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S. Dovgalets, Cand. Sc. (Eng.), Assist. Prof.; V. Tomkiv, Student; O. Goncharuk, Post-Graduate; O. Mochulska, Student

REMOTE SURFACE MEASUREMENT

There hade been analised the possibility of the application of the gradient fibres for the creation of 3-dimmenssional remote microscope. The structure of microscope and scheme for phase front correction was suggested. There had been conducted the metrological research of the devises' possibilitie, namely the dependence of the objects' under research size on the systems' parameters.

Keywords: *microscope, fiber-optical, gradient fiber.*

Introduction

When building and operating the technical systems, the different methods of visual control are used along with the common measuring equipment. Such kind of control can be done using video cameras, endoscopes and microscopes. Microscopes are used for micro-deformations, micro-cracks, surface flatness studying.

Important microscope property sometimes can be the possibility of remote viewing the object of interest. Another useful microscope property may be the possibility to obtain the three-dimensional image of the object of interest, to make conclusions about its state.

The existing achievements in this sphere

Metal-graphing and video microscopes provide the ability to perform the remote control. Video-microscopes are widely used for the state of optical fibers control. Presence of tentacles in this type of microscopes allows to use them for making researches in the pleases with the complicated access [1]. Inability to gain three dimensional images is a big disadvantage of microscopes of this type. There are microscopes of other type that allow gaining 3D object images. They are based on confocal scanning of micro-objects principle. This process can last several hours [2]. Devices build on the SDCM (Spinning Disk Confocal Microscopy) principle work much faster. A disk with thousands of holes is used in microscope of this type [3]. More voluminous and sharp image is obtained by using scanning two-photon or multi-photon microscopy. Defect of microscopes of this type is inability to use them for remote control.

Microscopes that exist now provide the possibility either to get 3D image, or to make the remote examinations, but there is no combination of these two properties.

Work objective

The objective of this work is to elaborate the microscope that would be able to gain three dimensional images of the object in the place with the complicated access.

Theoretical part

Having done the analysis of the technologies which can be used for building the devices for remote control and methods of three dimensional images gaining, fiber optics in combination with the digital holography methods were decided to be used. Such an approach would allow us to create a device with the high metrological characteristics and the ability to work in hard to access places.

The diagram of the device with single multimodal fibers using for image transmitting from the object of the research to the register is suggested (image 1).

Beams, radiated by laser, create modes in the fiber. Modes spread along fiber axis. On the opposite side of the fiber, the beams reflect from the object of research and spread in the opposite direction in the same waveguide. Reflection of the beams from the object of the research leads to phase front of the surface forming. Aggregation of all the beams that spread backwards in the waveguide contains the information about every point of the surface. When phase correction stage is passed, the optical information about the surface is captured by the digital camera because of interferential occurrence, that takes place between the reflected and the reference wave.

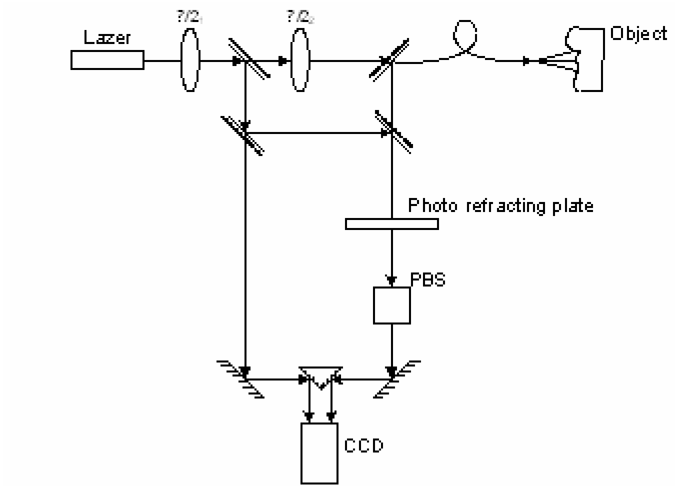


Image 1. Device for gaining 3D images schema

When spreading in waveguide, the beams create modes with indexes *i* and *j* and phase velocity ω. For each mode there is different spreading constant h_{ij}. Because of this there is differential phase incursion for each of the mode. This fact makes some distortion to phase front. Out of multimode waveguide optimal for using in this case is gradient fiber, because its average squared deviation of phase incursion for each mode is smaller than for the other multimodal fibers [4]. That's why the gradient fiber will be used for the under research device.

