Holographic 3D imaging – methods and applications

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Holographic 3D imaging - methods and applications

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Abstract. In this paper, different techniques of three-dimensional holographic imaging with respect to particular applications are discussed. The realization techniques based on image synthesis at the hologram plane and at the observer's eye pupil plane are presented and compared with classical image holography approach. Each technique is accompanied with an example of the hologram, that was created using some of the in-house developed devices.

1. Introduction

Modern 3D visualization techniques can be applied in many sectors (entertainment industry, medical applications, etc. [1, 2]). During the last decade, the non-holographic computer based techniques took the lead in the 3D displaying industry [3, 4]. Although 3D visualization using these so called stereoscopic techniques can be sometimes even more realistic than holography (true color, motion), it brings also specific problems. For example accommodation of observer's eye is often in disagreement with vergence of eye-pair, which can be significantly disturbing for some observers. Therefore, for some applications, the holographic approach still represents the only sufficient alternative.

Nowadays, the progress in holography is mostly carried by the synthetic approaches. These approaches allow us to employ and take the advantages of the stereoscopic methods in holography [5, 6]. For example it is possible to create holograms of large sceneries, holograms of living objects or even holograms of moving objects. The model for the synthetic hologram can be fully virtual, created in a 3D modeller in a computer.

First approach, that will be discussed is direct writing of the hologram structure using a lithographic device. Mostly these holograms are created using either electron beam lithography or laser beam lithography [7]. Not to say, that e-beam technology is not suitable for synthetic holography, however in the particular case of synthetic image holograms it is kind of overkill. Therefore, in this case, we will focus on laser beam lithography. The laser lithography can not achieve such a resolution as e-beam, but it has way lower operational costs and higher throughput.

Using the laser (or e-beam) lithography, one of the most important problems is joining the exposed elements into larger area with high accuracy. This puts very high demands on the positioning systems of the lithographs and restricts the area of the hologram up to a few square centimeters (considering reasonable costs and reasonable exposure times) [8]. Therefore, these techniques are not very suitable for creating larger synthetic holograms.

Synthetic holograms of larger scale can be created using the method, where the multiplexing of the stereoscopic images is not created at the plane of the hologram, but at the plane of

the observer's eyes. This kind of synthesis is mostly done in two-step setup. The set of 2D stereoscopic views is recorded into a master-hologram (first step) and then it is transferred into a final hologram (second step).

The image synthesis, however, can be used also in "classical" image holography. By classical, we mean recording the hologram from a real model in an optical setup on an optical table. Several different objects can be recorded into one hologram, for example to create an artistic impression. In our case, we used synthesis in classical image holography to create an object for opthalmologic system for dynamic measurement of ocular deviations [9].

All of these methods have its advantages and disadvantages and are suitable for different particular applications. A comparison will be given in the following text.

Before presenting the synthetic holography techniques, it is necessary to understand the stereographic principles.

2. Stereography

The visual sense of a 3D scene is caused by our brain interpreting the image information from both eyes. Due to the relative position of our eyes, the image from the left eye slightly differs from the image from the right eye. This is the crucial aspect causing the 3D sense and that is why it is used in hologram synthesis. There are also other cues that enter the image processing in our brain, however they are not that strong [10].

In fact it is possible to use only a stereoscopic pair of images to create the 3D sensation. The displaying methods that use only a pair of planar views are called binocular and it can be for example Anaglyphs or the modern 3D cinemas [11, 12]. The main disadvantage of these methods is the lack of movement parallax.

