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Field Reconstruction of Holograms for Interactive Free Space True Three Dimensional Display

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Abstract: Nowadays, the 3D display technology has attracted great academic and industrial attention due to its rapid development and applications in providing more realistic, natural, and extra depth images far superior than the traditional 2D display. But traditional 3D techniques suffer from many drawbacks and hard to meet the requirement of commercialization. In the present study, the field reconstruction method of holograms is proposed for the first time to realize the display of true 3D image in free space which is more practical and better than traditional holographic technique in image quality. An optical switch array (OSA) and a projection lens are used to generate a series of 2D image slice, which can form a virtual 3D object, in free space. Then the light from the virtual object and reference light interference with each other forming an interferometric fringe on the screen and thus the 3D image of the virtual object is reconstructed in free space, timely. Meanwhile, the OSA can work as an image generator and sensor simultaneously which allows user to interact with the reconstructed 3D scenery without extra equipment.

Keywords: 3D Display, Hologram Displaced, Field Reconstruction of Holograms

1. Introduction

Nowadays, the 3D display technology has attracted great academic and industrial attention due to its rapid development and applications in providing more realistic, natural, and extra depth images far superior than the traditional 2D display [1]. To achieve natural 3D visual perception, a considerable amount of efforts have been dedicated, and some practical designs have been proposed. Among them the 3D display technology based on two eyes parallax is the most mature one [2]. But this kind of 3D displays easily cause visual fatigue because of the accommodation–vergence conflict [3, 4] besides some other disadvantages, i.e., the fixed range of the viewing distance, view position, and the fixed interpupillary distance value (usually 65mm). Also, the parallax barrier technology seriously reduces the brightness of images, so it is replaced by lenticular sheet technology in most products. In thelenticular based autostereoscopic display, the role of the lenticular lens is to magnify and transfer the information of specific pixels to adesignated position [5]. However, the depth-reversal is considered as an inherent disadvantage of thelenticular based or the parallax barrier based autostereoscopic displays. Integral imaging is a kind of true 3D technology based on the principle of reversibility of light [6, 7]. But due to the poor resolution and complex structure, even it has been proposed by Lippmann for around a century, it has not got wide acceptance. Volumetric 3D display is another kind of true 3D displays, which has also some inherent limitations [8]. The mechanical rotating components limits the image's spatial and reduces the resolution at the centre of the display.

It is difficult to construct a three-dimensional image in free space allowing view from all directions or positions. From a mathematical point-of-view, the construction of 3D image in free space is a definite boundary solution problem of passive space. If the boundary condition (wavefront) is reconstructed the light field in the passive space will also be reconstructed. In traditional hologram technology the recorded interferogram is used to set the "boundary condition" to get a static 3D image [9]. In order to display a dynamic 3D image a dynamic "boundary condition" is needed. In a typical computer-generated holograms system, spatial light modulator (SLM) is usually used to generate the dynamic patterns [10]. But this kind of hologram display cannot display large and clear 3D image due to the limitations of SLM [4]. A delicate design, proposed by Takaki, overcomes this defect to some extent [11]. In order to get a large computer generated hologram, a horizontal scanner is introduced to scan the elementary hologram generated by the anamorphic imaging system. However, the default shortcoming of computer-generated holograms is that it is difficult to provide a SLM with the pixel counts high enough. A further complexity is to provide the data in realtime.

In fact, there is no need to achieve a full view 3D image display. Audiences usually sit or stand at one side of a 3D display, so they don't care about other sides of 3D images that cannot be seen at their position. Based on these considerations, a new approach to display hologram was proposed by R. Häusslerur [12]. Instead of reconstructing the image that can be seen from a large viewing region, the primary goal is to reconstruct the wavefront that can only be seen at a viewing window (VW). This holographic display omits unnecessary wavefront information and significantly reduces the requirements on the resolution of the spatial light modulator and the computation effort compared to conventional holographic displays.

