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Optical Methods for Damage Assessment of Artworks

D. Buchta, G. Pedrini, W. Osten

Artwork is an important part of our culture and should be prevented from any damage. But a continuous decay due to ageing can lead to different changes. Furthermore transports and the occurring vibrations or fast variation of climate accelerate this decay. To avoid irreversible damaging of artwork an early and complete detection of these defects is necessary. In addition to obvious defects, non-visible deteriorations like changes of surface in micrometer range or defects under the surface like delaminations should be detected reliably.

To get access to all of the mentioned defects we are developing a multimodal measurement system, combining fringe projection and shearography.

The fringe projection uses structured illumination to generate a 3D point cloud containing the information about the shape of the object [1]. As example in fig. 1b) the point cloud of a canvas painting (fig. 1a) is shown.

The shearography is an interferometric technique, which uses a comparison of two phase maps to detect subsurface damages. Between the recordings of these phase maps, the object is stressed by a loading device for example by an infrared lamp [2]. Defects can then be recognized as irregularities in the phase map, as can be shown for the canvas painting in fig. 1c), where larger cracks on the surface as well as subsurface cracks are detected.

To simplify the recognition and the localization of defects for the conservator we combined the point cloud and the shearogram with a daylight photo. In the resulting representation, the irregularities in the shearogram are colored and mapped on the photo and afterwards on the point cloud. The result for the canvas painting is shown in fig. 2. In the zoomed window the advantage of the combination of the two measurement techniques become clear. While the cracks (on surface and subsurface) can only be detected with shearography others like small holes can be easily recognized by the fringe projection. The use of the daylight photo allows furthermore the identification of discolorations. Moreover, cross correlation is applied to compare two states for example before and after a transport. This enables the possibility to detect changes of the surface also in micrometer range [3]. So the system can be used to distinguish between transport and ageing induced defects and therefore to improve the rules for a save transport of artwork.

Fig. 1: a) Daylight photo of canvas painting. b) 3D point cloud recorded with fringe projection. c) Phase map with detected defects recorded with shearography.

Fig. 2: Result of the combination of daylight photo, 3D point cloud and phase map. In the zoomed and tilted representation the complementary properties of the two techniques become clear.

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In the opposed-view approach the holograms are captured concurrently from the top and bottom views of the imaging system. Each hologram is analyzed separately and the intensity images, obtained for each layer from each view, are fused together to create the final multilayer images. Figure 1 shows a schematic of an opposed-view dark-field DHM. The system is a symmetric combination of two off-axis dark-field DHMs. Two Nikon bright/darkfield microscope objectives with 20x magnification and NA = 0.45 are placed face to face for imaging from both views. As the object is illuminated simultaneously using the objectives, both transmitted and reflected light from the structures make contribution in image formation. A camera is installed in each view to concurrently record the dark-field (DF) images.

To easily extract the fine structures from each image view, dark-field imaging mode is favourable. To combine the information obtained from the opposed views, first the counterpart images for each specific object layer, obtained from both views, should be selected and the image combination should be applied to each corresponding pair. The images are fused together using a pixel-based approach. For each pixel, a region of 10x10 pixels, centred by the initial pixel point, is selected. The standard deviation (Std) of the intensity distribution over the selected region is calculated and compared with the same value for the corresponding pixel in the opposed-view image. The pixel value with the larger calculated Std is then set to the corresponding pixel position in the final image. This process is done for each single pixel of both images to derive the final image, which is shown in fig. 2(a) for a given layer of a Drosophila embryo. Sub-figures in fig. 2(b) represent the highlighted images of the regions marked by numbers in fig. 2(a), which are separately obtained from top and bottom views. For the sake of better visibility, some structures have been marked with arrows in fig. 2(b), which are present in one of the views while missing in the other. The fused sub-images of the same regions have been shown in fig. 2(c). The structures presented in both views are visible together in the fused images, without reducing the image quality.

