# New approaches and concepts for engineering objects monitoring and measurements based on digital holography and interferometric principles

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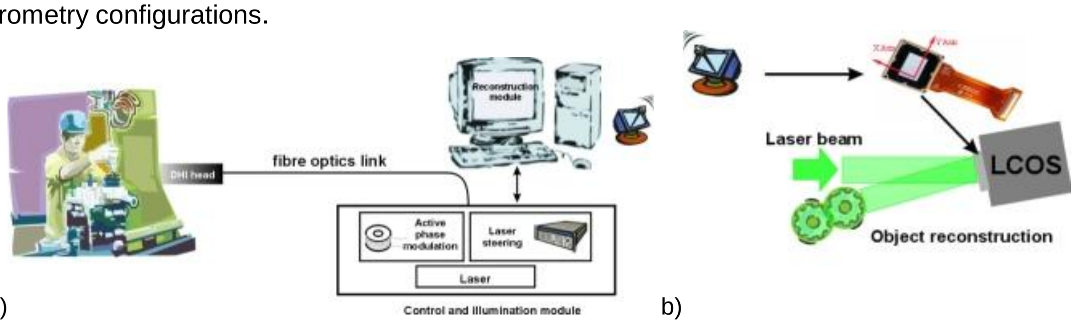
**ABSTRACT**

The work presents two approaches to build compact, digital holographic (DH)/interferometric cameras and sensors allowing flexible, automatic and outdoor measurements of shape, displacements and strains of small engineering objects or selected regions of interests of large engineering structures.The first concept is based on fiber optics based DH cameras with flexible measurement head in two configurations: (1) for shape and deformation measurements and (2) for full displacement vector determination (u,v,w)..The second concept is based on an interferometer design in a form of massive glass or PMMA block in which an object and reference beams are traveling in different relative configurations providing alternatively the digital holography, speckle, grating interferometry and conventional two beam interferometry configurations. These two different concepts show the new possibilities which are created in digital holography and other interferometric techniques due to the rapid development of a variety of optoelectronics and photonics devices as well as low-cost photonics replication technologies.

## 1. INTRODUCTION

Digital holography provides a way to record and digitally restore amplitude and phase of an investigated object [1]. It also allows distant monitoring of an object and its remote, optoelectronic reconstruction [2,3]. Proper manipulation of phases provides information about shape of an object, its out-of-plane and in-plane displacements during internal or external loading. All these capabilities locate digital holography among the methods with high potential for industrial and outdoor measurement applications. Several systems and cameras dedicated for a variety of applications have been reported. Below we present two novel and very different architectures of digital holographic systems based on: (1) a measurement digital holography/speckle interferometry head connected with the source and control modules with a fibre optics link and (2) an interferometer structure design in a form of massive glass or PMMA block in which an object and reference beams are traveling in different relative configurations providing alternatively the digital holography, speckle or grating interferometry configurations.

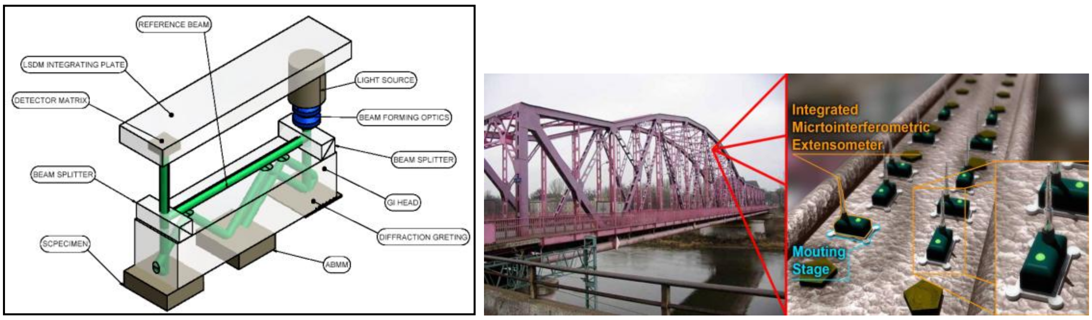



a) b)

Figure 1. The scheme of DH system for mechanical parts monitoring a) measurement module, b) optoelectronic reconstruction module.

