination is reducing the effective spatial coherence of a traditional laser using, e.g. a spinning diffuser, a colloidal solution, or a MEMs mirror. However, these techniques require averaging over many speckle patterns in time, mitigating the advantage of using bright sources such as lasers or superluminescent diodes for high-speed imaging applications. Another approach to suppress speckle is by taking advantage of the low temporal coherence of broadband sources like superluminescent diodes (SLD) and supercontinuum sources. However, these sources maintain high spatial coherence and still produce speckle with notable contrast in most imaging contexts. Moreover, this approach cannot be adopted for applications that rely on narrowband illumination such as deep UV photolithography with excimer lasers.

2. Reducing spatial coherence for speckle-free laser imaging.

We took an alternative and more effective approach to design a laser that generates emission in an intermediate number of spatial modes, producing sufficiently low spatial coherence to suppress speckle, while maintaining higher power per mode than an LED or a thermal light source. Recently we showed that a random laser can be engineered to provide low spatial coherence [1], and demonstrated speckle-free full-field imaging in the setting of intense optical scattering [2]. To avoid optical pumping, we fabricated an electrically-pumped semiconductor laser that produces intense emission with low spatial coherence [3]. Specifically, we designed a chaotic microcavity to support highly multimode lasing, and experimentally realized lasing in ~1000 mutually incoherent modes in a single cavity. The chaotic microcavity laser was fabricated by photolithography and wet etching, and hence was relatively simple and compatible with mass production. The lasing performance was robust against cavity shape deformation and boundary roughness. It offers a compact and low-cost illumination source for a host of imaging applications, from high-speed microscopy to handheld laser display and machine vision.

3. Efficient coherence switching for multimodality microscopy.

While speckle formation is a limiting factor when using coherent sources for imaging and sensing, it can provide useful information about the motion of an object. Illumination sources with tunable spatial coherence are therefore desirable as they can offer both speckled and speckle-free images. We invented a fast and efficient method of coherence switching with the degenerate laser. After an initial demonstration with a solid-state degenerate laser [4], we built a semiconductor-based degenerate laser system with an adjustable degree of spatial coherence [5]. It is based on vertical external cavity surface emitting laser (VECSEL) and is electrically pumped, mechanically compact. The continuous-wave (CW) laser operation can be switched between a high number of mutually incoherent spatial modes and few-mode operation at little power-loss. With this system we performed multimodal imaging, using the low spatial coherence illumination for structural image and high spatial coherence illumination to extract dynamic information of blood flow process. The initial demonstration is performed on Xenopus, which is an important animal model for human heart disease.

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10333-34, Session 8

Metrological study of varifocal limited angle optical diffraction tomography for biological applications

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Limited angle optical diffraction tomography (LAODT) is a nondestructive method, which gives precise information about the investigated biological sample without the need of using markers. It is a powerful tool when weakly scattering microbiological samples are to be measured directly from Petri dishes and microscope slides. Illumination scanning setup allows for reconstructing three-dimensional refractive index distribution of a stationary investigated object, like biological cell cultures, tissue samples, bacterial colonies, etc. The main problem with LAODT is highly anisotropic resolution: it is high in the plane perpendicular to the optical axis, and reduced in the direction of the optical axis. Previously we have proposed a solution which addresses this issue through implementation of the reconstruction method, called Generalized Total Variation Iterative Constraint (GTVIC). It is a two-step iterative algorithm which exploits the fact, that most biological cells that are investigated have sparse boundaries. Based on this assumption, in the first step a support constraint is generated, which then is used in the second step: a tomographic reconstruction method based on the Fourier Diffraction Theorem. However, when thicker biological samples are investigated and the ratio of object's thickness and Depth of Field increases, this approach fails resulting in reconstruction with reduced resolution. Thus, we propose a new method which combines numerical and experimental modifications to enhance resolution of LAODT, namely Varifocal LAODT (VLAODT), where varifocal lens is introduced into the tomography setup. This approach increases the isotropy of the resolution in the reconstruction through acquisition of multiple projections for each illumination direction with different defocus values. As a consequence, multiple reconstructions are calculated for different sections of the object being in focus. In the last step, a final reconstruction is stitched from in-focus sections of the intermediate reconstructions. VLAODT approach combined with GTVIC reconstruction method constitutes a complete solution for measuring biological microsamples. However, there was no attempt to determine metrological capabilities of this combined technique. In this paper, we determine metrological parameters of the VLAODT system through determination of: (1) spatial resolution of the reconstruction – both in the plane perpendicular to the optical axis and in the direction of the axis, (2) phase resolution. The analyzes are performed in two ways. First, numerical simulations are calculated – a numerical phantom object is measured and reconstructed with GTVIC method. What is important, these investigations are carried out for different numerical phantoms: they vary in thickness and in distribution of refractive index (peak-to-valley and gradient values). Later, experimental analyzes are conducted to confirm the values obtained in numerical part of the study. A real micro-phantom with a geometry determined with a reference method is analyzed in VLAODT setup and reconstructed with GTVIC algorithm. Results from numerical and experimental parts of this study are confronted to specify metrological capabilities of VLAODT.

10333-35, Session 8

Optical metrology of the eye and of ocular tissues *(Keynote Presentation)*

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Low coherence interferometric (LCI) biometry of the eye was the first application of this technology to biological tissue and a predecessor of optical coherence tomography (OCT). On occasion of the recent 30th anniversary of LCI ocular biometry and the 25th anniversary of OCT, this talk builds the bridge from the first axial eye length measurements by LCI to modern functional OCT extensions that enable quantitative metrology of parameters like ocular blood flow, ocular tissue pulsations, and birefringence of ocular tissues.

10333-36, Session 8

Tomographic flow cytometry assisted by intelligent wavefronts analysis

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High-throughput single-cell analysis is a challenging target for implementing advanced biomedical applications. An excellent candidate for this aim is label-free tomographic phase microscopy. However, in-line tomography is very difficult to be implemented in practice, as it requires complex setup for rotating the sample and/or illuminate the cell along numerous directions [1]. We exploit random rolling of cells while they are flowing along a microfluidic channel demonstrating that it is possible to obtain in-line phase-contrast tomography by adopting strategies for intelligent wavefronts analysis, thus obtaining complete retrieval of both 3D-position and orientation of rotating cells [2]. Thus, by numerical wavefront analysis a-priori knowledge of such information is no longer needed. This approach makes continuos-flow cyto-tomography suitable for practical operation in real-world, single-cell analysis and with substantial simplification of the optical system avoiding any mechanical/optical scanning of light source. Demonstration is given for different classes of biosamples, red-blood-cells (RBCs), diatom algae and fibroblast cells [3]. Accurate characterization of each type of cells is reported despite their very different nature and materials content, thus showing the proposed method can be extended, by adopting two alternate strategies of wavefront-analysis, to many classes of cells.

In particular, for RBCs we furnish important parameters as 3D morphology, Corpuscular Hemoglobin (CH), Volume (V), and refractive index (RI) for each single cell in the total population [3]. This could open a new route in blood disease diagnosis, for example for the isolation and characterization of "foreign" cells in the blood stream, the so called Circulating Tumor Cells (CTC), early manifestation of metastasis.

For what concerns diatoms, a key issue is the estimation of their three-dimensional shape and biovolume, providing important information useful in several research areas from taxonomy to the study of ecosystem health. By the proposed technique, we demonstrate the quick and accurate calculation of such parameters for different classes of diatoms, and reconstruct the precise shape and location of chloroplasts, responsible of

the photosynthesis of these algae and very sensitive to the presence of contaminants in oceans.

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10333-37, Session 8

3D-stitching of depth data of porous surface coatings based on 3D phase correlation and the trimmed ICP algorithm

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A critical factor of endoprostheses is the quality of the tribological pairing which is strongly influenced by the surface texture and microstructure. In this work stochastically porous Al2O3 surface coatings, manufactured by a thermal spraying process, are investigated. The objective of this research project is to manufacture surfaces with high wear resistance and an active friction minimization. This is approached by embedding a channel system beneath the surface, which is to serve as a reservoir for lubricants. Due to the porosity of the surface layer, which is affected by the parameters of the thermal spraying process, the lubricant is to pass through the coating and escapes on the top level.

This work focuses on the examination of the porous network of the surface coating. Although, there are many experimental and computerized techniques known from mercury porosimetry to imaging methods for studying porous materials, the characterization of disordered pore networks is still a great challenge. To meet this challenge it is striven to gain a three dimensional high resolution reconstruction of the coating. This is achieved by repeatedly milling the surface with a fixed decrement while measuring each layer using a confocal laser scanning microscope (CLSM), which provides depth data of each layer. After preprocessing the acquired depth data in each layer using a Gaussian filter for noise reduction and a least square plane fit for tilt correction, the depth data of the successive layers are stitched pairwise. Image stitching is an active research area and can in general be categorized in two approaches: direct and feature based techniques. Within this work the former is implemented in two steps, a coarse and a fine alignment. The coarse alignment of the depth data is limited to a translational shift which occurs in horizontal direction due to placing the sample in turns under the CLSM and the milling machine and in vertical direction due to the milling process itself. The shift is determined by an approach utilizing 3D phase correlation, which has a high robustness regarding the discontinuity of the microstructures in each layer. Based on the coarse alignment in three directions the successive depth data is further processed and narrowed down to the most likely common pixels which serves the fine alignment. The fine alignment is implemented by the Iterative Closest Point (ICP) algorithm, matching the data by minimizing the mean square error. Because it is not to be guaranteed that all matched data points are outlier-free the Trimmed ICP (TrICP) rather than the original ICP algorithm is used. The TrICP estimates the rigid transform according to a given overlap rate and takes only the trimmed point pairs, the Least Trimmed Squares, respectively, into account. With this two-step approach a volume representation of the surface coating is obtained.

Conclusive, an approach is presented to gain a high resolution 3D reconstruction of porous surfaces or material by an alternating process of measuring and milling a surface and a subsequent 3D stitching of the obtained data. This serves a better understanding of the porous network and further allows e.g. to measure both the open and the closed porosity independently.

10333-38, Session 8

Red blood cells as microlenses: wavefront analysis and applications

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Great advances have been done in the last years in the field of photonic techniques applied to medical science with the aim of making less invasive and more efficient current therapies or for developing new ones. In this context, we propose a completely new concept where cells can be manipulated and adopted as functional and active optical elements at Lab-On-Chip scale. Specifically, we model Red Blood Cells (RBCs) as fluidic nanolenses by demonstrating their focus tunability and imaging capability. By an optical point of view, we take benefit of the intrinsic great deformability and the lack of nucleus and organelles thus modeling the RBC as a sort of disk-shaped micro-structured envelope changing its shape and exploitable as a tunable liquid lens.

One important application is in blood diagnostics. Indeed, RBCs anomalies are significant symptoms for identification of health disorders. In particular, several blood diseases involve modification in the morphology of such cells, i.e. sickle-cell disease, malaria, and spherocytosis. We demonstrate that, exploiting the new concept of bio-nanolenses and in analogy to Indirect Adaptive Optics (IAO) testing tools (i.e. Shack-Hartmann), it is possible to discern between healthy and anomalous RBC, thus providing a completely new, faster and much more objective diagnostic criterion. Correlation between an RBC's morphology and its behavior as a refractive optical element has been established. In fact, any deviation from the healthy RBC morphology can be seen as additional aberration in the optical wavefront passing through the cell. By this concept, accurate localization of focal spots of RBCs can become very useful in blood disorders identification.

Moreover, By modelling RBC as bio-lenses thorough Zernike polynomials it is possible to identify a series of orthogonal parameters able to recognise RBC shapes. The main improvement concerns the possibility to combine such parameters because of their independence conversely to standard image-based analysis where morphological factors are dependent each-others. Demonstration on RBC phenotypes identification is supplied in case of Iron-deficiency Anaemia, Thalassemia and Hereditary Spherocytosis, which are the most common causes of anemia in the world and have to be considered often in differential diagnosis.

Finally, we study the optical behavior of RBCs under an optically-induced mechanical stress. Detailed wavefront analysis provides comprehensive information about the aberrations induced by the deformation obtained using optical tweezers. This could open new routes for analyzing cell elasticity by examining optical parameters instead of direct but with low resolution strain analysis, thanks to the high sensitivity of the interferometric tool.

10333-39, Session 9

Algorithm for multiframe full-field heterodyne digital holographic microscopy

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Based on interference recording and diffraction reconstructing, holography can measure the object's three-dimensional profile. Digital holographic microscopy (DHM) is a non-contacting and non-dyeing imaging technique, which could be used in biology to measure the profile of living cell and other phase objects.

In DHM system, the twin-image and the random noise are two major problems, which limit the reconstruction precision and applications of DHM.

In phase-shifting digital holography, 4-step holograms of $\varpi/2$ phase-shifting are detected. Using corresponding processing algorithm, the twin-image could be eliminated. The phase-shifting is achieved by moving a mirror in optical path with a piezoelectric transducer (PZT), and the phase-shifting accuracy is affected by nonlinear error.

Alternatively, full-field heterodyne holography uses two acousto-optic modulators (AOMs) to create low frequency heterodyne interference, in which 4-step phase-shifting holograms could be detected with full-field camera. Processing the holograms with 4-step phase extracting algorithm, the twin-image term can be eliminated.

Usually Multi-periods of holograms are recorded to suppress the influence of random noise though time-averaging. In the case of high precision phase-shifting interferometer, multiple steps of phase-shifting interference patterns are detected and processed with corresponding algorithms to reduce the non-linear error of a PZT.

To combine the advantages of multi-period and multi-step phase-shifting technology, a multi-frame full-field heterodyne DHM is proposed. Low frequency heterodyne AOMs? high speed camera and multi-frame temporal signal processing algorithm are applied to this DHM system.

The algorithm for this system is discussed in this paper, which mainly includes phase extracting and phase unwrapping steps. In phase extracting step, temporal frequency spectrum analysis algorithm is applied to extract the object information, by which the twin-image problem can be solved and the random noise can be significantly suppressed. In phase unwrapping step, the unwrapping path is designed to overcome the effect of noise in two-dimensional wrapped phase, and the 'wire drawing error' is corrected with digital image processing method. The algorithm will be discussed with theory and demonstrated by experimental results.

10333-40, Session 9

Adaptive lens aberrations correction in in-vivo optical coherence tomography

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The recently introduced Multi-actuator Adaptive Lens (MAL) can be used in closed loop with a wavefront sensor to correct for time-variant wavefront aberrations. The MAL can guarantee a level of correction and a response time similar to that obtained with deformable mirrors. The advantage of the use of adaptive lenses instead of deformable mirrors can simplify the implementation of an adaptive optics system. The adaptive lens uses piezoelectric bimorph actuators and, without any obstruction or electrodes in the clear aperture, can guarantee a fast response time, less than ~10ms.

The experimental results we present show that the adaptive lens can be used both with closed loop wavefront sensor modality and with wavefront sensorless optimization algorithms.

Sensorless optimization used together the one or more adaptive lenses allowed us to design compact and clinical compatible instruments.

The Multi-actuator Adaptive Lens has been tested in OCT high resolution human retina imaging.

The system was composed by two adaptive lenses: one for coarse focusing (electrowetting variable focus lens) and the Multi Actuator Adaptive Lens for fine focusing and aberrations corrections.

In order to maintain the same retinal layer throughout the optimization process we correct for axial motion during the acquisition by using real time automated retinal tracking software. The image quality metric was calculated based on this en face image; the optimization procedure was a coordinate search. In this procedure each aberrations to be corrected is scanned in order to find the higher merit function value. The procedure was lasting few seconds. The system we designed has a compactness and reliability compatible with clinical requirements. We tested as well the same method in in-vivo two photon retinal imaging system in mice. To reduce the amount of high intensity retina irradiation we exploited the low coherence of the laser source to generate OCT imaging to be used for wavefront correction. Those experiments were carried out using coordinate search optimization algorithm.

We tested and compared different optimization strategies such as coordinate search and the DONE algorithm. The results suggests that the MAL optimization can correct for eye aberrations with a pupil of 5mm or sample induced aberrations in microscopy.

10333-41, Session 9

Simultaneous real-time application and direct comparison of optical resonance sensing and fluorescence tagging techniques for biochemical component detection

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We introduce a new opportunity to perform a real-time biochemical component detection based on simultaneous analysis of spectral changes for whispering gallery modes (WGM) and fluorescence markers used for biochemical components tagging. Standard fused silica microsphere resonators (100 microns in mean diameter) have been used as sensitive elements for WGM-sensing approach and hydrophilic quantum dots have been chosen for protein labelling. Conjugation of biomedical components with carboxyl stabilized quantum dots has been performed via reaction between sulfo-NHS (N-hydroxysulfosuccinimide sodium salt) and EDC (1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride).

