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In minimally invasive surgery the haptic feedback, which represents an important tool for the localization of abnormalities, is no longer available. Elastography is an imaging technique, which results in quantitative elastic parameters. It can hence be used to replace the lost sense of touch, as to enable tissue localization and discrimination. For the implementation of optical elastography, we have chosen digital image correlation based on a spectrally engineered illumination source, that enables imaging of biological surface markers (blood vessels) with high contrast. In digital image correlation, two images (loaded and unloaded) are recorded. The displacement introduced by loading is calculated using locally defined cross-correlation within a small window. Our window is 65x65 pixels with 50% overlap between consecutive windows.

The mechanical loading is generated using a rolling indenter shown in fig. 2, which enables the investigation of large organs (size of the kidney) with reduced measurement time compared to a scanning approach. Furthermore, the rolling indentation results in strain contrast improvement and an increase in detection accuracy based on averaging approach, as demonstrated in [1].

From the displacement measurements the strain distribution, representing a quantitative elastic parameter, can be calculated. However, other elastic parameters such as stress, shear modulus cannot be obtained from the measurements. An under-defined inverse problem has to be solved to access these parameters. This is commonly accomplished using a well-defined forward problem that is implemented in a finite element model (FEM), which starts with the desired parameters of interest (input) and results in the measurable parameters (output). In an iterative manner, adjustment of input parameters, a good match between experimental and simulated data can be ensured and in that manner, other elastic parameters are retrieved, as schematically depicted in fig. 2. The amount of necessary iterations can further be reduced via the application of a priori knowledge.

In our case, only one iteration was necessary to obtain a good match between measured and simulated strain, see fig. 3. Our simulation is based on the implementation of a 3D hyperelastic model into an FE environment (Arruda-Boyce model).

Not only the uniaxial 3D distribution of strain, stress and shear modulus but all the different corresponding tensor components are retrieved for different indenter position. The results of which are presented in [1].

The application of digital image correlation was also demonstrated for a biological sample (kidney). The strong absorption of blood vessels in green light compared to the surrounding tissue could be used to generate traceable surface markers. The strain map obtained, as shown in fig. 4.
Fig. 1: Roll-indenter with silicone phantoms

Fig. 2: Parameter-identification based on the comparison between the outcome of the FE-model (solution of direct problem) and experimentally measured values (displacement field and strain map).

Fig. 3: Comparison between FE Simulation (top) and experimentally obtained strain map (bottom) with cross-section plot, highlighted by dark line in experimental data.

Fig. 4: Strain map obtained from porcine kidney.

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References:
Residual stress analysis of ceramic coating by laser ablation and digital holography

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 (see fig. 1) 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 holographic interferometry. The residual stresses at different depth of the coating are calculated from the deformations obtained after incremental loading, the profile (shape, depth) of the machined surface and the material parameters. 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) show the wrapped phase and the corresponding 3D deformations produced by the milling. Figure 3 shows the results of the residual stress calculations by using conventional mechanical incremental hole drilling with strain gauges and the proposed method with laser ablation and digital holography. The coating used for the investigations had a thickness of 200 µm.

The results obtained by the conventional hole drilling and the proposed methods show the same qualitative behaviour but of course there are differences between the two curves. The mechanical incremental hole drilling determination alone cannot validate the results. I.e. X-Ray diffraction measurements near the surface proved high residual stresses around –600 MPa. The inaccuracies are due to the non-ideal geometry produced by laser ablation that produce errors in the calculation of the residual stresses in particular for the very first step.
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References:


Nano-scale measurement of in-plane displacements of microscopic objects

A. K. Singh, G. Pedrini, W. Osten

Digital image correlation (DIC) digital speckle pattern interferometry (DSPI), digital holographic interferometry (DHI) and phase singularities tracking (PST) may be used to measure displacements. DIC is very robust due to its simple arrangement and is commonly used for the measurement for in-plane displacements. DSPI and DHI are interferometrical techniques allowing the measurement of in-plane and out-of-plane displacements. PST is a new tool for optical metrology that may provide displacement measurements with nanometric accuracy since a displacement of the object involves a shift of the singularities of the wavefront reflected by the object. We need phase information to find the singularities. One way to record the phase is by using digital holography. The other way is to use the intensity pattern and to process it using a Hilbert filtering in order to obtain a pseudo phase.