**Fig. 1:** Setup of an opposed-view dark-field digital holographic microscope.

**Fig. 2:** The reconstructed image of a Drosophila embryo. (a) The fused image obtained using the pixel-based approach. (b) The top and bottom view images of the regions marked with numbers in (a). The arrows represent some of the structures visible in one view, while missing in the other. (c) The images of the same regions as (a) after performing image fusion process. The scale bar in (a) is 25 μm.

**References:**


Quantitative phase imaging using a deep UV LED source


Imaging with deep-ultraviolet (DUV) light sources has many practical advantages. According to the Abbe’s criteria, the diffraction-limited lateral resolution is given by $0.61 \frac{\lambda}{NA}$, where $\lambda$ is the wavelength of the light source and NA is the numerical aperture of the imaging system. Thus, the lateral resolution can be increased by reducing the wavelength.

DUV digital holography was successfully applied for high resolution imaging using a short coherence laser source with wavelength 193 nm [1]. Although, the system performance proved promising for high resolution imaging, the presence of a separate reference beam and the use of an Excimer laser made the setup expensive and sensitive.

Recently, some digital holographic systems utilizing LEDs in the visible range were reported; however, compensating for the optical path difference between the object and the reference wave in such systems requires many optical elements, which increases the complexity of the system and makes it very sensitive to vibration.

We report a single beam phase imaging system that avoids the shortcomings of the existing techniques using an incoherent DUV LED source. Thanks to recent technology developments, LEDs are now available in this spectral range and are cost effective. For the phase retrieval, we apply a technique using intensity diffraction patterns recorded at different planes and an iterative algorithm and thus a reference beam is not necessary [2, 3].

Figure 1 shows the experimental setup for the applied phase retrieval method using the DUV LED source. The emitting area of the source is less than $0.3 \times 0.3$ mm$^2$ and the central wavelength is 285 nm and the FWHM is 12 nm. To increase the spatial coherence for phase imaging, a lens of diameter 10 mm with the focal length of 15 mm was inserted between the LED and the sample and the light was loosely focused onto the sample. The temporal coherence of the light source is calculated to be $6.77 \mu$m and the spatial coherence region for this configuration is $40 \mu$m which is measurable using a Michelson interferometer. The magnified image of the sample is then projected onto the CCD camera using a microscope objective (MO), having the NA 0.75. No additional component e.g. pinhole or spatial filter is necessary to increase the spatial coherence of the source. The separation between the camera and the MO is kept relatively large (80 cm in this case) so that a very small area of the sample is imaged onto the CCD with a magnification of more than 200 times and the field of view is approximately 35 $\mu$m. Since the coherence region is larger than the field of view, this method can be used for retrieving the phase.

We have performed experiments on a nano-structured template. The SEM image of the sample is shown in fig. 2(a) to provide a better visual comparison with the obtained results. Because of its ultra-small size and low power illumination source, a very small amount of the LED light could transmit through the sample. Therefore, higher integration time is required for the camera (4 seconds in this case). Here, only five on-axis images were acquired at an interval of 10 mm for retrieving the phase and the initial guess of the phase varies between 0 to $2\pi$. Figs. 2(b) and 2(c) show the obtained amplitude and phase in the image plane. Because of the low irradiance the intensity image is not so sharp but the phase image is providing finer details. The phase profile of the dashed line segment shown in fig. 2(c) is plotted in fig. 2(d). The width of the lines are 500 nm, and are well resolved. The phase information can be used to show the surface profile in 3-D as is shown in fig. 2(e).

The proposed system can be used for imaging technical structures as well as biological samples.
Fig. 1: Experimental setup with Deep UV LED as the light source. The ray diagram is shown to visualize the imaging of the object using MO (microscope objective). I₁, I₂, I₃… Iₙ are the intensity samplings at S₁, S₂, S₃… Sₙ planes, respectively.

Fig. 2: (a) The SEM image of ‘ITO logo’, (b) amplitude image in the image plane, (c) the phase image, (d) the height variation of the dashed line segment shown in (c) and (e) the phase profile of the sample in 3-D. The scale bar is 3 μm.