Sensitive elements are ordered in a grid structure, so called array sensor. It is produced by applying additive manufacturing techniques and contains series of cells where resonators are localized. Each cell has been designed for 8–10 chosen sensitive units. So that a thin adhesive layer (refractive index is equal to water, n = 1.33) could be deposited within the cells, we have used a digital dosage pump combined with a fused silica capillary tube and spin-coated system. Microspheres are directly fixed in each cell and functionalized with an agent corresponding to the analyte. The whole grid structure is placed inside the microfluidic cell and connected to the peristaltic pump in order to obtain a controllable liquid environment around the sensing cells. The cell has been designed as a multilayer construction consisting of two cover glasses and plexiglas structure, where the water flow should take place.

Tunable diode laser (New Focus, 680 nm) with narrow linewidth 200 kHz is used to provide WGM spectrum detection and green light laser system (Oxxius, 532 nm) — for quantum dot fluorescence generation. Incoming light from both laser systems is coupled into the WGM resonator via the near prism-based evanescent light coupling mechanism. Light scattered by the resonator is collected by the microscope objective and filtered out from the fluorescence excitation signal. Two different detection schemes have been tested: the first one consists of a CCD-camera that was utilized for simultaneous WGM spectrum and fluorescence monitoring; the second scheme includes the CCD-camera for WGM spectrum observation and a photodiode for fluorescence detection. Data processing scheme containing wavelet noise reduction and modal structure determination utilizing optimization methods based on evolutionary and swarm intelligence algorithms suitable for simultaneous analysis applying several sensing techniques is discussed.

This paper represents experimental data on detection of bovine serum albumin protein solution of different concentrations utilizing label-free and fluorescence tagging methods. Sensing capabilities, efficiency and saturation effects of both techniques were directly compared. Experimental results demonstrate advantages of the WGM detection scheme for quantification of low-concentrations of protein solutions and advantages of the fluorescence detection technique for quantification of high-concentration protein solutions. This is mainly related to the size of

the effective sensing area. In its turn, sensing area of the WGM detection technique is limited by the area where light propagation takes place, whereas for the fluorescence detection technique the whole sensor area is sensible for proteins.

Results of the experiment demonstrate that the proposed approach can be expanded on both existing and perspective high-throughput optical sensor systems. Simultaneous real-time application of the discussed sensing techniques in a single device can extend possible range for detectable concentrations.

10333-42, Session 9

Hybrid nanoparticles for therapy and diagnosis: au nanoprisms for gastrointestinal cancer *(Keynote Presentation)*

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In the last decades, inorganic nanoparticles have been steadily gaining more attention from scientists from a wide variety of fields such as material science, engineering, physics or chemistry. The very different properties compared to that of the respective bulk, and thus intriguing characteristics of materials in the nanometre scale, have driven nanoscience to be the centre of many basic and applied research topics. Moreover, a wide variety of recently developed methodologies for their surface functionalization provide these materials with very specific properties such as drug delivery and circulating cancer biomarkers detection. In this talk we describe the synthesis and functionalization of magnetic and gold nanoparticles as therapeutic and diagnosis tools against cancer.

Gold nanoprisms (NPRs) have been functionalized with PEG, glucose, cell penetrating peptides, antibodies and/or fluorescent dyes, aiming to enhance NPRs stability, cellular uptake and imaging capabilities, respectively. Cellular uptake and impact was assayed by a multiparametric investigation on the impact of surface modified NPRs on mice and human primary and transform cell lines. Under NIR illumination, these nanoprobes can cause apoptosis. Moreover, these nanoparticles have also been used for optoacoustic imaging, as well as for tumoral marker detection using a novel type of thermal ELISA nanobiosensor using a thermosensitive support.

10333-51, Session PS2

Polarization visualization of changes of anisotropic meat structure

Anastasia A. Blokhina, Anastasiya Y. Lobanova, Victoria A. Ryzhova, ITMO Univ. (Russian Federation)

The work is devoted to the study of a biological sample, being examined in the course of time, with the polarimetric method. Analysis of the polarization characteristics of the radiation scattered by biological tissues in some cases provides a qualitatively new results in the study of biological samples. These results can be used in medicine as well as in food industry.

In general, the biological objects are considered to be difficult and heterogeneous complexes belonging to the class of highly scattering turbid media. When dealing with such tissues in optics one pays special attention to the following polarimetric effects - linear birefringence, optical activity and depolarization. Their presence is explained by the fact that the biological tissue is composed of anisotropic muscle fibers and contains optically active (chiral) molecules. The phenomenon of depolarization, moreover, is explained by the residual light scattering by biological tissues. Mueller matrix formalism is applicable to analyze the characteristics of such biological mediums. The study of the polarization properties of biological tissues requires the determination of the sample matrix Mueller using different polarimetric techniques and tools for measurement. In the course of the work it is expected to quantify the parameters of the monochromatic coherent source emission scattered forward by a biological sample, with the ability to use the results to monitor the freshness of food products.

A thin cross section of meat product is considered as a sample, the meat of different animal species can be used. It is cut along the most expressed fibers, which, according to the results of histological examination, are destroyed in the process of spoilage. In the experiment, a meat slice is placed between two plane-parallel plates in order to avoid forming of a drying crust and simplify its surface geometry. In this position, under the favorable conditions for rotting the sample remains for the duration of observation conducting.

First of all, laser radiation with a particular polarization state illuminates the examined sample. Radiation, scattered forward by biological tissue fibers, passes through an optical system and forms a scattering spot on the receiver of optical radiation. With the help of special software the luminance, obtained in the course of the experiment on the photodetector with all the necessary relative positions of a polarizer, an analyzer and a phase plate, is analyzed. In addition, the data of the luminance distribution on the sensitive area of the optical radiation receiver are measured and stored separately for red, green and blue channels. Parameters are taken only six times: for the first four only axis of the polarizer and analyzer are subjected to the rotation, in the last two measurements the phase-shifting element is introduced into the ray path. The registered scattering spot is divided into a certain number of elementary cells. Information about the luminance of each of them over time is considered separately. For each such cell is calculated a Stokes vector, and then azimuth, ellipticity and polarization degree.

In general, the experimental apparatus includes a light source, a polarizer, a sample fixed on the specimen stage with glasses, further there is an analyzer, a phase-shifting element, an optical unit and an optical radiation detector. The source is the laser with a wavelength ? = 650 nm, as the receiving device - television camera VEC-545 with matrix receiver of optical radiation made on the basis of a CMOS sensor is used.

In the experiment, the cut of the product was under supervision about one day. During this day the clear changes of the sample freshness state were noticed. In the fresh state in sensory evaluation, the following features were observed: the color was of the uniform pale red color, the meat was dense and elastic on the cross section; longitudinal striation of muscle fibers was expressed clearly and precisely. Over time, the colour became more faded and uneven, slimy areas appeared on the surface. By the end of the observations it was clearly seen complete disappearance of the muscle fibers striation, the disruption of nuclei, and the coloration was barely visible and there was musty, putrid odor. The tendency of decreasing the polarization degree over time was traced during the measurement cycle.

10333-53, Session PS2

The original method for imaging of biological tissues in optical coherence tomography with usage of hyperchromatic lens

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Our study focuses on an analysis of the original method of investigation biological tissues in the spectral OCT (optical coherence tomography) with usage hyperchromatic lenses of the microscope. Using hyperchromatic lens, i.e. the lens with uncorrected longitudinal color allows scanning in the depth of the object by changing the wavelength of the emitter. In this case, the depth of the scan will be determined not by the microlens depth of field, but the value of longitudinal color.

OCT has been progressing rapidly with the ability to create a high-quality three-dimensional picture of the internal structure of the object. OCT has emerged because of the development and expansion of a variety of optical methods for studying the internal structure of biological objects. The appearance of OCT was preceded by the development of such scientific fields as optical measurements using femtosecond lasers, time-resolved spectroscopy, reflectometry, etc. The layering surface scanning in the optical coherence tomography is like the methods of confocal microscopy. However, the OCT methodic has a specific characteristic. For example, the resolution limit of the longitudinal axis (scanning resolution in depth) depends on the coherence length of the radiation source and does not depend on the numerical aperture of the focusing lens. Another important feature of the method is that it is extremely sensitive, OCT techniques can fix the signal reflected from the surface of 1E10-1 the magnitude of the incident radiation.

OCT techniques are widely used in many fields of science and technology. OCT methods are useful in biology in the study of microstructures of plant tissue, analyzing the impact of internal and external factors on the development of plants or degradation. The OCT method has found application in the study of surface layers and lacquer art. OCT techniques could be performed to identify paintings and other ancient objects without compromising their safety, to assess the age, to determine the degree of contamination or destruction, to study the technique of applying paint or other coatings. The OCT gained widespread in various fields of medicine. Due to the high image quality method allows you to restore the architecture study of biological surface, to analyze the lifetime operation of the tissue or mucous membrane. The method is more safe and comfortable for the person as it does not require surgery, no traditional biopsy contraindications. The importance of the optical coherence tomography acquired in ophthalmology for the study of the cornea and anterior chamber of the eye, producing a detailed picture of the retina and optic nerve. The OCT has been used successfully in research and early diagnosis of skin diseases, including skin cancer - one of the most common cancers.

Nowadays, methods of optical coherence tomography received a significant development. OCT systems can be divided into two conditional groups: low coherence scanning interferometry, in other words, the correlation of OCT and spectral interferometry, in other words, the spectral OCT. Correlation methods OCT, or the time domain OCT, has advantages in the accuracy of the transmitted image - limit longitudinal axial resolution as high as 1 micron. But at the same time, the implementation of such a scheme and the OCT has a serious drawback - it is the speed of scanning and imaging, as well as the presence of complex mathematical equations for data processing. Another embodiment of the method of OCT, spectral interferometry, is fundamentally different from the correlation methods OCT. There are no moving parts in the interferometer channels. Scanning of the object in such systems is carried out simultaneously throughout the thickness. However, the depth scan in such systems is determined by the depth of field microscope objective, which is limited by the size of the numerical aperture.

In our study, we show that the usage of the hyperchromatic lens in spectral OCT schemes while preserving the advantages of the method allows to increase the depth of spectral scanning, eliminate the use of multi-channel systems with a set of microscope objectives, reduce the time of measurement. In our paper, we show the developed method of calculation of hyperchromatic lenses and hybrid hyperchromatic lens consisting of a diffractive and refractive component in spectral OCT systems. And also, are shown the results of aberration calculation designed microscope lenses. We show examples of developed hyperchromatic lenses with the diffractive element and without it. There are also developed completed analysis of transmission.

10333-54, Session PS2

The box fractal dimension in speckle images

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The box fractal dimensión (BFD) concept has been found to be a useful concept as an aid to characterize images composed by textures and this result has been applied to numerous applications in biology, medicine, geology, engineering, satellite images, etc.

To calculate the BFD images are binarized and the result is covered with grades of different sizes. Then the number of points in each square box is counted and this number is log log represented as a function of the box size. The slope of the best fitted straight line of this plot is defined as the Box Counting Dimension. As a threshold is required for binarization, structures behind and over the threshold are disregarded and information is eventually lost.

To overcome this limitation, in a recent development we proposed the definition of the Box Fractal Curve. It is the result of the measurement of the Box Counting dimension of an image as a function of the binarization threshold. The curve spans the 0-2 domain.

The concept can be applied to different kinds of images including textures.

In some cases of objective speckle images this curve can be fitted by an expresión similar to the one found in the Fermi Dirac (FD) statistics for fermions. In this case, the curve is determined by a single parameter that is similar to a temperature. The time evolution of the temperature, when applicable, is a useful tool to follow dynamic speckle phenomena. Also, the box fractal dimension of the time series defined by the history of the intensity of every pixel in a subjective dynamic speckle can be characterized using box counting dimension and activity images constructed with the result. We add here the comparison of the box fractal calculation of profiles by including a reference profile of a known experimental situation.

Besides, in this paper, for FD shape of the Box Fractal Curve we show how the temperature can be found as the full width at half máximum of the derivative of the Box Fractal Curve. When the curve consists in the sum of two FD components the temperatures of each component can be separately determined provided that the components are well resolved.

Alternatives to the BFC can be constructed using several definitions according to how many points in each box are used for the definition of the fractal dimensión. They are the usual "one or more"," precisely one" and "all". The effect of reducing the number of boxes used in the calculation is also commented.

The concepts defined in this abstract are applied to simulations and experiments in dynamic speckle patterns both in single images and to stacks of patterns evolving along time. These examples consist of both biological and non biological cases.

Some examples of applications to speckle in medical ultrasound images and atomic force microscopy will also be proposed. We intend to call the attention on the possibility of using this approach to extend its use in biology and medicine, where the single threshold description has proved to be useful in the past.

10333-55, Session PS2

Quantitative phase imaging of red blood cell by diffraction phase microscopy

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More precise surface measurement systems are necessary for reliable production in research and industry. Medical and biological sciences need such systems which can measure without touching and non-invasive. Retrieving quantitative phase information of red blood cell by diffraction phase microscopy (DPM) is presented in this study. DPM maintains the single shot measurement and low speckle noise associated with white light [1,2]. Surface measurements of micrometer-size samples are done by using interferometer, microscope and CCD. In this setup, a microscope with halogen lamp and a Mach–Zehnder interferometer are combined. To generate diffraction orders, an amplitude grating, located at the front of the microscope, is used. These diffraction order beams, containing full spatial and phase information of the sample, are focused to the mask by a lens. A mask is used to filter the diffraction orders. The zero-order and +1 order beam is filtered using this mask so that zero order component can be used as a reference, +1 order component can be used as a sample beam. After filtering process, two beams interfere with each other to create the interferogram on the CCD plane by a second lens. Hence the sample and the reference image with interference fringes are saved for the analysis. By this way blood samples are imaged with fringe pattern. The phase values are extracted from these images by using continuous wavelet transform (CWT) phase method. The choice of the analyzing wavelet for a given application has an important role for success in the CWT analysis. Morlet wavelet was commonly used as the mother wavelet in the CWT phase technique and many studies have been made to extract the phase of the fringe pattern employing this complex mother wavelet

[3–6]. Morlet wavelet has the minimum uncertainty and maximum constant resolution by the fixed spatial frequency, which is chosen to be about 5 or 6 to satisfy the admissibility condition [7]. On the other hand, Morlet wavelet may not be successful to analysis the signal when the resolution of the analyzing wavelet is not compatible with the repetition frequency of the signal. Unlike Morlet wavelet, Paul wavelet has the ability to control the resolution of the analyzing wavelet by the degree of Paul wavelet [8]. In this study, the Paul wavelet was chosen as the mother wavelet because of resolution properties. Experimental results of the CWT phase method with Paul wavelet are discussed at the end of the study. Consider the following one dimensional fringe signal corresponding to any y-pixel (row) of the fringe pattern given by Kocahan [9]. The one dimensional CWT of the fringe signal is defined by Meyers [10]. In this study Paul wavelet is chosen as the mother wavelet and its analyzing wavelet form in Fourier domain is given by Co?kun [11]. Inserting Fourier transform of the fringe signal and Paul wavelet into CWT equation, and noting the necessary conditions, CWT with Paul wavelet is obtained. The phase of CWT with Paul wavelet is used to recover the phase distribution of red blood cell from images taken by DPM setup (shown in figure 1). The results are presented that Paul wavelet is very convenient for different applications because of the extra degrees of freedom by varying parameter n.

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10333-56, Session PS2

Nonlinear absorption coefficient measurement of nanofluids using Moiré deflectometry technique

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Nanoparticles with second-order optical nonlinearities have been widely studied because of their applications in clinical and industrial applications. In order to fully grasp the implications of this material, comprehensive knowledge of its optical properties is essential. The nonlinear absorption coefficient is an important parameter which is used in manufacturing saturable absorber.

In the late 80s and early 90s, a new single-beam method, Z-scan, was proposed by Sheik-Bahae and coworkers to determine nonlinear coefficients. In this technique, the sample is moved along the optical axis, Z, in the focal region of the beam. In open aperture configuration, as the sample is translated through the focal region of the beam, detector measures the total transmitted intensity. The deviation in the total transmitted intensity is due to multi-photon absorption. The main disadvantage of this scanning method is the requirement to a sensitive and calibrated detector in addition to sensitivity to laser beam stability. The other problem is the effect of misalignment in the transmittance curve. Moiré deflectometry is a well-known measurement technique. This technique was used to measure linear absorption coefficient in the previous work [6]. Moire´ deflectometry set up is simple and easy to align. It is also insensitive to environmental noise.