Figure 1 shows the setup used for the measurements of in-plane displacements of microscopic samples. The object is illuminated with coherent light emitted by a laser. The light scattered by the sample is again collected by the lens L2 which images the surface of the object on the pixelated sensor. The images recorded at different deformation states of the samples are then processed to find the in-plane displacement. A reference wave can be used when the phase of the wavefront is needed.

The test object was a rough metallic surface mounted on a calibrated piezoelectric device (Physik Instrumente P-611.1, accuracy ±2 nm). Windows of 100x100 pixels was considered and the results obtained with the different methods are shown, together with the expected displacements (blue lines) in fig. 2. In figs. 2, a, b the measurements obtained by digital image speckle correlation and vortices analysis, are reported. For obtaining these results the same intensity pattern were used, just the processing was different. The difference between measured and expected displacements may be used for the calculation of the accuracy of the measurements which is ±5.6 nm for the correlation and ±9.5 for the vortices tracking methods. The correlation method gives better results, the vortices method overestimate the displacement. We recorded also digital holograms for different displacements and calculated the intensity and the phase of the wavefront. The in-plane displacements were evaluated by intensity correlation and by vortices analysis. For both evaluation methods, the displacement is underestimated and the deviation from the expected values is quite large (see fig. 2. c, d).

![Fig. 1: Setup for the measurement of in-plane and out-of-plane (when the reference is used) displacements.](image1)

![Fig. 2: Comparison of in-plane displacements measurements by different methods.](image2)

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References:

The preservation of artwork is an important as well as a challenging task for conservators. In recent times, the increase of museum loan services and the associated increasing number of transports makes this task even more challenging. Especially hidden defects like delaminations or woodworm tunnels in wooden panel paintings are difficult to detect. While tactile methods are rather unsuitable for the application on artworks, optical techniques provides the possibility of non-destructive testing.

Among others the so called shearography has proven its suitability for the detection of subsurface defects [1-2]. The typical shearographic setup, shown in fig. 1, consists of an expanded laser beam, a Michelson interferometer, a camera and a loading device. Due to a slightly tilted mirror a self-reference is generated, which makes the setup very robust. The comparison of two states (before and after loading) gives information about the surface displacement induced by the loading and so about underlying damages.

The main disadvantage of this technique is that the “indirect” measurement allows only limited conclusions about the defects. Especially, the depth cannot be determined uniquely.

To get access to this information, the deformation of the surface due to the defects under stress has to be analyzed. We do this by combining FEM-simulation with shearographic simulation. Therefore a displacement-map is generated with a standard FEM-software (COMSOL) and inserted in the shearographic simulation (matlab), which calculates sensitivity vectors and generates the phase images. In our approach we add furthermore multiplicative speckle noise to the intensity images before the phase maps are calculated to get on one hand more realistic results and on the other hand the possibility to investigate noise-reducing techniques.

Fig. 2 depicts a first comparison of measurement and simulation with different variance of the speckle noise for a wooden panel with milled notches (defects) at the backside. The panel was heated by an infrared lamp from 24°C to 26.3°C (reference state) and cooled afterwards to 25.7°C (loaded state). The good agreement especially for large speckle noise is a very promising result. In near future the simulation environment can be used to investigate different types of defects in various depth and so enlarge the information content in shearographic measurement.

References:

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In cooperation with: Staatliche Akademie der Bildenden Künste Stuttgart, Prof. Christoph Krekel
Focus and perspective adaptive digital surgical microscope

D. Claus, C. Reichert, A. Herkommer

Conventional surgical microscopes suffer from the drawback that during the operation the surgeon has to remain in the same position for a long period of time. This causes musculoskeletal strain possibly resulting in severe headaches and chronic pains. It is our goal to provide the surgeon with a digital surgical microscope, which offers all the functionality the surgeon experiences with a conventional microscope, albeit offering the freedom of free head movement via displaying the image on a screen or digital stereoscopic displays.

