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PRINCIPLES OF RECORDING IMAGE-MATRIX HOLOGRAPHIC STEREOGRAM

Abstract
A method for producing holographic stereograms by image-matrix recording technology with reduced geometrical constraints is presented. The type of holographic stereogram produced can offer a combination of large viewing zone, arbitrary viewing distance, minimal image distortion, and high spatial resolution, depending on alterable parameters in the image processing software. The techniques described are applicable to one step recording stereograms with horizontal parallax. Because of the difficulty of recording a full two-dimensional array of parallax images, the holographic stereograms are horizontal parallax only, using a linear series of view to present horizontal parallax while eliminating less-useful vertical parallax. For producing 3D effect holographic stereograms present a series of discrete apertures to the viewer, each contains information from a single two-dimensional image of an object.
Keywords: holographic stereogram, image-matrix holography, stereo vision

Introduction

Recently, dot-matrix and image-matrix holograms based on diffraction gratings have become widely used as anti-counterfeiting devices where they are employed to protect documents against forgery [1-4]. Such protective holograms cannot be reproduced by conventional colour scanning or printing technique and therefore find a wide range of applications in document security field. In order to increase protection efficiency, holograms are rapidly integrated with other protective elements one of which is a stereogram. The digital holographic stereogram is one of the highest quality methods for displaying three-dimensional objects with help of computer-generated synthetic images. Holographic stereograms present a series of discrete viewpoints (apertures) to the viewer, each contain information from a single two-dimensional image of a scene. Instead of recording a three-dimensional 'real' object a sequence of flat two-dimensional images of an object are recorded. Each image is a single view from a sequence of 'parallax images' and all of them are recorded together in the sets of complex pixels on the master hologram. One complex pixel contains diffraction pattern for reconstruction of one graphical dot of all initial parallax images in to the corresponding viewing zones. The 'image-matrix' technology for optical recording of protective holograms is currently dominate in applied holography [5]. This technology can be considered as laser beam interference lithography and allows fast and large area periodical structures to be patterned with relative simple equipment. The interference lithography principle is based on the interference of two or more coherent lights to form a horizontal standing wave for grating pattern which can be recorded on the photoresist. This paper presents the theoretical and experimental results to create holographic stereograms using "image-matrix" recording technology.

Theoretical background

The principle of dot-matrix holography is based on decomposition of a hologram image into a two-dimensional array of elementary pixels containing diffraction gratings with parameters that need mathematical calculation. Their size usually lies in the range of 10-100 μm and depends on the technology of optical recording that is used. In each elementary pixel of the hologram there is a diffraction grating with certain period ***d*** and orientation angle φ relative to horizontal axis in the plane of hologram (**Fig. 1a)**. Size and shape of pixels may also change.

The calculation task is to define the condition that a particular pixel of a hologram would direct a given spectral part of diffracted light towards the observer. The observer can see diffracted light from each element of a hologram only at a certain angle; and the total perception of diffraction of all elements makes a visual effect that corresponds to the initial graphic design. It is obvious that the main factors for reconstruction of the whole hologram are orientation and period of diffraction grating in each pixel, as well as position of an observer and the light source during the reconstruction. In these conditions, the holographic image will correspond to the initial graphic design. If the positions of an observer and the light source are defined, period ***d*** and orientation angle $\boldsymbol{\varphi}$ (**Fig. 1b)** of the grating completely determine the conditions when an incident white light can be diffracted with the given spectral region towards the observer. In this case, the color of the hologram element corresponds to the color of a dot in the initial graphic image.

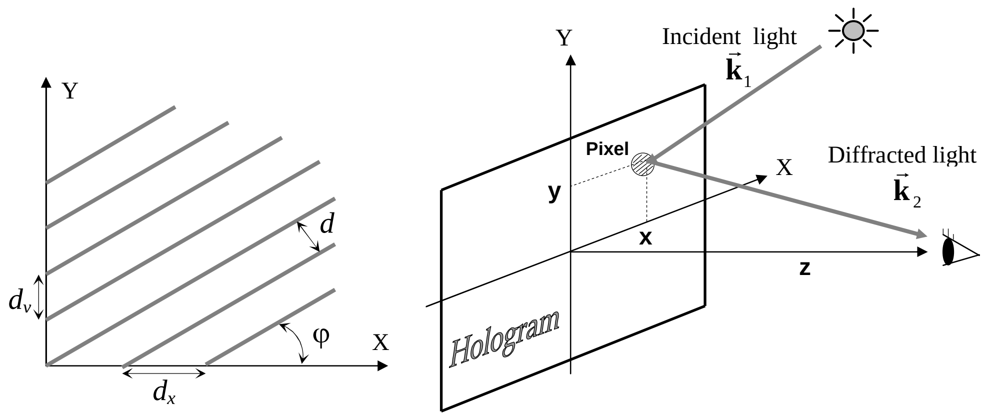


Fig. 1. a) Parameters of diffraction grating. **b)** An image element formation by diffraction pixel.