In this work Moire´ deflectometry method is used to measure the nonlinear absorption coefficient of nanoparticles. In the proposed method the divergence of beam is measured instead of measuring the intensity of divergent ray. Two beams are used; one is a comparatively high intensity laser beam with a wavelength in the absorption spectrum range of the sample and the other is used as probe; wide beam with low intensity that is radiated to the first beam vertically. The fringe pattern which is used as reference data is taken when the interacting laser is off. Then by turning on the laser beam, energy will be absorbed by nanoparticles and the probe beam will deflect consequently. So the Moiré fringes will deflecte too. By measuring the displacement of Moire´ fringes, nonlinear absorption coefficient can be measured easily. Absorption coefficient is measured using two fringes. By plotting measured absorption coefficient as a function of intensity, a line is obtained. This line represent the absorption coefficient relationship: ?(I)=?+?I. This technique is non-scanning and fast. It is also capable of measuring very weak or very large non-linear absorption coefficient.

10333-57, Session PS2

Nonlinear refractive index measurement of nanoparticles using optical trapping

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Optical trapping is a well-known method and emerged as an essential tool for manipulating nanoparticles but still, trapping particles remains quite challenging because it should meet the requirement of a wide range of application. In addition, tracking many particles adds more complexity in this matter. During these years, trapping benefits from the linear interaction between optical electric fields and particles like the holographic optical tweezer, cylindrical vector beams, and polarization techniques. Although nonlinear properties of a various material are completely studied but it has no role before in optical trapping of nanoparticles. In this paper, we investigate the effect of the nonlinear effect and it changes upon various nanoparticles.

Nanoparticles such as gold have a large nonlinear refractive index which found much application in medical and industrial research. In this paper using these Nano-particles, we investigate the effect of refractive index change on trapping of this material. In addition, we analysis and report the polarization behavior of Nanoparticles.

The trapping laser radiated from 980 nm Thorlab's fiber coupled diode laser with 330 mW power that collimated and expanded through Thorlab's optical trapping kit. After reflecting from hot dichroic Mirror it focused through the objective. We emit a high power laser with 532 nm wavelength into the cell for generating the nonlinear effect. The short pass filter is placed in front of the CCD to have a low noise view of the particles which is going from white LED.

This method represents the possibility of using a nonlinear refractive index as the best way to reduce aberration and effectiveness of the trap. Also, this method could suggest possibilities of joining linear light methods such as the holographic technique in the optical trapping with nonlinear effect. In addition, it opens a new way for analyzing new nonlinear effects. It also will have novel application in the future of optical trapping due to refractive index importance in trapping efficiency and offers an effective and low-cost method for manipulating nanoparticles with the nonlinear response.

10333-58, Session PS2

Real-time quantitative phase microscopy with single-shot transport of intensity equation

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Compared to traditional intensity and fluorescence based microscopy, quantitative phase imaging is a promising technique since it can retrieve sample phase maps providing another perspective for cellular observations and measurements. Compared to those complicated interference based methods as quantitative interferometric microscopy and digital holographic microscopy, transport of intensity equation (TIE) based microscopy is one cost performance design: it can be easily integrated in commercial microscope with simple additional devices. Additionally, both sample intensity and phase can be acquired by TIE proposing multi-mode imaging. However, applying classical TIE method for phase extraction, at least three multi-focal intensities are necessary in order to solve the Poisson equation, which not only increases time consuming in image recording, but also limits its potential applications as real time observation. Though fast focus tunable lens was adopted, additionally, prism was also introduced in the imaging system, these methods often suffer from complex system. In order to realize real time quantitative phase imaging, as well as with compact optical system and high signal to noise ratio, single-shot TIE (ssTIE) based microscopy with simultaneous multi-focal imaging is designed here. A 4-f system with programmed phase mask located at its frequency plane is designed for simultaneous multi-focal recording. The programmed phase mask plays two roles as wavefront division and defocus modulation: tilting phase distributions are applied to separate single wavefront into three beams; in addition, spherical phases are attached on these separated beams to generate under-focus, in-focus and over-focus images at single focal plane. Moreover, defocus distance can be accurately ensured with programmed phase modulation, thus according to high-speed Poisson equation solver, quantitative phase can be calculated with fast speed and high accuracy. Both numerical simulation and practical measurements are proposed to illustrate the designed ssTIE, as well as prove capability of the simultaneous quantitative phase microscopic method. In numerical simulation, correlation coefficient between original setting sample and retrieved one is 0.9913, indicating high accuracy of the proposed ssTIE. Moreover, a random phase mask is applied for system verification in practical measurement. The result proves that proposed ssTIE technique can provide accurate phase information in real time. Additionally, biological cells are also measured with a commercial human RBC smear. Though compared to full FOV image recording, FOV of the proposed method is limited, while with mechanical or microfluidics based sample scanning, large amount and high throughput sample testing can be realized. In addition, with programmed phase mask fabrication by lithography, spatial phase modulator can be replaced, thus the cost is obviously decreased, and the system is simplified as well. It is believed the presented ssTIE method is of great potential in real time and high throughput live cell observations and quantitative measurements.

10333-60, Session PS2

Line-field swept source optical coherence tomography system for evaluating microstructure of objects in near-infrared spectral range

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Analysis of internal micro structure of objects is important for various fields of science and modern technologies and widely used in biomedical applications. Optical coherence tomography (OCT) is one of the most promising non-contact methods for high resolving imaging of internal micro structure of objects1. In OCT, a sample under investigation is illuminated by optical radiation with subsequent determination of reflection degree through a sample depth. Therefore, it is possible to evaluate a sample internal micro structure. One of the most perspective technologies presents the spectral OCT with swept laser source (SSOCT) [1]. Application of a swept source allows simplifying the optical setup configuration because there is no need in spectral instrument that is utilized in conventional spectral OCT with low-coherent light source.

In this paper, we consider special aspects of optical design of the line-field swept-source OCT (LF SSOCT) system for short-wave infrared spectral range. The spectral range selection is defined by investigated samples. In our system, we have chosen the spectral range ? = (1.26-1.36) mkm that is preferable for biomedical applications due to reduced multiple scattering and deeper penetration of radiation into a sample in comparison with shorter wavelengths. Line-field photo registration is performed by a line-array photo detector that allows to avoid problems with stability, phase nonlinearity, beam jitter, etc. inherent in conventional mechanical scanners such as galvanometer actuated mirrors.

In order to increase light source power efficiency, line-field illumination has been used in the OCT system by utilizing cylindrical lenses. This makes possible to obtain B-scans electronically without a need in lateral mechanical scan, increases tomogram imaging rate and provides compact design of the device. As mentioned in [2] the energetic efficiency of a line field lighting is comparable with the "flying spot" scanning method. Line field lighting presents an extensive light source with low radiation power density at each point. Therefore, local effect of radiation to a sample is not strongly intensive in comparison with "flying spot" scanning method. This allows studying biological objects that are not resistant to high-intensity radiation.

Commercially available fast CCD/CMOS cameras employing silicon-based photo detectors have low sensitivity around 1300 nm. The InGaAs cameras provide higher sensitivity, but currently offer low frame rates. To provide real time investigation of objects (about 20 fps) in the case of sweep over 1000 wavelength, acquisition rate of the detector at least 20 kHz is required. Currently various technical solutions [3, 4] are known. However, when employing 2D photo sensitive matrices, acquisition rate at full resolution hardly exceeds 500 Hz. Application of high-speed line-array detectors provides necessary speed of tomograms registration and visualization because the acquisition rate reaches in this case 20 kHz and more. In our system, we used InGaAs line-array photo detector model Lynx-1024-CL containing 1024 pixels with pixel size 12,5 mkm and acquisition rate up to 40 kHz.

In our design, a beam reshaper has been added into optical system based on Linnik micro interferometer scheme to obtain linear top-hat light intensity distribution at the sample and the detector planes. It makes possible to avoid decreasing of the signal-to-noise ratio at edges of tomogram. The power effective optical system for the line-field lighting based on anamorphic optical scheme has been designed. This optical system provides diffraction limited image quality and focal shift less than 6 mkm within the illumination spectral range 1.26-1.36 mkm. In the paper, experimental investigation results of the LF SSOCT system are given and discussed. Experimental tomograms of different biological objects are presented.

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10333-61, Session PS2

Programmable phase contrast microscopy with spatial light modulators

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Phase contrast microscopy is a standard method for observing small transparent specimens. Although powerful, it is usually not capable of providing quantitative phase information and also "static", i.e. not able to adapt to the optical properties of individual specimens.

We demonstrate "adaptive phase contrast microscopy", where spatial light modulators in the Köhler illumination and in the objective exit pupil of a microscope allow one to optimize the imaging performance in real time.

10333-62, Session PS2

Food quality inspection by speckle decorrelation properties of bacteria colonies

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In the framework of coherent imaging, the intrinsic nature of the light source is responsible for the presence of the so-called speckles. Whenever a coherent beam reflects from an object surface whose roughness is comparable to the source wavelength, multiple contributions arise that reach the recording device after experiencing different paths in their own travel. Since any sensor is only able to measure intensity variations, each detector element receives the resultant of the coherent superposition of these multiple waves, which is strongly dependent on the relative phase delays of each contribution. The phenomenon is mathematically modelled as a random walk in the complex plane. Hence, any coherent imaging system represents an apparently flat surface as a nonhomogeneous pattern of dark and bright spots, since this is rough at the wavelength scale. From the imaging point of view, speckle is treated as a noise source and many denoising strategies have been proposed to remove this unwanted disturbance. The most intuitive way to mitigate this effect is to acquire and incoherently combine multiple images representing the object under test but seen under different noise conditions (multi-look techniques). A trivial way to reduce the source coherence is to introduce a moving diffuser along the path of the beam scattered by the object, which has the effect of providing coherent noise diversity due to decorrelation of the speckle grains between the images. Recently, we analysed the speckle decorrelation properties of biological elements, namely E. coli bacteria species forming aggregates in a liquid solution [1]. In particular, we demonstrated that high-density volumes of bacteria forming long aggregates can provide time decorrelation of the light scattering effect they provoke, thus behaving just like a moving diffuser. As a proof of concept, decorrelation of the speckle grains was used to perform coherent microscopy imaging of a target hidden behind the bacteria volume in a condition where the single image could not do the job. Starting from these considerations, here we think at the speckles not as sources of disturbance, but as useful indicators of the presence of bacteria colonies. In particular, speckle decorrelation is measured using a coherent laser source as a probe. A simple setup is used, only requiring a laser source and a CCD camera as a detector. Speckles are usefully exploited since they make the bacteria detection system more sensitive to spatial variations of the surface roughness occurring over micrometric scale. We demonstrate the possibility to use this approach to detect the presence of small concentrations of bacteria (such as Bacillus cereus, Staphylococcus spp or E.coli) contaminating food. Indeed, different behaviours of the correlation coefficient between multiple measures can be found, and a threshold correlation value can be set to discriminate between the cases. Above all, bacteria detection is carried out in a condition where the single element is not visible, but the properties of the ensemble can be used for monitoring food quality and its conservation properties. Hence, optical microscopes with high magnification factors are not required anymore, and the small magnification allows inspecting a large Field-of-View (FoV). Moreover, the simple setup is suitable to be employed out of the lab, e.g. as a tool for quality testing by food producers in factories or the customer itself in specific installations at the market place.

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10333-63, Session PS2

Interferometric measurement of film thickness during bubble blowing

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Thin liquid films, such as soap bubbles, are ubiquitous in nature and technology. Biological vesicles, magma bubbles, insulating and food foams, detergents and oil foams, all share most of the physics, chemistry and engineering beneath the bubble formation and evolution and their study is very important since they mediate a wide range of transport processes. These "bare" films display unusual dynamic behaviours in drainage and measurement of the thin fluid film thickness evolution during drainage is key to understand such phenomena. In turn, such knowledge can be utilized to design new materials, to guide technologies involving bubbles and to control biological functions involving bubbles and bubbles rupture.

We propose digital holography in transmission configuration as an effective method to measure the time-dependent thickness of polymeric films during bubble blowing. In this work, we designed a complete set of experiments to measure bubble thickness, including the evaluation of the refractive index of the polymer solution.

Digital holography is a widespread tool for quantitative phase imaging with applications ranging from non-disrupting testing for industry to label-free imaging of biological samples. Thanks to its efficient phase imaging ability, digital holography microscopy can accurately measure the change in optical path length caused by transparent films down to fractions of the illumination wavelength. To measure the film thickness, we use an off-axis Mach-Zehnder interferometer system with a number of phase reconstruction methods adapted to retrieve the variations of the thickness due to the application of a constant pressure.

We report the measurement of thickness distribution along the film during the bubble formation process to the time before bubble burst. Based on those data, the variation range and variation trend of bubble film thickness are clearly measured during the process of expansion to fracture is indicated. In addition, we show that our system allows us to identify and measure very thin regions such as Newton black films.

10333-64, Session PS2

Label-free imaging and analysis of small lipid droplets in adipocyte cells by stimulated Raman microscopy

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Recently, there has been an increasing in the level of interest in label-free bioimaging. Despite, confocal and multiphoton fluorescence microscopy are important and powerful techniques for biological imaging, they show some limitations that could be overcome with the implementation of a real time, three-dimensional imaging with high spatial resolution, high sensitivity, and high chemical selectivity of unlabeled living cells. Therefore, in order to comply with these issues, nonlinear optical effects are investigated, such as the basics of novel microscopy techniques. In particular Stimulated Raman Scattering (SRS) was studied as an alternative way to provide vibrational contrast mechanism. The Raman signal, generated by the nonlinear interaction among pump and probe signals and the sample, is much more intense respect to linear Raman microscopy, being coherent and propagating along the axis of oscillating molecules. SRS is a shot-noise limited and non-resonant background technique, exhibiting an identical spectrum as the spontaneous Raman it is linearly proportional to the concentration of the analyte, reducing considerably the acquisition times and allowing fast image acquisition rates.

In this paper, we outline the implementation of a microscope based on the femtosecond Stimulated Raman scattering (f-SRS) not commercially available, and we propose a methodology for the studying and identification of small structures.

In the life science field, there is interest in the studying of lipids and densely packed structure of them, lipid droplets (LDs), since participating in a broad variety of physiological processes and being in many different cell types. The relatively isolated Raman peaks associated with vibrational states of the C-H bond, which are abundant in fatty acid molecules, provide a unique signature for lipids inside a cell. This has suggested and proven that SRS is particularly powerful for studying lipids. We study the LDs present in fixed adipocytes, detecting microstructures inside the cells and evaluating the sizes. For this reason, we report SRS label free images on adipocytes, and the relative analysis.

10333-43, Session 10

Bio-derived and biodegradable microlasers and optical waveguides for biosensors, cell tracking and photomedicine *(Invited Paper)*

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We have made microlasers and optical waveguides out of biocompatible, biodegradable and biological materials and embedded them in cells and tissues. We have demonstrated a laser completely embedded within a single live cell. The lasers were made out of solid fluorescent beads few microns in diameter. These laser beads were fed to live cells in culture, which engulfed the lasers within a few hours. The lasers can act as very sensitive sensors, enabling us to better understand cellular processes. For example, we measured small changes in the refractive index of the cytosol, which is related to the concentration of chemical constituents within the cells. Further, lasers were used for cell tagging. Each laser within a cell emits light with a slightly different fingerprint that can be easily detected and used as a barcode to tag the cell. With careful laser design and multiplexing, up to a trillion cells (1,000,000,000,000) could be uniquely tagged. This would enable to uniquely tag every single cell in the human body, providing the ability the study cell migration including cancer metastasis. Further, by using a micro pipette droplets of high refractive index oil containing fluorescent dye were injected into a cell. By analyzing the light emitted by a droplet laser, we can measure that deformation and calculate the forces acting within a cell. We also realized that fat cells already contain lipid droplets, which can work as natural lasers. The operation of fat cell lasers was demonstrated in the skin tissue. Lasers made out of biodegradable materials or cholesterol were also tested in skin, making so called laser tattoos. A new class of optical waveguides for use in deep-tissue photomedicine, were demonstrated as well. These waveguides were made out of biocompatible and biodegradable polymer materials, which can be implanted into the body and are naturally degraded over time. The waveguides enable the use of a number of medical laser treatments and diagnostics deep into the body, which were till now only limited to the surface due to limited penetration of light into the tissues. As an example of a possible application, laser wound closure is demonstrated, which could lead to faster healing and less scarring. Biocompatible and biodegradable waveguides can also be directly applied to other light-based diagnostics, surgery and therapeutics.