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References:
Phase imaging is of fundamental importance for technical and biomedical investigations, since the phase contains information about the 3D shape and the inner structure of transparent or translucent samples. Holography is the most commonly used approach to retrieve the phase, where an additional reference wave is superimposed to the object wave and the phase is reconstructed from the generated interference pattern. This approach has high accuracy, but the use of an independent reference wave makes it sensitive to external perturbations, such as vibrations, temperature changes, etc., and leads to an increase in the setup complexity. The beam propagation based methods estimate the phase by iteratively propagating of the wave among a sequence of diffraction patterns. The diffraction patterns may be recorded at different axial planes; with different wavelengths; by flipping the sample; modulating the object wave with different phase patterns or by scanning an aperture over the object wave. There are as well deterministic methods retrieving the phase by using the transport of intensity equation (TIE). The TIE method records two or three diffraction patterns at closely spaced planes and reconstructs the phase without iteration process and without the need of phase unwrapping.

We propose a phase retrieval method by using time-sequential spatially modulated illuminations [1, 2]. For wave fronts with smooth phase, a deterministic phase retrieval is performed by solving the phase gradient instead of the phase second derivative (Laplacian). Thus, the boundary condition problem of the traditional TIE method, is avoided. An iterative process is used to reconstruct the phase of wavefronts having discontinuities and at the same time enhance the spatial resolution. Unlike the traditional TIE which records the object wave intensities in two or more axially spaced planes, this method records the intensity patterns in a single plane.

Based on the configuration shown in fig. 1, an experiment has been carried out to demonstrate the feasibility of the method. The obtained results are shown in fig. 2. Five random patterns (fig. 2(a)) were loaded sequentially on the SLM to generate spatially modulated illuminations. The diffraction patterns of the sample under these illuminations are shown in fig. 2(b). The recorded intensity obtained when a plane wave is used to illuminate the sample and the phase derivatives of the sample in x direction are shown in figs. 2(c) and 2(d), respectively. The phase distribution of the sample (fig. 2(e)) is reconstructed from the derivatives along the x and y directions. For comparison, the same sample was also investigated by digital holographic microscopy (fig. 2(f)). The consistence between the results shown in figs. 2(e)–2(f) demonstrates the feasibility of the proposed method.

**Fig. 1:** Setup of the phase retrieval by using spatially modulated illuminations; SLM, Spatial light modulator; L1–L4, achromatic lenses; IM, Image plane; dz is the distance between imaging plane and CCD plane.
Fig. 2: Reconstruction results of a slice of mouse kidney; (a) intensity distributions of five illuminations; (b) intensity distributions of five generated diffraction patterns; (c) intensity image of the sample under plane wave illumination; (d) reconstructed phase derivative of the object wave in x direction; the reconstructed phase distributions obtained by the proposed method (e) and by digital holographic microscopy (f). The arrow in the fig. 2(d) denotes the direction of the phase derivative.

References:


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Incoherent digital holography

D. Naik, D. Claus, G. Pedrini, W. Osten

Digital holography holds many advantages over conventional imaging techniques such as non-destructive full field measurement, numerical refocusing to enable the recovery of a 3D scene, single shot recovery of quantitative phase information and the ability to multiplex information. It has therefore been applied to many different fields among others optical metrology and biomedical imaging. However, due to the coherent nature of the light sources employed, digital holography suffers from coherent noise artefacts also known as speckles, which decrease the image quality of the reconstructed hologram. Many attempts have been made to reduce the speckle noise in the reconstructed hologram, most of which are based on speckle de-correlation. This has either been implemented by reducing the spatial coherence via the introduction of a rotating diffuser or via the averaging of multiple holograms recorded at different wavelengths. Our approach addresses both, spatial and temporal coherence, via the usage of a partially coherent broadband light source or a self-luminous object (fluorescence). In that manner the averaging of speckle de-correlated holograms already takes places in the recording process. In order to enable the recording of incoherent holograms, self-referencing schemes can employed. The underlying theoretical principle addressing the spatial incoherence is based on the analogy of the diffraction integral with the van Cittert-Zernike theorem. The van Cittert-Zernike theorem states that the Fourier transform of an incoherent source’s planar intensity is proportional to the spatial coherence function measured in the far field.

