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Augmented reality using holographic display

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Abstract: Augmented reality (AR) provided extra information to the user by applying virtual image onto the real environment. There are many methods achieving AR. Holographic display is one of the potential ways due to its perfect 3D demonstration. Holographic display can provide the virtual 3D object with depth information. It can be realized an AR device with real 3D scene by combing holographic display. However, it is difficult to realize a compact holographic display with wide viewing angle and enough resolution. It limits holographic display to apply to AR. In this paper, we will discuss the requirements of holographic display based on the development of LCD, including resolution (ppi), viewing angle, image quality and backlight. We wish this article can provide preliminary direction for the LCD industry to develop AR technology using holographic display.

1 Introduction

Augmented Reality (AR) and Virtual Reality (VR) have brought a lot of attention and investment in recent years. Either AR or VR devices are one kind of head-mounted displays. VR provides an immersive virtual world to the user and mainly applies to video game industry. The structure of VR devices consists with lens or lens group and display element. The image on the display is then projected and magnified in a distance where people can observe. The 3D images can be formed by displaying parallax images for each eye [1, 2]. AR integrates virtual image into viewer's environment to provide additional information. Although the optical structure of the formation of virtual image is the same as VR devices, the structure of AR is more complicated than VR. In order to combine digital world and the physical world, AR devices use couplers to integrate the light from environment and the display. Different kinds of couplers are commercially used, they can mainly classify into three groups: half-mirror or prism used by Google Glass; Free-form prism used by military helmet; waveguide coupler used by Hololens [3, 4].

User needs to observe both the real object and the virtual object while wearing AR devices, thus we need to consider about accommodation of eye. If the image plane of the virtual image is the same as the real object, we can see both real and virtual objects at the same time. If the image plane of the virtual image is different from the real object, the human eyes need to re-focus while looking at different object. Since the virtual object may place at different distance from the real object, we may not see both real and virtual object at the same time even they look like at the same location. Although the location of the virtual object can be adjusted by voice-coil motor or electrically tunable lens [5], all the virtual objects are still at the same plane. In the real world, all objects spread out over all the space with different distances. The combination between virtual and real object is not perfect since all the virtual object is at the same plane. In order to have a perfect integration between display image and physical world, we need to give additional focal depth to virtual objects. There are some methods can provide the different focal depth of the virtual object. In the using of the electrically tunable focal lens, the LC lens is used to electrically adjust the position of the projected virtual image synchronized with the information displayed [6]. The perceived depth of the depth-fused display varies according to two 2D displays at different depth by displaying different luminance [7, 8]. Light field display and holographic display can provide the real 3D image to the user [9]. Therefore, both methods are suitable for the application of AR system. Compared to light field display, the holographic display can show a real 3D image by simply using a spatial light modulator. Thereafter, AR system using holographic display is similar to commercial AR devices.

Figure 1 shows the simplified structure of the AR using holographic display. The AR system also uses a prism to couple the light from holographic display into the environment. Different from normal AR system uses lens to magnify and imaging, holographic display directly modulates

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the wavefront pass through it by using the spatial phase modulator and the coherent light. The modified wavefront is the copy of the light that comes from different object. People can see a 3D object at different distance through the holographic display. The location of the object shown on the holographic display can be assign to different place, thus the perfect integration with real world can be expected. Compared to normal AR system, AR system using holographic display can be more vivid and natural.