The movement parallax can be "added" using the autostereoscopic methods, when more than two angular views of an object are multiplexed together [13, 14]. In such a case, the displaying device creates the viewing zones and the observer, while moving, enters the different zones and sees the object from a different angle. The examples are integral photography, synthetic holography, or the classical image holography (see Figure 1).
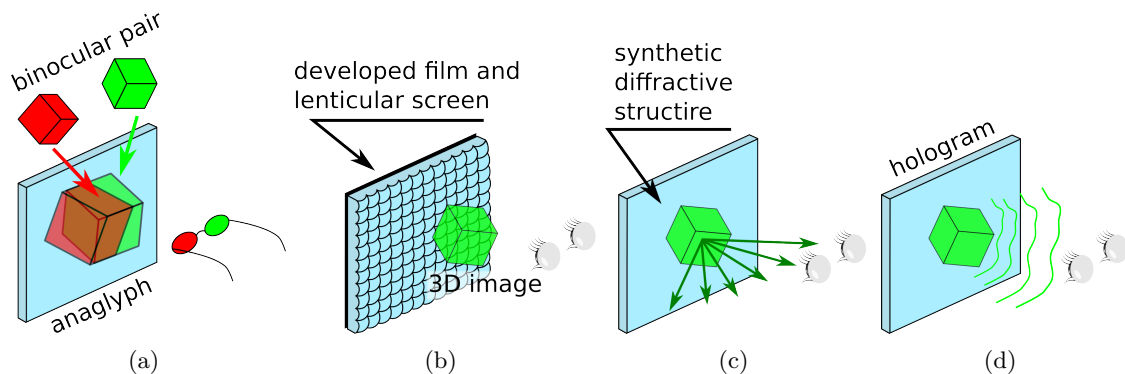
Figure 1. 3D displaying methods: **(a)** In binocular methods, only two channels are employed which overlap each other in space. In this case, an anaglyph is shown. **(b)** Integral photography is an example of non-diffractive autostereoscopic methods, in which multiple viewing zones are spatially separated. **(c)** Diffractive autostereoscopic methods create the spatially separated viewing zones as in case (b). **(d)** Hologram is capable of reconstructing the image wavefront in its full complexity. It acts as if there is infinite number of viewing zones.

To create the synthetic hologram, it is necessary to capture the set of 2D stereoscopic views. These images can be obtained using a real camera taking pictures of a real object or using a

virtual camera capturing a virtual 3D object in a PC. The way of capturing depends on the demands on the 3D behavior of the reconstruction - if the final hologram should be composed of both parallaxes or if it should be single parallax only. Figure 2 shows one of the possible capturing setups for both the single-parallax and the full parallax case.
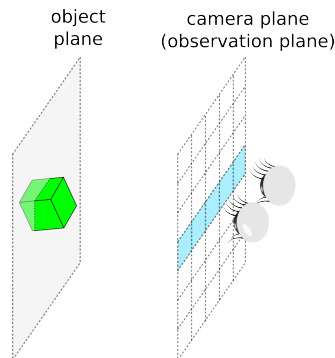

Figure 2. The positions of the viewing zones are coincident with the positions of a camera during the capturing process. Therefore the setup is the same for both cases except that the "capturing" camera lens is changed for the "viewing" eye lens. The figure shows the equidistant capturing with linear movement of the camera. The blue line represents the single parallax case - in each "square" one snapshot is taken. The whole array represents the case of capturing both parallaxes when the camera moves in two mutually perpendicular directions.

3. Synthesis at the hologram plane

Holograms of this kind are directly written using some of the lithographic techniques. The method is based on the limited resolution of the human eye in the image plane. When the hologram is observed from the conventional distance $\sim 25\,\text{cm}$, the approximate resolution limit of the human eye is $\sim 0.1\,\text{mm}$. From the point of view of diffractive structures such a dimension is large enough for carrying much more than just the information about a single point. As a rough estimate, if we assume an elementary diffraction grating with period $\sim 800\,\text{nm}$ and area $4 \times 4\mu\,\text{m}$ (which contains 5 periods of such a grating), we can place more than 600 different gratings within the area of $0.1 \times 0.1\,\text{mm}^2$. The main idea of image multiplexing at the hologram plane is based exactly on this idea.

To understand the method one has to realize how the principle of stereoscopy applies for the given geometry. Let us assume the situation according to Figure 2. If the observer sees the 3D image floating in the neighborhood of the hologram plane, it means, that each point on the hologram should send different information to the different directions (meaning that the visibility of the particular point on the hologram surface in terms of color and intensity is dependent on the observation angle). The idea of realizing an angularly selective image on the base of diffraction is pretty straightforward. Therefore, each distinguishable point on the hologram surface (a macro-dot) is divided into a set of smaller units (micro-dots). Each micro-dot is filled with a regular grating with appropriate period and orientation. By changing these two parameters, it is possible to adjust the proper color and direction of diffraction. An illustration of the macro-dot/micro-dot structure can be seen in Figure 3.

Most holograms synthesized using this method are of rainbow type, thus the vertical parallax is omitted and angular views are captured only in the horizontal direction. This significantly reduces the number of necessary micro-dots. In practice, usually 9-16 angular channels are used to create a satisfactory 3D perception.
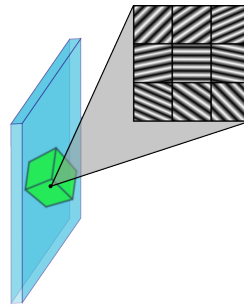
Figure 3. Basic idea of generating the spatial image channels using diffraction gratings.