The coordinate system XYZ is chosen in such a way that the hologram is lying in the plane XY, and the Z axis directed to the observer from the center of the hologram (**Fig. 1b**). Assume that the observer's eye is on the Z axis at the distance of about 30 cm. The light source illuminating the hologram has a continuous spectrum in the visible region, and the direction of the incident radiation is given by the unit vector $\vec{k}_1$. We must define the parameters (d,φ) of the diffractive pixel with the coordinates (x,y), which the observer can see in the color with the wavelength λ_0. If the light with the wavelength λ falls on a flat diffraction grating along the unit vector $\vec{\mathbf{k}}_1 = (\cos\alpha_1, \cos\beta_1, \cos\gamma_1)$ the direction of diffraction, which is defined by the unit vector $\vec{\mathbf{k}}_2 = (\cos\alpha_2, \cos\beta_2, \cos\gamma_2)$, can be determined by the formulas [6]:

$$\cos\alpha_2 = \cos\alpha_1 \pm \frac{\lambda}{d_x}; \quad \cos\beta_2 = \cos\beta_1 \pm \frac{\lambda}{d_y}; \quad \cos\gamma_2 = \sqrt{1 - \cos^2\alpha_2 - \cos^2\beta_2}\,. \qquad (1)$$

We take the position of a point source with continuous spectrum of light in the plane YZ. If the angle between the Z axis and direction from the light source to the hologram center is θ, then $\vec{\mathbf{k}}_1 = (0, -\sin\theta, \cos\theta)$, where the change of the Z-component of incident light after reflection from the hologram surface is taken into account. The direction of the +1 diffraction order from the pixel with the coordinates (x,y) to the eye of the observer is defined by the ort vector $\vec{\mathbf{k}}_2 = (-\frac{x}{L}, -\frac{y}{L}, \frac{z}{L})$, where $L = \sqrt{x^2 + y^2 + z^2}$ is the distance between the pixel and the eye of the observer. Taking into account the above mentioned conditions, the formulas in (1) will look like the following:

$$\cos\alpha_2 = -\frac{\lambda\sin\varphi}{d}; \quad \cos\beta_2 = -\sin\theta + \frac{\lambda\cos\varphi}{d}; \quad \cos\gamma_2 = \sqrt{1 - \cos^2\alpha_2 - \cos^2\beta_2} \qquad (2)$$

For the central pixel of the hologram with coordinates $(0,0)$ and the color λ_0 based on the formulas in (2), we obtain the following parameters of the diffraction grating: $(d,\varphi) = (d_0, 0) = (\frac{\lambda_0}{\sin\theta}, 0)$, where $d_0 = \frac{\lambda_0}{\sin\theta}$.

At the next step, we can define the parameters (d,φ) of a pixel with the coordinates (x,y) having the same visual characteristics (color, brightness) for the observer as in the case of the central pixel. This requires solving a system of equations for the variables d and φ:

$$\cos\alpha_2 = -\frac{\lambda_0\sin\varphi}{d}; \quad \cos\beta_2 = -\sin\theta + \frac{\lambda_0\cos\varphi}{d}; \quad \cos\alpha_2 = -\frac{x}{L}; \quad \cos\beta_2 = -\frac{y}{L}\,. \qquad (3)$$

From the equations in (3) we can find the formulas for calculating the parameters of diffraction gratings of the pixel:

$$\operatorname{tg}\varphi = -\frac{\cos\alpha_2}{\cos\beta_2 + \sin\theta} \quad \Rightarrow \quad \varphi(x,y) = \operatorname{arctg}\left\{\frac{x}{L\sin\theta - y}\right\} \qquad (4)$$

$$d = -\frac{\lambda_0\sin\varphi}{\cos\alpha_2} \quad \Rightarrow \quad d(x,y) = \frac{d_0\, L\sin\theta}{\sqrt{(L\sin\theta - y)^2 + x^2}} \qquad (5)$$

Calculation of pixel parameters for stereograms performs according to formulas (4,5) It is only necessary to take into account a position of observation for each parallax image of the hologram that can be achieved by replacing the old variables (x, y) in formulas (4,5) by the new ones $(x - x_i, y - y_i)$, where (x_i, y_i) indicate the positions of viewing zones in the observation plane (**Fig.2**).

