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FULL-FIELD OPTICAL METROLOGY AND SENSING: FROM MICROMEASUREMENTS TO MONITORING OF CIVIL ENGINEERING STRUCTURES

In the paper we present recent trends in full-field optical metrology. The systems based on classical interferometry, digital holography, grating interferometry interferometric and photoelastic tomography and fringe/Gray code projection applied to static and dynamic objects studies are presented. Opto-numerical methodologies for novel materials studies and MEMS, MOEMS analysis are described including LCOS SLMs based active interferometers and digital holographic systems. The designs of novel interferometric and holographic cameras and their usage in outdoor conditions are presented. The concept of new generation of waveguide based full-field microinterferometers for micro-optics characterization is discussed and the progress on their realization is reported. Also 3D/4D data capture and processing systems for computer graphics, virtual reality and industry are presented. Numerous examples of measurement results and their applications in engineering illustrate the importance of progress in this field.

POLOWA METROLOGIA OPTYCZNA: OD MIKROPOMIARÓW DO MONITOROWANIA DUŻYCH STRUKTUR INŻYNIERSKICH

W pracy zaprezentowano współczesne trendy w optycznej metrologii w zastosowaniach do mikromechaniki, optomechatroniki i monitorowania struktur inżynierskich. Przedstawiono systemy bazujące na metodach: klasycznej interferometrii, cyfrowej holografii, interferometrii siatkowej, projekcji prążków i korelacji obrazu. Zaprezentowano optonumeryczne metodyki badania nowych materiałów i systemów MEMS/MOEMS wykorzystujące m.in. aktywną interferometrię i cyfrową interferometrię holograficzną. Przedstawiono nowe układy kamer interferometrycznych i holograficznych oraz ich wykorzystanie poza laboratorium. Przedyskutowano koncepcję nowej generacji mikrointerferometrów falowodowych oraz przedstawiono stan zaawansowania ich realizacji. Dodatkowo zaprezentowano system pomiaru kształtu i deformacji obiektów trójwymiarowych oraz ścieżkę przetwarzania danych wspomagającą ten system. Przedstawiono również koncepcję połączenia w przemysłowych pomiarach kształtu możliwości maszyn współrzędnościowych i polowych systemów optycznych bazujących na cyfrowej projekcji prążków.

1. INTRODUCTION

The success in implementation of optical full-field measuring methods in industry, medicine and commerce depends on the capability to provide quick, accurate and reliable generation, acquisition, processing and evaluation of data which may be used directly in a given application or as the initial data for CAD/CAM, FEM, specialized medical or computer graphics and virtual reality software. The need of accurate and full-field measurements is increasing due to quick development of new materials and technologies (industry), development of extensive diagnostic systems in medicine and introduction of 3D and 4D technologies in multimedia technologies [1]. However the new requirements of the methods and measurement systems are also loudly articulated by the end users.

Recent needs determined for full-field optical metrology include:

- provide convienient tool for nanomaterials and microsystems characterization with extended resolution capabilities,
- provide experimental data for Computer Aided Engineerimng (CAE) incl. industrial measurement and reliability analysis,
- provide extended range of 3D (x,y,z)/4D(x,y,x;t) data with the automatic path of their processing.

In order to respond to these requirements designers should, depending on the application, include in their measurement systems the following capabilities:

- active shaping of the wavefronts in interferometers,
- integrate with users equipment: microscopes, standard loading machines, technology lines and others,
- selfcalibrating/ selfadjusting systems,
- delivering 3D (x,y,z), (x,y,t) and 4D (x,y,z,t) information,
- gathering data *in-situ* and in *real-time*,
- high accuracy in large field of view (stiching),
- often low cost measuring sensors (disposal?).

Below the selection of optical measurement instrumentation developed in Institute of Micromechanics and Photonics, Warsaw University of Technology, in which the mentioned above requirements are strongly addressed is presented. Many of the systems have been design and manufactured in cooperation with the partners of the European Network of Excellence for micro-Optics NEMO [2].

2. MICROMEASUREMENTS

Microoptics and MEMS/MOEMS are nowadays frequently used in many fields of industry. The number of their applications increases and their functions became more and more responsible. Therefore precise knowledge about their optical, geometrical and mechanical (static and dynamic) parameters is necessary. Due to its small sizes and fragility non-contact and high sensitive measurement methods are required. However often conventional methods and instrumentation are not sufficient due their complicated sizes, large shape or refractive index gradients and dimensions comparable with a wavelength applied in the system [3]. Also the classical tools often cannot meet the requirements of micromeasurements which include: integrated multiple functions, improved performance, specifically high spatial and temporal resolution, nanometer accuracy, inexpensive, compact and batch-fabricated, portable, low power consumption and easily massively parallel.

Below we focus on two approaches which address some of the new requirements:

- modification and development of bulk optics (conventional) optical systems with extended measurement capabilities,
- development of a new generation of measurement systems based on novel on novel strategy which fits the dimension of an object to the measurement tool [4].