The temporal incoherence is addressed via the Wiener-Khintchine theorem, which refers to the Fourier transform relation between the spectral density function and real correlation function.

Other than applying the tedious and time consuming Young’s double pinhole point wise measurement approach to obtain the spatial coherence function, a full field measurement system is used, which obtains the spatial coherence function as the contrast and phase distribution of interference fringes.

Such a system, which in addition also enables the application of temporally incoherent light, can be implemented via a phase shifting radial shearing interferometer, as shown in fig. 1.

Radial shearing enables the recovery of 3D information and adds equal weight to all spatial frequencies (orientation independent) compared to other shearing arrangements such as rotational shearing (no depth information) and lateral shearing (orientation dependent), respectively. It is advantageous to record the interference patterns in the far field region. Here the optical field is shift invariant, so that every object point has the same impulse response, which significantly reduces the numerical effort, as pointed out in. Radial shearing is implemented via a Mach-Zehnder interferometer, whereas a different magnification is applied to the optical system in each arm. Phase stepping is made possible via the introduction of a piezo mounted mirror (arm 1 in fig. 1). In that manner a series of incoherent phase stepped holograms can be recorded e.g. 1024 incoherent holograms. The reconstruction scheme, which is then employed, is depicted in fig. 2, where the star of a 1 cent Euro coin has been used as the object under investigation. The temporal interference signal along one pixel column is Fourier-filtered, to result in a stack of wavenumber corresponding holograms. The reconstruction of each wavenumber corresponding hologram is obtained via the application a 2D Fourier transformation. Hence, compared to the other incoherent/short coherence digital holography approaches implemented by ITO [1–4], the...
spectral information can also be recovered, which in combination with the recovery of 3D information, made possible via numerical refocusing, completes the description of the object under investigation [5,6].

The recovery of spectrally filtered holograms is demonstrated in fig. 3, where a toy airplane composed of different colours is used as the object under investigation.

In summary, alongside the aforementioned advantages of digital holography, spectrally resolved holography furthermore offers a speckle noise reduced reconstruction and the recovery of spectral information, which opens the passage to new applications.

Fig. 2: Flowchart diagram displaying the different image processing steps applied to the recorded phase stepped shearing interferograms.

Fig. 3: Images have been taken from reference [5], the individual subfigures display (a) a toy aircraft as polychromatic object, (b) the reconstruction for 635 nm, (c) the reconstruction for 530 nm and (d) the reconstruction for 450 nm.

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References:


Determination of Material Parameters of Biological Tissue

Minimally invasive surgery has for many applications replaced open surgery, since the amount of tissue, which has to be cut, is reduced to a minimum, resulting in a quicker recovery of the patient connected with reduced post operational stress. Moreover, it offers some aesthetical advantages in particular for exposed parts of the human body e.g. face. However, minimal invasive surgery has restricted the working environment of the surgeon due to the loss of two major human senses, three dimensional vision and haptic feedback. The haptic feedback is an important tool which helps the surgeon in localizing tumors due to the increased stiffness compared to healthy tissue (palpation). Tumorous tissue is 7–14 times stiffer than healthy tissue. Our goal is to re-establish the surgeon’s sense of touch in minimally invasive surgery, albeit with an increased sensitivity, increased lateral resolution and the new feature of depth localization, made possible by the information from preoperational data and template matching with FE-simulation.

Our working principle is based upon the combination of multiscale and multimodal elastographic measurement techniques and a soft tissue applicable FE-Model, which correlates well with the measurement. From the FE-model a large data bank will be created, which can be used to solve the under-defined measured data in real time. Therefore, the project involves different partners combining different expertise and facilities (IAP at University of Tübingen, Klinikum at University of Tübingen, IMWF at University of Stuttgart, ISYS at the University of Stuttgart).