Traditional optical hologram records interference pattern of object wave and reference wave by using high resolution emulsion. The reconstruction is performed by illuminating the hologram with coherent light. Digital hologram means the interference pattern is digitalized. Instead of emulsion, digital hologram uses CCD (charge-couple device) or photo-sensor to record the interference pattern. Digital hologram can also be obtained by computer simulation such like CGH (Computer Generated Hologram). The reconstruction of digital hologram can be performed by using spatial light modulator (SLM) such as LCoS (Liquid Crystal on Silicon) panel. There is a huge amount of computation while CGH directly generated from the 3D object model and calculated by using Fresnel-Kirchhoff diffraction equation [10–13]. It is not suitable for AR since the fast refresh rate of virtual image is required for head movement. To fix virtual object at the right place and interact with the user, AR systems continuously do the calculations and update the information of the display for the head movement. In the conventional AR, the updated information is only 2D virtual objects moved with user's head based on the eye-tracking system. The information on the holographic display is more complicated. The transform from the 2D virtual objects to the digital hologram is needed by using Fresnel-Kirchhoff diffraction equation. Nevertheless, it can reduce the amount of calculation since AR device usually shows 2D simple pictures and the relative position between AR and human eye is fixed. Some of the non-iterative method, such like accurate compensated phase-added stereogram, can be used in computation [20, 21]. The simplified calculation make the implementation become more practical. In this paper, we would discuss how to realize the AR using holographic display based on the resolution (ppi), viewing angle, image quality and backlight unit. We wish this study can provide a clear technology direction for the future development of AR using holographic display.

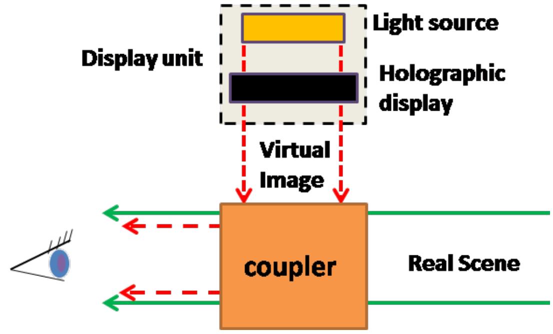

Figure 1: The schematic model of an AR device using holographic display.

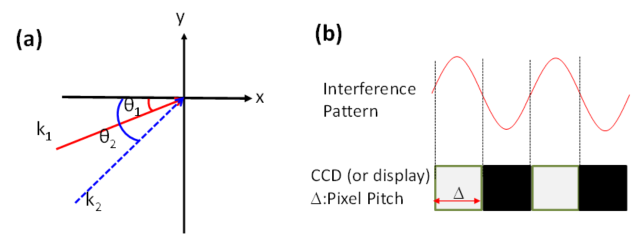

Figure 2: (a) Two beam interference (b) Recording the interference pattern by a CCD or displaying by a display.

2 Resolution requirement and viewing angle

Since the information shows on the holographic display unit is more like interference pattern, we first consider the simple case of two beam interference. As shown on Figure 2(a), two plane waves with wave vector k_1 and k_2 are both on the plane $z = 0$ and then impinge into the y-z plane with angles θ_1 and θ_2 separately. Considering the constructive interference, we have to fulfill the following equation [14, 15]

$$x(\cos\theta_2 - \cos\theta_1) + y(\sin\theta_2 - \sin\theta_1) = m\lambda, \quad |m| = 0, 1, 2, 3, \ldots \tag{1}$$