10333-44, Session 10

Implementation of stimulated Raman losses and stimulated Raman gain microscopy using three femtosecond laser sources

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With the aim of overcoming some limitations induced by fluorescence microscopy, in last decades, nonlinear optics microscopy has become increasingly an attractive tool in biomedical research. By exploiting nonlinear optical effects, novel microscopy techniques have been developed, which afford high chemical selectivity of unlabeled living cells, and in addition, implement real time three-dimensional imaging with high spatial resolution and sensitivity. In our paper, the attention is focused on Stimulated Raman Scattering (SRS) technique. This technique is sensitive to the same molecular vibrations probed in spontaneous Raman spectroscopy, but unlike linear Raman spectroscopy, it exhibits a nonlinear dependence on the incoming light fields and produce coherent radiation. In SRS microscopy, two laser beams, a high power pump laser and a low power Stokes laser with different frequencies (?L> ?S), are focused into a sample. When their difference matches the vibrational frequency of the molecular bonds of interest, energy is transferred from the pump beam to the probe beam. Therefore, an increase in probe signal intensity (Stimulated Raman gain, SRG) and a decrease of the pump signal intensity (Stimulated Raman Loss, SRL) are achieved.

In this paper, we describe the design and the implementation of a nonlinear microscope based on Stimulated Raman scattering, not commercially available, which is equipped with three femtosecond laser sources: TiSa, OPO and OPO+SHG. In order to cover all the regions of Raman spectra: the fingerprint region (400 cm-1 – 1600 cm-1), the silent region and the CH region (greater than 2700 cm-1), they can be used in two different combinations. The first one, using TiSA and OPO+SHG, can cover in SRL modality the fingerprint region and the silent region. The second one, using TiSa and OPO, can cover the C-H region in SRG modality. In order to validate the realization of imaging experimental setup, testing images of polystyrene beads, in SRL and SRG modalities, are acquired and discussed.

10333-45, Session 10

Using Shack-Hartmann wavefront sensors and Zernike coefficients for beam characterisation in ophthalmic optics: numerical procedures

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When using Shack-Hartmann wavefront sensors (SH) and Zernike coefficients (Zs) in applications where the position of the measurement and the point of interest are far apart, as it is common practice in ophthalmic optics, problems arise related to how the measured values propagate along the beam. One typical example is pupil conjugation where an auxiliary lens is added to match the size of the area of the

interest of the beam with the size of the entrance pupil of the SH used for measurements.

In the present work, we address the problem in the framework of a numerical scheme for modelling the beam propagation. We calculate the wavefronts with exact ray tracing plus the fitting of the impacts so as to match a rectangular grid. This procedure allows the subsequent calculation of the Zs or, similarly, the pupil function at an arbitrary plane perpendicular to the optical axis. In this case just mentioned, we model the beam propagation within the Fresnel diffraction scheme and the corresponding PSF can also be calculated. In this context, the problem of pupil conjugation can also be addressed using similar methods as well.

Several examples are presented to illustrate the previous ideas and to show the real capabilities of our procedures. They will help to clarify the issues actually found in practical setups for beam manipulation, often encountered in ophthalmic optics.

10333-46, Session 10

Systemic imaging with light sheet microscopy *(Invited Paper)*

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Light sheet fluorescence microscopy is a powerful tool to image biological samples and biomaterials at systemic level, being able to image whole tissues while maintaining high spatio-temporal resolution of cells morphology and dynamics. Here we describe the principle of light sheet microscopy and we show examples of applications including long term acquisition of developing specimens and calcium imaging. We then show how high throughput acquisition can be obtained by combining the technique with optofluidics.

10333-47, Session 11

Micro-Raman analysis of glisterings in intraocular lenses

Giulia Rusciano, Giuseppe Pesce, Gianluigi Zito, Antonio Sasso, Univ. degli Studi di Napoli Federico II (Italy)The phenomenon of inclusions or microvacuoles in intraocular lenses (IOL), often referred to glistenings due to their appearance when visualized in slit-lamp exams, is main cause of decreased visual in people after IOL implantation. For this reason, there is a huge request by the market of new polymers able to reduce, or even eliminate, the formation of such microvacuoles. In such frame, the use of advanced optical techniques, able to provide a deeper insight on the glistering formation, is strongly required. In particular, Raman spectroscopy (RS) is ideally suited for the analysis of polymers, due to its well-know sensitivity to highly polarizable chemical groups, commonly found in the polymer chains backbones. Moreover, the combination of RS with optical microscopy (Raman micro-spectroscopy) paves the way for real, information-rich chemical mapping of polymeric materials (Raman imaging). In this paper, we analyze the formation of microvacuoles in IOLs following a thermal treatment. In particular, we performed a chemical mapping of a single microvacuole, which allowed us to infer on its effective chemical composition. In order to investigate on the reversibility of glistenings formation, this analysis was repeated as function of time after thermal treatment, in different IOL environments. It turns out that this phenomenon is partially reversible, with an almost complete disappearance of microvacuoles in a dry environment.

10333-48, Session 11

Using engineered point spread functions in image scanning microscopy

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A confocal microscope equipped with a pixelated detector has been shown to enable high resolution images at a high light efficiency. This property is based on the large amount of data collected during a scan. We show that by suitably tailoring the point spread function of the imaging system it is possible to collect alternative information from the specimen as well, such as its three-dimensional structure or optical aberrations that are present in the system.

10333-49, Session 11

Design of the algorithm of photons migration in the multilayer skin structure

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Design of approaches and methods of the oncological diseases diagnostics has special significance. It allows determining any kind of tumors at early stages. The development of optical and laser technologies provided increase of a number of methods allowing making diagnostic studies of oncological diseases. A promising area of biomedical diagnostics is the development of automated nondestructive testing systems for the study of the skin polarizing properties based on backscattered radiation detection. Specification of the examined tissue polarizing properties allows studying of structural properties change influenced by various pathologies. Consequently, measurement and analysis of the polarizing properties of the scattered optical radiation for the development of methods for diagnosis and imaging of skin in vivo appear relevant.

The purpose of this research is to design the algorithm of photons migration in the multilayer skin structure. Optical radiation propagation modeling using the Monte Carlo method is the most promising and accurate. This modeling method allows simulating of photons propagation in a scattering medium by tracking random trajectories of individual photons, but it is time consuming.

Monte Carlo modeling method allows estimating the percentage of the number of backscattered photons for each of the skin layers. Using the modeling approach provides the ability to select a range of incidence angles of the optical radiation in the experimental measurements scheme construction and to obtain the backscattered photons propagation on the surface of the epidermis model sample. In addition, modeling allows determination of the relation of backscattered photons intensity to the location.

In the analysis of certain types of tissues, the degree of light depolarization and the polarization conversion nature (between the forms) may be additional informative parameters characterizing the structure. Object polarization parameters depend on the sample thickness, wavelength and temperature.

In this research, the algorithm of photons migration in the multilayer skin structure was designed. It is based on the use of the Monte Carlo method. Implemented Monte Carlo method appears as a tracking the paths of photons experiencing random discrete direction changes before they are released from the analyzed area or decrease their intensity to negligible levels. Modeling algorithm consists of the medium and the source characteristics generation, a photon generating considering spatial coordinates of the polar and azimuthal angles, the photon weight reduction calculating due to specular and diffuse reflection, the photon mean free path definition, the photon motion direction angle definition as a result of random scattering with a Henyey-Greenstein phase function, the medium's absorption calculation. Biological tissue is modeled as a homogeneous scattering sheet characterized by an absorption, a scattering and an anisotropy coefficients. Anisotropy coefficient is defined as the average cosine of the biological tissue deviation angle and it is from 0.7 to 0.99 in the skin. The simulation model of the plane-parallel sample of skin is composed of layers, each defined by the following parameters: thickness, refractive index, absorption coefficient, scattering coefficient and the anisotropy factor.

10333-50, Session 11

Sapphire terahertz photonic crystal waveguides for nondestructive evaluation and medical diagnosis technologies

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Nowadays, terahertz (THz) science and technologies are rapidly developed offering significant scientific and technological applications in many fields [1]. Such novel instruments of fundamental and applied research as THz pulsed spectroscopy, THz backward-wave oscillator spectroscopy, passive and active (continuous-wave and pulsed) THz imaging have considerable prospectives in non-distractive evaluations of constructional materials (composites and ceramics) [2], security tasks [3], medical diagnosis [4]. Despite the great progress in THz technologies, the problem of designing THz waveguides and fibers to deliver THz waves to the object of measurement and exposure still remains challenging.

Numerous types of THz waveguides, which are based on various physical principles, have been recently proposed, namely, (i) waveguides based on hollow-core metal tubes and dielectric-metal structures [5]; (ii) plasmonic waveguides employing metal wires and ribbons [6]; (iii) flexible polymer photonic crystal (PC) fibers [7]; (iv) foam-based waveguides [8]. Unfortunately, all the existed types of THz waveguides have significant disadvantages, such as high THz wave losses (coupling and propagation) and dispersion. This limits their reliability in rapidly developing THz technologies of non-destructive evaluations and medical diagnosis.

In this paper, we offer novel approach to guide THz waves, which employs non-flexible PC waveguides based on sapphire shaped crystals [9,10]. Such waveguides are characterized with lower THz-wave loss and dispersion comparing with the advanced analogues. We manufacture several type of sapphire PC waveguides and characterize them using both numerical simulations and experimental studies. We demonstrate that sapphire PC waveguides allow guiding the THz waves in multimode regime with the minimal dispersion in wide frequency range and lowest power extinction coefficient of 2 dB/m at 1.45 THz. These waveguides allow transmitting broadband THz pulses over long distances. They could be used to study hardly accessible remote object of measurements in THz non-destructive evaluations and medical diagnosis.

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10333-52, Session 11

Method and device based on human skin autofluorescence investigation for characterization of patients with coronary artery disease

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There are increasing numbers of death caused by heart diseases like coronary artery dis-ease all over the world. Recent studies to address this issue are focused on different approaches to diagnose people that are near to the heart attack. However, it is still hardly possible to predict severe state before heart attack in order to hospitalize patients earlier and prevent the death. One of the most effective noninvasive ways to diagnose people is utilizing advanced glycation end-product (AGE). It is well known that AGE relates not only to the aging processes but also to the diabetes, heart disease and renal failure. The concentration of the AGE can be evaluated using autofluorescence of the human skin. There are several instruments that can be used for estimation of the AGE by autofluorescence measurement but all of them are quite complicated and therefore they are not affordable for each clinic and patient. In addition, we should mention that existing methods of autofluorescence signal processing can not give accurate information and should be improved.

In this study we focused on developed by us fluorimeter that is aimed to investigation of AGE in human skin. It consists of two channels, one of them is used for autofluorescence esti-mation, another one is a reference and it gives the information about human skin photo type. Reference channel utilizes backscattering radiation from the skin. The excitation source is an LED with the peak wavelength of 365 nm. Silicon photodiodes are used as receivers. In the auto-fluorescence measurement channel is put an optical filter in order to cope with scattered radia-tion. The developed tool is relatively small and should be connected to the computer through USB. The measurement time is not exceeded 30 seconds.

In this study we also introduce the results of experiments with developed fluorimeter on roughly 100 healthy people and on 70 patients with coronary heart disease. We also studied our statistical approach for the results processing. We calculated Spirmen rang correlation coefficient of diagnostic parameter with the human age and the level of statistical significance for healthy people as well as for patients. It was found out the meaningful statistical correlation between di-agnostic parameter and the age in reference healthy group as well as the reasonable level of sig-nificance of this correlation. Obtained correlation is agreed with the point of view that AGE have significant influence on tissue biotransformation and relate to the aging processes. It was not true for patients because correlation was insignificant while statistical significance was absent. This result can be explained by pathological processes breaking the dependence of the age. In addi-tion, we proposed the method of making the groups by the age that can be used to reveal the ten-dency in the autofluorescence level fluctuations without any complicated statistical approaches.

Generally, the results of experiments can be considered as the evidence of the diagnostic potential of the developed tool and the method. They also can be recommended for differentia-tion of the risk in patient groups with the range of diseases like diabetes, coronary heart disease, renal failure because all of them have relation with more intensive processes caused by metabolic stress like glycation and oxidation.

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10334-1, Session 1

Motion blur characterization and compensation for line scan (1D) cameras

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For online quality inspection of moving products (wire, cords, etc.), line scan (1D) cameras are often used, mostly due to their low cost in combination with the high framerates they can achieve. In this paper, we investigate the effect of motion on the data acquired with such 1D sensors. We use a setup developed to measure the dimension (e.g. thickness) of a moving object placed in front of a 1D sensor, with backlighting. The object could be a wire or string moving at high speed. Motion and vibration of the object or the 1D sensor introduce artefacts commonly referred to as (uniform) motion blur.

Motion blur and methods to compensate for it, including both blind and non-blind deblurring methods, have been widely studied and applied for standard 2D cameras (see e.g. [1] for an up-to-date survey). Yet for 1D cameras, and especially when using backlighting, the amount of redundancy in the image is limited, making it hard to directly transfer these solutions to the 1D setting. The main contribution of this paper is to investigate motion blur characterization and ways to compensate for it for 1D cameras.

First, we describe our setup (see also Figure 1). It consists of a line scan sensor, a collineated light source directed towards the camera and an opaque object placed in between these two. We then formally describe the effect of motion on the image formation process and derive parameterized blur kernels for linear and sinusoidal motion in each of the three dominant motion directions. Next, a 1D equivalent for non-blind motion deblurring based on inverse filtering is proposed. This assumes that the relative motion between object and camera is known. To this end, we estimate the local motion using Savitzky-Golay filtering [2]. Experiments on real and simulated data show the effectiveness of this method.

While the above technique allows to compensate for motion blur to some extent, it is still recommended to avoid motion blur by proper configuration at the hardware level. To this end, we propose a simulation tool that allows visualizing and quantifying the effect of motion blur for 1D line-scan cameras. Based on this tool, a practitioner can evaluate a specific setup and adapt the design or hardware as needed to reduce the motion blur problem. A screenshot of the simulation tool, which will be made publicly available, can be found in Figure 2.

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10334-2, Session 1

Structural influence of a spatial light modulator on generated wavefronts for speckle-based shape measurement

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Electronic speckle-pattern interferometry (ESPI) is a powerful technique for the measurement of deformation, shape, roughness, or vibrations of technical surfaces. Technical surfaces are optically rough, i.e., the height variations of adjacent surface points are in average higher than a quarter wavelength and speckles are developed. In specular interferometry, the order of the illuminating wavelength is sufficient to transfer the surface function into an intensity modulation, which leads to the characteristic interferometric fringe pattern. On the contrary, for interferometric measurements of technical surfaces, a much lower sensitivity than provided by the laser is necessary.

Depending on the surface parameter of interest (e.g., shape or deformation), a proper method for desensitizing the measurement to the desired scale has to be selected. For shape measurements, the two-wavelength phase-shifting technique is well-known and widely used. Here, an optical beat frequency is generated by superimposition of two wavelengths in the visible range, whose envelope serves as a low-frequent synthetic wavelength, mostly in the range of 1-100 µm. According to this, a fringe pattern with a fringe distance of the synthetic wavelength is generated. Due to a phase-shifting procedure, the fringe pattern is transferred into a phase map, which reflects the shape of the measurement target.

The problems and limitations of shape measurements by ESPI are at hand. Due to the modulo-2ϖ periodicity of the interferometric principle, the resolution of the phase map is defined by the synthetic wavelength and is therefore a global parameter of the measurement system. Thus, ESPI is restricted to surfaces with low variations of the phase gradient and low structural density relating to the synthetic wavelength. An approach to extend the mentioned constraints is the utilization of multiple synthetic wavelengths to provide different sensitivities. Nevertheless, the obvious drawback of this method is the high measurement and data processing effort. A promising alternative is the implementation of a high-resolution generated reference wavefront (HRGW) adapted to the measurement task. Thereby, the resolution of the measurement setup can be varied locally in just one phase map.

This method is straight-forward and easy to implement by replacing the reference object in an interferometric setup by a phase-only spatial light modulator (SLM). From this point, we have an adaptive speckle-interferometer that does not require any movable parts because the phase-shifting can also be realized by the SLM.