The first architecture consists of two types of measurement heads, fibre optics link and control/illumination module (Fig.1). One of the measurement heads is configured to perform out-of-plane displacement and shape measurement. The second one (with four illumination beams) allows to measure (u,v,w) displacement fields. Due to fiber optics light delivery system the DH head is able to work in a distance from its electronic/processing part and it allows direct access to all mechanical parts

of machinery (Fig.1a). The DH head can be hand-held or mounted directly at a machine. The data from both cameras can be transferred remotely to an optoelectronic reconstruction station based on Liquid Crystal on Silicon (LCOS) spatial light modulator (Fg.1b).
The second approach allows to configure a small, low-cost sensor (Fig. 2a) for local measurements of displacements and strain fields [4,5]. Such rigid “waveguide configuration” ensures low sensitivity to vibrations which is very important in outdoor conditions. The interferometer head is supported by the unified low-cost illuminating/detection module, while the interferometric block is produced by low-cost replication technologies e.g. hot embossing. These DH/interferometric heads may work with battery operated cameras and sources (VCSEL) and provide the measurement data remotely to a computer. The future vision of possible outdoor application of such sensors is shown in Fig.2b.




a) b)

Fig. 2. The scheme of a digital holographic sensor a) and the vision of its application as an array of sensors with remote data readout at large engineering structure.

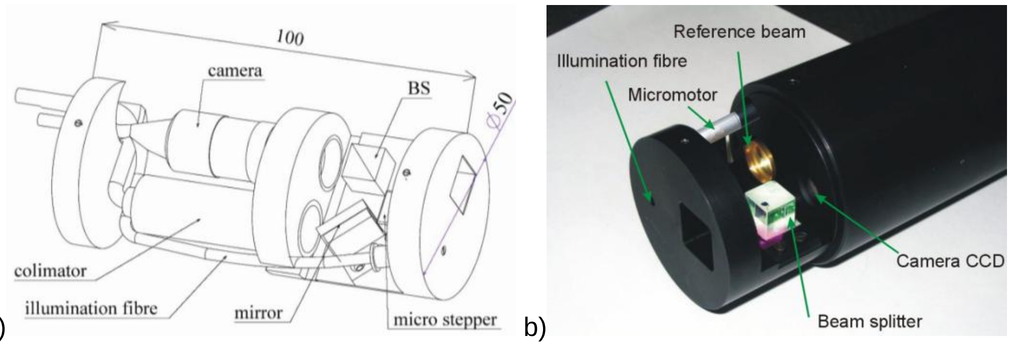
In the paper we describe in more details the introduced concepts as well as show the exemplary results of measurements perfored directly at mechanical parts or small regions of interest at big civil engineering structures.

## 2. DIGITAL HOLOGRAPHIC CAMERAS BASED ON FIBER OPTICS LINK

In instrumental practice most often two basic configurations are applied depending on the choice of measurand i.e. the out-of-plane displacement/shape (w,h) measurement setup and in-plane displacement measurement setup. However in digital holography the new opportunity arises namely the possibility of phase manipulation. Therefore it is relatively easy to build a full displacement vector (u,v,w) setup. The hardware and software solutions are a bit different for both systems ((w,h) and (u,v,w) and therefore in order to provide user friendly cameras for industrial inspection two separate devices have been designed and built: DH_SHAPE and DH_UVW [6]. In both cameras all optical elements and detector are closed in a tube with the diameter 50 mm. Electronic module with laser and PZT controllers and synchronization is separated from holographic head. Also for specific applications the cameras are equipped with the remote data transfer and used for both numerical or optoelectronic distance reconstruction systems.

### 2.1. DH_SHAPE Holocamera

The holocamera DH_SHAPE, designed for out-of-plane displacement measurement and shape determination, is shown in Fig. 3. The light source is a pigtailed laser with output power 7mW and operating wavelength 532 nm. The beam is delivered by a single mode fiber SM450 and is splitTed by single mode fiber optic coupler in 90/10 ratio to form the object and reference beams. The tip of object illumination fiber can be subjected to the linear shift introduced by micromotor. Reference fiber tip is placed in the focal point of collimator lens and the plane reference beam is impinging at CCD matrix directed through mirror and beam splitter. The light scattered from object recombine with the reference beam at the 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 $\mu$m and resolution 752x582 pixels.




a) b)

Fig. 3. Measurement head for out-of-plane displacement measurement and shape determination: a) scheme of camera, b) the camera head without cover.