2.1. Active interferometry and tomography

Below two different measurement systems are reported in reference to the studies of two classes of microobjects:

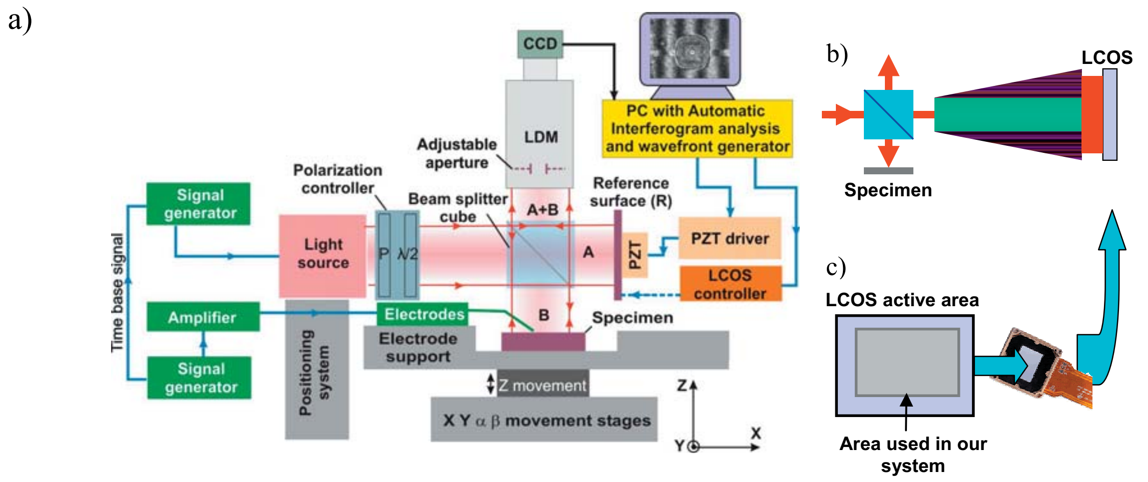
- MEMS/MOEMS with reflective surfaces [5],
- phase, transmissive microobjects, namely photonics fibres, gradient optics, 3D waveguides [6].

Both systems use the advantage of the numerical or/and optoelectronics correction of the object or reference wavefront in order to facilitate the measurements of elements which had been difficult or impossible to characterize.

For the first class of objects modification of classical Twyman-Green interferometer is proposed by implementation of Liquid Crystal on Silicon (LCOS) spatial light modulator as the reference mirror [5]. It allows introducing arbitrary (numerically or optically generated) phase in the reference wavefront. This special capability is applied to facilitate the measurements of shape and deformation of active microelements and extend range of such measurement. This can be realized by introducing linear or circular spatial carrier frequency into interferogram or by compensating object wavefront deformation.

The scheme of measurement platform is presented in Fig. 1. The main optical module consists of Twyman-Green interferometer and long working distance microscope (LDM). The interferometer is formed with a beam-splitter cube and exchangeable reference element (R). This element may be a mirror placed at piezoelectric transducer (to introduce phase shift in interferograms), or LCOS. Depending on the reference element (R) used the system may work as:

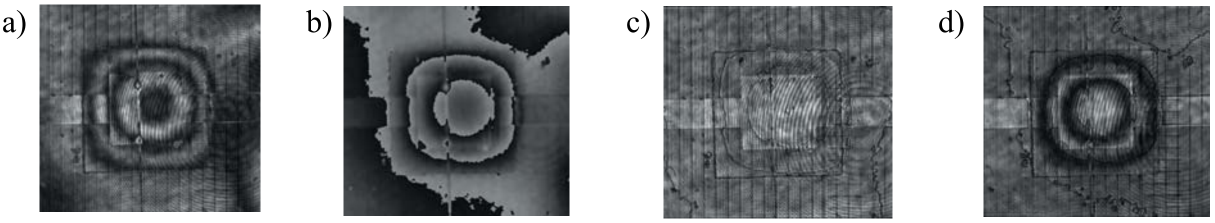
- conventional two-beam interferometer (R: mirror);
- active two-beam interferometer (R: LCOS).



d)

Fig. 1. The scheme of active interferometric platform: a) overall scheme of the system, b) scheme of the reference arm when LCOS is used, c) mutual relationship between LCOS active area and size/location of the reference beam and d) photo of the system; A, B – reference and object beams respectively.

The exemplary results of the measurement of out-of-plane displacement of an micromembrane with PZT layer [7] are shown in Fig. 2. The membrane, due to the residual stresses of in the PZT layer had significant initial shape. This shape had been compensated by the wavefront generated with LCOS reference mirror and allowed further direct monitoring of out-of-plane displacement of the electrically loaded micromembrane.



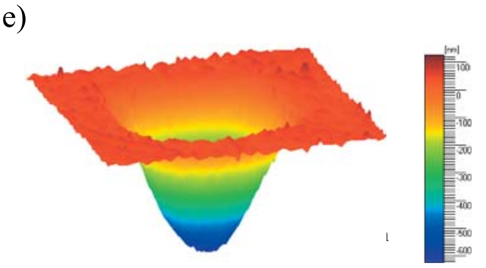


Fig. 2. Interferograms and results obtained during micromembrane out-of-plane deformation measurement: a) initial interferogram, b) PCM for the phase of the object beam and systematic error compensation, c) corrected interferogram of unloaded and d) loaded membrane, e) calculated out-of-plane deformation.