Another point to consider is to be interactive with the 3D image. This article describes a novel real 3D display method based on field reconstruction of holograms or real-time reconstructed holograms. The novel system introduces the reference light and the virtual object light and let them interfere upon a screen, and then the interferogram is obtained on the screen. Just like the holographic technique, which can show depth information of scenery for that it has recorded the phase of light, in a field reconstructed holograms system, the depth information of scenery can also be provided by modulating the phase of light. And by designing an interactive image generation chip, the 3D display allows user to interact with the 3D display.

2. Design of the Interactive True 3d Display

2.1. Design of an Interactive Image Generation Chip

Firstly, let's design a "T" type optical switch (TOS), which has three ports (A、B and C). As shown in Figure 1a, port A and port B are in a line and the port C is located in between and perpendicular to the line. The function of the TOS is that it can control the incident from port A, which can exit either from port B or port C. Using such several TOSs, an optical switch chain (OSC) can be constructed by stringing several TOSs together in a way that port B of a TOS connects to the port A of the TOS at its right side while the port A of the TOS is joined to the port B of the TOS at its left side. The assembly is completed by placing a quarter wave plate followed by a polarization beam splitter at one end of the OSC. The two unoccupied ports of the splitter are used to connect a laser light source (the angle between the polarization direction of the light and the optical axis of the quarter wave plate should be 45°) and a light sensor respectively, as shown in Figure 1b.

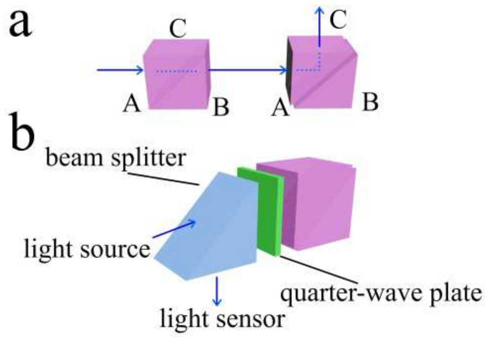

Figure 1. *Illustration of basic function of TOS. (a) Two TOS in series (b) a TOS connected with a quarter wave plate followed by a polarization beam splitter.*

This design allows the light coupled into the OSC to exit through any of the ports Cs of the TOSs in the OSC under control. When the emitted light (from the OSC) hits on an object, some light will be reflected. The reflected light will go reversely along the original light path. The polarization direction of the reflected light will be rotated by 90 degrees when it is transported through the quarter wave plate again. Under the action of polarization beam splitter, the reflected light finally hits the sensor, thus the information (such as finger touch action) brought back by the reflected light can be interpreted.

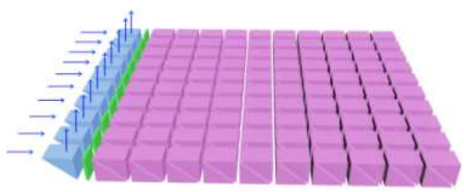

Figure 2. *Schematic of the OSA.*

Figure 2. depicts a two dimensional optical switch array (OSA) composed of several OSCs. The function of the OSA is greatly extended as compared to OSC. Since the color, intensity and position of the output light of the OSA can all be controlled, it can be used to generate images. It can also be considered as a SLM (to generate image), nevertheless it can also be used as an image sensor and the two functions of the OSA can work simultaneously without interplay.

2.2. Principle of Field Reconstructed Holograms

The configuration and principle of the proposed field reconstruction of hologram method is shown in Figure 3 and Figure 4 respectively. It contains an OSA, an imaging lens, a screen, a reference light source (denoted as R in the picture) and an eye tracking sensor. The OSA is used to generate the image and the imaging lens is used to project the image to free space and forms a virtual object (the projected image). It is better to choose the screen made of transparent materials (such as rear projection screen). It is different from the traditional projection system that there is no need to place the screen at the image plain of the lens and also the light source used here are coherent lights. Thus, rather than forming a bright spot on the screen, light from every point of the virtual object lit up a zone on the screen. Meanwhile, if the zone of the screen lit up by reference light overlaps with the zone light by point light source on the virtual object, an interferogram will be formed, which is also the hologram of the virtual object. The light emitted from the virtual object can be mathematically expressed as:

$$O(x,y) = A_o(x,y)e^{i\varphi_o(x,y)} \quad (1)$$

And for the reference light:

$$R(x,y) = A_r(x,y)e^{i\varphi_r(x,y)} \quad (2)$$

Then the amplitude and intensity of interferogram on the screen satisfies:

$$A(x,y) = O(x,y) + R(x,y) \quad (3)$$

$$I(x,y) = A(x,y) \cdot A^*(x,y) = O^2 + R^2 + 2A_rA_o\cos(\varphi_r - \varphi_o) \quad (4)$$