Even though the measurement range is improved by the HRGW, previous studies indicate that the microstructure of SLMs causes diffraction errors which in turn introduce errors into the reference wavefront. Therefore, the realization of HRGWs is not trivial. In this article, the influence of the microstructure of SLMs in adaptive ESPI is analyzed. Two different types of reflective, liquid-crystal (LC) based SLMs are integrated in a Michelson interferometer consecutively. The first LC-SLM is electrically addressed and the phase modulating liquid-crystal layer shows a quadratic pixilation. As mentioned above, the pixel structure of the SLM leads to diffraction errors, and consequently another modulator type without pixilation shall be surveyed. The second device consists of two serial LC-modulators: an electrically addressed intensity modulating layer which is coupled by a lens to an optically addressed and non-pixelated LC-layer for phase modulation. However, the absence of the pixilation leads to a cross-talk between neighboring areas of the modulator, which has the effect of low-pass filtering to the desired phase distribution of the generated wavefront.

Both LC-SLMs are used to adapt the HRGWs and receive the respective phase maps. The influence of the microstructure to the quality of the phase map is analyzed and discussed. Furthermore, the limitations of the modulators are examined, i.e., the highest possible local desensitization of each modulator type. The properties for an ideal phase-only modulator design, referred to the present task, are discussed according to the information received by the experiments.

10334-3, Session 1

Robust and efficient modulation transfer function measurement with CMOS color sensors

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Assembling camera modules used in Advanced Driver Assistance Systems (ADAS) is a critical operation, as these cameras are usually not equipped with an automatic focusing system and must be correctly focused from a few meters up to a distance of up to 100m in the production phase. Since, in the miniaturized design of the imager modules, the focusing range of the sensor is in the order of micrometers, it is extremely sensitive to mechanical adjustment. Therefore, a comprehensive and efficient sharpness test of the imaging system is required for the focusing process and at the end of the manufacturing process.

The complexity of the focus adjustment of ADAS cameras is further increased, as image sensors are often equipped with a Color Filter Array (CFA), to support object classification, using color information. In commonly used CFAs only every second pixel of a line is assigned to the same pixel class which complicates the contrast determination.

The increasing challenges of the industry to improve camera performance with control and test of the alignment process will be discussed in this paper. The main difficulties, such as special CFAs that have white or clear pixels instead of typical Bayer pattern and non-homogeneity of the back light illumination of the targets, used for such tests, will be outlined and strategies on how to handle them will be presented.

To ensure the quality of the fully assembled camera and its imaging performance, tests using slanted-edge targets, inclined towards the pixel orientation of the image sensor have been established. The focus quality is measured with the Modulation Transfer Function (MTF), fulfilling the ISO standard 12233 which proposes the calculation on edges that are inclined by 5°. Particularly, to determine the contrast in the image, ISO 12233 describes the usage of several pixel lines along the edge by means of oversampling, so that the MTF values for the higher spatial frequencies can be calculated more precisely. However, there are no considerations of using the raw image data without the availability of a full resolution color image and it is shown, that the sharpness will be affected by the choice of the interpolation method. Therefore, an extension of the algorithm with 3D-representation of the pixel positions with their corresponding illumination, can simplify the oversampled edge transition determination within a one-step-calculation. Furthermore, analytical modeling of the oversampled points will be demonstrated and compared, using various parametrical functions. This results in a reduction of the systematic errors of the subsequent steps and a more robust MTF evaluation.

The mentioned processes are applied to synthetically generated edges, as well as experimental images taken from ADAS cameras in standard illumination conditions, to validate the approach. In addition, to consider the influence of the chromatic aberration of the lens and CFA's influence on the total system MTF, the on-axis focus behavior of the camera module will be presented for each pixel class separately.

It will be shown that the repeatability of the measurement results of the system MTF is increased, as a result of a more accurate and robust edge angle detection, elimination of systematic errors using an improved lateral shift of the pixels and analytical modeling of the edge transition. Results also show the necessity of separate measurement of pixel classes, to ensure a precise focus position and sharp images.

10334-4, Session 2

Simulation of light fields of rough metal surfaces based on topography measurements

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In order to optimize machine vision systems for automated visual inspection it is necessary to have enough representative and realistic images of objects to be inspected and their typical defects. However, obtaining such realistic images is often difficult, sometimes even impossible when planning such a system. The lack of sufficient knowledge concerning the expected defects under different illumination and viewing directions and the variety of permitted object or surface variations poses a major problem to machine vision for automated visual inspection. To solve this problem, synthesized images would be an interesting alternative to measured images.

Unlike computer graphics, the synthesized images in machine vision systems should be accepted by image processing and other machine algorithms but not human eyes. Therefore, it should render the whole scene in an accurate way according to the physical phenomenon.

The crucial issue of the synthesized image is dealing with the scattering properties of the rough surfaces. The distribution of the scattering light from the rough surface is represented by Bidirectional Reflectance Function (BRDF). BRDF can be obtained by analytical calculation or measured instrument. The analytical BRDF is simple and easy for the modeling process. However, it is not easy task to find out the best parameters of BRDFs to obtain realistic images, especially for the spatially varying surface. Therefore, measuring the BRDF is still popular today. However, the BRDF is a four dimensional function (depending on incident angle and view angle), and the accurate dense measured BRDF data needs precise measuring instruments with a high dynamic range. Furthermore, according to different applications, light sources with different wavelengths make the cost of the instrument more expensive.

In this contribution, we apply GPU based ray tracing for imitating the light field propagating into a certain direction, e.g. to the camera. The intensity of different incident angles and output angles from the experiment and simulation will be compared. The microgeometry is measured by confocal microscopy with a lateral resolution of 3 μm. The reflectance on each microfacet of the surface is calculated by Fresnel equation.

10334-5, Session 2

Image formation simulation for computer aided inspection planning of machine vision systems

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In this work, we present a simulation toolset for Computer Aided Inspection Planning (CAIP) of systems for automated optical inspection (AOI). In addition, a versatile two-robot-setup for verification of simulation and system planning results is presented. We implemented our concept by taking the example of planning a 3D laser scanner application.

CAIP reduces the time and equipment needed for engineering of inspection systems and the dependency on individual expert knowledge by automating the exploration of the system configuration design space and algorithm parameter optimization. While CAIP is good practice for mechanical inspection by coordinate measuring machines, it still did not make its way into widespread application for development of machine vision systems. We consider both the higher simulation complexity of image formation compared to touch probing and unanswered questions about the transferability of planning results based on synthetic images to real-world applications to be obstacles in adopting CAIP for machine vision systems.

We propose to address the image acquisition simulation by introducing a hybrid system design and image rendering toolchain. It makes use of commodity GPU rasterization for interactive image display and fast system design space exploration, e.g. to calculate the visibility of surface patches from a given camera position or the first surface-light-intersection for fast illumination checks.

Since our concept is based on the idea of having all information required to calculate sensor-realistic images included in the annotated CAD-model, the system components (camera, light source) and the scene data, the same set of input data is used in a physically-based renderer to predict the sensor output data using sophisticated light-transport calculation. Our physically based renderer takes the type of light source (e.g. emission profile, spectrum, coherence) and sensor characteristics (e.g. lens, response curve, EMVA1288) into account as well as the optical surface characteristics of the scanned object(s) (e.g. BRDF). For laser light sources, also the speckles phenomenon is simulated.

Since rendering images at this quality level is costly in terms of CPU/GPU-power and time, we narrow down the number of possible solutions to solve the measurement task specified in the annotated CAD-model of the object satisfying the constraints given by the application. Our optimizer dynamically chooses the appropriate kind of simulation providing the output quality required for an optimization step.

Applied to the example application of 3D laser triangulation, our approach covers the automation of system design from accepting CAD-Data annotated with tolerance information, high-speed exploration of the triangulation sensor design space, the positioning of object(s) and the sensor in the scene and the physically based predictive rendering of what the camera sensor output will look like.

We used a manufactured test object with known design data (CAD) to evaluate the applicability of our approach to real-world problems. The object's surface BRDF was measured and with a two-robot-setup we acquired real-world data for a substantial subset of the design space. Camera and laser can be positioned freely in the hemisphere above the object. Comparison of simulation with real world data per geometrical, photometrical and meteorological criteria shows that CAIP for the laser scanning setup outputs feasible results.

10334-6, Session 3

Detection of cracks on concrete surfaces by hyperspectral images processing

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All large infrastructures worldwide must have a suitable monitoring and maintenance plan, aiming to evaluate their behaviour and predict timely intervention. In the particular case of concrete infrastructures, the detection and characterization of crack patterns is a major indicator of their structural response.

In this scope, methods based on image processing have been applied and presented. Mainly, the methods are focused in image binarization following by applications of mathematical morphology to identify cracks on concrete surface. In most cases, publications are focused on restricted areas of concrete surfaces and in a single crack. On site, the methods and algorithms have to deal with several factors that interfere with the results, namely: dirt, grease and moisture stains; biological colonization; graffiti; among others. Thus, the automation of a procedure for on site characterization of crack patterns is of great interest. This advance may result in an effective tool to support maintenance strategies and interventions planning.

This paper presents a research based on the analysis and processing of hyper-spectral images for detection and classification of cracks on concrete structures. The objective of the study is to define the wavelengths of the electromagnetic spectrum suitable for the classification of cracks in concrete surfaces. An image survey considering wavelengths between 350 μm and 1200 μm was performed on concrete specimens, with bandwidths of 10 and 25 μm. The concrete specimens were produced with several surface textures and a crack pattern was experimentally induced by applying a load with displacement control. The tests were conducted in different scenarios, aiming to simulate real situations. In this context, the surfaces of the specimens were alternately subjected to: laying of soil; moss placement; grease; moisture; and graffiti. To evaluate the suitability of each bandwidth for enhancing the crack pattern in all of the situations mentioned, a previously validated algorithm, MCrack, is being applied.

The research conducted allows to enhance and define the proper wavelengths for crack detection on concrete surfaces, considering cracking combined with other usual concrete anomalies and/or damages.

10334-7, Session 3

Optical determination of material abundances by using neural networks for the derivation of spectral filters

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Hyperspectral images (HSI) differ from widely spread color images by not only consisting of three channels within the examined wavelength range, but accounting for up to several hundreds of narrow wavelength channels resulting in spectra at each pixel. The increase of information provided by HSI allows to detect materials and, in addition, enables to estimate their relative abundances in mixtures, which is referred to as spectral unmixing. Particularly, complex and expensive hardware for the time-consuming recording process ending up in a data cube demanding notable memory space is required. Moreover, spectral unmixing is based on computationally expensive calculations. To overcome these drawbacks of spectral unmixing of HSI and continue taking advantage of its properties as a non-invasive non-destructive and contact-free analysis tool, we design spectral filter functions describing the exposure time of each wavelength. Instead of HSI, grayscale intensity images are recorded corresponding directly to material abundances.

For the derivation of sophisticated spectral filters leading to precise estimates of material abundances, knowledge of the spectra of pure materials and of a model describing their mixture suffciently well is vital. The linear mixing model is most frequently used and the needed spectra of the materials are assumed to be available (supervised unmixing). Deviations from the linear mixing model occur due to both nonlinear mixing and endmember variability. Endmember variability denotes spectral variations between pixels which are caused by chemical, microscopic and macroscale geometric effects. As a consequence, deviations may substantially mitigate the reliability of the result of the optically estimated abundances.

In contrast to [5], where the use of spectral fiters is already considered relying on point spectra to shift the major amount of computational efforts to the optics, our approach exhibits a spatial application of spectral filters. In addition, we increase the robustness of the results for the materials' abundances by using neural networks, such as self-organizing maps. Therefor, we discretize the range of abundances. The number of material mixtures becomes finite and we artificially create representatives for spectra referring to all possible material mixtures incorporating deviations from the linear mixing model to train the neural networks. The challenge of the estimation of material abundances results in a classification task and is tackled optically by the use of spectral filters. The approach requires a one-time computationally demanding preparation, namely the training of the considered neural networks to derive spectral filters, whereas the determination of the material abundances by physically applying the filters exhibits low computational costs and a significantly increased reliability.

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10334-13, Session PS3

Study of landmarks stability estimation produced by AAM

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Machine recognition and object tracking are very active research areas nowadays. Active Appearance Model (AAM) is an accurate and robust tool and is suitable when it's needed to estimate shape of object when its' approximate shape is known but varies within a certain range from instance to instance.

Here are some examples of AAM fields of application.

The first application is in medicine, for example swelling detection on the MRI images. For this you should determine the start position of the existing model. Consequently, the model will fit the given MRI image. The shape and dimensions of the swelling will be identified. Also, it allows estimating spinal curvature, length and shape of bones on electrographs.

The second significant application area is face image processing. For example, in biometry: AAM allows to estimate position, shape and dimensions of mouth, nose, eyebrows, eyes and distance between them. Also, AAM could be used for emotions recognition. In this case templates of emotions are used (sadness, happiness, anger, neutral).

One more application is speech recognition. Audio information is analyzed together with video, which increases the recognition accuracy. In addition, AAM can be used for biological or nonbiological objects parameters estimation, for example counting the number of bacteria in a population.

In summary, AAM is very useful in numerous areas and helps to save labor costs, ensure the people safety and health.

Most algorithms allow detecting separate and independent feature points of the objects while AAM detects and tracks multiple landmarks in aggregate as an object of interest description.

An AAM allows complex models of shape (for example human face) and appearance to be matched to new images rapidly. An AAM contains a statistical model of the shape and gray level or color appearance of an object of interest.

The associated search algorithm exploits the locally linear relationship between model parameter displacements and the residual errors between model instance and image. To match to an image we measure the current residuals and use the model to predict changes to the current parameters. The algorithm converges in a few iterations. This relationship can be learn during a training phase.

Since AAM is a deformable model, it has several variations.

Owing to the variations, the model is adjusted to the input test face image using iterative searching and fitting. The error, which measures the difference between the model and a test image, is minimized with the proposed searching algorithm.

Factors, influencing stability and accuracy of AAM are:

– image acquisition light conditions;

– image signal to noise ratio;

– human pose variation;

– individual characteristics of a person, such as beard and mustache, eyeglasses.

AAM is widely used but the research of its' accuracy and stability still remains an important and not fully learned issue. In this paper, we study landmarks stability and error estimation produced by AAM in different lightning conditions and signal to noise ratio (SNR). To achieve the results, we've processed images from several databases with varying light, face expression and pose. We added noises to get images with signal to noise ratio from 14 dB to 40 dB. The models of noise used in study are Gaussian and salt-and-pepper noises. The main criterion used in our research was general error of landmarks coordinates estimation. Our experiments showed the impact of signal to noise ratio variation on AAM accuracy.

10334-14, Session PS3

Stereo matching using the neighboring system constructed with MST

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Stereo matching is a hot topic in computer vision, which has many industrial applications, such as 3D reconstruction, autonomous driving and view synthesis. Although a great progress has been achieved over decades, the stereo matching in both large textureless regions and slanted planes are still challenging problems.

Many methods have been proposed to handle the two problems respectively. Tree Filter is proposed to filter the cost volume by Yang [1], which is a non-local cost aggregation method. In this method, a minimum spanning tree (MST) structure is derived from the image, and each pixel is one node of the tree. Thus every pixel contributes to all the other pixels during cost aggregation through the tree. Thanks to the structure, the performance in large textureless regions is improved. However, it cannot work well in slanted planes because of the implicit assumption that similar pixels have the same disparity. Another method denoted as MeshStereo [2] uses superpixels for cost computation and disparity optimization. It uses slanted plane model over superpixels and effective optimization scheme, so it works well in slanted planes. But it cannot obtain accurate and smooth disparity in large textureless regions for the reason that neither the superpixel nor its neighboring system can provide enough information for matching.

In order to achieve a good balance between the effectiveness of stereo matching in both large textureless regions and slanted planes, we propose an algorithm which novelly utilizes MST to construct the superpixel-based neighboring system. The neighboring system is used to improve the matching performance in textureless regions. In our method, the stereo pair is firstly segmented by SLIC, then two MSTs are constructed with superpixels respectively. Secondly, a degraded optimization is performed to obtain coarse initial disparity maps of the two views, thus matching confidence of each superpixel is obtained through cross checking. The confidence reflects the degree of matching difficulty of one superpixel, which is relevant to the texture strength. Hence, the new neighboring relationship is constructed according to the confidence with the MST. Finally, the proposed neighboring system is applied to MeshStereo. The smooth term is modified with the new neighboring system without changing the optimization scheme of MeshStereo. Note that the use of the new neighboring system is efficient and effective.