The system presented in Fig. 1 has wide capabilities of MEMS/MOEMS characterization, however it is not convenient for testing at production floor. Therefore the new approach is recently considered (Fig. 3), which provides the possibility of parallel measurements of microelements through an array of microinterferometers easily placed over the wafer.

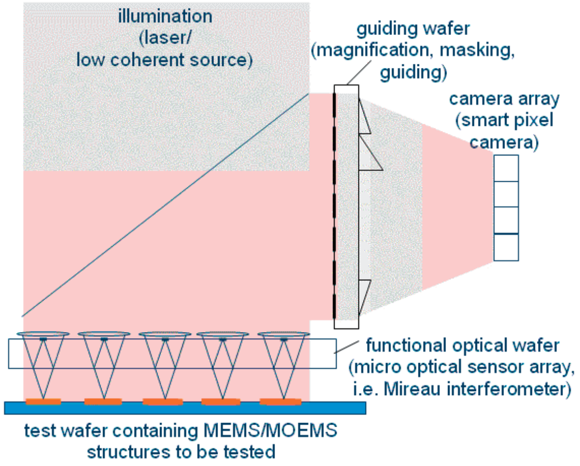
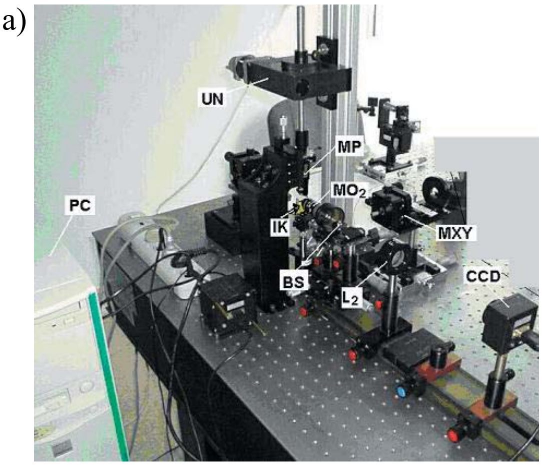


Fig. 3. General concept of on-wafer parallel measurements of MEMS structures.

For the second class of objects the modifications of interferometric (IT) and photoelascics (PT) tomography are proposed [6,8]. The photos of the interferometric tomography system based on Mach-Zehnder interferometric configuration and photoelastic tomography setup are shown in Fig. 4 and 5 together with the exemplary results of measurements. These systems have been proven to be extremely useful for determination 3D distribution of refractive indices and birefringence in such elements as optical fibres, waveguides, gradient optics as well as capabilities of new technologies as deep lithography with protons or laser writing.



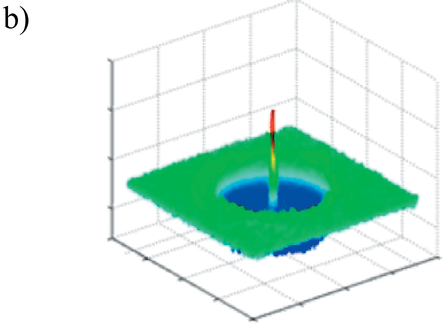


Fig. 4. Interferometric tomography based on Mach-Zehnder interferometer configuration: a) photo of the system and b) 3D plot of refractive index distribution in a layer of singlemode optical fibre.

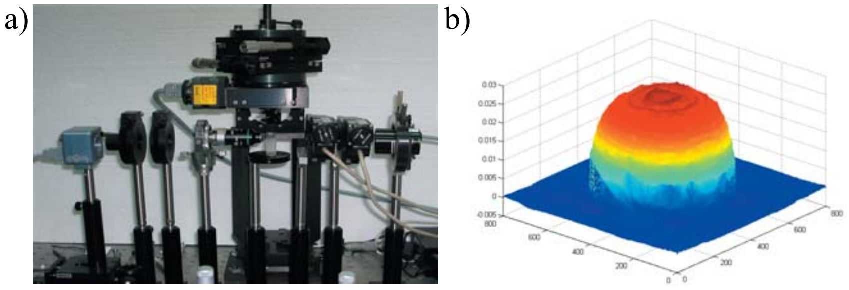


Fig. 5. Automated photoelastic tomography: a) photo of the system and b) the 3D plot of reconstructed birefringence in LC infilled fiber.

The applicability of IT and PT (in reference to 3D phase microelements) is limited by low dynamic range, i.e. only objects with small deviations of refractive-index distribution can by measured. In work [9], which is presented during OPERA2015 Conference it is shown that these limitations can be reduced by introduction of additional numerical focusing in the tomographic reconstruction algorithm. Additionally new tomographic reconstruction (solution of reverse problem) algorithm for optical microelements measurement with known design is proposed. This hybrid reconstruction algorithm allows significant extension of IT and ET applicability in measurement of elements having small dimensions and large deviations of refractive-index distribution

2.2. New generation of microinterferometers

The bulk optics measurement systems cannot fulfil such requirements as being inexpensive, compact and batch-fabricated, portable, low power consumption and easily massively parallel [1,4]. Therefore the new measuring architecture based on micro-optics has been proposed. The general scheme of the proposal is shown in Fig. 6 and presents the multifunctional waveguide microinterferometer.