Where * denotes complex conjugate. For simplicity, the $\varphi_r(x,y)$ can be chosen as 0 and this is easy to implement under actual conditions. Then at the modulating action of $O(x,y)$, the transmitted part of reference light can be written as;

$$R_t = (T + \beta \cdot I(x,y)) \cdot R(x,y)$$

$$= (T + \beta \cdot (O^2 + R^2))R(x,y) + \beta \cdot {A_r}^2 \cdot O^*(x,y) + \beta \cdot {A_r}^2 \cdot O(x,y) \quad (5)$$

Where both T and β are constants. At proper condition T becomes negligibly small. In the equation 5, the first term represents the attenuated reference light while the second term is the complex conjugate of $O(x,y)$, which means that it will generate a real image. And this real image can be seen by eyes at the conjugate position of the lens, as shown in Figure 4. The third term has the same form of $O(x,y)$, which will produce a virtual image. The difference between the real image and virtual image is that the former is a converged image while the latter is an emanative one. Thus the light from the real image converges to a certain position (the conjugate position of the lens) and can be seen completely at this position. But the light from the virtual one diffuses to different directions so it can't be seen completely at any position. This phenomenon is depicted in Figure 4. The function of the sensor is tracking the position of eyes and helps to make sure that the eyes are located at the watch window. Because the light source is emitted from the plane surface of the OSA, the image generated on it is a two-dimensional graph. It is well known that lens can project a plain picture to another plain (image plain) and form a magnified image or a diminished image. Although, the field reconstruction of holograms method can translate an image to its conjugate image, it still can't convert a 2D picture into a 3D one. So it's still necessary to find another ways to obtain a 3D image. Since the field reconstruction of holograms method can display a real image at free space, in fact, it's quite easy to generate a 3D image with the help of this method. Putting it simply, the main function of the field reconstruction of holograms method is to convert a diffused real image (such as the image casted to free space by a projection system, which can't be seen completely) to a visible converged image at its conjugate position (conjugate image plain). If the image plain of the projection system is changed then the conjugate image plain will change, correspondingly. In this way, the depth of field of the reconstructed holograms can be controlled by the projection system. As shown in Figure 3, we can change the distance between the OSA and the lens to control the position of conjugate image plain (equals the scan of depth of field) to obtain a real 3D image at free space. A feasible method to realize the scan of depth of field is to make the OSA and/or the lens to oscillate near a certain position.

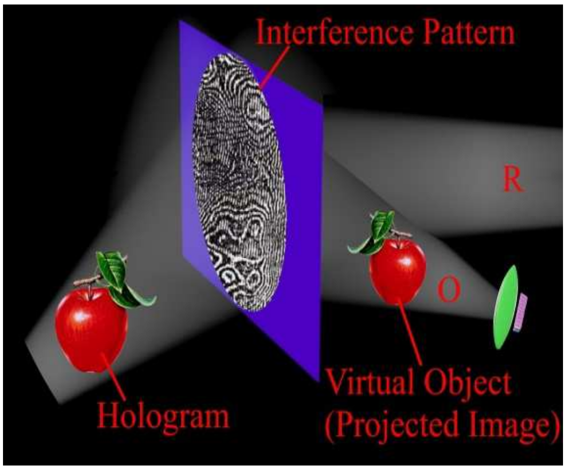

Figure 3. *The configuration of the proposed field reconstruction of holograms method. It contains an OSA (the pink component at right side), an imaging lens (the green component at right side), a screen (the blue square in the middle), a reference light source and an eye tracking component (not shown in the picture).*

