Very Wide FOV in Holographic AR Display Using a Large HOE Fabricated by Area Segmentation and Multiple Exposures

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Abstract

A large holographic optical element (HOE) has been fabricated by an originally developed recording system enabling the area segmentation and multiple exposures. An augmented reality (AR) 3D display with a very wide FOV of 34° and 25° has been successfully demonstrated based on the time division method.

1 Introduction

Recent explosion in demand for businesses using the virtual reality (VR) or augmented reality (AR) has been accelerating progress of the optical devices and optical elements. At the same time, the commercial realization of holographic three-dimensional (3D) displays has been strongly expected. A long-term research on the holographic 3D displays has revealed what is required to put the holographic 3D displays into practical use. The most important requirement is to drastically increase the number of pixels of hologram display devices. Recently, display devices with 8K resolution begin to become widely used. Nonetheless, the necessary number of pixels is more than 400K × 300K [1], which is far from the currently-available maximum resolution. Even the recent remarkable progress of semiconductor technology cannot solve this problem.

One approach to technically overcome the serious shortage of the number of pixels is a time division method [1]. In this method, a spatial light modulator (SLM) with a very high frame rate is used as a hologram display device, and the displayed patterns on the SLM are synchronously controlled with a high-speed deflecting optical element such as a galvano mirror. Because the scanning speed exceeds the human perceptual response speed, viewers can recognize reconstructed 3D images temporally seamlessly. The time division method can generate wavefronts with various spatial frequencies by the deflecting element, which means that the time division approach yields the equivalently same effect as the increase of the number of pixels of an SLM.

In spite of the time division method, the shortage of the number of pixels is still problematic. A further approach is reduction of a viewing zone. There is a trade-off relationship between a viewing zone and field of view (FOV) in holographic 3D displays. Thus, when the viewing zone is limited to a fixed small area, the FOV can be enlarged instead. We realized an aerial holographic 3D display with a large FOV of 12° × 12° [2]. However, in this method, the enlargement of FOV is limited by spherical aberration of a large convex lens. Moreover, the existence of the large convex lens, which converges wavefronts to a fixed viewing point, does not only preclude AR representation with real-existing objects, but also degrades floating feeling of the reconstructed virtual 3D objects.

In this study, we introduce a large holographic optical element (HOE) instead of a large convex lens. This approach can overcome the limitation of the above FOV enlargement. Furthermore, because a volume-type HOE has a sharp wavelength selectivity and behaves as a transparent mirror, it enables AR representation and high realistic sensation without degrading floating feelings. The key point of this method is the fabrication of a large HOE. It is very difficult to record interference fringes on a large area in one exposure. Thus, we originally developed a recording system enabling area segmentation and multiple exposures. The large HOE of 35 cm × 25 cm was fabricated. Our optical experiment successfully demonstrated the effect of this large HOE and realized a very wide FOV of 34° and 25° in the vertical and horizontal directions, respectively.

2 Optical System Realizing a Wide FOV Based on the Time Division Method

The optical system used in this study is shown in Fig. 1. In this system, a digital micromirror device (DMD) is used as a high-speed SLM for the time division method. Incident plane wavefronts enter the DMD, and then they are modulated by the DMD. After passing through the 4f optical system, the modulated wavefronts arrive at a horizontal galvano mirror Mh. A spatial filter is placed at the Fourier plane of the 4f optical system to remove unnecessary diffracted waves. After the reflection on the galvano mirror Mh, the wavefronts arrive at another galvano mirror Mv by a large concave spherical mirror Ms, which gives the two galvano mirrors imaging relation. Furthermore, the DMD is also in the imaging relation with the two galvano mirrors. Because the galvano mirrors Mh and Mv deflect the wavefronts in the horizontal and vertical directions, respectively, it can be
regarded that the wavefronts modulated by the DMD come out from the point Mv in the directions controlled by the two galvano mirrors. Then, the direction-controlled wavefronts enter the large HOE. The optical property of this large HOE is off-axis concave ellipsoidal mirror, one focus of which is set to the outgoing point Mv. The other focus is set to the viewing point P (eye box) as shown in Fig. 1. Thus, all the wavefronts outgoing from the point Mv arrive at the viewing point. The FOV can be enlarged both in the horizontal and vertical directions, and is determined by the mechanical scanning ranges of the two galvano mirrors Mv and Mv.

3 Fabrication of a Large HOE by Area Segmentation and Multiple Exposures

To make maximum use of scanning by the two galvano mirrors and maximize the FOV, the HOE must be large enough to receive all the wavefronts; otherwise, the FOE is limited by the effective aperture size of the HOE. It is, however, very difficult to record a large HOE because the practical aperture size of many commercially available optical systems such as lenses is less than 10 cm. Thus, area segmentation and multiple exposures are necessary to make a larger patched HOE than 10 cm. For the area segmentation and multiple exposures, the optical axis of individual recording must be movable.