For the phase distortions, which take place while wave spreading in waveguide, the correction phase distortion schema is used. This schema is described in details by G. Jeffrey [5]. This method is based on the properties of photo refracting polymer plates that appear when differently polarized reference and distorted waves are illuminating plates.

After the compensation of all the deformations, the phase front is directed to the video camera lens together with the reference wave. In such a way the digital hologram is recorded. The process that takes place on video camera lens can be described as [6]:

$$I(x, y) = |O(x, y) + R(x, y)|^2 = (O(x, y) + R(x, y))(O(x, y) + R(x, y))^{*} =$$
$$= R(x, y)R^{*}(x, y) + O(x, y)O^{*}(x, y) + O(x, y)R^{*}(x, y) + R(x, y)O^{*}(x, y), \quad (1)$$

where $O(x, y) = o(x, y)\exp(i\varphi_O(x, y))$ – complex amplitude of the wave, reflected from the object with real amplitude *o* and phase φ_O, and $R(x, y) = r(x, y)\exp(i\varphi_R(x, y))$ – complex amplitude of the reference wave with real amplitude *r* and phase φ_R [6].

Intensity in every point of the camera can be calculated as:

$$h(x, y) = h_0 + \beta\tau I(x, y), \quad (2)$$

where β – constant, τ – exposal time, and h_0 – intensity of not illuminated camera which can be neglected.

Using the mathematical methods the digital hologram can be reconstructed and the surface of the under research object can be obtained. Let's take a closer look at this process.

Diffraction of the wave can be described by following integral:

$$\Gamma(\xi,\eta) = \frac{i}{\lambda}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y)R(x,y)\frac{\exp(-i\frac{2\pi}{\lambda}\rho)}{\rho}\left(\frac{1}{2}+\frac{1}{2}\cos\theta\right)dxdy, \quad (3)$$

where $\rho = \sqrt{(x-\xi)^2 + (y-\eta)^2 + d^2}$ – distance between the points in hologram plain and in reconstruction plane. *h(x, y)* – holographic function. Reference wave *R(x,y)* is described only be real amplitude $R = r + i0 = r$.

Diffraction is calculated on distance *d* behind the cameras lens. This means that the complex amplitude is reproduced in real image plane.

Expression (3) is the basement for digital holograms reconstruction. It is possible to calculate the intensity and the phase, because the reconstructed wave matrix $\Gamma(\xi,\eta)$ is complex function.

For *x* and *y*, in the same way as for ξ and η, which are small comparing to *d* – distance between hologram reconstruction plane and recording plane. Expression for *ρ* is substituted by first member of Tailor sequence:

$$\rho = d + \frac{(\xi - x)^2}{2d} + \frac{(\eta - y)^2}{2d} - \frac{1}{8}\frac{[(\xi - x)^2 - (\eta - y)^2]}{d^3} + \ldots \approx d + \frac{(\xi - x)^2}{2d} + \frac{(\eta - y)^2}{2d}. \quad (4)$$

Changing multiplier in expression (3) to *d*, following formula is obtained:

$$\Gamma(\xi,\eta) = \frac{i}{\lambda d}\exp(-i\frac{2\pi}{\lambda}d)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y)R(x,y)\exp(-i\frac{\pi}{\lambda d}((\xi - x)^2 + (\eta - y)^2))dxdy. \quad (5)$$

When carrying out multiplier in exponent power out of integral, expression will look like this:

$$\Gamma(\xi,\eta) = \frac{i}{\lambda d}\exp(-i\frac{2\pi}{\lambda}d)\exp[-i\frac{\pi}{\lambda d}(\xi^2 + \eta^2)]\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y)R(x,y)\exp[-i\frac{\pi}{\lambda d}(x^2 + y^2)]$$
$$\times\exp[i\frac{2\pi}{\lambda d}(x\xi + y\eta)]dxdy. \quad (6)$$