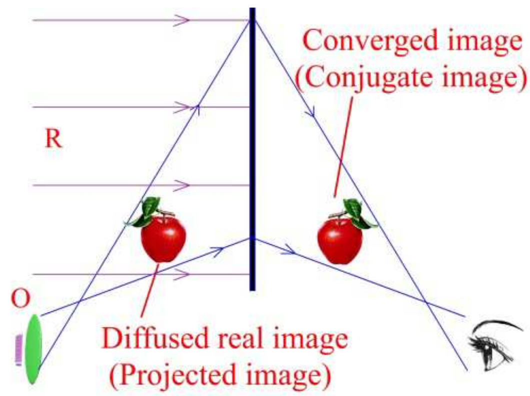

Figure 4. *Illustration of the principle of the field reconstructed holograms. The field reconstructed holograms can convert diffused real image (such as the image that has been casted to free space by a projection system, which can't be seen completely) to a visible converged image at its conjugate position (conjugate image plain). A 3D image thus can be displayed at free space when the image plain of the projection system is changing.*

The next point that needs to be taken into consideration is how to interact with the obtained 3D image? The answer is to touch it with your fingers directly. When the 3D image is touched by finger, some of the light from the 3D image will be reflected by fingers. Due to the reversibility of the physical process, the reflected light will go through the screen, lens, OSA and finally received by light sensor. Then the light sensor can read the information (touch action) brought back by the light. Now the desired 3D image display and interactive functions are both realized in the designed system.

3. Analysis and Discussion

People, those don't familiar with optical physics, may doubt about the feasibility of the scan of depth of field scheme. Does it need large amplitude to acquire an acceptable display volume? Well, take mobile phones as an example. Even the moving distance of the charge coupled device (CCD) in a cellphone camera is much smaller than a centimeter (the thickness of a cell phone is only about 1cm), the camera can take photos clearly at a distance from one tenth meter to several meters. According to the reversibility of optical path, it means that using a similar system we can acquire a display volume of about several cubic meters even the oscillation amplitude of moving parts (image generation chip) is much less than a centimeter. What we need to do is to replace the CCD of a cellphone camera with an image generation chip, such as the above designed OSA, a digital mirror device (DMD) or some other things with the similar function. In order to realize a proper display space we need to configure the system reasonably. We can use the imaging properties of lens to analyze and design a proper system.

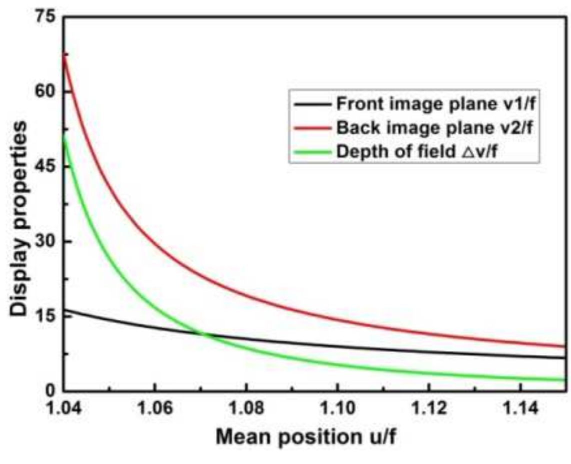

Figure 5. *Display properties of the system (the data is normalized with the normalized coefficient f).*

The mean position (u) and the amplitude of oscillation of the image generation chip besides the focal length (f) of the lens are all the important parameters that need to be set delicately. Once these parameters are established, the properties of the system i.e., the farthest display plain (denotes as v1) and the nearest display plain (denotes as v2) and the depth of field (v1-v2), can be been determined. As depicted in Figure 5, even with the same oscillation amplitude (2.5 percent of the focal length of the lens), when the equilibrium point (mean position) of the image generation chip is located at different distance from the lens, the effective display volume is varied. When the image generation chip moves from farthest position to the nearest place from the lens, the conjugate image plain also moves from one plane to another plane. These two boundary planes can be called front image plane and back image plane and the zone between them is the effective display volume. In fact, when the mean point becomes closer to the focal position of the lens, both the front image plane and back image plane gets further away from the lens. Meanwhile the effective display volume, the zone between front image plane and back image plane, also gets bigger. Furthermore, if a proper mean position is chosen, a large display volume can be obtained even at the condition where the amplitude of the moving component in the system is negligible. Rather than using a moving chip, tunablelens [13, 14] can also realize the function of scanning of field depth. There are some other alternative ways, for example inserting a transparent media with controllable refractive index between OSA and lens. By controlling the refractive index of the transparent media we can also control the effective distance between the OSA and lens, and thus we can control the position of conjugate image plain. In this way we can obtain an all solid system without moving components.