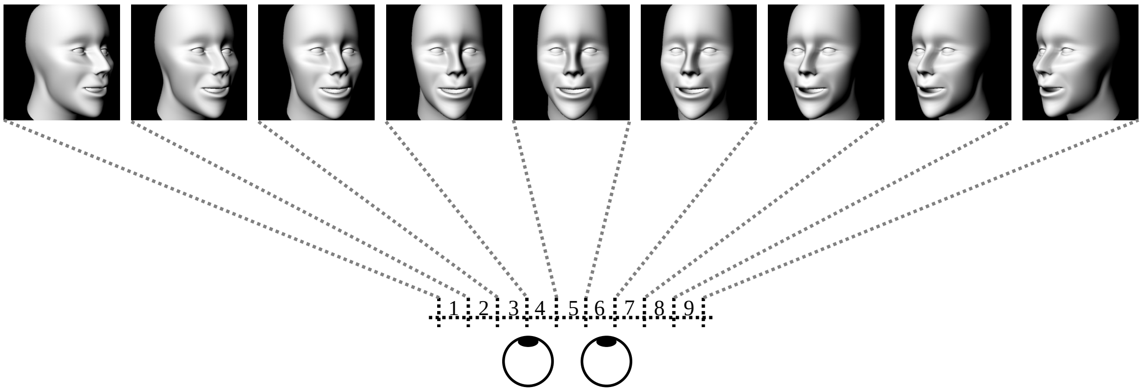
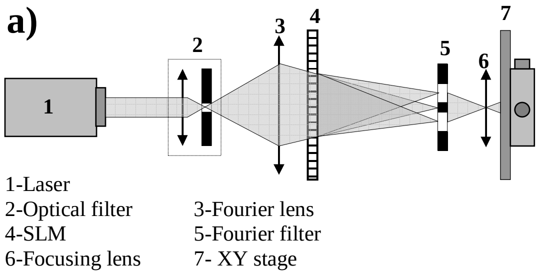


Fig.2 Reconstruction from holographic stereogram the set of parallax images into successive zones of viewing (apertures).

Results and discussion.

The most important thing which helps us to see the world in three-dimensions is the phenomenon of parallax. When you look at an object, you see only the front side. When you move your head to one side you see the front and another side of the object. This is also very important in holography and constitutes the most common difference between photography and holography. When you are look at a hologram, you can see the image in different visual angles when you move your head to the side just as and when you are looking at a real object. This phenomenon is called parallax. During the reconstruction of a hologram with horizontal parallax, the observer sees the image of the object in two different perspectives. When we look at a real object, we also see the object in two different perspectives, because there is a space between our eyes. The basic principle of stereogram formation lays in the combination of several photographs of an object from different angles in to one hologram. Each of these pictures are then to be recorded onto a little areas of the holographic film plate and can be recovered with help of illumination into the different viewing zones.

For recording a diffraction grating with certain size, period and the orientation angle the image-matrix optical set-up shown in **Fig. 3** was used. It utilizes a diode laser (100 mW, 405 nm), whose cleared and expanded beam illuminates a transparent SVGA (800x600 pixels) spatial light modulator (SLM) located behind Fourier lens.



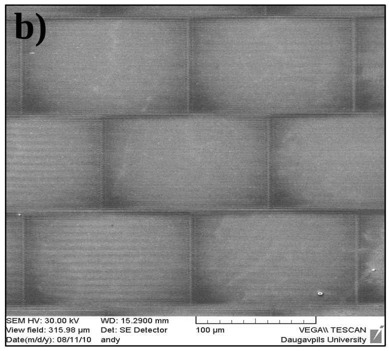


Fig. 3 a) Optical scheme of recording device.
b) Structure of image-matrix hologram.

A spatial filter is positioned in the Fourier plane behind the SLM to block a zero order and the orders higher than both first orders. After the inverse Fourier transformation, a hologram is created with the help of a micro objective by interference of the I_{+1} and I_{-1} orders of the wave diffracted at the modulator. An image is displayed on the SLM is reduced to a microscopic size by a lens system and recorded in a photoresist plate placed on a XY-stage. Each separate matrix image displayed on the SLM contains a set of gratings with a grating pitch and orientation adjusted to the requirements.