In case of the real image, this equation makes it possible to reconstruct the wave front in plane behind the hologram. The phase, as well as the information on the relief, is calculated in following way:

$$\varphi(\xi,\eta) = \arctan\frac{\mathrm{Im}[\Gamma(\xi,\eta)]}{\mathrm{Re}[\Gamma(\xi,\eta)]}. \quad (7)$$

For the computer calculation, the discrete conversion is applied. Let's introduce the following substitutions:

$$\upsilon = \frac{\xi}{\lambda d};\ \mu = \frac{\eta}{\lambda d}. \quad (8)$$

Equation (6) will be rewritten as follows:

$$\Gamma(\xi,\eta) = \frac{i}{\lambda d}\exp[-i\pi\lambda d(\upsilon^2 + \mu^2)]\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y)R(x,y)\exp[-i\frac{\pi}{\lambda d}(x^2 + y^2)]$$
$$\times\exp[i2\pi(x\upsilon + y\mu)]dxdy. \quad (9)$$

Value $\exp(-i2\pi/\lambda d)$ is omitted, because it influences only the general phase. This value doesn't change intensity and the phase interference of digital hologram.

Comparing (9) and the Furies transformation it's noticeable that this is reverse Furies transformation for $h(x,y)R(x,y)\exp[-i\frac{\pi}{\lambda d}(x^2 + y^2)]$, multiplied on spherical phase factor:

$$\Gamma(\upsilon,\mu) = \frac{i}{\lambda d}\exp[-i\lambda d(\upsilon^2 + \mu^2)]\zeta^{-1}\left\langle h(x,y)R(x,y)\exp[-i\frac{\pi}{\lambda d}(x^2 + y^2)]\right\rangle. \quad (10)$$

Function Γ is calculated if *h(x, y)* saved in *NxN size matrix*, with steps Δx and Δy along coordinates. Δx and Δy are distances between two pixels on the camera in horizontal and vertical directions. By using discrete values the integral (9) can be rewritten in the form of sums:

$$\Gamma(m,n) = \frac{i}{\lambda d}\exp[-i\pi\lambda d(m^2\Delta\upsilon^2 + n^2\Delta\mu^2)]\sum_{k=0}^{N-1}\sum_{l=0}^{N-1} h(k,l)R(k,l)\exp[-i\frac{\pi}{\lambda d}(k^2\Delta x^2 + l^2\Delta y^2)]$$
$$\times\exp[i2\pi(k\Delta x m\Delta\upsilon + l\Delta y n\Delta\mu)]. \quad (11)$$

According to the theory of Furies transformation there is some dependence between Δ*x*, Δ*y* and Δυ, Δμ:

$$\Delta\upsilon = \frac{1}{N\Delta x}\ \Delta\mu = \frac{1}{N\Delta y}, \tag{12}$$

then

$$\Delta\xi = \frac{\lambda d}{N\Delta x}\ \Delta\eta = \frac{\lambda d}{N\Delta y}. \tag{13}$$

Considering (12) and (13), (11) is rewritten as:

$$\Gamma(m,n) = \frac{i}{\lambda d}\exp[-i\pi\lambda d(\frac{m^2}{N^2\Delta x^2} + \frac{n^2}{N^2\Delta y^2})]\sum_{k=0}^{N-1}\sum_{l=0}^{N-1} h(k,l)R(k,l)\exp[-i\frac{\pi}{\lambda d}(k^2\Delta x^2 + l^2\Delta y^2)] \times\exp[i2\pi(\frac{km}{N} + \frac{\ln}{N})]. \tag{14}$$

Formula (14) is the discrete transformation for digital hologram reconstructing and for further obtaining the surface information.