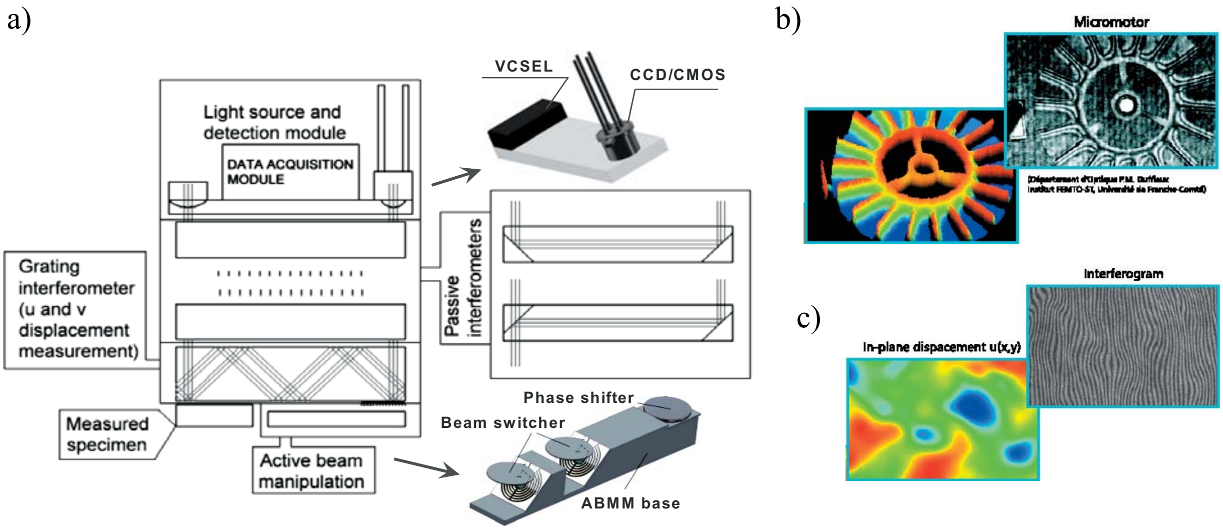


Fig. 6. Multifunctional integrated waveguide microinterferometric system: a) the scheme and exemplary results: b) shape measurement of silicon micromotor, c) in-plane- displacement field at the region of a few grains of metal.

It consists of one or several measurement modules including:

- grating (moire) microinterferometer (or ESPI) for in-plane displacement/strain measurements,
- Twyman-Green interferometer (or digital holographic interferometer) for out-of-plane displacement/shape measurement,
- digital holographic interferometer for u, v, w displacements determination.

The interferometric modules will be produced with low cost technologies (e.g. hot embossing) and material (PMMA). The system include also an Illuminating/Detection module in which VCSEL light source and CMOS matrix are integrated at one platform. It may include Active Beam Manipulation module which allows to introduce phase shifting or linear carrier fringes for rapid interferogram analysis.

3. WORKSHOP AND OUTDOOR MEASUREMENT SYSTEMS

3.1. Optical full-field extensometers

Optical methods of strain measurement are a generic technology, which support life cycle performance, safety and reliability assessments, and design optimization of objects varying in scale from micro-machines to civil engineering structures like buildings and bridges. Interferometric (ESPI, ESPSI), grid/moiré fringe and image correlation based methods form a powerful set of tools for use in strain fields analysis.

One of the most useful optical methods for in-plane displacement/strain measurement and monitoring is grating interferometry (GI). The grating (moiré) interferometry (Fig. 7a) is an experimental method to determine the components of displacement (u, v) or strain (ε_x, ε_y) [11]. On a object under test, a high frequency grating is deposited. When the object is subjected to stresses, deformation of the object, and consequently of the grating attached to it, occurs. The deformed grating is then symmetrically illuminated by two mutually coherent beams with plane wave fronts Σ_A and Σ_B (see Fig. 1). The incident angles of these beams are tuned to the plus first and minus first diffraction order angle Θ of specimen grating SG. In such configuration diffracted beams, with wave fronts $\Sigma_{A'}$ and $\Sigma_{B'}$, propagate co-axially along the grating normal, interfere and generate the fringe pattern which can be observed at detector plane D optically conjugated with specimen surface by imaging objective OB. The captured fringe pattern can be described as follows:

$$I(x,y) = a(x,y) + b(x,y)\cos\left[\frac{4\pi}{p}u(x,y)\right], \tag{1}$$

where $a(x,y)$ and $b(x,y)$ are the local values of background and contrast in an interferogram, $u(x,y)$ is the function describing in-plane displacements, p is the period of the grating. The interference fringes represent lines of constant in-plane displacement with basic sensitivity of $p/2$. If the setup is based on Czarnek's configuration (system with grating beamsplitter in sample illumination arrangement) the measurements are insensitive to vibrations and environmental changes and the GI based extensometer can be placed directly at the loading machine as shown in Fig. 7b [11].