The digital surgical microscope is composed of two units. First, a recording unit represented by a digital recording stereo microscope, which offers accommodation and pupil shift, enabled by the application of an adaptive optomechanical system. Second, a displaying unit, which can be represented by a digital stereo displaying microscope or a 3D monitor. Head and eye tracking are applied to the displaying unit in order to obtain a signal for shifting the pupil in the recording unit. The signal relevant for the accommodation adjustment in the recording unit can be obtained from a refractometer or via eye tracking combined with scanning the topography and refocusing on the region of interest. The digital recording stereomicroscope is based on the application of focus adjustable lenses for mimicking the eye’s accommodation and an x-y shifted stage for mimicking the eye’s pupil movement. Furthermore, an additional optical system has been designed, which enables eye-tracking through the displaying stereomicroscope.

The digital displaying stereo microscope used is a prototype developed by Carl Zeiss Meditec. The developed pupil tracking system is easily attachable to the existing digital displaying stereomicroscope. A beamsplitter plate was used to enable the combination of the eye-tracking system with the displaying system, as shown in fig. 1.

The temporal requirement imposed on the digital recording stereomicroscope is to deliver a temporal resolution better than 50 ms (20 Hz) in accordance to the human eye’s latency. Therefore, fast focus adjustable lenses from Optotune AG (EL-10-30-C-VIS-LD, 60 Hz, focal length 80 mm–200 mm), and an in-house configured fast moving x-y stage with actuators from Nanotec Electronic GmbH (L2818L0604-T6X5, max. speed 140 mm/s) have been selected. The important optical parameters have been derived from a conventional stereomicroscope (Zeiss OPMI Pico) comprising of a field of view of 30x30 mm² and an optical resolution of 50 µm. Furthermore, special attention during the optic design was given to maintain a large NA via the introduction of the reflection prisms positioned behind the main objective, and by mounting the Optotune lens in a horizontal orientation as to minimise the effect of coma on the image quality. The final realized setup and the corresponding images obtained for different foci and different position of the pupil are shown in fig. 2.

![Fig. 1: Pupil-monitoring setup through digital displaying stereomicroscope.](image1)

![Fig. 2: Schematic setup digital recording stereomicroscope with images obtained from different foci and perspective.](image2)

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References:
Replacing conventional microscope objectives by a scattering plate: a comparative study


Traditional lens-based microscope objectives have fixed focal length, short working distance, limited depth of focus and magnification, which often sets restrictions in applications. The correction of aberrations for microscope objectives requires a combination of spherical lenses, which increases complexity, bulkiness, and price. Aspherical elements can reduce the complex multiple-lens system and make the objectives more compact, but they demand more complex fabrication and testing procedures, which also raises the cost. Figure 1(a) and (b) show the impulse response of a conventional microscope objective and the imaging operation, respectively.

Contrary to the common belief, we regard the diffusing media itself as a useful imaging device. We exploit the lens-like behavior of a scattering layer, and develop unconventional lensless microscope objectives. The impulse response in this case is a speckle pattern as shown in Figure 1(c) which remains shift invariant in the close vicinity of the point source. This phenomenon is called memory effect, which states that each elementary point source that constitutes the object, placed in the vicinity of the reference point source, produces a shifted but similar speckle pattern to that of the point source. The images are produced from the cross-correlation of the object intensity distribution and the PSF (see Fig. 1(d)). Examples of conventional microscope imaging and image reconstruction via intensity cross-correlation are shown in Figs. 1(e-h).

A result of diffuser microscope imaging of a 1951 USAF test target and a comparison with images from a conventional microscope is shown in Figure 2. It can be seen that the quality of the images, in terms of resolution and contrast, of the diffuser microscope is almost comparable to that of a conventional microscope even though the edges look less sharp.

The scattering layer microscope has following unique characteristics that are not available with traditional microscopes:

- flexible working distances,
- compatible in reflection and transmission modes,
- immune to phase disturbances and aberrations,
- easy to fabricate with scalability in device size, robust to environmental changes.