The basic colors of the hologram are the spectral ones. If a non-spectral color is required (e.g. white), the additive color mixing must be introduced. The most common way of achieving a mixed color is to use two or three spectral colors, usually red, green, and blue (RGB). These colors are obtained by the means of diffraction from the gratings.

The true-color micro-dot is divided into three smaller areas, each filled with one grating. The relative areas of these three gratings control the contributions of each of the colors to the true-color mix. Furthermore, the area of the micro-dot is divided into two major parts - one filled with grating and the second empty. The ratio of these areas defines the overall luminosity of the image point. An example of this kind of hologram, created at the department is shown in Figure 4.


(a) (b) (c)
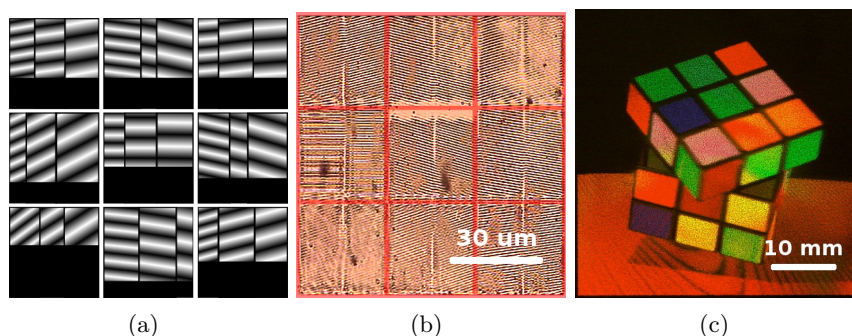
Figure 4. Directly written synthetic hologram: **(a)** Theoretical idea of macro-dot segmentation for RGB color mixing, **(b)** image of a real micro-structure, and **(c)** an example of the real reconstruction of the true-color RGB synthetic 3D rainbow hologram.

Advantages of the directly written holograms are mainly in the high achievable contrast, color saturation, and in the big variety of the features that can be implemented into the final hologram (especially in the field of optical document security). The biggest disadvantage is in the area limitation due to the necessity of very precise positioning of the recording material and due to low throughput for the holograms bigger than a few square centimeters.

4. Synthesis at the eye-pupil plane

In the case of synthesis at the eye-pupil plane, the final hologram is created in two steps. Recording the master-hologram and transferring it into the final one. The discretization of the spatial information is not processed at the plane of the final hologram as it was in the previous case. The micro-structure of the final hologram is continuous as in the case of classical

holography. The discretization is brought in during the step of transferring the synthetic master-hologram. The master-hologram consist of many "small" separated holograms representing the particular viewing zones (as in Figure 2). These primary holograms create multiple signal beams that interfere with the reference beam during the transfer process and create the final continuous micro-structure. The name of the method is derived from the fact that the position of the former master-hologram coincides with the eye-pupil plane when viewing the final hologram. The principal method of this synthesis is shown in Figure 5.

(a)   (b)
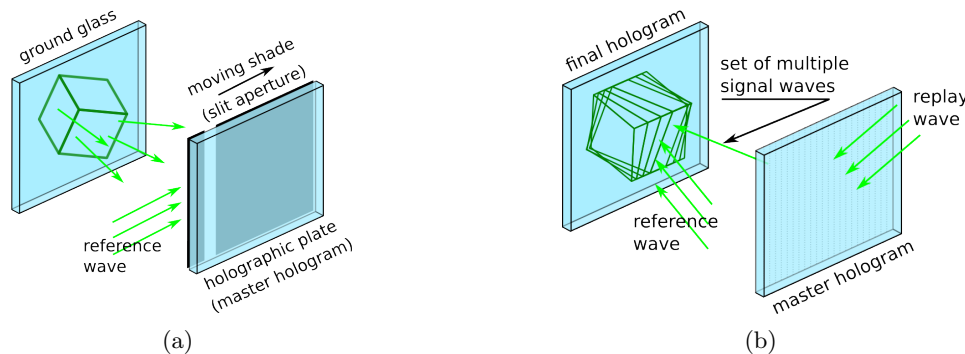
Figure 5. Hologram synthesis in the eye pupil: **(a)** The 2D views are sequentially displayed on a ground glass screen and recorded as elementary holograms in the form of narrow stripes. This means that the master-hologram is composed of a number of these elementary holograms placed next to each other. **(b)** The transfer scheme. All the stripes from the master-hologram are replayed at once using a conjugate "reference wave" from (a). All the reconstructed images overlap in the former ground glass plane and the final hologram is recorded.