ITO has been involved in the development of a large scale (organ level) elastographic real time measurement tool. For this purpose a roll indenter, enabling lateral movement across the sample combined with a feedback loop controlled force or indentation depth, has been designed and manufactured at ITO’s electrical and mechanical workshops, which is displayed in fig. 1. A two dimensional displacement field was measured employing image correlation technique.

At first, silicon phantoms without [1] and with stiffness inclusions [2], characterized by well-defined geometry and elastic behavior have been studied in order to generate a ground truth and to validate the system.

The displacement field obtained has then been compared with the FEM-simulations, based on the Arruda-Boyce model, created by our partners from the IMWF. As a result a good agreement between the FEM simulation and experimental data was obtained, as displayed in fig. 2 for silicon phantom with stiffness inclusion.

Fig. 1: Experimental setup for roll-indentation and optical imaging system.

Fig. 2: Displacement maps obtained, top to bottom: FE-Modell, experimental results, cross-section plot (good match at central position).

References:


Navigation During Laparoscopic Abdominal Surgery

M. Wilke, D. Claus, P. M. Schumacher, G. Pedrini, W. Osten

During minimally invasive surgery a surgeon is dependent on a detailed anatomical orientation to achieve the goal of the procedure (e.g. to locate and remove a tumour). While available pre-operation data such as MRI (Magnetic resonance imaging), X-Ray, or CT (X-ray computed tomography) images can support the surgeon, matching its information to the changed orientation of the patient on the operating table poses a challenge due to the shift of inner organs, the occlusion of the target by interposed tissue, and the degradation of the endoscopic image due to interference inherent to the surgical procedure itself (blood, smoke from electrical cutting and cauterization). A navigation system capable of identifying anatomical markers gained in the pre-operation data during the actual operation and making it available to the surgeon in the endoscopic image would accelerate surgical procedures, limit the tissue damage to the patient, increase the chance of success and improve the recovery of the patient.

The approach taken in this project involves three stages: 1) the creation of a 3D-model of the patient based on pre-operation CT data, 2) the registration of the absolute position and orientation of the patient and the surgical tools in the fixed coordinate system of the surgical theatre using optical, inertial, and ultrasonic tracking, and 3) matching the image of the endoscope to the 3D model (fig. 1). The project involves the ISYS (optical, inertial, and ultrasonic tracking) and the ITO (3D Model from CT data) at University of Stuttgart, as well as the Institute for Cognitive Systems (tracking markers in the endoscopic image and blending the CT data into images) and the UKT (medical expertise, test Ops and provision of CT data) at the University of Tübingen.

The role of the ITO consisted of the segmentation of CT/MRI data to identify relevant anatomical structures for the creation of a pre-operative, patient-internal coordinate system and corresponding 3D model. Since the segmentation and 3D modelling of CT data is a well-researched field with powerful, free and commercial software solutions available, we chose 3D Slicer for this task. In a first step, the skeleton was segmented using a simple thresholding algorithm applied to the Hounsfield coefficients of the CT data set. The skeleton plays a key role in the 3D model as it provides easily identifiable anatomical markers (the pelvic bone or the lower ribs) and a relatively rigid framework. In a second step, the general position of the kidneys was marked manually and the kidneys themselves segmented using a robust statistics segmenter starting with those manually placed seeds. The final 3D model combines these two features and is stored in VTK, PLY, or STL format for further processing (fig. 2).

A test surgery creating one fully consistent data set of CT, registering of the body and the surgical tools in the surgical theatre, and recording the endoscopic image has been performed to test the current state of the system to be developed in this project.

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Residual stress analysis of ceramic coatings

G. Pedrini, W. Osten

Ceramic coatings are commonly used to improve the wear or heat resistance of many technical components, but due to their deposition process, e.g. plasma or high velocity oxygen fuel spraying, rather high residual stresses can build up within the coating and underneath. The reason for that are differences in the coatings and substrates expansion coefficients, inhomogeneous temperature distribution during the process and the quenching of splats. The mechanical hole drilling technique can be used for the detection of residual stresses in coatings. The residual stresses are locally relieved due to the material removal process, which leads to a deformation of the surface around the hole. These deformations, measured as relaxed strains through strain gauges rosettes, in combination with appropriate calibration data (separately determined by simulation for the layer composite), allows the quantitative determination of the residual stress depth profile. The disadvantage of the strain gauges is that they can only be used on flat and relatively smooth surfaces, where the rosette is applied.