Let's consider the dependence between the diameter of the surface under research and the waveguide parameters. The number of modes that can spread in gradient waveguide is calculated using the formula $M=V^2/4$, where $V = \frac{2\pi}{\lambda}a\sqrt{n_1^2 - n_2^2}$. To be able to record surface in the right way, the phase difference in two nearest pixels shouldn't exceed λ/2. That's why Δx – distance between two pixels, that should be registered by the device, depends on the object of studying. The diameter of the surface that is observed is calculated using formula:

$$d = 2\sqrt{\frac{\pi a^2(n_1^2 - n_2^2)\Delta x^2}{\lambda^2(1 + 2\Delta x + \Delta x^2)}}. \tag{15}$$

Taking into consideration that the normalized frequency depends on other parameters, we get:

$$V = \frac{2\pi}{\lambda}a\sqrt{n_1^2 - n_2^2}. \tag{16}$$

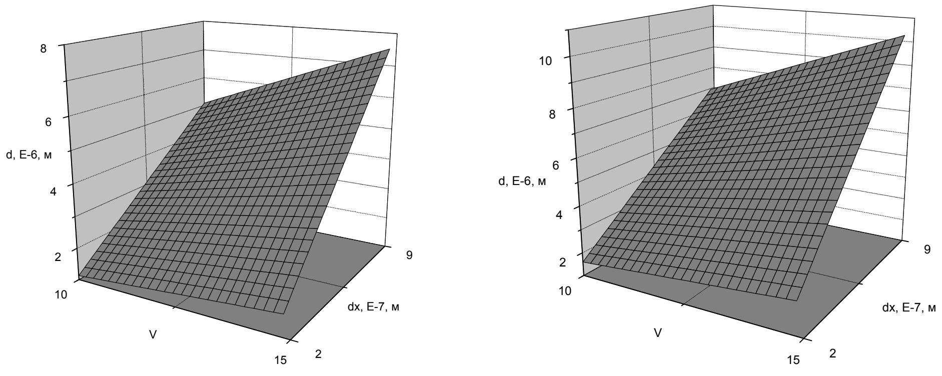
Let's transform formula (15), using the expression (16). Formula for calculating the diameter of the surface of studied object using gradient waveguide is as following:

$$d = 2\Delta x V\sqrt{\frac{1}{\pi(4 + 8\Delta x + 4\Delta x^2}}. \tag{17}$$

For comparing, let us write the formula for calculating the diameter of the surface of studied object that can be obtained using waveguide with stepped refraction value. Taking into consideration that for this type of waveguide number of modes that can spread in it, is calculated by using formula $M=V^2/2$ [7], we will write the formula for calculating the diameter of the measured surface:

$$d = 2\Delta x V\sqrt{\frac{1}{\pi(2 + 4\Delta x + 2\Delta x^2}}. \tag{18}$$

Let's make some calculation using formulas (17) and (18), to get some numeric results as for transferring possibilities for two waveguide types: gradient and fiber with stepped refraction value. Graphics displayed on the image 2 show the dependence of the measured diameter from accurateness of measurements *dx* and normalized waveguide frequency *V*. It is seen on the graphics that the fiber with the stepped refraction value gives better results for image transmitting, the diameter of measured surface is bigger than when using gradient fiber. But this difference is not that big and the gradient fiber is going to be used because of it’s better characteristics when different modes phase incursion measuring [5].



а) б)

Image 2. Dependence of the measured surface diameter on normalized frequency for: a) gradient fibers; б) fibers with stepped refraction value

Conclusions

The conducted researches allow to make a conclusion that the application of the described model allows to create the device for obtaining the three dimensional images from the places which are difficult to get access to. Optical waveguide presence allows to use it in different fields. Even when using it under the conditions of radiation illumination, the transferred image would not be distorted. There is the possibility to record with future reproducing the objects view, using computer for image processing. The diameter of optical waveguide is very small and this fact allows to use the device for studying the places which are difficult to get access to in places with small holes. Setting the appropriate distance between the nearest points on the object of studying, the parameters of the device can be easily changed to fit the requirements.

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Sergey Dovgalets – Dean of the faculty of Automation and Computer Control Systems;

Vityalii Tomkiv – student;

Oleksandr Goncharuk – Post-Graduate student;

Elena Mochulska – student.

The Department for Automation and Informational Measurement Techniques, Vinnytsia National Technical University