In this configuration out-of-plane displacement is calculated from the phase difference $\Delta\phi$ obtained from two holograms captured for two different states of an object according to the relation:

$$w(x,y) = \frac{\lambda \Delta\phi(x,y)}{2\pi(1+\cos\Theta)} \tag{1}$$

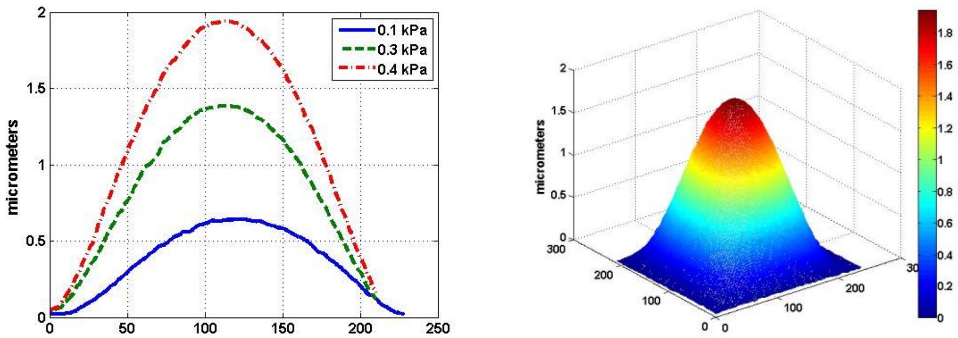
where *w(x,y)* is out-of plane displacement , $\lambda$ – wavelength of laser, $\Theta$ – angle between illumination and reference wave directions.

For a shape measurement the two-sources contouring method is applied [4]. The change of sensitivity vector is introduced by a tilt of the illumination beam through shifting of the fiber tip. The value of the height of the object *h* is given by:

$$h(x,y) = \Delta h \cdot \frac{\Delta\phi(x,y)}{2\pi} = \frac{\lambda}{2\sin\frac{\Delta\Theta}{2}} \cdot \frac{\Delta\phi(x,y)}{2\pi} \tag{2}$$

where $\Delta h$ = depth of contouring surfaces, $\Delta\Theta$ – angle between two illumination directions.

As the angle $\Delta\Theta$ introduced by the shift of fibre tip ranges from 0.05 ° to 1°, the values of single contours vary from 0.6 mm to 30μm.The applicability of this camera was shown at an example of silicon membrane studies. The quasi-flat silicon membrane (3.5 mm x 3.5 mm) was fixed at the edges and loaded by changing pressure. The results of out-of-plane displacement measurements performed for loads differences 0-0.1 kPa, 0-0.3 kPa and 0-0.4kPa are shown in Fig. 4a, while 3D representation of membrane displacement under 0.4kPa pressure is shown in Fig. 4b.




a) b)

Fig. 4. The results of measurement of the silicon membrane under pressure load: a) central crossections of out-of-plane displacements for different loads and b) 3D map of out-of-plane displacement for 0.4 kPa

In the next step we checked the system capability to measure object shape. Test was perform for the same micromembrane loaded with pressure 2 kPa. The P-V shape value after scaling according to the sensitivity factor reached 21 μm (Δh≈10 μm) and the results are shown in Fig.5.

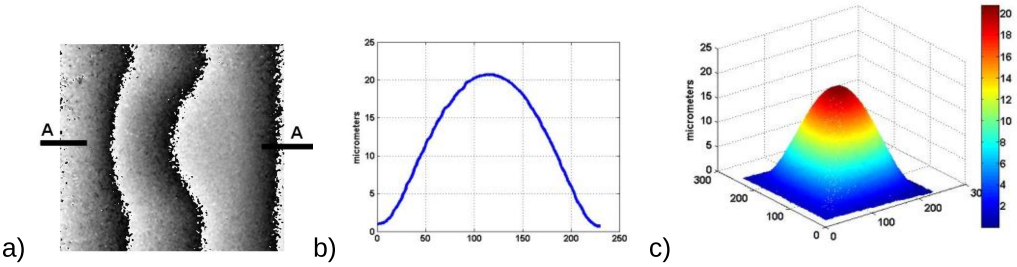



Fig. 5. Shape of silicon micromembrane loaded with 2.0 kPa, a) mod2π fringes, b) cross-section A-A, c) 3D shape representation

Another object under test was a transistor (Fig. 6a) subjected to thermal load due to voltage applied to the element. We had stored a series of digital holograms captured with video rate 5 frames/s during heating of the transistor. The exemplary phase fringes illustrating the out-of-plane displacement after 0.5s, 3s and 6s are shown in Fig. 6b-d respectively. The transistor deformed linearly. The P-V values of out-of-plane displacement vary in the range 0.2 – 1.8 μm for different states.