In the case shown in Figure 5, there is only horizontal parallax recorded. Therefore, the final hologram is of the rainbow type. However, it is possible to modify the recording setup to create master holograms with both parallaxes. Such a master hologram can be then copied into final reflection hologram. To create the master hologram with both parallaxes, we have developed a fully automatic recording device. The scheme of this device can be seen in Figure 6.

The 2D image, representing a particular view, is uploaded to a transparent SLM. The signal wave passes through the SLM and the 2D image is focused by the writing objective onto its image plane with some magnification. Near the output pupil of the objective, the pattern of interference between the signal and reference beam is recorded onto a holographic plate. Then the plate is moved, the image on the SLM is switched for the next view and the next viewing channel is recorded, and so on. The movement of the holographic plate is compensated by moving the SLM in opposite direction (to keep all the views in register). When exposing hologram with two parallaxes, the procedure is repeated in two perpendicular axes.

Since the reference wave was collimated during the recording, the replay beam can be a wide collimated wave that reconstructs all the recorded views at once. All the reconstructed images overlap at the place where the object was situated during capturing. The final hologram plate is placed into this place and the final hologram is recorded (similar to Figure 5b).

The color mixing in this case of synthesis is processed already during the recording of the master hologram. Since the complete recording process is performed using a single laser (including the transfer process of the master-hologram), the three different color channels are achieved using three separate master-holograms. Reconstruction of these three masters during the transfer process provides three angularly separated sets of signal waves and three different "color" gratings are recorded. In practice, the master-hologram for color mixing consists of three independent vertically shifted rows of exposures. Each of the signal waves coming from the three
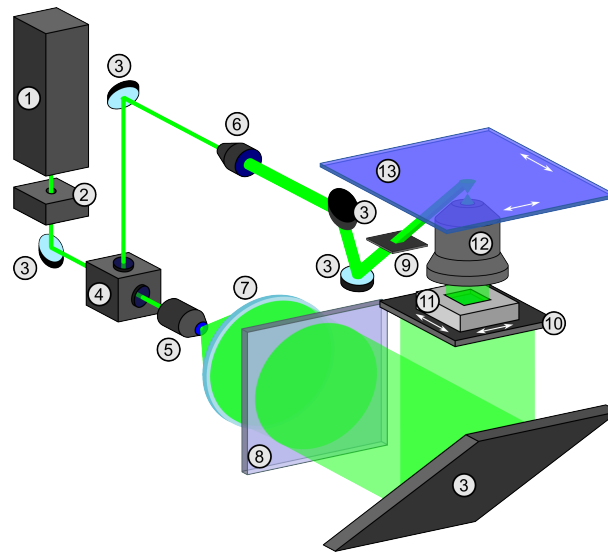
Figure 6. Scheme of the eye pupil synthesis device: **1** laser, **2** shutter, **3** mirror, **4** beam splitter, **5** microscope objective with spatial filter, **6** beam expander, **7** collimator, **8** holographic ground glass, **9** square aperture, **10** signal shade, **11** SLM, **12** special objective, **13** holographic plate.

channels carries the same spatial information about the object and the relative intensity of the waves is adjusted according to the desired color. Figure 7a shows copying of such an RGB synthetic master into the final hologram and Figure 7b shows the diffraction of white light on the final rainbow hologram.

(a)   (b)
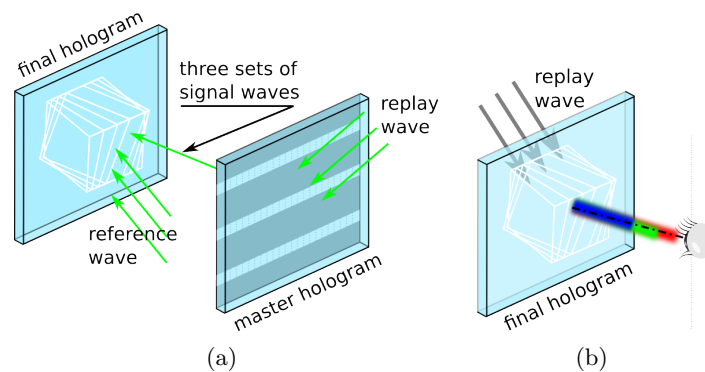
Figure 7. (a) Transferring three color masters into final RGB color rainbow hologram. **(b)** Reconstruction of the final hologram from the step (a) with white light replay beam. Only the orders that are diffracted in the direction of the observer are indicated in the figure.