Nowadays, there are some commercial 3D display device, such as virtual/augmented reality helmets [15], but they can't display real 3D object and will introduce the accommodation–vergence conflict problem. WEITAO proposed a omnidirectional-view 3D display [16], which is composed of a rotating selective-diffusing screen and multiple mini-projectors. But the system is very complex and can't display real 3D image. And a default defect of conventional projection system is the low brightness, which makes it almost impossible to work outside. This is mainly because of the reason that the light scattered by the screen attenuates as the inverse square of the distance from the screen. Nevertheless, this problem is eradicated in the novel 3D display. The field reconstruction of hologram process makes sure that the diffractive light will converge at the watch window. In fact, the field reconstruction of hologram method is a combination of volumetric 3D display and traditional hologram technology. It combines the advantage of volumetric 3D display and traditional hologram technology and avoids the weakness of both. An obvious advantage of the field reconstructions of hologram is that the generated holographic interferogram gets rid of the constraints of the resolution of photographic film. This in turn helps a lot in improving the quality of the image. In traditional hologram technology, the image quality is easily affected by speckles that generated by the random interference among object points [4, 17]. Also, the recording condition of a conventional hologram is really strict, even the vibration caused by talking causes the failure of the recording process. All of these inherent disadvantages of tradition holographic technique have been addressed in the field reconstructed holograms technology. Meanwhile, the 3D image generation process of this special 3D display is just like extruding 2D pictures into a 3D one. In a computer generated hologram system, the interferogram is calculated by computer, which is computationally expensive; and the more complex the displayed object, the longer is the computation time [10]. Another weakness of computer generated hologram is that it is difficult to display color images [18]. But in the novel designed system, the interferogram is generated by the direct interference of the reference light and the object light, and this physical process takes almost no time (no matter how complex the displayed object is). So, there is no need to generate the data for the interferogram. Hence, a commonly used mobile phone processor is quite sufficient for the associate data processing and this in turn ensures the affordability of the system to a large extent. Volumetric 3D display，such as volumetric bubble display developed by kota, is also a practical way to realize a 3D display, but it has some shortcomings difficult to overcome. Volumetric 3D displays usually contain movement parts [8], can't display large 3D image and there is no effect way to interact with the 3D image [19]. In the field reconstruction of hologram technology, this problem is avoided. The OSA allows user to interact with the reconstructed 3D scenery without extra equipment. Another benefit of the system is that the visible solid angle can be very large. The visible solid angle is the solid angle that is determined by the boundary of the screen and the watch widow ($\sim \frac{\text{the area of thescreen}}{\text{distance from the screen to watch window}}$). Any image point inside the solid angle, no matter it is in front of the screen or behind the screen, is visible. The feeling of using such a 3D display is similar to that watching the real scenery through a window. So, by using larger screen, the larger visible solid angle can be obtained. This feature makes sure that enlarging the image's spatial does not increase the cost of the system obviously. For example, a screen of about one square meter with a watch distance of one meter having solid angle around 1 can be easily achieved. In addition, even the viewpoint is limited in the above designed system; there are a number of ways to extend it to a multi-view one.

4. Conclusion

The present study proposed the field reconstruction of holograms method (or real-time reconstruction of holograms) for the first time. By combining the advantages of volumetric 3D display and traditional hologram technology, a true 3D display is successfully designed. And by designing an interactive image generation chip, the 3D display allows user to interact with it in a direct way. The feasibility and properties' of the designed system were analyzed in detail. Even this article is focus on the 3D display, the proposed principle and methods have instructional significance for many other fields, such as taking 3D photos, augmented/virtual reality device and so on.

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