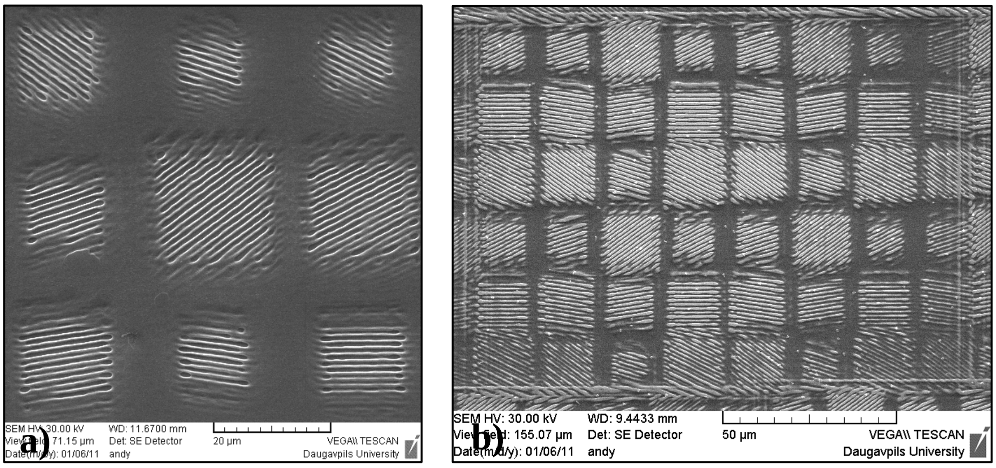


Fig. 4. a) Electron microscope image of stereogram complex pixel consisting from nine sub pixels corresponding to the different parallax images. **b)** Electron microscope image of one frame of holographic stereogram.

The figure **Fig. 4a** shows us the method how the pixels of nine parallax pictures are multiplexed into one complex pixel of stereogram. **Fig. 4b** shows a SEM image of one frame of the stereogram containing 9 combined images for creating an illusion of a 3D object. In this case, each frame consists of an array of 8x6 pixels of size 15 μm. Every pixel in the array corresponds to a graphic point in one of the combined images. Each of the combined images is visible from a certain angle that is determined by the orientation of diffraction grating of pixels, appropriate to this image. The size of a pixel is proportional to a level of grey color of the appropriate graphic point. The **Fig. 5** shows the results of the recording a holographic stereogram by the described method.

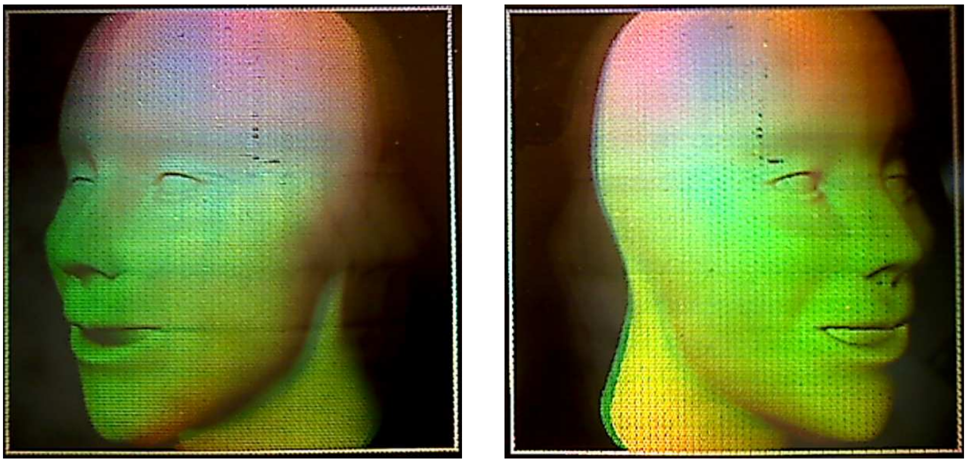


Fig.5 Photo of images recovered from holographic stereogram and received from different viewing zones.

Conclusion

The proposed method allows for calculation and integration of a holographic stereogram elements into the structure of an image-matrix hologram with help of self made computer programs. This method of recording stereogram can be considered as alternative to the existing methods in terms of competitive efficiency. The presented technology has been tested and can be readily used as an additional degree of protection in the production of 'image-matrix' holograms.

Acknowledgments

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