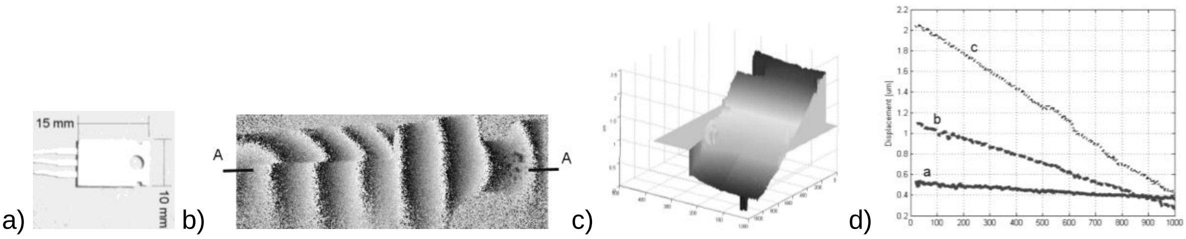



Fig.6 Measurement of transistor under electric load a) image of the object, b) phase( mod2π) reconstruction, c) 3D representation out-of-plane displacement for object after 6 s.; d) profile A-A of out-of-plane displacement maps for the loaded object after 0.5 s, after 3s and after 6s.

As it was mentioned in the section 1 the camera has capability of remote transfer of data (digital holograms) to computer which controls LCOS device. This provides the very interesting feature of the system, which facilitate the capability of remote monitoring of the behaviour of an investigated object. The LCOS used in our experiment has the resolution 1024 x 768 pixels, 8 bit quantization of intensity signal, high fill factor and relatively small pixel (□□□m□), which however did not matched to the CCD pixel so the hologram rescaling was required. Below we present the results of a series of optoelectronic reconstruction of interferograms obtained from hologram captured for different thermal load of the transistor (Fig.7). The first hologram captured by camera is transferred to the computer which controls LCOS, then the sequential holograms captured according to the measurement protocol are also transferred and the intensities are added in the computer. Finally the resultant intensity is displayed in real time at LCOS. When LCOS is illuminated by plane coherent wavefront the holograms are reconstructed and interferograms are obtained at the background of the reconstructed image of transistor.

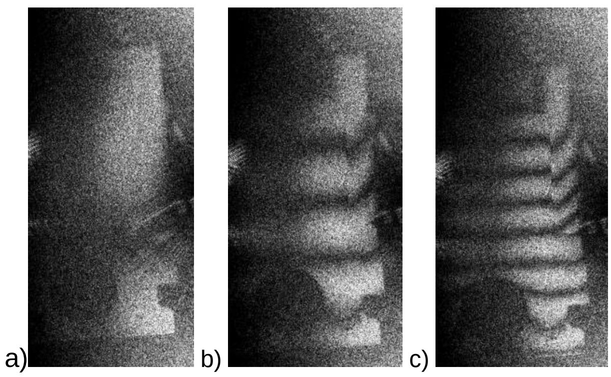
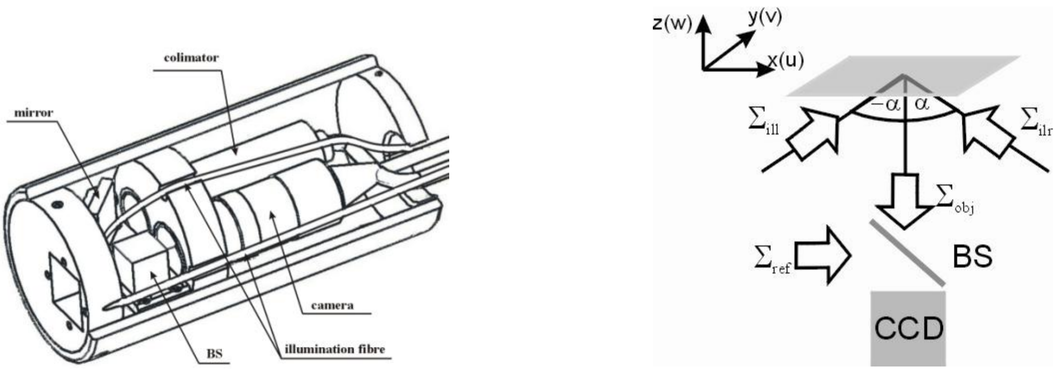


Fig. 7 Optoelectronic reconstruction of the heated transistor after a) 0.5s, b) after 3 s, c) 6 s.