We propose an approach to avoid the mechanical drilling operation and the application of strain gauges, where a pulsed laser is used for the object machining (ablation process) leading to 3D residual deformation by stress relaxation which are measured by an optical system based on digital holography. For the validation of the method, test plates were prepared, where aluminium/titan oxide coatings are deposited by atmospheric plasma spraying technique on aluminium substrates.

The experimental setup for residual stress analysis (fig. 1) can be divided into two parts: one for the machining of the object and the other for the measurement of the resulting 3D deformations. The harmonic separator (HS), transmits the infrared light for the laser machining (wavelength: 1064 nm) and reflects the visible green light (wavelength: 532 nm), for the deformation measurement, allowing at the same time machining and deformation measurements. Laser pulses with a power density higher than 109 W/cm² are used for the ablation of material, in order to obtain such density a laser beam of a few nanoseconds pulse length is focused by a lens on the sample surface. Complex structures are machined by using a spatial light modulator (SLM), where a given light distribution is produced by writing a phase/amplitude pattern (computer generated hologram) on the SLM. The release of residual stresses by the laser machining system produces 3D deformations that are measured by the system based on digital holography shown in the bottom part of fig. 1. Light from a laser is divided into two beams by the beam splitter BS, one is coupled into a single mode optical fibre and serves as the reference beam and the other one is further divided into four beams illuminating the object sequentially from four different directions. The phase of the object scattered wave changes as a function of the deformation and by processing holograms recorded from different illumination directions it is possible to measure the 3D deformation around the machined surface.

Fig. 1: Setup for laser machining and measurement of the 3D object deformation by digital holography. SLM: Spatial Light Modulator, HS: harmonic separator; BS: Beam splitter; AP: Aperture.
The SLM based system was used for machining structures with different shape and depth on the coated surface. Figure 2.a shows a milled horizontal bar obtained after 64000 laser pulses, the depth of the machined structure is 130 µm. Figures 2.b–g shows the wrapped phase and the corresponding 3D deformations produced by the milling. By incremental loading structures (bars, crosses, rings) having different depth are produced and the resulting 3D deformations are measured. The residual stresses at different depth of the coating are calculated from the deformations together with the profile (shape, depth) of the machined surface and the material parameters. The coating used for the investigations shown in fig. 2 had a thickness of 70 µm, at this depth the residual stress was ~250 MPa.

![Image of the bar shaped machined structure after 64000 laser pulses (a). Phase modulo $2\pi$ (wrapped phases) and calculated displacements along the x (b, e), y (c, f) and z (d, g).](image)

**Fig. 2:** Image of the bar shaped machined structure after 64000 laser pulses (a). Phase modulo $2\pi$ (wrapped phases) and calculated displacements along the x (b, e), y (c, f) and z (d, g).

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**References:**

Deformation can be attributed to the change in the shape of an object in presence of load, heat, gravity etc. The measurement of deformation at micro and macro level is equally important for various applications. Many techniques have been proposed for the same in past but NDT techniques have an edge over others mechanical techniques, and are applicable for measuring the nano-metric changes in the surface. Also, the non-destructive measurement techniques are applicable to biological samples, which could be useful for bio-medical studies. The deformation in a surface can be divided into two components (1) in-plane and (2) out of plane. For years Holography is providing a fitting solution for measuring the out-of-plane deformation by calculating the phase difference but measuring in-plane deformation is another challenge. Interferometric techniques were proposed to measure the same, based on multidimensional measurements. Such methods either need multiple references which makes the setup quite complicated or required to record multiple holograms in a sequential way from different directions. Such methods could make the measurements quite slow and are prone to errors.