![Fig. 1: Microscope imaging systems: (a) PSF of a conventional microscope objective (b) conventional microscope imaging (c) PSF of a scattering layer, which in this case is a speckle pattern, (d) microscope imaging using a scattering layer ('diffuser microscope'). The image plane is far from the diffuser, to have a larger magnification. The images are produced from the cross-correlation of the object intensity distribution and the PSF. (e) Conventional microscope image, (f) a part of the PSF of the scattering layer (speckle pattern), (g) a part of the recorded object intensity distribution and (h) the image reconstruction via intensity cross-correlation. The scale bar is 3 µm in object space.]

![Fig. 2: Comparison of conventional and scattering layer microscope imaging. A 1951 USAF test target was used as an object. We imaged the highest resolution area of the test target, i.e. the 7th group, with smallest line thickness of 2.19 µm; (a) and (b) are the images obtained with a conventional microscope for NAs 0.16 under monochromatic and white light illuminations, respectively, whereas, (c) is their diffuser microscope counterpart for the same NA. The scale bar is 21.5 µm.]

References:

Spectrally resolved digital holography by using a white LED

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

Usually, coherent light sources are employed in digital holography, but short coherent light sources such as emitted by a LED can likewise be employed. The spatial coherence of the light source was increased via locating a pinhole straight after the LED. Due to the reduced temporal coherence both interfering arms had to be well matched with sub-micrometre accuracy using a combination of a precision stage and a piezo actuator both attached a roof prism in the reference arm, as shown in fig. 1.

A series of more than 1000 interferograms have then been recorded while a shift of 100 nm between each recording position was introduced by the piezo. The piezo scanning results in a z-stack. According to the Wiener Khinchin theorem, the application of the Fourier transformation along the z-direction results in the spectral distribution, whereas the spectral components are defined by the wavenumber \( k = \frac{1}{\lambda} \) and not by the wavelength. The setup as it stands shares some similarities with white light interference microscopy or optical coherence microscopy. However, the acquisition and interpretation of the data are based on lensless holography, by which lenses, which may introduce wave-aberrations as well as chromatic aberrations or result in increased manufacturing efforts and consequently cost, can be discarded. Moreover, the holograms can be refocused. The advantage of spectrally resolved holography is demonstrated for the investigation the shape of an object with a thickness larger than the product of wavelength and the difference of refractive indices between the object and surrounding medium. In this case phase jumps occur as shown in fig. 2(a), which require unwrapping routines that can introduce errors. Moreover, at very steep surfaces the density of \(2\pi\) phase jumps becomes very dense so that resolved any longer. The application of the dual wavelength method (DWM) can help to overcome this issue. The difference phase map of the holographic reconstruction recorded at two different wavelengths, which are in close proximity, can be associated with a much larger synthetic wavelength \(\lambda_{\text{syn}}\)

\[
\frac{1}{\lambda_{\text{syn}}} = \frac{1}{\lambda_1} - \frac{1}{\lambda_2} = k_1 - k_2 = \Delta k. \quad (1)
\]

Besides the aforementioned advantage, DWM enables the application of optical and electrical devices in the visible light regime although the synthetic wavelength lies in the infrared regime. However, the speckle noise is increased by a factor that equals the ratio between synthetic and mean wavelengths of the chosen wavelength pair.

The large amount of wavelength pairs available in spectrally resolved holography helps to reduce the speckle via averaging over multiple dual wavelength phase maps of different wavelength pairing. The recovery of the wavenumbers \( k \) instead of the wavelength holds the further advantage that selecting the same difference between wavenumber pairs always results in the same synthetic wavelength \(\lambda_{\text{syn}}\), which is not the case in the wavelength regime, as indicated by Eq. (1). The image quality is demonstrated in fig. 2(b) and fig. 2(c), for individual and averaging over multiple dual wavelength phase maps (particularly significant for upper left corner of both image). The cross-section plot along horizontal centre of both images is shown in fig. 3.
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References:

Light field endoscopy and its parametric description

J. Liu, D. Claus, A. Herkommer, W. Osten

Imaging in minimally invasive surgery is performed via endoscopy or laparoscopy. Besides the many advantages it offers in comparison to open surgery (smaller scars, quicker recovery, and reduced risk of infections) it lacks three-dimensional vision, which makes it difficult to estimate the depth of objects and organs; useful information to navigate the instrument within the body. In fact, clinical reports demonstrate 97% of surgical accidents during laparoscopic intervention occur as a result of visual misperceptions. These errors can significantly be reduced when using 3D vision in minimally invasive surgery. We, therefore, introduce the snapshot light field imaging technique into endoscopy and build a 3D prototype, which we may thus call light field endoscope (LFE).