The proposed method is compared with not only the two methods mentioned above but also some other popular methods. First, the Middlebury dataset is tested. The average matching error in the dataset is less than 2.5. Then we carefully choose some stereo pairs with the two kinds of regions we mentioned, and test the performance in the specified regions. The average matching error in the textureless regions is 20% less than the other methods. The average matching error in the slanted planes is superior to most comparable methods. The experiment demonstrates that the proposed method obtains more accurate disparity in textureless regions while maintaining a comparable performance of matching in slanted planes.

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10334-15, Session PS3

High-reflection microprismatic material as a base for passive reference marks in machine vision metrology applications

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Position estimation of an object is necessary in many industrial applications, such as fabrication tools positioning, inspection of large-scale structures such as buildings, parts of ships and airplanes, nuclear plants turbines etc. These tasks can precisely and automatically be solved by machine vision systems. The systems traditionally utilize reference marks (called fiducials) mounted on the object to improve quality of detection and position measurement. Active reference marks traditionally use controlled LEDs to simplify detection process and to improve signal-to-noise ratio in the mark image. But the active marks require power supply, which is often inconvenient in maintenance. To avoid the problem passive reference marks made as black-and-white or colored printed patterns are used. Passive marks provide good quality of registration but complicate image processing and pattern recognition procedures.

In this work we suggest to replace traditionally used non-reflective scattering substrates for printed patterns by retroreflective tape to improve the visibility of marks and performance of measuring process. There are different kinds of retroreflective tapes technologies available on the market. The most effective tapes with highest retroreflectivity are based on micro-prismatic technology with hermetically sealed pockets. The air pockets placed under clusters of microprisms increase total internal reflection of the incident light. The drawback is that edges of the pockets become visible on the image captured by the machine vision system. The edges form netting pattern distributed all over the surface of the reference mark. This additional undesired pattern distorts registered shape of the printed pattern, that affects accurate coordinates extraction from the reference mark image.

Five different types of high-reflection microprismatic tapes were experimentally tested and compared with an intend of use for the machine vision metrology applications. The tested tapes had different shapes of printed patterns to define the possibility of the compensation of the interfering effect of netting pattern. Possible image processing algorithms were tested for suppressing undesired pattern from the images with marks. The tested algorithms were based on median, morphological filtering, Fourier descriptors and suppression in frequency domain. It was shown that the Fourier descriptors algorithm shows the best accuracy of center coordinates extraction close to 0.1 px.

The results of tapes comparison were experimentally verified with developed setup for linear coordinate measuring. The setup was based on a camera with Sony ICX274 CCD sensor with 25 mm lens, LED backlight (six 860 nm LEDs with maximal radiant flux 1000 mW and viewing angle 7?) and a developed reference mark. Firstly, the mark was made of high reflection microprismatic substrate covered with black industrial paint to form a desired pattern. Images of the reference mark with different scales, shifts and rotations were processed to provide quality estimation of the developed image processing algorithms. Secondly, we used a reference mark made by the same microprismatic substrate but covered with black metal mask, which could move in different directions relative to the substrate. A relative position change of the desired and undesired patterns affecting the accuracy of the image coordinate extraction was examined.

10334-16, Session PS3

A novel sparse-to-dense depth map generation framework for monocular videos

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Depth map is widely used in many applications, e.g. 3D modelling, 3DTV, thus generating the depth map from monocular videos is a fundamentally important issue in computer vision. Although the monocular depth map generation problem has been studied in the past decades, there still exists some problems.

Generally, the process of monocular depth map generation consists of two stages: structure from motion and multi-view stereo. The structure from motion estimates camera poses and reconstructs the scene. The multi-view stereo relies on the accuracy of the estimated camera pose and the photo-consistency assumption, which means that the matching points between multi-frames should have the similar intensity. Traditionally, local-based methods utilize the winner-takes-all strategy to generate the depth map, while global-based methods, such as graph-cut or loopy belief propagation, treat this problem as optimizing an energy function. However, they cannot tackle the multi-view matching problem well because of the dependence on the accurate camera pose. The depth map would be produced incorrectly when the camera pose is misestimated. Furthermore, more mis-matched points will appear while facing illumination-changing circumstances.

In this paper, we propose a new framework to handle these issues. To overcome the inaccuracy of camera pose of some certain frames, we employ the reconstructed scene information from SFM (Structure From Motion) rather than the camera pose. SFM can reconstruct the scene and generate the sparse point clouds. Then we reproject point clouds of the scene to every frame and obtain sparse depth points in every view. As far as we concern, point clouds are able to guide the procedure of generating the depth map. Inspired by the colorization insights, we use sparse depth points in place of interactive color scribbles. According to the assumption that nearby pixels in space in a frame with similar color would have similar depth, we can construct relevant energy function with a closed-form solution. Finally, we propagate the depth to the remaining pixels. In additional, we use the edge detectors to make the propagation better-regulated. The experimental results show that detected edges can improve the performance in some cases.

We formulate the monocular depth generation problem as an edge-assisted sparse-to-dense diffusion. There are three main contributions. First, we propose a new framework which does not rely on the estimation of the camera pose. Second, we define an energy function to generate the depth map and the function has a closed-form solution. Third, the use of edge detector can improve the vision effect.

We compare our results with the state-of-art methods. First, we compare with the method proposed by Zhang[1]. In his datasets, we obtain comparable depth map but cost less time. However, when we use narrow-baseline videos for experiments, they cannot generate the depth map while our method can still work. Second, we compare the narrow-baseline SFM[2] proposed recently. Its results can generate larger depth discontinuity in some selected video clips while ours are more smooth. It can be demonstrated that the proposed framework can robustly generate the depth map from monocular videos.

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10334-17, Session PS3

Airport extraction in remote sensing images based on superpixel feature analysis and saliency detection

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Target detection is one of the important aspects in remote sensing image analysis, which has wide applications in images compression, image fusion and change detection. Among different targets, airport has attracted more and more attention due to its significance in military and civilian. On the premise that runways in airports are usually regular lines, some researchers try to detect airports by recognizing runways. Those methods are heuristic and depend much on the ability to extract characteristics of runways. Some researchers regard target detection as classification and introduce supervised learning. Those methods all include training stage and testing stage. With the help of much prior knowledge acquired in the training stage, many approaches based on classification achieve good results. However, the need of prior knowledge and classifier will cause high computation complexity. Humans tend to pay attention to particular objects, which are more salient than others, in an image. Accurate and fast detection of targets in an image can make recourse distributed reasonably and is of great importance in both theory and practice. Selective visual attention, as one of the most important mechanisms of the human visual system (HVS), doesn't require prior knowledge but can detect salient regions in an image directly, which inaugurates a new perspective for target detection. If it can be applied to target detection in images, the complexity will be reduced and the efficiency will be improved. Recently, saliency analysis has been introduced to target detection for natural images and videos and gotten some good results. Saliency analysis has also been used in target detection for remote sensing images. Zhang employs the discrete moment transform (DMT) to strengthen the edges in residential area detection, and Li extracts gist features and introduces a support vector machine (SVM) to train these features for detecting board areas. However, Zhang's biological model imitates the low-level vision of human eyes, so the ROIs detected are generally only the outlines of objects without details and boundaries, while Li's model that requires prior knowledge and SVM is not a pure bottom-up approach. In this paper, we propose an airport detection model based on superpixel feature analysis and saliency detection. The input image is segmented into superpiexl blocks first. Then saliency analysis is performed by calculating differences between superpixels and corresponding weights in R, G and B colour channels to get the saliency map. Finally we utilize the limitation in the ratio of perimeter and area and morphology operation to eliminate the interference and the final detection result is obtained. In experiments, remote sensing images with airports in them from Google earth are chosen to compare the performance of our proposed model with three saliency analysis models including the Itti model, the SR model and the FT model. The Otsu method is used to segment saliency maps. We use the ROC curve to compare the proposed model with the other three models. The ROC curve is a significant objective evaluation of saliency models. Results show that the proposed model is better than the three comparative models in the abilities of keep clear boundaries, eliminating interference in the backgrounds and maintaining intact targets.

10334-18, Session PS3

Real-time detection of abandoned bags using CNN

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Today it is a challenging task to design a good computer vision algorithm suitable for large-scale and multitasking video surveillance systems. Mainly because such systems have high requirements in terms of software performance and limit the amount of computer resources available for build-in algorithms. Another important demand is to ensure a high probability of correct detection and low false alarm rate. In this paper, we propose an algorithm for abandoned bag detection that is designed taking into account the requirements listed above. It consists of two parts. The first part is very fast and simple. It does the preliminary detection of abandoned objects-candidates. The second part is much slower and smarter. It does verification of candidate objects using CNN.

It is convenient to use background modeling techniques for preliminary detection, since it allows distinguishing moving objects from stationary objects and stationary objects from the background. The background model uses advanced adaptive Gaussian mixture model [1]. Each pixel uses three Gaussians. The first Gaussian with the largest weight models the background, the second Gaussian helps to highlight stationary objects, and the third - moving. This Gaussian mixture model allows to quickly and flexibly adjust for lighting changes and remove shadows. In addition, the recovery technique called «healing» [2] is involved, which prevents stationary objects to fall into pieces, when background model pixels are updated at different rates. It allows precise positioning of the bounding box on the object of interest. This is crucial for the success of the second part of the algorithm. As a result, the preliminary predetection generates a list of candidate objects that need to be classified as abandoned bags or background.

In the second part we use image recognition technique based on convolution neural networks to test the candidate object. Bags dataset, including real and model images of size 32 ? 32, was prepared. We use local contrast normalization and ZCA whitening (zero-phase component analysis whitening filters [3]) to highlight edges for data preprocessing, because it helps when images are small. During designing a convolutional network, we determined which building blocks of convolutional networks are necessary for successful recognition and which can be neglected. The following rule of building of the network architecture was heavily utilized [4]: a stack of convolution layers with a small filter size is better than one layer with a large filter size. We also can neglect the fully connected layers and discard the maximum pooling layer between the stacks of convolution layers. It is important to place a dropout layer before stacks of convolution layers [5]. Finally, the proposed architecture consists of 9 convolution layers, after each convolution layer follows ReLU (rectified linear unit) layer; first 3 layers have size 64, 4-8 layers have size 128, 9 layer have size 2; all layers have padding set to 1; layers 3, 6 have stride 2; dropout layer precedes every stack of convolutional layers; average pooling layer is on the top and have filter size set to 8. This net is developed to work on CPU, and can process 10 images per second on average PC. So, the preliminary detection and the network are working in parallel and communicate concurrently. In our experimental setup 99.5% recognition accuracy was obtained in Saint-Petersburg underground in very challenging conditions (different lightning, overcrowded areas).

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10334-19, Session PS3

A novel vehicle tracking algorithm based on mean shift and active contour model in complex environment

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Vehicle tracking technology is currently one of the most active research topics in machine vision. It is an important part of intelligent transportation system. However, in theory and technology, it still faces many challenges including real-time and robustness. In video surveillance, the targets need to be detected in real-time and to be calculated accurate position for judging the motives. The contents of video sequence images and the target motion are complex, so the objects can’t be expressed by a unified mathematical model.

Vehicle tracking methods can be divided into four major categories: region-based tracking, active-contour-based tracking, feature-based tracking, and model-based tracking. Useful mathematical tools for vehicle tracking technology include the Kalman filter, the Condensation algorithm, the dynamic Bayesian network, the geodesic method. The current vehicle tracking technology can achieve reliable results in simple environment over the target with easy identified characteristics. However, in more complex environment, it is easy to lose the target because of the mismatch between the target appearance and its dynamic model. Moreover, the target usually has a complex shape, but the tradition target tracking algorithm usually represents the tracking results by simple geometric such as rectangle or circle, so it cannot provide accurate information for the subsequent upper application.

In this paper, we combine mean shift algorithm with a kind of image segmentation algorithm, C-V active contour model, to get the outlines of objects while the tracking process and automatically handle topology changes. First, the position of the object is found based on mean shift algorithm, which can always use the mean shift vector to point to the direction of the largest density variations. Second, a C-V active contour model based on the level set method is used to detect all of the contours automatically, no matter where the initial contour starts in the image. Finally, the outline information is used to aid tracking algorithm to improve it.

Experimental results show that the proposed algorithm is a robust and efficient tracking algorithm, which cannot only get the accurate tracking results of the vehicle, but also display the edge and contour of the vehicle in a number of complex scenes. In real life, this proposed vehicle tracking algorithm can provide a proof to the determination of accident and violation by the accurate outline of vehicles and pedestrians.

10334-20, Session PS3

The method of measuring linear displacements of objects based on Fresnel diffraction pattern position

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The diffraction method of measuring linear displacements based on illuminating an object by a spherical wave is offered in this work. It is shown that at the optimal choice of radius of a wave it is possible to receive a big shift of the diffraction pattern at the small displacement of an object. The results of the research show a possibility to measure in the diapason of ±20 mm with measurement error about 0.1%.

Nowadays optical systems for measuring the linear displacements and geometrical parameters are widely used in science and technology. They are used to control linear dimensions of the details, deviations of the geometrical shape, runouts, profile of a surface, straightness of the guide, positions of executive elements of actuators, etc. The most accurate measurement systems are those, which use methods based on diffraction and interference. They have high accuracy, but are sensitive to external influences, demand tight tolerances on elements of the system and they measure within one coordinate.

We offer the diffraction method of measuring linear displacements, which allows to simplify the measurement scheme and to increase the accuracy and sensitivity of measuring. Studies have shown that at illuminating the object by the spherical wavefront a displacement of the object concerning the center of curvature of the wavefront causes the shift of the Fresnel diffraction pattern, which is several times greater than the displacement of the object. The analytic expression connecting the displacement of the object with the shift of the diffraction pattern: Dy = Dx*(1+z/R) , where Dy – the shift of the diffraction pattern, Dx – the displacement of the object, z - distance between object and receiver plane, R - radius of curvature of the wavefront falling on the object.

Experimental tests with values of z = 120 mm and R=40 mm have shown that at the Dx = ±0.1 mm and ±1 mm displacements of the object the margins of error are ?Dx = ±0.8 and ±1.8 ?m, respectively.

A computer simulation has shown that the measurement error is strongly depends on the discretization error of an image of the diffraction pattern. To decrease this error it was offered to use digital moiré fringes formed by subtraction arrays of images of the diffraction patterns from radiation sources with different wavelengths. Comparing of digital moiré fringes, which appropriate to different coordinates of the object, makes it possible to measure the shift of the diffraction pattern's image with error of 1/50 of pixel. The shift of the moiré fringe is connected with the displacement of the object as Dy = Dx*(1+z/R)*(?1/(?2-?1)) . The experiment using moiré fringes formed by laser radiation sources with wavelengths ?1 = 0.632 ?m and ?2 = 0.532 ?m has shown that ± 0.1 mm displacement has the ± 0.4 ?m margin of error. These results correspond well with the results of the computer simulation.

Calculations have displayed that the limiting error can be reduced to 0.1 % by using the radiation sources with a small difference of wavelengths or by application of more complicated digital processing algorithm of a moiré pattern. In the presence of the diffraction fringes oriented on orthogonal coordinates, two-axis measurement can be realized by means of offered method.

10334-21, Session PS3

Saliency analysis and focus of attention detection based on dynamic feature combination and region growing

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The study of human visual system has found that when people are facing a complex scene, the human visual system can quickly focus on a small number of salient objects. This process was known as visual attention and these salient objects are called focus of attention (FOA). The visual attention mechanism is used to extract the salient regions and analyze saliency of object in an image. It is time-saving and can avoid unnecessary costs of computing resources. According to the visual psychology, the visual attention mechanism is divided into two types in accordance with the different ways of information processing: one is task-independent and a bottom-up manner. The other is task-dependent and a top-down manner. The bottom-up manner can be realized by saliency analysis of an image quickly.

The traditional saliency analysis models, including Itti model and Graph-Based Visual Saliency (GBVS) model, have attempted to accomplish the saliency analysis and the FOA detection based on the human visual system biological construction. In these models, multi-scale image features including intensity, color and orientation are extracted to generate the saliency map through center-surround difference. Many experimental results have shown that these models produce satisfying results but they still have some obvious defects. First, the contribution of each feature channel is equal. In fact, this assumption is unreasonable. For example, in the image which has intense color contrast, the color feature should have larger contribution to the saliency map. As for the image which has relatively richer texture features, the orientation feature should be attached with more importance. Second, Itti's model used circles with a fixed radius to describe FOAs which can't accurately describe the shape of FOAs. When the radius of the circle is large, the detected FOAs will contain a large amount of redundant information. In applications such as image compression and encoding, the more the redundant information is, the lower compression efficiency will be. When the radius of the circle is small, the detected FOA cannot cover the whole salient object, bringing difficulties in applications such as image retrieval and pattern recognition.