**2.2. DH_UVW holocamera**

The second holocamera designed for an arbitrary displacement vector measurement is shown in Fig. 8. The light source is the pigtailed laser with output power 7mW and operating wavelength 1064 nm. The beam is splitted into object and reference beams by single mode fiber optic coupler in 90/10 ratio. The object beam goes to optical switch 1x4 and produces 4 object illumination beams, which one-by-one illuminate an object. Reference fiber tip is placed in the focal point of collimator lens and the plane reference beam, directed through mirror and beam splitter, is impinging at CCD matrix. The light scattered from an object recombines with the reference beam at beamsplitter cube and the resultant interference field is captured by CCD matrix. The CCD applied here is the same camera as in the case of DH_SHAPE camera. The dimensions of measurement head are: diameter 46mm and length 100mm.




a) b)

Figure 8. The holographic camera for arbitrary vector displacement determination: a) 3D view of DH_UVW and b) the scheme for an arbitrary displacement vector measurement; BS – beamsplitter

The protocol for the measurements of an arbitrary displacement vector is more complicated and requires at least three object illumination beams. Sensitivity vector depends on the angles between one of the illumination directions and reference beam direction. In order to simplify the calculations we describe DH system which provides in-plane displacement u(x,y) and out-of-plane displacement w(x,y) from two pairs of holograms captured before and after loading [6]. The specimen is illuminated symmetrically by the beams impinging from left $\Sigma_{ill}$ and right $\Sigma_{ilr}$ directions (Figure 8b). They interfere with reference beam $\Sigma_{ref}$ and four holograms are sequentially captured. The relevant phases are calculated from holograms by using conventional (Fresnel) or phase shifting reconstruction procedures. The phases include the following information:

$$\phi_{l1} = k(\sin(\alpha)u_1 + (\cos(\alpha)+1)w_1) \tag{3}$$

$$\phi_{r1} = k(\sin(-\alpha)u_1 + (\cos(-\alpha)+1)w_1) \tag{4}$$

$$\phi_{l2} = k(\sin(\alpha)u_2 + (\cos(\alpha)+1)w_2) \tag{5}$$

$$\phi_{r2} = k(\sin(-\alpha)u_2 + (\cos(-\alpha)+1)w_2) \tag{6}$$

where: r - right direction of illumination, l -left direction of illumination, $\alpha$ -angle of the incident light, u,w - displacement vector components, 1,2 – sequential states of object

In order to obtain u(x,y) and w(x,y) displacement vector components the following equations are used:

$$u_2 - u_1 = \frac{\lambda(\Delta\phi_l - \Delta\phi_r)}{4\pi\sin(\alpha)} \tag{7}$$

$$w_2 - w_1 = \frac{\lambda(\Delta\phi_l + \Delta\phi_r)}{4\pi\cos(\alpha) + 4\pi} \tag{8}$$

where $\Delta\phi_{r,l} = \phi_{r1,l1} - \phi_{r2,l2}$

The same procedure is applied for the holograms captured with the object beams obtained after illuminating the object by beams located in vertical direction (upper and lower beams- Fig. 8a) and as the result the ($v_2$-$v_1$) and ($w_2$-$w_1$) maps are calculated.
As two pairs of beams are used for displacement measurement the out-of-plane displacement ($w_1$-$w_2$) is calculated two times, so the systematic errors can be more easily detected and removed. Displacement fields

obtained by such phase manipulation will be correct under assumption of flat object. In the case of 3D object studies its shape has to be known for correct displacement vector determination [1].

The applicability of this camera had been demonstrated through performing measurements of u,v,w displacement fields obtained during fracture test of short fibre reinforced composite specimen. The material studied was a phenolic short glass fibre reinforced composite IXEF 1022 supplied by Solvay-Belgium. The samples were machined from 5 mm thick sheets prepared by injection molding technology (Fig. 9a) The Mode I fracture tests had been performed and the pairs of holograms (right - left, up - down) had been captured for the series of tensile forces applied. Sample was loaded with tensile force ranging from 0 N to 70 N.