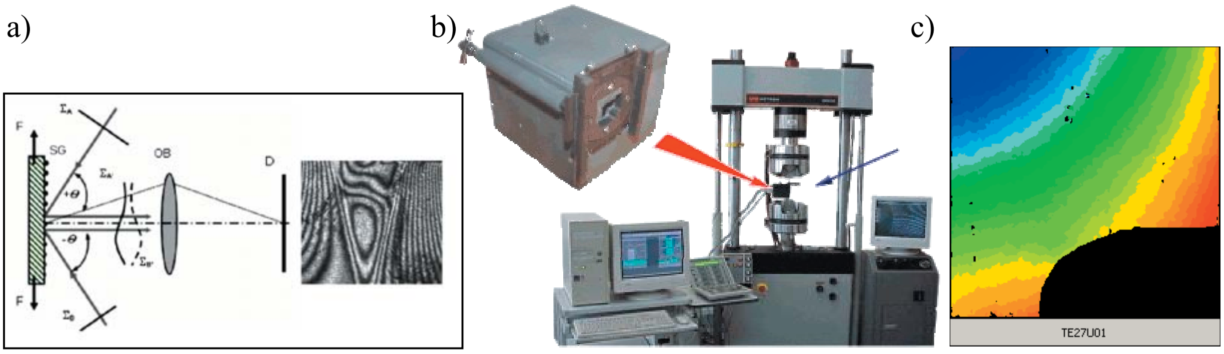


Fig. 7. Optical extensometer based on grating interferometry (GI): a) the scheme of GI, b) GI extensometer at loading machine, c) exemplary u in-plane displacement map.

Optical extensometers are also highly desired for a variety of outdoor measurement tasks including monitoring of health of big engineering structures. In order to provide the instrumentation for realization of these tasks the GI based sensor for in-plane displacement/strain monitoring (see Fig. 8) is proposed.

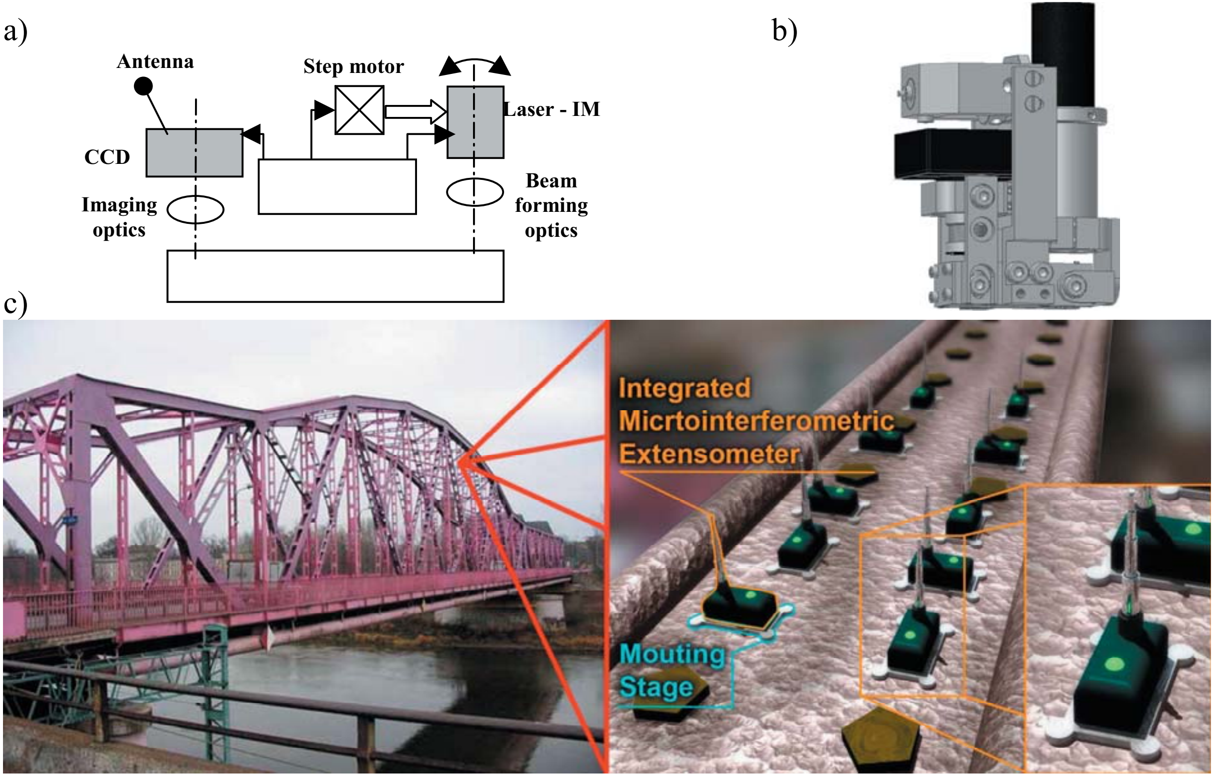


Fig. 8. Scheme a) and design b) of the out-door optical extensometer based on grating interferometry, c) integrated microinterferometric extensometer based on waveguide grating interferometer concept (see Fig. 5).