In Figure 8a there is an example of the RGB color master for a rainbow hologram synthesized using our device. The final hologram (copy of the master) is displayed in Figure 8b.

The main advantage of this method over the method of synthesis at the hologram plane is in the achievable size of the final hologram - unlike the directly written synthetic holograms, there is no high demand on accuracy of the positioning of the recorded stripes. Furthermore, the size of the final image is not limited by the size of the master-hologram, but by the size of the image on the screen. The general disadvantage of this method is in lower contrast and color saturation compared to the directly written synthetic holograms.

(a)   (b)
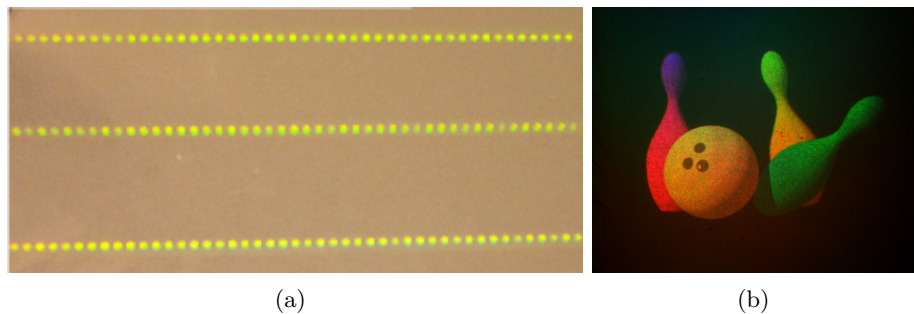
Figure 8. **(a)** Photograph of the "RGB color" master-hologram. The three color channels can be clearly seen. **(b)** Photograph of the final color synthetic rainbow hologram, that was obtained using the master from step (a).

5. Synthesis in classical image holography

It is not that common to use hologram synthesis in classical holographic setup, however there are several areas where the synthesis of more models into one hologram may be very useful. An example of such a synthesis conducted at the department is a synthetic hologram for opthalmologic system for dynamic measurement of ocular deviations. The task was to create a hologram for the measurement according to Figure 9. The hologram includes four images of a digger in two different positions. The examination consists of rapid switching between the reconstruction sources, while the camera is observing the eyes of the patient in IR.
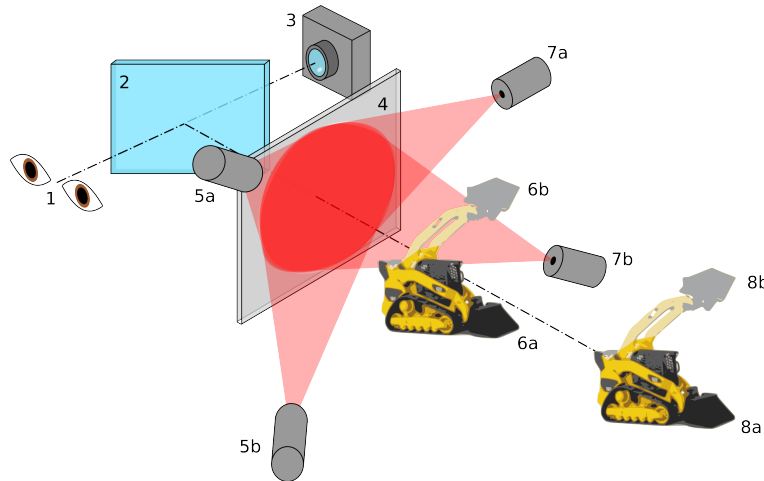
Figure 9. Dynamic measurement of ocular deviations:**1** pacient, **2** beam splitter, **3** camera, **4** synthetic hologram, **5** reconstructing lasers for closer images, **6** closer image, **7** reconstructing lasers for distant images, **8** distant images.

To make such a hologram work, all the sub-holograms should be approximately of the same efficiency. Therefore, the final hologram is composed of two plates, each for one position of the digger. Each plate than has two exposures in it. Each with different reference wave for a different position of the bucket. The two holograms are sealed together so that the emulsions are in contact.

Advantages of this method would be in the continuous change of the viewing angle, high achievable contrast and high versatility of the recording scheme. However, since everything in

the process has to be "hand-made", this technique is extremely time demanding. Also, a big disadvantage is the need for a real model for the synthesis.

6. Conclusions and Acknowledgements

The three synthetic holographic methods have been presented and compared. All the methods have been accompanied by examples of holograms that have been created at the department. Each of them has its specific advantages and disadvantages which determine/limit their usage. Therefore, it is certain, that none of the methods would vanish, no matter how some of them would be prioritized.

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