In order to overcome these defects, a novel saliency analysis model based on dynamic feature combination and region growing algorithm is proposed in this paper. In the proposed model, we first generate multi-scale feature maps of intensity, color and orientation features using Gaussian pyramids and the center-surround difference for the original image. Second, we evaluate the contribution of all feature maps to the saliency map according to the area of salient regions and their average intensity, and attach different weights to different features according to their importance. Third, we choose the largest salient region generated by the region growing method to perform the evaluation. Finally, the region growing method was used to describe the FOAs more accurately than the circles with a fix radius. Experimental results show that the proposed model cannot only achieve higher accuracy in both saliency map computation and FOA description compared with other traditional saliency analysis models, but also extract FOAs and salient regions with arbitrary shapes, which is of great value for the image analysis and understanding.

10334-22, Session PS3

The experimental evaluation of position control error in swarming visual sensor network for multiple object tracking

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The automatic spatial coordinates control of the multiple objects is one of the most actual tasks in many arear of technology and science. Application of a single device for multiple targets tracking in objects with complex geometry is usually complicated. Using distributed optical-electronic systems for such kind of tasks is seem to be an optimal suggestion.

Swarming visual sensor network (SVSN) is developing scalable distributed optical-electronic measuring system with decentralized data processing. Sensors of this system are movable and their spatial positions are linked to the global coordinate system using active visual marks mounted on sensors body. If there are a-priori knowledges about geometrical parameters of mark, coordinate estimation of sensor is possible by applying projective geometry. When spatial position of system camera is estimated, we can obtain object coordinates in global coordinates system by coordinate transformations.

Measuring data of the tracking objects are translated to all accessible neighboring devices by wireless data transfer channel. This feature makes possible object tracking in global coordinate system without direct eye contact between object and all of near located devices of the system. If object is being simultaneously tracked with multiple cameras of the system, SVSN calculates optimal measuring routes to the object for maximum accuracy of spatial coordinate estimation. Systems with such architecture are demanded in technical means to position control of multiple targets for resolving multiple objects tracking problems in different tasks: mines, rescue operations in blockages, traffic situation control in poor visibility conditions etc.

In this paper, experimental evaluation of position control error in distributed optical-electronic systems depending on distances between system devices and quantity of cameras in measuring chains are shown.

Influences of mark geometrical parameters to the resulting error are studied. Comparative study of active and passive visual marks in different viewing conditions are made. As a result of experimental data analysis, conclusions on the limits of applicability of swarming measuring systems are made.

For future work, development of the automatic coordinate transform algorithm from local coordinate system of single device to global coordinate system is planning.

10334-23, Session PS3

Automatic 3D inspection metrology for high-temperature objects

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3D Visual Inspection for high-temperature objects has attracted more and more attention in the industrial and manufacture field. Until now it is still difficult to measure the shape of high-temperature objects due to the following problems: 1) The radiation and heat transfer through the air seriously affect both human and measurement equipment, so the manual measurement is not capable in this situation. 2) Because of the difficulties to handle the surfaces of the hot objects, it is hard to use artificial markers to align different pieces of data. In order to solve these problems, an automatic 3d shape measurement system for high-temperature objects is proposed by combing industrial robot with the optical measurement equipment. The system fixes an optical 3D measurement device on the wrist of an industrial robot. In this system, the route for inspection is planned by manual operations to scan the cooled object. And then the route planned is executed automatically when the cooled object is replaced with the same object in hot state. The route still works for the shape of the object changes little. The route is carefully planned according to some principles to make sure that the measurement equipment is near to the hot object only when it reaches the position where the scan is taken. This reduces the exposure time of the measurement equipment under the high-temperature situation. Then different pieces of data are pre-mapped during the planning procedure. We use artificial markers on the cooled object to align different pieces of data. And the alignment parameters of each piece of data is recorded. In the executing procedure, when the robot reaches one position, the data acquired there can be aligned accurately using the corresponding parameters recorded before. Thanks to the good repeatability of the industrial robot, the alignment precision can be satisfying. Finally, different pieces of data are merged without artificial markers. The results are better than methods with hand-eye calibration because that the repeatability of the robot is usually far better than its accuracy. Experiments verify that the proposed system can conduct the inspection of forging parts under the temperature of 900? and the alignment precision is better than 0.08mm/500mm.

10334-24, Session PS3

CPU architecture for a fast and energy-saving calculation of convolution neural networks

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The increasing computing power in recent years allows more and more complex algorithms for the implementation of adaptive artificial intelligence. Deep Learning is one approach for adaptive intelligence. For the task of pattern recognition the family of Convolution Neural Networks (CNN) is applied. The best example is the image search on the internet. Here CNN are used for classifying 1000 different objects in one picture [1]. In addition these networks are used for example for autonomous driving. These networks learn how to behave on the street and also the recognition of the road signs [2]. Another application is the detection of human faces [3] and there emotions. The CNN is used as an interface between humans and robots [4]. CNN can even be trained to calculate the calories in a meal. The user only has to make an image of his meal with a smartphone [5]. Another use of the CNN is to recognize emotions in audio data or images [6]. The first CNN worked for optical character recognition (OCR). Le Cun has developed networks with an accuracy of about 98% [7]-[8].

In this paper a CNN is used for plant detection in organic farming. In paper [9]-[10] the basics, the sensor-configuration and parts of the classification task of the project were already presented. The biggest problem is still the speed and power consumption of the algorithms. Although large search engine companies own specially developed hardware to provide the necessary computing power, for the conventional user only remains the state of the art method, which is the use of a graphic processing unit (GPU) as a computational basis. Although these processors are well suited for large matrix computations, they need massive energy. Therefore a new processor on the basis of a field programmable gate array (FPGA) has been developed and is optimized for the application of deep learning. This processor is presented in this paper as well. The processor can be adapted for a particular application (in this paper to an organic farming application). The power consumption is only a fraction of a GPU application and should therefore be well suited for energy-saving applications.

To further increase the performance of the FPGA solution, the ALU should be set up several times so that more calculations are possible at the same time. Since we have only consumed about 3% of the FPGA's required resources at present, a multiplication of the ALU is not a big problem. A further optimization is the implementation of a pipeline structure to eliminate unnecessary course times. We hope that we can present the next generation of our CPU in the future.

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10334-25, Session PS3

Pedestrian and car detection in video surveillance using fully convolutional YOLO neural network

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More than 95% of video surveillance systems are used for monitoring people and cars. Old detection algorithms, based on background and foreground models, couldn't even deal with a group of people, to say nothing of a crowd. Recent robust and highly effective pedestrian and car detection algorithms are a new milestone of video surveillance systems. These algorithms can distinguish different persons in a group, cars in a traffic, deal with sufficient enclosures of human bodies by the foreground, detect various poses of people, views of cars.

Over the last decade it was proposed a huge number of approaches (more than 1000, including the approaches and their modifications [1,2]) to detect people and cars. Comparative testing and brief overview of the key components of these approaches can be found in [3]. At this point it is obvious that the approaches, based on the convolutional neural networks (CNN) provide much better results than other ones. In the first papers on neural networks for pedestrian and car detection authors used prior detection systems that repurpose classifiers or localizers to perform detection. They apply the model to an image at multiple locations and scales. In this paper we use a modified by us, fully convolutional, version of YOLO ("You Only Look Once") neural network [4], trained on the small images of people and cars in various scenes and locations. YOLO is a well-known, state-of-the-art and real-time object detection system. This network is very fast compared to the other state-of-the-art approaches as R-CNN [5], Fast R-CNN and slightly faster than DetectNet [6]. Its architecture, like the most of the CNN architectures, includes a set of convolution and pooling layers alternating with each other, and several fully-connected layers. Because of the fully-connected layers this network works with images of a certain size, since these layers accept only input and output data of the fixed size. In this paper we propose a fully convolutional version of YOLO without the necessity for retraining. Once the network is fully convolutional, the prediction of the CNN output is a 2-dimensional array in which each column contains a network prediction by a separate part of the image. The amount of these parts depends on the size of the input image. To join the predicted bounding boxes we use a clustering algorithm. It clusters all the input rectangles using the rectangle equivalence criteria that combines rectangles with similar sizes and similar locations. Then, the small clusters are rejected. In each other cluster, the average rectangle is computed and put into the output rectangle list. Also in this paper we train it on images from our own dataset that contain people and cars of small sizes, starting with 12 pixels wide. This dataset is a mix of Pascal VOC, KITTY and video sequences from Moscow city surveillance system. We achieve about 90% accuracy of pedestrian detection and 92% accuracy of car detection on this dataset even on very small images of people and cars.

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10334-26, Session PS3

Development of optical-electronic system for the separation of cullet

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Glass cullet - crushed glass, formed during the production and usage of glassware. There are two types of cullet in the glass industry: the returned cullet and the imported cullet. The returned cullet made up from glass waste from the glass factory, this waste is being returned to manufacturing process. The imported cullet this used glass, collected and recycled in certain way, designed for further use in the glass production process. The Imported cullet may contain refractory inorganic impurities (such as corundum, mullite, quartz, porcelain etc.), magnetic metal and non magnetic metal impurities (tins, metal plugs, metal rings etc.), and also organic impurities (paper, cardboard, plastic). When refractory impurities get into the glass mass it cannot be completely dissolved, and this leads to flaws in the end product. Developing the methods of separation of cullet will reduce the number of damaged product.

During the process of complex system analysis of cullet separation following was revealed: it is rational to install an optical-electronic system based on the machine vision. Analysis of bulk fractions (of glass and impurities) was carried out by such criteria as color and transparency. Type of fractions will be recorded by detecting equipment, located in the record channel of the system. The system consists of 2 record channels which consist of exposure source and the matrix receiver. Recording channels are connected to the critical devices for informational analysis of channels.

The authors had designed a scheme of zone control exposure for analysis of color and transparency. The authors analyze possibilities of placement main blocks of the developed system into the main line of cullet separation. In the course of the calculations of the optical system major parameters of the system components was chosen, they are included in each recording channel. Also the author selected electronic components for recording unit.

In the course of study fractions of cullet and various impurities were investigated. Differences in the optical characteristics can be used for sampling of useful raw materials from the starting mixture. Research has been carried out using the installation for the color analysis of static objects, as well as the device analyzing transparency. Due to object detection algorithm for color and transparency development, and design of theoretical model of the system authors could consider various options for constructing a device of registration channel.

Basic experimental studies confirmed the possibility of separation of objects under different conditions of material contamination.

According to the results of experimental studies analyze the effectiveness of the mutual work of two registration channels, as well as the possibility of upgrading the device of cullet registration.

10334-27, Session PS3

Accurate localization and pose estimation of model-based 3D object in cluttered scenes

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In this paper, we present an effective method for accurately locating and estimating the 6D pose of model-based 3D object in cluttered scenes. A local feature descriptor is adopted to perform efficiently recognizing and locating the 3D model in the clutter scenes. Then the generated 6D pose hypothesizes are checked with a novel combinational verification algorithm to obtain the final pose estimation result. Experimental results demonstrate that our method is able to reliably locating and estimating the 6D pose of objects under a variety of scenarios.

10334-28, Session PS3

Schungite raw material quality evaluation using image processing method

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High-carbon schungite rocks of Karelia are promising mineral raw material for production of active fillers for composite materials (because of new technological and operational properties of these fillers), radio shielding materials, silicon carbide, stable aqueous dispersions, sorbents, catalysts, carbon nanomaterials, and other products.

An intensive evolution of radiometric separation and sorting methods based on different physical phenomena occurring in the interaction of minerals and their constituent chemical elements with different types of radiation open new enrichment opportunities for schungite materials.

An optical method based on the evaluation of the color or brightness differences between mineral components by machine vision methods followed by separation of the useful fraction of the original ore flow by means of the pneumatic system is one of these methods.

The present work is devoted to the research and development of preliminary quality assessment principles for raw schungite on the basis of image processing principles and perspectives of the optical separation for its [schungite] enrichment.

The following results were obtained during this work:

– The theoretical studies of schungite rock samples with vein textures were conducted, making it possible to describe the selective criteria for separation of mentioned raw material by optical method;

– The experimental studies of various sizes of schungite rock samples with vein textures and an extensive system of quartz veins from 2 to 7 mm in thickness as well as samples of schungite breccia with predominantly black type of cement were conducted, allowing us to establish objective (measurable) parameters and characteristics and to identify and to define the amount and values of borders necessary for efficient separation;

– A method of quality indicator assessing for schungite raw materials, which takes the estimated mineral composition of the sample's surface (the presence of quartz-sulfide inclusions, as well as cement schungite breccias inclusions) into account was developed.

10334-29, Session PS3

Express quality control of chicken eggs by machine vision

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It is generally known, that quality of chicken egg and its capacity for long-term storage are directly linked to the homogeneity of the color of eggshell, as well as the presence of various defects (cracks, cavities, etc.) in it. Furthermore, the basic color tint of eggs (that had just laid) may vary depending on the breed of chicken, its age and its nutrition peculiarities.

At the moment color parameters of eggshell and yolk are usually measured by sight (i.e. subjectively) with the help of standard color etalons. Structural features of the shell are also determined by means of visual ovoscopes.

The present work is devoted to the investigation of application possibilities of machine vision and image processing technologies for monitoring quality parameters of chicken eggs. So, the analyzer prototype with the appropriate software was designed, as well as experimental studies on a representative sample of eggs from hens of different breeds were conducted. In total, more than 300 eggs were analyzed.

A spectrometry analysis in the visible spectrum was used as a control method.

According to the obtained results the correlation between optical parameters of the eggshell (color uniformity) and evaluation criteria of eggs quality was found.

It was shown that the proposed analyzer can effectively perform the following functions:

– the definition of integrated color parameters of eggshell surface;

– the estimation of the analyzed egg's size in mm (length, width, volume);

– the evaluation of shape parameters for analyzed eggs by obtained and corrected image;

– the definition of external defects on the egg's surface (pollution, glare area, growths, wrinkles, visible cracks) by obtained and corrected image;

– the detection of fine cracks and estimation of marbling degree for analyzed eggs.

The results can be used to solve problems of process inspection in poultry farms, as well as in food industry for assessing the quality of the incoming products.

10334-30, Session PS3

Distance error correction for time-of-flight cameras

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Time-of-fight cameras acquire 3D scene information at high framerates. This enables new opportunities for improving existing systems and entirely new applications. Probably the most well-known time-of-fight camera is the Kinect V2, which is used both in entertainment systems, but also has also been adopted by the research community. More recently, time-of-flight sensors have also been integrated in mobile devices, like for example in Google's Tango Phablet.

However, current time-of-flight cameras provide only limited depth accuracy. The total depth error may accumulate to multiple centimeters [1]. Depth errors can be categorized into scene-dependent and systematic errors. A manufacturer has little to no influence on scene-dependent errors. However, even most recent cameras exhibit typical systematic errors. In the last years, researchers aimed to develop error compensation methods to reduce the impact of these errors. Some approaches aimed at modelling the physical error sources, while others model the resulting errors with parametric and non-parametric models [3]. More recently, the community started to exploit machine learning approaches4 to model the error behavior more accurately. From an industry perspective, an ideal error compensation method shall include a) effective reduction of measurement errors, b) time-efficient, automated calibration, c) no additional hardware requirements and d) real-time capability.

In this work, we propose to use random regression forests for compensating systematic measurement errors of time-of-flight cameras. The method aims at reducing several errors: temporal noise, the absolute distance error, and the so-called amplitude related error. The method makes use of a specifically tailored feature vector that consists of distances, amplitude, statistical measures and filter outputs which can be calculated efficiently. In our experiments we evaluate different features which include: mean and median values of distances and amplitudes, deviations from the median, standard deviations, partial derivatives, distances from the image center as well as filtering results of guided image filters. A small subset of these features is illustrated in the supplemental material.

We demonstrate how to train the random regression forest and how to generate training data during the intrinsic calibration process which is performed with well-established methods. The method makes the common, mild assumption that the calibration pattern is planar. However, this only constraint is typically already required for intrinsic calibration.