It consists of: WIH, illuminating module IM with micro-laser (λ = 532 nm), detection module DM with wire-less CCD camera and phase shifter module PSM. Phase shift required for automatic fringe pattern analysis by temporal PSM method is realised by tilting of illuminating module IM towards to WIH. The extensometer works in 2 mm x 2 mm field of view and with basic sensitivity: 417 nm/fringe while the accuracy with automatic fringe pattern analysis equals ±20 nm. It is battery driven and the data can be read remotely. The further miniaturization of such extensometer is based on the waveguide grating microinterferometer concept which had been explained in Section 2.2. Such microinterferometter produced by low cost technologies as hot embossing may provide in future even disposal highly sensitive devices for extensive application at civil engineering structures (Fig. 8).

3.2. Digital holographic cameras

One of the optical techniques which are recently developing rapidly is digital holography and digital holographic interferometry. The method is characterized by all advantages of classical holography and additionally it des not require photographic material and its processing as all data are captured by CCD/CMOS camera. The holograms are reconstructed numerically in order to obtain amplitude and phase of an object. Holography can be used for recording and quantitative analysis of all types of objects diffusive, reflective, transmissive) so its applications range from engineering to medicine.

Below we present digital holography cameras which are based on fibre-optics beam delivery scheme (Fig. 9). It combines a miniature DH head with the source and electronics. In the system we use single mode fiber SM450. The source is pigtailed laser SDL-532-020-SFL with output power 20 mW and operating wavelength 532 nm. The fibre optics deliver beam to FO module where the beam is splitted by single mode fiber optic coupler in 90/10 (object-to-reference beam) ratio. The reference fibre RF is spooled at PZT cylinder in order to introduce phase shifts or phase modulation in the reference wave. The optical paths of reference and object illuminating beams are equalized by introducing the additional length of object illuminating fibre (spooling at the additional cylinder AC). The light for illuminating object is delivered by OF which tip can be subjected to the linear shift introduced by micromotor Mot. Reference fibre tip is placed in the focal point of collimator lens and the plane reference beam is impinging at CCD matrix directed through mirror M and beamsplitter BS. The light scattered from object recombine with the reference beam at beamsplitter cube and the resultant interference field is captured by CCD matrix. The CCD is the standard microhead B/W camera JAI M536 CCIR with pixel size 8.6 μm and resolution 752x582 pixels.

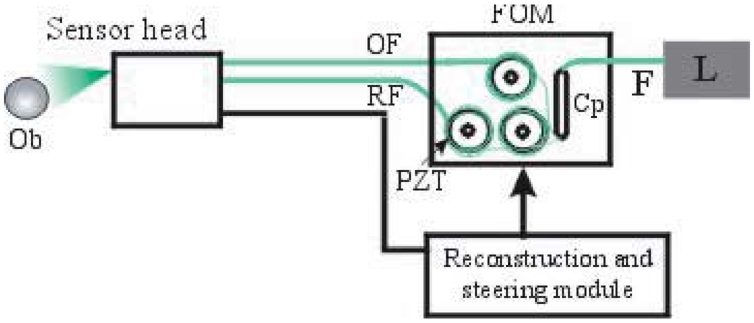


Fig. 9. Scheme of the system: L – laser with pigtailed fibre, F – monomode optical fibre, FOM – fibre optics module with: Cp – FO coupler, PZT cylinder, OF – object illuminating fibre, RF – reference beam fibre, Ob – object.

The design of the miniaturized digital holographic camera and interferometer for out-off-plane displacement and shape is shown in Fig. 10. It has diameter of 50 mm and length 100 mm. The compact design allows to work in unstable conditions however the instability of the object often brings problems so it is planned to adopt it to work with double impulse laser source. The second version of camera constists of four independent illumination beams and reference beam and it is used for monitoring of arbitrary displacement vector.

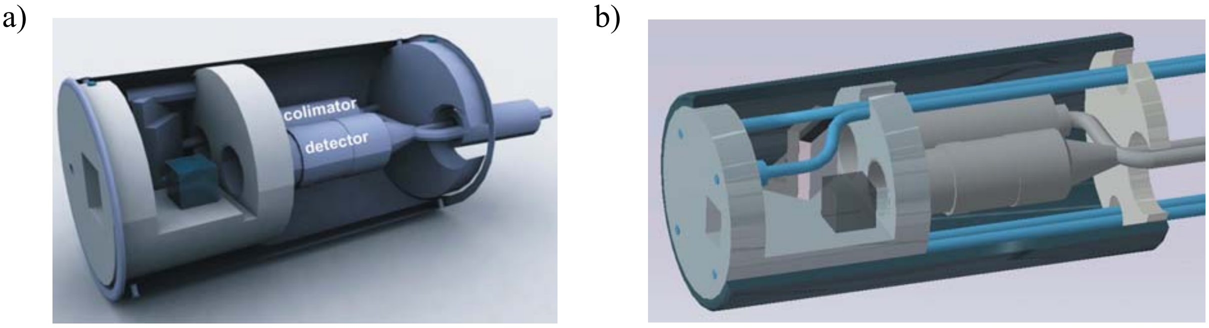


Fig. 10. The 3D overview of miniaturized digital holographic camera and interferometer for: a) out-of-plane and shape measurements and b) full displacement vector measurements **d**(u,v,w).