Our LFE works according to the following principle. A fibre based white light source is used as an illumination source. A conventional industrial endoscopy (KARL STORZ ENDSKOPES 86030SF) is employed. After the passage of light through the eye piece, the endoscope can be treated as infinity corrected optical system. In order to record images on the sensor, a lens is used between the endoscope and the CCD. A Schneider-Kreuznach 50 mm fix focus lens, of adjustable F-number ranging from 1.9 to 22, is employed in our setup. A microlens array (Thorlabs MLA150-5C, 10 mm x 10 mm size, 150 µm pitch size, 5.2 mm focal length) is placed at the image plane resulting in the so-called lightfield setup 1.0. A camera (SVS-Vistek eco655MVGE, 2050 x 2248 pixels, 3.45 µm pixel size), which is used to capture the light field of the specimen, is placed at the focal plane of the microlens array. The light field endoscopy setup and the light field image recorded are shown in fig. 1 and fig. 2(a), respectively.

By rearranging the pixels with respect to the location within each microlens subimage, an array of perspective images can be obtained, see fig. 2(b). At the next step, the acquired 4D light field was used to reconstruct the object at the different depth planes. According to the Fourier Slice Theorem, images focused at different depths correspond to 2D slices at different trajectories. Therefore, the reconstruction of different depth planes from the perspective images can be accomplished via shifting and adding procedures. The results of this shifting and adding procedure are shown in fig. 3 for two objects placed at different z-positions.

References:

Quantitative phase imaging enables the visualization of transparent objects with high contrast such as biological thin sections. In that manner, morphological features can be revealed intraoperatively without having to stain the sample resulting in a significant reduction of investigation time in histopathology. An environmentally stable setup is preferable to interferometrically based setup. This condition can be fulfilled via the application of phase retrieval imaging, which relies on the recording of diffraction pattern only. The key to phase retrieval imaging is the recording of the same information on multiple speckle de-correlated patterns. Various techniques have been developed based on this principle such as recording two or more intensity patterns while changing the object to sensor distance while moving an aperture across the object while illuminating the object with multiple wavelengths. The latter suffers from the problem of dispersion effects that result in different responses of the object under investigation with respect to the wavelength employed. Therefore, each of the recorded wavelength’s corresponding speckle pattern may hold different information, which hinders or makes the application of the iterative phase retrieval approach impossible. Changing the object to sensor distance restricts the optical resolution, which corresponds to the diffraction pattern that is recorded furthest distant from the object (same spatial frequency content of all diffraction patterns). Here we discuss an alternative approach, whereas due to previous reasons not the distance between object and sensor, but the distance between the point source and object is changed. This has the same effect as changing the object sensor distance, albeit offering the advantage of preserving the resolution. Moreover, it is possible to employ the direct Fresnel propagation method without having to worry about the different pixel size in the reconstruction plane. Figure 1, shows the setup used to retrieve the object wavefront. The object is illuminated by a divergent wavefront originating from a point source (single mode fibre). The distance between point source and object are changed as to introduce longitudinal speckle decorrelation. The iterative reconstruction approach is based on the application of the direct Fresnel method. Due to its parabolic approximation, the Fresnel method cannot be applied in a step-wise propagation between the different diffraction planes, which are separated by a few millimeters only. In our case, the propagation is performed at each individual diffraction plane, at which the modulus is replaced by the square root of the measured intensity. In a second step, from each diffraction plane, the wavefield is back propagated to the object plane. At the object plane, Parseval’s theorem is applied, as to ensure the correct contribution of each diffraction pattern to the recovered complex amplitude. The phase retrieval approach and the results obtained are depicted in fig. 2. Furthermore, slight displacements between the individual reconstructions in the object plane could be corrected via the calculation of the amount of displacement using cross-correlation algorithm.