The pitch Δy between two bright (or dark) fringes on the y-axis is

$$\Delta y = \frac{\lambda}{|\sin\theta_2 - \sin\theta_1|} \tag{2}$$

The spatial frequency on the y-axis can be expressed as $f_y = 1/\Delta y$. Considering the viewing angle of hologram while reconstructing, an optical grating with the same pitch Δy. The first-order diffraction angle of the grating is same as the interference angle while recording, thus the viewing angle of the holographic display also depends on the resolution of the pixelated display [16]. The theoretical maximum spatial frequency can be obtained as half wavelength of incident light while the incident angle $\theta_1 = -90°$ and $\theta_2 = +90°$. For example, the theoretical requirement of resolution is 5000 lines/mm when we use blue light with wavelength 400 nm. The resolution of commercial emulsions for holography can be higher than 5000 lines/mm, thus the theoretical viewing angle of optical hologram can reach 180°. We use display or CCD to show or record the information in digital hologram. In order to record or show the completed wavefront, the pixel pitch need to be smaller than 1 μm in the range of visible light. However, it is difficult to implement this idea in the current display process. Moreover, as shown in Figure 2(b), every bright fringe needs a pair of pixel to record. For instance, a display with a subpixel pitch Δ =5 μm, the display resolution is around 1700 ppi. The maximum viewing angle is around 3 degree with wavelength of 500 nm. It is smaller than the requirement of the commercial AR ~40 degree. In order to obtain the maximum viewing angle of 40°, the pixel pitch of the display needs to be smaller than 0.4 μm with wavelength of 550 nm. The pixel pitch of commercial LCoS panels are normally around 5 μm to 10 μm. The extremely small pitch of the commercial LCoS panels is around 4 μm, thus there is still a gap between the requirement of the holographic display and the selling products. We can adopt multiple displays and complex optical systems to increase the viewing angle; the complex system usually increases the device volume or decreases the image quality [17]. The limited resolution and viewing angle is the main issue of holographic displays.

The image quality of commercial AR depends on the pixel pitch of the display and the magnification of the optical systems between the exit pupil and the display. Instead of the pixel pitch and the magnification, the image of the holographic display is reconstructed by the diffraction from all the pixels on the panel, as shown in Figure 3. The diffraction pattern form at the image plan with a distance d away from the display. In order to simplify the discussion, Figure 3 shows only 2-dimension drawing. Considering about a point P at the image plane, the theoretical finest point of P would be a diffraction pattern formed by two outmost pixels, as shown in the dashed line in Figure 3 [10–13]. The finest dot of the image can be expressed as Δ_d=λd/$N\Delta$, where λ is the wavelength of the incident light, Δ and N is the pixel pitch and the total amount of the pixels respectively. It shows the image quality depends on the size of the display, which means the aperture of the system, not depends on the pixel pitch Δ. However, the pitch of the finest grating that can be shown on the display is 2Δ. We can have the first-order diffractive angle θ from Equation (2) is ~ $\lambda/2\Delta$. Therefore, the image quality depends on the diffraction angle θ if θ is smaller than θ_d. On the other

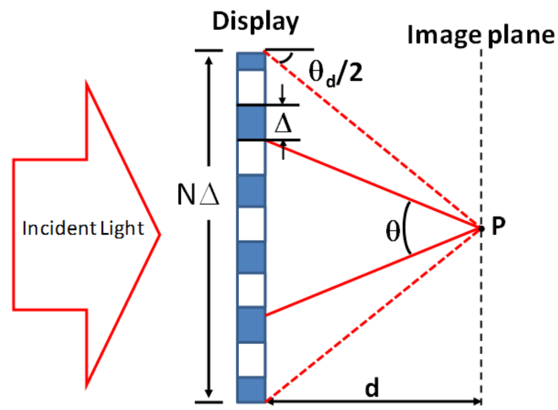

Figure 3: A point P is formed by a display with pixel pitch Δ and panel size NΔ.

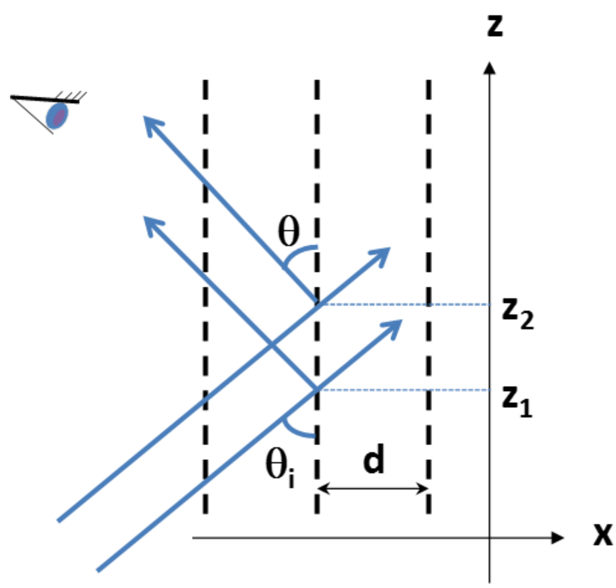

Figure 4: The diffraction of volume hologram.

hand, the image quality depends on the aperture size $N\Delta$ and the distance d if the pixel pitch is small enough. The limited pixel pitch Δ is functioned as a low-pass filter based on the sampling theorem while recording by a CCD or displaying by a pixelated modulator [15]. Therefore, high resolution displays is still necessary in order to increase the image quality of the holographic display.