4. 3D/4D MEASUREMENTS SYSTEMS

New image processing methods and active photonics apparatus have made possible the development of relatively inexpensive optical systems for complex shape and/or deformation monitoring and measurements of static and variable in time 3D object with extended applications in engineering, medicine and multimedia technologies. The most effective systems are based on fringe and Gray code projection techniques [12] as shown in Fig 11a. If constant monitoring of moving and morphing 3D object is required the system consists of several directional modules working in common coordinate system and providing extensive data processing (Fig. 11b). The output of such system can be linked with commercial virtual reality or medical systems to make it more realistic [13, 14].

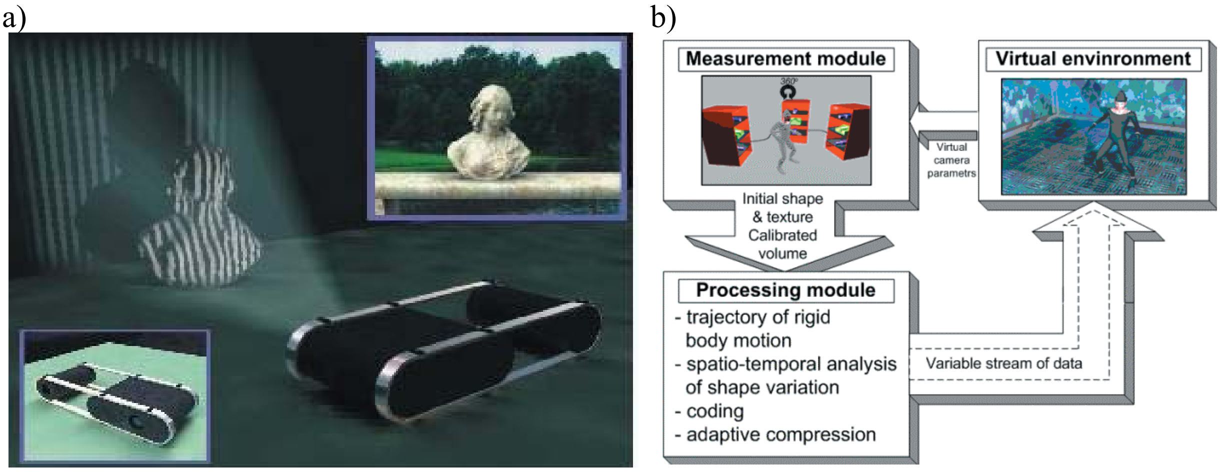

a) b)

Fig. 11. True 3D shape measurements: a) fringe/Gray code projection with data conversion system, b) exemplary results Fig. 5. Gathering data to active virtual reality system.

On the other hand the tendencies of modern industry are to increase the quality of manufactured products simultaneously decreasing production time and cost. Functional, ergonomic and aesthetical parameters are under constant optimization, thus forcing the objects to be of more complex shape. The geometry of the object has to be described accurately by thousands or millions of measurement points. Large-size production process, especially in the aviation, automotive and power industries, requires more effective measurement techniques. These new methods should introduce faster measurement speed with high accuracy. The systems used recently have insufficient means to accomplish this. The commonly used Co-ordinate Measurement Machines (CMM) have one serious disadvantage: their scanning speed (points per second) fails to satisfy the modern needs. This is related with the scanning process. The measuring probe needs to get into physical contact with the object for the measurement to take place. High speed measurement can be realized by use of optical methods (specifically fringe/Gray code projection method [12]) however their accuracy is still too low for some applications. For example it is sufficient for the measurement of overall car body, but insufficient for measuring finer details like holes in the body. Another downside is that there are no metrological standards for the evaluation of its measurement uncertainty.

To solve these problems the idea to combine the advantages of the mentioned above methods: the accuracy of CMMs and speed of full-field optical methods [15]. The proposed Opto-Mechanical Measurement Machine (OMMM) concept is based on integration of non-contact optical measurement system with a contact CMM [16] .