The change in phase due to the change in path length is an inherent property of holography, which makes the out-of-plane deformations measurement quite easy and can be done using a single illumination beam. The intensity information in such experiments are usually a waste product. We propose a setup using single illumination beam to measure full-field deformation. For such measurement system we will utilize the phase as well as intensity information. The schematic diagram is shown in fig. 1. The holographic interferometric technique is employed for measuring the out of plane movements and the in-plane deformation are measured using the correlation of intensity distribution before and after the deformation. The proposed setup can be used for sub nano-metric deformation measurements.

Fig. 1: The schematic diagram of the setup for deformation measurement.

Fig. 2: Deformation measurement; (a) in-plane measurement with a resolution of 10 nm was achieved with the help of subpixel interpolation. Red, green and blue curves in the plot are showing the PZT measurement, the optical measurement and the best fit to the experimental data, respectively. (b) out-of-plane deformation, red and blue color curves are showing PZT measurement and the optical measurement, respectively. The PZT measurements were obtained with the help of a feedback loop.

3D single shot deformation measurements by using a remote controlled system

A. K. Singh, A. Prakash, G. Pedrini, W. Osten
An off-axis holographic setup was arranged and a He-Ne laser was used for illumination. The beam outgoing from the laser is coupled into a single mode fibre and the output beam is collected by the lens L1 and further reflected by the mirror M1 towards the beam splitter BS, which splits the incoming beam into two parts, the reflected beam passes through the lens L2 (f=4.7 mm) and illuminates the sample. In order to illuminate the sample with a parallel beam, the lens L1 is adjusted to produce a converging beam focusing in the back focal plane of L2. The light reflected by the sample is collected again by L2 which images the sample surface on the CCD sensor with a magnification of 48x. A reference beam obtained from the light transmitted by the BS is superimposed on the beam scattered by the object surface. There is an angle of few degrees between these two waves and thus their interference forms an off-axis hologram, which is recorded by the CCD. The image sensor used in the setup was a PCO Pixelfly with dynamic range 12 bit, 1392×1024 pixels and pixel size 6.45×6.45 µm². A shutter was inserted in the setup to block the reference wave, the setup without reference was used to obtain the in-plane deformation. The setup was calibrated using a PZT nano positioner system from Physik Instrumente, with a resolution of 2 nm and a repeatability <10 nm. The setup can be remotely controlled via internet and was utilized to measure the out-of-plane and in-plane deformations of MEMS structures. The calibration measurements for in-plane and out of plane deformations are shown in fig. 2(a) and (b), respectively.

References:
Looking Through a Diffusing Medium and Around a Corner


Is there a way to see an object obscured by a strong diffuser such as a transmissive ground glass or an opaque plate with a reflectively scattering surface? Such a question has long been addressed in the context of inverse scattering problems, and a technique has been known that can detect a 2-D periodic grating structure hidden by a diffuser. Recently a technique of ultrafast time-of-flight 3-D imaging that can look around the corner using diffusely reflected light was demonstrated. Also SLM-based technique that compensates the random phase and permit imaging a 3-D object through a diffuser have been reported. The applications of such technique ranges from medical imaging through turbid medium or cell to rescue operations in hazardous condition.

We propose two different techniques for the imaging of 3D object obscured by a diffuser or hidden around a corner. We interpret that the obscuration of the object image is due to the loss of phase information caused by the scattering due to the diffuser. Then we note that the clue to the solution is to find an imaging technique that can cope with the loss of phase information. Indeed, holography is the technique that can recover phase information that is lost by intensity recording in conventional photography. Intensity correlation is another way to reconstruct the object as the mutual intensity of the diffracted field. The reconstruction scheme of the Intensity correlation involves the fourth order correlation of the optical field.

Though our approach based on holography is functionally more restrictive than time-of-flight 3-D imaging, but is much simpler and requires no special equipment such as a femtosecond laser and a high-speed streak camera. We use a reference beam for holography, just as a reference point source used for the SLM-based random phase compensation. Our techniques can be realized easily by the combination of a common CW laser and a conventional camera and does not even require a SLM and the iterative search of the phase distribution that compensates the random phase introduced by the diffuser. The schematic diagram of the setup and the reconstructed object through a scatterer are shown in fig. 1(a) and (b) respectively.