3 Light source

The optical transmission hologram records the interference pattern using coherent light. Since the diffraction angle is wavelength dependent, the reconstruction image would be only clear while using the same light source of recording. The blurred image would be formed if we use the white light source, such as the LED backlight used in the commercial LCD. On the other hand, we can use white light as a light source if we increase the emulsion thickness. The volume hologram is a reflective type hologram; it can show the right image with the color of recording under the white light source. As the dash lines shown in Figure 4, the interference pattern in the thick emulsion is a 3D pattern. It is not only a two-dimensional grating with pitch d in the x-direction, but also 3D pattern that along with z-direction. For the constructive interference in x-direction, we have [18, 19]

$$dn(\sin\theta - \sin\theta_i) = m\lambda \quad (3)$$

For the constructive interference in z-direction, we can also obtain

$$n(z_2 - z_1)(\cos\theta_i - \cos\theta) = m\lambda \quad (4)$$

where θ_i, θ, m and n are the incident angle, diffraction angel, integers and the refractive index, respectively. Since we have fulfill both Equation (3) and (4) for all the position along the z-axis. We have

$$2nd\sin\theta_i = m\lambda \quad (5)$$

where the diffraction angle θ is equal to the incident angle. Equation (5) is the result of Bragg reflection. It shows the light reflects and diffracts only with the same wavelength of recording. The 3D interference pattern of volume hologram can perform the function as a wavelength selector, thus we can have a diffraction image by using a white light source. We still need to use the coherent light as a light source since there is no commercial products can spatially modulate light in three-dimension.

Except the diffraction issues, the influence of broad bandwidth of the light source is also significant. Assumed a point object located at (x_o, z_o) in the x-y plane, the reference light of recording is a plane wave with the incident angle θ_R with respect to the z-axis and the wavelength λ. Assumed the reconstruction light is also a plane wave with the angle θ_P with respect to the z-axis and the center wavelength is λ. The band width of the reconstruction light is $\Delta\lambda$. If the reconstructed image is a point located at (x_P,z_P), the transverse image blur due the finite spectra bandwidth $\Delta\lambda$ of the source can be expressed as [22]

$$|\Delta x_p| = \tan\theta_P z_o \frac{\Delta\lambda}{\lambda},\ |\Delta z_p| = z_o \frac{\Delta\lambda}{\lambda} \quad (6)$$

From Equation (6), the image blur is direct proportion to the spectrum bandwidth $\Delta\lambda$. In the commercial LCD, it usually uses a blue LED with yellow phosphor or with red and green phosphor to generate a white light source. The yellow phosphor stimulates a wide bandwidth of the spectrum and usually applied to the products with low color gamut. The blue LED with red and green phosphor generates light with narrow bandwidth but with several peaks in the long-wavelength region. These peaks in long-wavelength are not suitable to holographic display. There are several technologies to improve color gamut by reducing the bandwidth of three colors. One of them is quantum-dot film (QDEF, 3M). The three color spectrum of QDEF is neat and narrow to further resolve the noise of the holography. Moreover, the backlight unit of LCD usually consists with several LED bins and multiple films. The phase distribution over the whole panel is not the same, and thus the output light is not a coherence light source even though the bandwidth is very narrow. In order to obtain the coherence light source using LED, one LED bin with a pinhole is usually adopted [23–27]. The volume of the system increases due to the bulky light source. The system volume becomes an important issue since there is not too much space in AR system. Therefore, the coherence surface light source with simple and compact structure is desired in developing a holographic display system.