Fig. 1: Schematic setup with longitudinally displaced illumination source between consecutive recording positions.

Fig. 2: (a) Phase retrieval approach, (b) modulus reconstruction, (c) RMS Error over number of iterations.

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References:
Digital Holography for erosion monitoring inside the ITER Tokamak

G. Pedrini, I. Alekseenko, G. Jagannathan, G. Vayakis, W. Osten

The Tokamak reactor (see Fig. 1) is the heart of the International Thermonuclear Experimental Reactor Project (ITER Project). It fuses the hydrogen isotopes deuterium and tritium into a helium atom and a free neutron. The resulting fusion energy can be used for power generation. In nature, the fusion process takes place in stars like our sun and occurs at temperatures around 14 million Kelvin and very high pressure.

In order to obtain fusion on earth within low pressure, the temperature has to be increased significantly and thus the temperature of the plasma within the Tokamak is about 150 million Kelvin.

Because there is no material, which could withstand temperatures like these, the plasma is guided contactless by magnetic fields within the vacuum chamber. However, these fields are not fully closed, resulting in the escape of high energy particles. These particles are constantly hitting the inner wall of the reactor, which leads wear effects, affecting the overall performance of the Tokamak. Thus, there is a need for the continually measuring of the erosion at the wall, after the Tokamak was operating. An erosion monitor able to measure the changes in the surface shape with a depth resolution of 10 µm is planned. The erosion (change of shape) measurement will be done not on the whole internal surface of the Tokamak but only on two surfaces having each a size of 10x30 cm².

Due to the high temperature and the radiation it will not be possible to have the measuring system inside the Tokamak, for this reason the measurements will be performed remotely where the electronic instruments (detector, laser, controlling electronic) will be located at a distance of about 15 m from the surface to be measured.

A two (or multiple) wavelengths interferometric technique (digital holography) will be used for the erosion measurement. This technique has the ability to tackle the challenging environmental conditions within the Tokamak by a long distance measurement where a relay optic composed by mirrors, lenses and windows will be used for imaging the investigated surface on the detector.

Figure 2. (a) shows a test objects used for the first investigations. It is a rectangular metallic plate (45 x 27 mm²) with steps having depths of 10, 20, 30, 50, 100, 150, 200 and 300 µm. The sample was located at a distance of 2.6 m and its shape was measured by multiple wavelengths digital holography. A titanium sapphire laser tunable in the range 700-820 nm was used to produce different wavelengths and digital holograms were recorded at: 757.82 nm, 758.08 nm, 758.86 nm and 759.89 nm. The phases of the wave fronts recorded at different wavelengths (φ758.08, φ758.86, and φ759.89) were determined by processing the digital holograms. The difference between phases recorded at different wavelengths results in phase maps containing the shape information of the object. Figures 2 (b, c, d) show the phase differences: φ758.08-φ757.82, φ758.86-φ757.82 and φ759.89-φ757.82, respectively. The phases are wrapped and have values in the range (-π, π). When the wavelength difference between the recorded hologram is small, the phase map difference (see fig. 2. (b) does not contain phase steps but the depth information is not accurate. On the oth-
er side phase maps obtained by larger wave-lengths differences contain phase steps but have better depth resolution. It is thus useful to combine different phase maps in order to obtain the shape with high resolution. Notice also that in the phase maps shown in figs. 2. (c, d) there are circular fringes due to the curvature of the wave front illuminating the sample. These fringes can be compensated by knowing curvature and direction of the illumination beam. By evaluating the phase maps it is possible to reconstruct the shape of the test object (see fig. 2.(e)). Figure 2.(f) shows the profile along a line.

With the sample located at a distance of 2.6 m from the measuring system, a depth accuracy of ±5 µm was obtained. The technique seems well suited for measurements inside the Tokamak. Long distance measurements (15 m) in perturbed conditions (vibrations) are planned.

Fig. 2: Measurement of the shape of an object located at a distance of 2.6 m. (a) Photo of the object; (b–d) phase-maps; (e) measured shape; (f) profile along a line.

Fig. 1: Cross section of the Tokamak [1].