We proposed another technique which is based on intensity correlation for imaging through the diffusing medium and around the corner. The schematic diagram of the setup is shown in fig. 2(a). The object and the reference point source are kept in the same plane in front of the diffuser in a way that they satisfy the condition of isoplanatism, which states that the light from two point sources, lying within the range of memory effect, after propagating through a diffusing media will produce shifted but correlated speckle patterns. Thus the light from the object and the reference produce similar speckle patterns. The image sensor which is kept on the other side of the diffuser records the scattered light as speckle pattern. To reconstruct the object we performed the averaging operation over the speckle pattern by using spatial averaging by means of auto correlation of the intensity distribution. Thus the proposed technique is a single shot, Lens-less and real-time imaging technique. By virtue of limited depth of field optical sectioning and the 3D reconstruction is also possible.
Fig. 2: (a) The schematic diagram of the setup to image through the diffusing medium using intensity correlation method, (b) the 2 mm long and 3 mm wide letter ‘H’ was pasted on a thin diffuser and was used as object, (c) the reconstructed object through the diffusing medium. L1 is a converging lens which is used here as beam expander, RD is the rotating diffuser to destroy the spatial coherence of the laser beam, L2 is the imaging lens, BS is the beam splitter, d1 and d2 are the distances between the object pane and the diffusing sample and CCD and the sample, respectively. The scale bar in (b) is 1.5 mm.

References:

Data Compression for the Transmission of Digital Holograms

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This project investigates the application of data compression techniques to digital holography. Advances in computational power and the decreasing pixel pitch of high-end cameras are moving real-time capable, digital holography into the realm of near future feasibility. Physical limitations impose large detectors with small pixels, resulting in very large images (typically 12 Mega-Pixels at 10 bit depth). Holographic video has been proposed. These large sets of data suggest the use of compression techniques to reduce the storage size or transmission bandwidth required in applications like holographic remote laboratories. However, while they are recorded on the same hardware (CCD or CMOS detectors) as natural images, holograms differ significantly from these. Holograms store information about both the amplitude, as in a normal image, and the phase in interference fringes. This difference requires a reevaluation of the standard compression techniques before they can be applied to holograms.

The holograms used in this investigation are Phase Shifting (PSI) holograms. It has been shown, that a JPEG2000 style compression scheme works best in the plane of reconstruction. To account for this, the algorithm being developed in this project applies a Fresnel transformation and separates the phase and amplitude for independent processing (fig. 1). The results of the statistical analysis have shown that the statistics of the wavelet coefficients for the amplitude of the reconstructed wavefront in the object plane show a distinct two-component behavior. One component, with the coefficient distributed Gaussian, represents the speckle field, while the other, with an approximately Laplacian distribution, correspond to the macroscopic shape of the object (fig. 2). The wavelet coefficients for the phase are Gaussian distributed, although the distribution is very noisy. This noise is the result of numerical instabilities in calculating the phase for amplitudes close to zero. We have shown that the noise can be suppressed using a mask based on the amplitude of the wavefront. These results indicate, that standard compression algorithms can be applied successfully to Fresnel propagated and wavelet analyzed PSI holograms, especially to the amplitude coefficients which are Laplace distributed.

The results also indicate that a separation of the wavefront into a speckle field and a remainder representing the macroscopic shape would be advantageous.

Current work is aimed at designing a compression algorithm based on these results. An efficient filter separating the speckle field from the rest of the hologram based on a maximum likelihood algorithm is being implemented. New quality measures are under investigation to define a hologram-optimized rate distortion theory for Fresnel propagated and wavelet analyzed complex-valued wavefronts to be used in a rate allocation algorithm and a corresponding compression algorithm.

Fig. 1: Encoding Process.

Fig. 2: Histogram of the intensity wavelet coefficients in logarithmic scale.

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