We propose an extended checkerboard pattern, which is augmented by an additional gray-level gradient strip. With this new calibration pattern both the intrinsic calibration and the depth calibration are performed. Distance measurements of the gray-level gradient allow capturing a wide

range of amplitude values which result in different errors and thus in more meaningful training data.

Based on the known geometry of the calibration pattern and the intrinsic camera parameters, the ground truth position of the pattern plane can be obtained. Ground truth distance values for all pixels within the pattern area can be calculated by intersecting a ray, starting at a particular pixel in the image, with the pattern plane. In summary, with the correct calibration pattern, the training data for the error compensation is generated fully automatically with no additional manual effort during intrinsic calibration.

We show that the presented method effectively reduces the amplitude-related error, the absolute measurement error as well as measurement noise, resulting in a reduction of the mean and standard deviation of the error by more than 40%.

One of our experiments evaluates the measurement error for the Mesa SR4000 time-of-fight camera in the range starting from 70 cm to 140 cm with and without the proposed method. Figures of this experiment are shown in the supplemental material.

In our results, two effects can be observed: a) without our error compensation method, a clear global offset of almost a centimeter can be observed, and b) with the proposed method the standard deviation of the measurement error can be reduced efficiently. This is achieved by including spatial features into the error compensation process which effectively performs edge-dependent smoothing.

In our experiments we also evaluate the impact of the random forest parameters, particularly the tree depth and the amount of trees. Furthermore, we analyze the importance of the individual features to obtain a feature subset that balances computational effort and error compensation performance.

One of the most relevant features, especially with comparably small forests is the difference of a pixel and the median of its neighborhood. By increasing the number of trees and their depth, the relative importance of this parameter decreases. A figure that visualizes results from this experiment can be found in the supplemental material.

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10334-31, Session PS3

Digital image processing for studying the colloidal systems

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Development of novel self-assembly based technologies for a synthesis of new materials with given properties is an actual problem of fundamental and applied studies in modern material science and soft matter physics. These systems are of high importance for a broad range of practical applications, from photonic crystals to various biomedical applications and chemical sensors. However, importance of colloidal systems is not limited only by practical applications.

Particles size of colloid systems commonly is of order of several micrometers [1-5] that allows us to observe their dynamics using simple, or confocal microscopy. Colloidal systems are the examples of soft matter systems whose properties and structures can be effectively controlled by external fields [1-3,6]. In our project, we elaborate the important problem of self-assembly in colloidal suspensions controlled by external electric fields. The applied external electric fields induce currents of anions and cations in the solvent, and polarize the colloidal particles so, that the interaction between them become tunable. It allows to perform self-assembly of the particles and also to study generic phenomena in two-dimensional fluids and crystals, in particular, the processes occurring at the molecular scale and study various phenomena at the most fundamental, kinetic level (with resolution of individual particles): pair correlations, transitions between structures in crystals [1-3,7-11] and fluids [12], melting [13-15], crystallization [2], nucleation [16-18], self-assembly of the clusters etc.

However, to solve this ambitious problem, we need to perform a very accurate tracking of the particles using the microscopy technique. Thus, the problem of the digital imaging is one of the most important for experiments with tunable interactions in colloidal suspensions: Development of highly-effective software packages, to receive information about the current system’s state in real-time, is the problem important both for practical applications and fundamental researches.

In the experiment, a structure composed by macroscopic particles is illuminated by external light source and then is captured by camera [1,5]. Our software package receives a stream of images from photo camera and recognizes the particle’s position. Then, package decomposes image to subdomains, and each subdomain is independently smoothed using the procedure of phase correlation [19]. Particles position’s in the current image are estimated with pixel resolution and then refined to the subpixel one using neighborhood data [20]. Based on this information, the algorithm allows computing different properties specified by the user: density, Voronoi cells geometry, local bond order parameter, other local structure parameters. The information about the particle’s position in different moments allows us to calculate such characteristics as particle velocity, temperature, phonon spectra (dynamical matrix), sound velocity, radial distribution function, to estimate screening parameter, and coupling parameter. This allows us to receive the comprehensive information in real-time about colloidal system state in the experimental station: identifying areas of different phases (fluids or crystals with different lattice modification), recovery phase separation boundary and they dynamics, tracking defects dynamics, registration system’s response to external influence, etc.

We implemented our package in CUDA C/C++ language, which allowed us to reach performance we need for real-time post-processing. We hope the developed software package will be useful for future experiments on colloidal systems and will allow improving the methodology of experiments to a qualitatively new, better level.

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10334-32, Session PS3

Towards automated human gait disease classification using phase space representation of intrinsic mode functions

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In this contribution, a new classification methodology for segregating healthy and neurological disorders from gait patterns is proposed by employing a set of amplitude and frequency modulated (AM–FM) signals called Intrinsic mode functions (IMF's). These IMF's are generated by the Empirical Mode Decomposition (EMD) of the gait time series and the analytic signal representation of these IMFs by means of Hilbert transformation forms the trace of the elliptical shaped analytic IMFs in the complex plane. The area measure of the polygon spanned by the Convex Hull of these analytic IMF's is taken as the discriminative feature. Annova analysis and Simulation results with Support vector machine classifier validates the adequacy of the proposed approach for computer aided diagnostic (CAD) system for gait pattern identification. Also, the efficacy of several potential bio-markers like Amplitude Modulation Bandwidth (BAM), Frequency Modulation Bandwidth (BFM) and Mean Frequency (MF) computed using Fourier-Bessel expansion for each of these analytic IMF's has been discussed for diagnosis of Gait pattern recognition and disease classification.

10334-8, Session 4

Incremental learning-based diagnosis of solar cells for smart repair and recovery

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The photovoltaic industry, as a consequence of the global efforts to reduce the dependence on fossil fuels and carbon dioxide emissions, is one of the fastest growing economic sectors. However, despite generation and use of solar energy is free of pollution, the industrial production of wafers, cells and photovoltaic modules is responsible for the consumption of considerable amounts of natural resources and energy. Thus, in a scenario of fast growing production capacity, the implementation of novel recovery and recycling strategies may have a great impact in the efficiency and sustainability of the whole process. In fact, it is estimated that the recovery of defective solar cells can save up to 70% energy in comparison with the production of new wafers and solar cells [1].

The aim of our work, as part of the Eco-Solar project [2], is to develop a diagnosis tool able to detect, localize and classify the different defects that can be present in a solar cell. Such a tool will support the evaluation of the potential reuse of the cell, as well as the specific localized recovery actions (laser isolation, deletion or cutting) to be taken afterwards.

In line with state-of-the-art tools and research, our system is based on ElectroLuminescence (EL) imaging, one of the most informative and versatile techniques for solar cell characterization. EL requires the cell to be electrically excited, which causes the emission of infrared light that can be captured by a high-sensitive camera (Si-CCD, InGaAs...). In the resulting image the areas of the cell with a higher conversion efficiency will appear brighter, while defective regions will be darker. Beyond that, each kind of defect will have a distinctive texture and shape enabling a visual discrimination of each defect class.

Many works in the literature have addressed this problem focusing on the detection of a single kind of defect [3,4], instead of the global detection and classification of a wide bunch of defect types [5,6]. Following the framework proposed by Rodríguez-Araujo and García-Díaz [6], in this work we will try to tackle the detection and classification of a whole set of defects in a single step, trying to do a wider comparative analysis among different characterization and training parameters.

One of the constraints of the previous systems is their limited ability to deal with a big batch of solar cell images (that can even be continuously growing as new labelled samples are available). Thus, the main contribution of this work is the use of an incremental learning approach with Stochastist Gradient Descent training, giving the system the possibility of managing a bigger and richer set of training examples, driving to a more accurate and precise classifier than that obtained with more classical approaches.

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10334-9, Session 4

Digital image processing algorithms for automated inspection of dynamic effects in roller bearings

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Roller bearings can be found in a wide range of mechanical engineering applications. Up to now, dynamic effects in roller bearings are not completely understood. Nevertheless, unstable movement in bearings leads to fatigue and damages or even a reduced lifetime and an early break of the bearing. Talking about roller bearing damages, there are a lot of symptoms like skidding, wear marks, discoloration or cracks with a lot of causes like slippage, excessive loading, insufficient lubrication or tight fits. Skidding manifests in spotted smear marks or roughness on the surface of rolling elements or the raceways. Eventually skid damage could lead to cracks and the total destruction of the bearing. Skid damage is caused by poor lubrication which can be induced by slippage or other factors such as vibrations or alternating load of the bearing. This work concentrates on slippage, which means a relative difference in velocity between the rolling-elements of the bearing. Under ideal conditions, all rolling-elements should be operating under pure rolling behavior. In case the radial load of the roller bearing is insufficient to develop an acceptable frictional force between the rolling-element and the raceway, slippage takes place.

To prevent slippage, inadequate operating states should be avoided. Therefore it is necessary to study the dynamic effects in the bearing. Unfortunately, there is only a limited number of measuring the dynamics of bearing components. Common methods for generating measurement data of roller bearings are using solely a high-speed camera or the combination of an image derotator and a high-speed camera. While the high-speed camera in itself is suitable for slow-moving bearings, higher velocities or longer exposure time could lead to the occurrence of blurring in the images and therefore to poor quality of the measurement data. This can be prevented by combining the high-speed camera with an image derotator. The derotator operates in tracking the rotation of the measurement object so that quasi-stationary images are acquired through multiple reflections of the object by a mirror assembly placed inside the derotator. This work presents an automated inspection algorithm which is flexibly applicable for both measurement methods. Initially, images of the roller bearing have to be derotated (either optically or by use of image processing) so that the influence of the rotational velocity is eliminated. In case only the camera is used, the image data is rotated via image processing around the center of the bearing. Either way, in the next step the measurement data is reduced to a region of interest which displays a particular rolling-element. This is done by a pre-segmentation of the image to emphasize the rolling-elements and a circular fit to detect them. A rolling-element is equipped with a linear

marker which, in the next stage, is segmented and classified by computer vision algorithms by segmenting only the circular region to multiple regions via a thresholding method. The region representing the marker is extracted from the background and the position is calculated by a principle component analysis.

Depending on the shift of the angular position and the lag time between two images, the rotational velocity of the rolling element is calculated. Thus, it is possible to determine whether the rolling element is operating under ideal conditions or slippage is present. In conclusion, it can be said that this approach enables a simple and flexible non-invasive method to quantify the occurrence of slippage in roller bearings. More than that, the algorithm could be extended to investigate even more dynamic effects which influence the operating behavior of a roller bearing.

10334-10, Session 4

Referencing of the powder bed for selective laser sintering

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More than ten years lie between the presentation of the first commercial selective laser sintering (SLS) machine and applications of inline test systems for these machines. Growing interest to the inline testing and quality assurance for SLS points out on the deeper penetration of this technology into industry, research and medicine. Measurement object for an inline test approach is the powder bed of the SLS-machine and its flat surface. It is covered with the thin layer of a thermoplastic powder, on which the workpiece's contour is sintered. Dimensional accuracy of the sintered contour depends on many process and material parameters and affects the shape of the final product.

For large amount of powder bed testing approaches and solutions, the industrial camera is often used as a sensor. Depending on the task, the detection of the melt pool, sintered contour or whole surface of the powder bed is provided. The height of each new powder layer is variable and could be set. There is also a range of variety for recoating systems: roller or blade with the linear direction of motion, blade with the radial direction of motion. All mentioned parameters, manufacturing strategy and type of the raw powder affect the manufacturing accuracy for each sintered layer. Displacement of the powder layer and sintered contour occurs due to speed of recoating instrument, pressure on the powder bed and wrong manufacturing strategy. One of the challenges for computer vision is the low contrast of the detected object. In most cases only single colour powders are used in SLS process and the difference between the sintered contour and not sintered powder is negligible, what obstructs the detection of reference points and features on the powder bed.

In this context the concept of optical referencing for the powder bed was developed. The idea is based on the integration of light conductive elements inside the powder volume which are detectable on the powder bed surface as the light markers. This paper describes the research of the concept for optical referencing of the powder bed, as well as the design of the first prototype. Software for the image processing, surface features detection and determination of their positions was developed using Matlab. Plastic pipes were selected as the free located light conductors inside the powder bed. For the detection of the light markers, two calibrated CCD cameras were used. The question of optical compatibility of the involved in the research equipment is considered. The test prototype is used for laboratory tests in order to investigate: lateral and vertical deviations of the powder bed; influence of the recoating mechanism's type on the quality of the new layer of plastic powder; position shift of the recoated layers (in relation one to another); using of the light markers as the height references for the surface test systems. Considering the high working temperature of any SLS setup, the position of the optical references can be used as a correction value for the camera based measurement systems - in which the position of cameras is extremely important.

Developed software, as well as the prototype, allows investigation and improvement of the powder bed referencing concept, with the fuse integration in the SLS setup.

10334-11, Session 4

Automated stent defect detection and classification with a high-numerical-aperture optical system

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Stent quality control is a highly critical process. Cardiovascular stents have to be inspected 100% so as no defective stent is implanted in a human body. However, this visual control is currently performed manually and every stent could need tenths of minutes to be inspected. In this paper, a novel optical inspection system is presented. By the combination of a high numerical aperture (NA) optical system, a rotational stage and a line-scan camera, unrolled sections of the outer and inner surfaces of the stent are obtained and image-processed at high speed. Defects appearing in those surfaces and also in the edges are extremely contrasted due to the shadowing effect of the high NA illumination and acquisition approach. Therefore by means of morphological operations and a sensitivity parameter, defects are detected. Based on a trained defect library, a binary classifier sorts each kind of defect through a set of scoring vectors, providing the quality operator with all the required information to finally take a decision. We expect this new approach to make defect detection completely objective and to dramatically reduce the time and cost of stent quality control stage.

10334-12, Session 4

Improved maximum likelihood estimation of object pose from 3D point clouds using curves as features

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The problem of estimating the pose of an object is a fundamental problem in machine vision. The use of 3D point clouds as opposed to 2D images removes the affine and scale uncertainties. However, the problem of detecting features and estimating the pose remains a complex one due to partial occlusions and the presence of additional objects in the scene. In a previous paper [1] we presented a probabilistic algorithm based on maximum likelihood (ML) estimation, in which surface features were used to estimate the pose of a modelled object in a cluttered scene. In the current paper we extend the algorithm to include curve features in both the model and the measured scene, and demonstrate that this provides significant improvements in the accuracy of the estimated pose.

The general formulation of the method involves developing an analytical expression for the likelihood of a given pose vector of a model of the object, given a set of scene features that are extracted from the measured point cloud. A nonlinear maximization algorithm is then used to find the pose vector that maximizes the logarithm of the likelihood function.

The surface features in both model and scene are, as previously, detected by connected component analysis on the surface normal, calculated from the X, Y, Z data of the point cloud. The newly incorporated curved features are lines defining the edges of the object, i.e. the lines of intersection of two adjacent surfaces. These features are detected by connected component analysis on the minor principal component at high curvature points. Both detected surfaces and curves were cut up into smaller segments to minimise the impact of partial occlusions. The degree of match between model and scene surface patches is characterised by the radial distance, the normal distance and the angle (surface normal) between patches, while the corresponding parameters for the curve segments are the radial distance, the tangential distance and the angle (curve tangent) between segments.

Testing of the performance of this new algorithm was achieved by creating models of three objects with differing surface properties: a CRT monitor, a conical transducer and a bike helmet. The models were created through the registration, with the aid of circular white targets, of multiple 3D point clouds obtained from a fringe projection based 3D scanner (Phase Vision Quartz 1200).

In the previous study [1], the algorithm was split into two steps - a coarse pose estimation with larger variances, followed by a pose refinement with smaller variances for the matching. In the current study, we obtained the coarse pose estimate by giving initially more weight to the surface features, and subsequently more weight to curve features. Once the coarse estimate had been obtained, the pose refinement was conducted with equal weight for both surface and curve features.

The pose estimates obtained using only surface features were compared with those from the new method, and the mean alignment errors for the three objects were calculated over the object surfaces detected in the scene. The mean alignment error was found to be reduced from 1.55 mm down to 0.40 mm for the CRT monitor, from 1.30 mm down to 0.29 mm for the bike helmet and from 0.26mm down to 0.18 mm for the conical transducer. There is therefore a typical 1.5 to 3 times improvement in mean alignment error produced by the incorporation of curves as features into the maximum likelihood estimation of object pose.

[1] Harshana G. Dantanarayana and Jonathan M. Huntley, ‘Object recognition in 3D point clouds with maximum likelihood estimation’, Proc. SPIE 9530, Automated Visual Inspection and Machine Vision, 95300F (2015).