Since the digital hologram is a diffractive optical element, the diffraction efficiency is also significant. Fresnel hologram obtained from Fresnel-Kirchhoff diffraction equation contained a whole information of the wavefront. The Fresnel hologram is composed of complex number with both phase part and the amplitude part. However, we usually use a phase-only modulator to reconstruct the image. Considering the diffraction efficiency of a simple grating, the maximum diffractive efficiency of a square-wave transmittance grating is 10.1% compared to 40.5% of a square-wave phase grating. Since the phase-only grating have no absorption, it can have higher transmittance and the diffractive efficiency can reach 100% theoretically [27]. The Gerchberg-Saxton method is usually used for generating the phase-only digital hologram [28]. But the GS method is an iterative algorithm and thus time consuming. There are some non-iterative methods proposed to encode the amplitude component of the Fresnel hologram into the phase component. They can both have high diffraction efficiency and good image quality [29]. Moreover, the brightness of the virtual image should be comparable to the environment brightness to have better performance. Since the average brightness of the outdoor environment is typically 2000fL, the target of brightness would be around 2000 fL [30].

A holographic display usually adopts a spatial phase modulator. Every fluctuation that can influence phase shift will cause a speckle or the distorted image, such like the fluctuation of driving voltage, cell gap variation, and every thickness variation of each film [28, 29, 31–33]. The fabrication requirements of holographic display is more precise than commercial LCDs. It is difficult to monitor a variation within a wavelength in the fabrication process. To make the fabrication become more practical, it is recommended to monitor the main factor affecting the image quality as well as the cell gap and the flatness of the glass substrate. Moreover, it is better to adopt some feedback system to actively compensate the phase changing. By improving the phase modulator, we may accelerate the development of AR technology using holography display

4 Conclusion

We discussed the AR using holographic display based on the view of display manufacturer. We can obtain the perfect integration of virtual image and real scene by applying holography technique to AR devices. The main obstacle is the limited resolution of display. For example, the viewing angle of the holographic display is around 3 degree if we use the display with 1700 ppi. To increase the viewing angle and image quality, we need multiple displays or the finest pixel with submicron pitch. Moreover, the volume of holographic display needs to reduce since AR device are usually head mounted displays. For further reducing the system size, the coherence surface light source with simple and compact structure is necessary. To develop a perfect AR using holographic display, we also expect a precisely-control phase modulator with compensated feedback algorism or even more a 3-dimensional controlled phase modulator in the future.