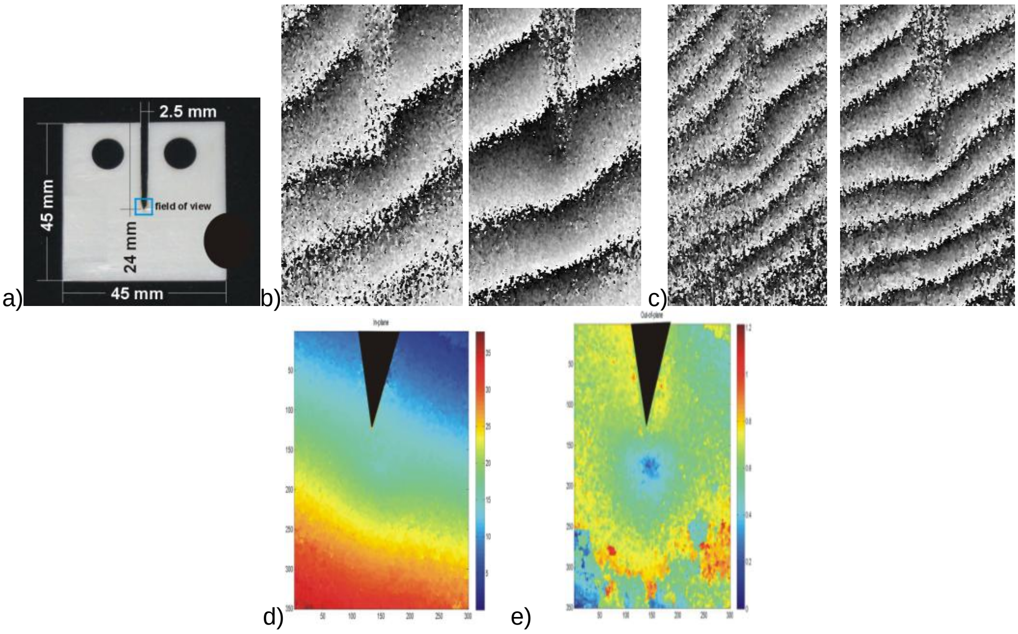



Figure 9. Exemplary pairs of phase mod 2π calculated from holograms illuminated by upper and lower illumination beams and captured for different loads a) specimen geometry b) 30N-10 N c) 50N-10 N, and the results of displacement determination for tensile load 50-10 N d) in-plane (v), e) out-of-plane (w) displacement maps.

At first the reference pair of holograms (for upper and lower beams) was captured with the initial load equal to 10 N (non zero force was applied in order to avoid ambiguous position of the sample). Then the series of holograms of the sample under increasing load with step 10N was taken. The phase of each hologram was calculated. These pairs of hologram allow calculating v and w displacement maps (Eq.7 and 8, here the perpendicular direction pairs of beams are applied so the v- displacement is calculated). The exemplary results of this procedure in the form of phase mod 2π are shown in Figure 10b,c. The phase fringes indicate increasing value of displacements and strong phase nonlinearities in the area of crack initiation and propagation. The quality of phase fringes obtained for the lower illumination direction is much worse, which indicate that the illumination conditions for this beam should be improved. However the displacement fields v and w were calculated by proper manipulation of the phases and the exemplary results calculated for the load difference 50N – 10N are shown in Figure 9d,e. The same experiment was performed for left and right illumination directions and the pair of w and u displacements were obtained.

## 3. Low-cost interferometric/holographic sensor based on massive waveguide measurement head

The bulk optics measurement systems cannot fulfil such requirements as being inexpensive, compact and batch-fabricated, portable, low power consumption and easily massively parallel [4]. Therefore the new measuring architecture based on micro-optics has been proposed [5]. The general scheme of the modular system is shown in Fig. 10 and presents the multifunctional waveguide microinterferometer.

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 (no imaging optics) for out-of-plane displacement/shape measurement,
- digital holographic interferometer for u, v, w displacements determination.