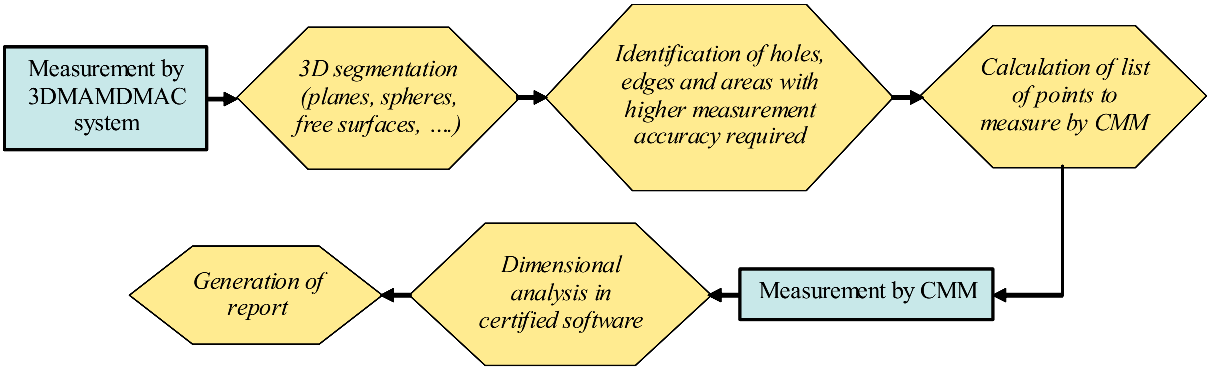


Fig. 12. Measurement sequence in OMMM.

To minimize measurement time, the measurement sequence presented in Fig.12 is proposed. At first, the examined 3D-object is measured by fast optical system. Then based on the automatic analysis of the measurement results (called cloud of points), the object is segmented and divided on the areas representing geometric features (like sphere, plane, cylinder, etc.) and other areas (free-form surfaces). Then for each area automatic decision is made, if it fulfills required geometrical accuracy or not. If this area has to be measured with higher accuracy then it is put in the list to be re-measured by CMM head. At all times we have the CAD model of an object to initially compare the results and to help in the decision process. Additionally some areas can be difficult to measure with optical methods (holes, edges, etc.) and they should be automatically detected and also added to the list with areas to re-measure by CMM. Then CMM perform its measurement sequence and a 3D virtual characterization of object is created. After that it is compared with CAD model and a report is generated.

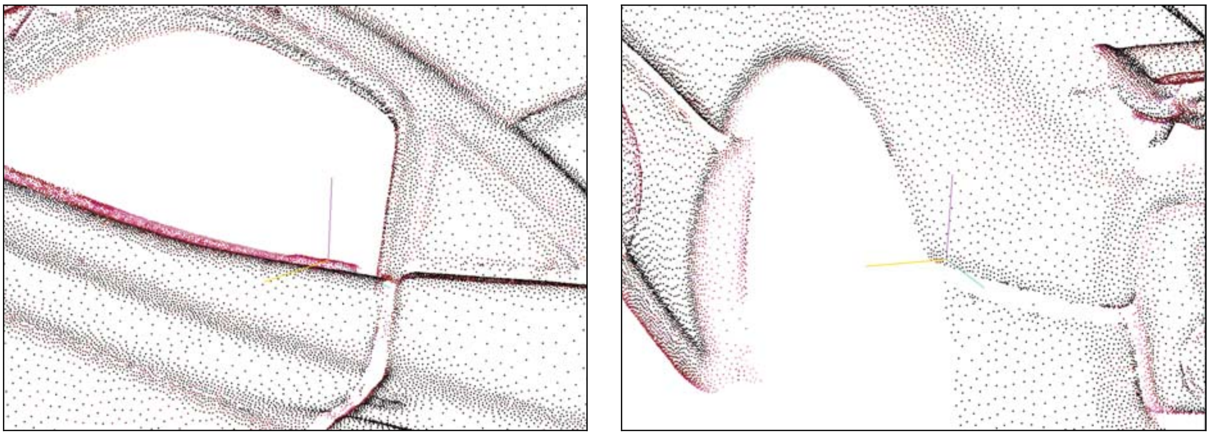


Fig. 13. Simplified measurements scanned by the optical system (Courtesy of Smarttech).

In Fig. 13 the exemplary results of measurement of a car body is presented. On current stage OMMM can measure in common coordinate space using several optical systems and CMM head. Data are automatically pre-processed and segmented.

Project of building OMMM is still under development. Now, extensive software development is performed. It is focused on several aspects: automation of measurement data processing, integration of different software packages, integration with certified metrological software and implementation of different strategies of fitting clouds of points into CAD model. We hope that in future it can efficiently support the measurements directly on the production line.

5. CONCLUSIONS

In the paper we present the measurement systems which represent recent trends in full-field optical metrology. The design of the systems based on interferometry, digital holography, grating (moiré) interferometry, interferometric and photoelastic tomography and fringe/Gray code projection applied to static and dynamic objects studies are presented. Opto-numerical methodologies for novel materials studies and MEMS, MOEMS analysis are described including LCOS SLMs based active interferometers, digital holographic systems and numerically enhanced tomography systems. The concept of new generation of waveguide based full-field microinterferometers for micro-optics characterization is discussed and the progress on their realization is reported. The designs of novel interferometric and holographic cameras and their usage in outdoor conditions including monitoring of civil engineering structures are presented. Also 3D/4D data capture and processing systems for multimedia and engineering applications are presented. The interesting concept of Opto-Mechanical Measuring Machine to support 3D measurements directly on production line is described.

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