References

[1] J. P. Rolland and H. Hua, “Head-mounted display systems,” in Encyclopedia of Optical Engineering, Taylor & Francis (2003).
[2] J. E. Melzer, "Head-mounted displays," In Digital Avionics Handbook, CRC Press (2000).
[3] B. Kress and T. Starner, "A review of head-mounted displays (HMD) technologies and applications for consumer electronics," Proc. of SPIE, 8720, 87200A-1 (2013).
[4] D. Cheng, Y. Wang, H. Hua, and M. M. Talha, "Design of an optical see-through head-mounted display with a low f-number and large field of view using a freeform prism," Appl. Opt., 48, 2655 (2009).
[5] S. Liu, H. Hua and D. Cheng, "A Novel Prototype for an Optical See-Through Head-Mounted Display with Addressable Focus Cues," IEEE Trans. Vis. Comput. Graphics, 16, 381 (2010).
[6] Y. J. Wang, P. J. Chen, X. Liang, and Y. H. Lin, "Augmented reality with image registration, vision correction and sunlight readability via liquid crystal devices,” Sci. Rep., 7, 433 (2017).
[7] X. Hu and H. Hua, "Design and assessment of a depth-fused multi-focal-plane display prototype," J. Dis. Tech., 10, 308 (2014).
[8] S. Suyama, S. Ohtsuka, H. Takada, K. Uehira, and S. Sakai, "Apparent 3-D image perceived from luminance-modulated two 2-D images displayed at different depths," Vision Res., 44, 785 (2004).
[9] D. Lanman and D. Luebke, “Near-eye light field displays,” ACM Trans. Graph. 32(6), 1–10 (2013).
[10] U. Schnars, W. Jueptner, "Digital Holography," Springer, Berlin, Germany (2005).
[11] U. Schnars and W. Jueptner, "Digital recording and numerical reconstruction of holograms," Meas. Sci. Technol. 13, R85 (2002).
[12] U. Schnars and W. Jueptner, "Direct recording of holograms by a CCD target and numerical reconstruction," Appl. Opt., 33, 179 (1994).
[13] U. Schnars, T. M. Kreis and W. Jueptner, "Digital reconrding and numerical reconstruction of holograms: reduction of the spatial frequency spectrum," Opt. Eng., 35(4), 997 (1996).
[14] B. E. A. Saleh and M. C. Teich, "Fundamentals of Photonics," Wiley, (2007).
[15] J. W. Goodman, "Introduction to Fourier Optcis," Roberts & company Publishers, US (2005).
[16] X. Wang, B. Wang, and P. J. Bos, "Limitation of Liquid Crystal on Silicon Spatial Light Modulator for Holographic Three-dimensional Displays," SID 04 Digest, 1522 (2004).
[17] Y. Z. Liu, X. N. Pang, S. Jiang, and J. W. Dong, "Viewing-angle enlargement in holographic augmented reality using time division and spatial tiling," Opt. Express, 21, 12068 (2013).
[18] D. B.-Ratcliffe, "Understanding diffraction in volume gratings and holograms," Holography-Basic Principles and Contemporary Applications, INTECH (2013).
[19] D. Senderakova, "White Light Reconstructed Holograms," Holography-Basic Principles and Contemporary Applications, INTECH (2013).
[20] F. Yaras, H. Kang, and L. Onural, "Real-time phase-only color holographic video display system using LED illumination," Appl. Opt., 48, H48 (2009).
[21] H. Kang, T. Yamaguchi, and H. Yoshikawa, "Accurate phase-added stereogram to improve the coherent stereogram," Appl. Opt., 47, D44 (2008).
[22] P. Hariharan, "Optical Holography," 2nd ed., Cambridge Univ. Press, US (1996)
[23] F. Yaras, H. Kang, and L. Onural, "State of the Art in Holographic Displays: A Survey," J. Disp. Tech., 6, 443 (2010).
[24] F. Yaras and L. Onural, "Color Holographic Reconstruction using Multiple SLMs and LED Illumination," SPIE-IS&T, 7237, 72370-1 (2009).
[25] K. Sato and K. Takano, "Consideration about HMD-type Holography 3D-TV," Proc. SPIE, 5599, 123 (2004).
[26] K. Takano and K. Sato, "Full-color electroholographic three-dimensional display system employing light emitting diodes in virtual image reconstruction," Opt. Eng., 46, 095801 (2007).
[27] S. A. Benton, V. M. Bove Jr., “ Holographic Imaging,” Chapter 6, Wiley, (2008).
[28] R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pic-

tures," Optik, 35, 1 (1972).
[29] V. Arrizon, U. Ruiz, R. Carrada, and L. A. Gonzalez, “Pixelated phase computer holograms for the accurate encoding of scalar complex fields,” J. Opt. soc. Am. A, 24, 3500 (2007).
[30] J. Rolland and H. Hua, “Head-mounted display systems,” Encyclopedia of Optical Engineering, R. G. Driggers, ed., Taylor & Francis (2003).
[31] C. K. Hsueh and A. A. Sawchuk,"Computer-generated double-phase holograms," Appl. Opt. 17, 3874 (1978).
[32] J. N. Mait and K.-H. Brenner, "Dual-phase holograms: improved design," Appl. Opt. 26, 4883 (1987).
[33] P. W. M. Tsang, "Generation of phase-only hologram," Proc. Of SPIE, 9271, 92711Q-1 (2014).