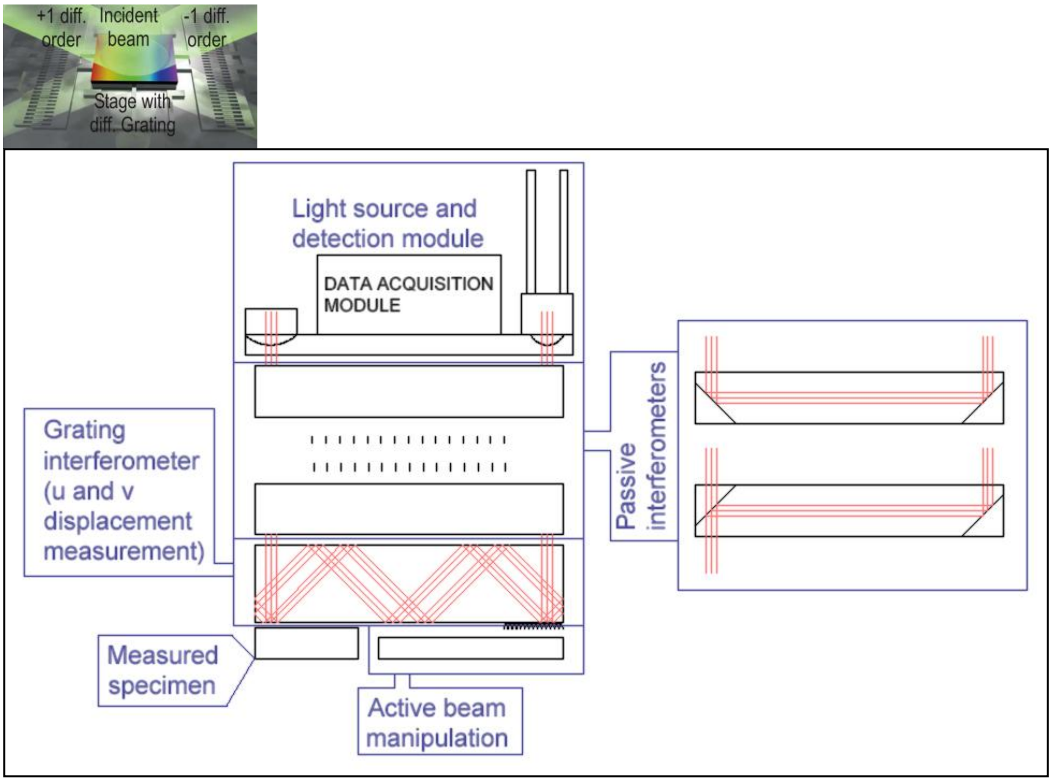



Fig.10. The scheme of the multifunctional waveguide microinterferometric sensor.

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. It is proposed to produce this module by MOEMS technology in the form of comb drive actuator with grating [8].

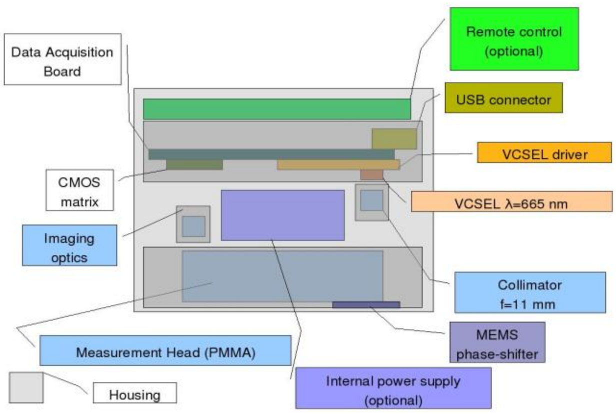



**Fig.11. The architecture of DHI sensor for in-plane displacement monitoring and measurement**

## 4. Conclusions

The presented work is one of many attempts undertaken by holographic groups to built holographic camera dedicated for arbitrary displacement measurement and shape determination of mechanical elements. The cameras presented use fibre optics light delivery system and compact design together with smart ideas for phase manipulation. Additionally it was proven that the remote data transfer capabilities can be used for both numerical and optoelectronic hologram reconstruction. It was shown that the DH_SHAPE camera is fully functional and provides quick and convenient way to measure shape and out-of-plane displacement of microelements.
The second camera DH_UVW is able to provide information about all displacement maps (u,v,w) at the sample surface, however its configuration needs further modifications and proper calibration. The quality of holograms has to be improved by better stabilization and intensity equalization of illuminating beams. Also results have to be verified by performing experiments with standardized mechanical samples. Authors are convinced that after these improvements also the DH_UVW camera will become an useful and convenient tool for out-of-laboratory studies of mechanical elements.

### 6. Acknowledgments

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