In this study, such a recording system moving the optical axis in the two directions was originally developed. The picture of it is shown in Fig. 2. A light from a laser light source whose wavelength was 532 nm was divided into two lights by a fiber coupler. These two lights were output as diverging spherical waves from the output points A and B, shown in Fig. 2. The diverging spherical wave from the point B converged to the point C by passing through the lens L2. The two points A and C are corresponding to the two foci of a concave ellipsoidal mirror whose optical property was going to be recorded as HOE. A large glass substrate where a photopolymer film adhered was placed in front of the lens L1. The diverging spherical wave emitted from the point A interfered with the converging spherical wave from the point B. The interference fringes by the two waves were recorded on the photopolymer film. Because the two waves propagated in the counter directions mutually, the interference fringes recorded in this optical setup was a volume-type hologram. The recording area was constrained by a rectangular aperture mask whose size was 6 cm × 6 cm, which was the recordable area size by a single exposure. The distance between the glass substrate and the point C was 52 cm. The output power of the laser was 90 mW. The irradiance on the photopolymer film was approximately 1 mW/cm². The exposure time was set to 25 sec. Under these conditions, an individual HOE was fabricated.

To make a larger HOE, our recording system had the two moving parts. One part is for the horizontal movement of the optical axis. This movement could be performed by sliding the glass substrate with the photopolymer horizontally, whereas the other optical parts such as a lens L1, output points A and B, and so on was fixed. Another moving part is for the vertical movement. In this movement, only the lens L1 and the output point B were rotated around the point C. Thus, the wave from the point B always converged to the point C, which was one of the two foci of the ellipsoid. In this study, HOE recording was repeated 7 and 5 times in the horizontal and vertical directions, respectively. As a result, the large HOE of 35 cm × 25 cm was fabricated.

4 Experimental Results

4.1 Construction of Optical System

To demonstrate a very wide FOV with a large HOE, the optical system based on the time division method was constructed as shown in Fig. 3. Unlike the case of recording, the large HOE was placed after rotating by 90° to switch the horizontal and vertical sizes. The green line indicates the typical optical axis. The pixel size and number of pixels of the DMD were 7.56 × 7.56 μm² and 1,920 × 1,080, respectively. The focal lengths f1 and f2 of lens L1 and L2 were 30 cm and 25 cm. The radius of curvature f0 of the spherical mirror Mv was 60 cm. The distance between the point Mv and the large
HOE was set to 52 cm, which corresponded to the distance between the point C and the glass substrate in recording. In this case, the size of the eye box was estimated to be \(12 \times 6.8\) mm\(^2\). The wavelength of the laser was 532 nm, which was the same as that in recording the HOE. As described in Sec. 3, the large HOE is a volume-type hologram, it has the sharp wavelength selectivity. It behaves as a transparent element for all the light except the recording wavelength of 532 nm. Thus, as shown in Fig. 3, a real-existing object of a soccer ball made of paper, which is located behind the large HOE, can be seen through the large HOE.

In our holographic AR display, a time division method was used to increase the FOV. The division numbers in the vertical and horizontal directions were 24 and 5, respectively, which means that \(24 \times 5 = 120\) holograms are required to display one 3D scene. The control signals for the two galvano mirrors are shown in Fig. 4. The DMD displays the holograms time-sequentially at the rate of 24 bit \(\times\) 60 Hz = 1,440 Hz. The synchronization signal is generated by the DMD at the rate of 60 Hz. This synchronization signal triggers the control signals for the two galvano mirrors. The control signal for \(M_v\) is a triangle wave while the control signal for \(M_h\) is a staircase wave. The frame rate of our display is 10 Hz, and the one period is divided into 6 regions. In Regions 1 to 5, 24 holograms are displayed on the DMD sequentially in one region, whereas in Region 6 the galvano mirror \(M_h\) returns to the original position and no hologram is displayed on the DMD. Figure 5 shows the scanning path on the large HOE in this system.

4.2 Optical Reconstruction and Blur Reduction

Under the conditions described in Sec. 4.1, optical experiments were demonstrated. A 3D scene used for this experiment is shown in Fig. 6(a). The color indicates the depth value of the 3D scene. Red parts are located relatively away from the viewing point P while yellow parts are located close to the viewing point P. The optically reconstructed images are shown in Fig. 6(b) – (d). Figure 6(e) – (f) are enlarged parts of the yellow dash lines in Fig. 6(b) – (g), respectively. The camera focus is set to the far distance (red parts). In our time division method, as shown in Fig. 4, the vertical scanning galvano mirror \(M_v\) always moves, which causes image blurring. Because the illumination from the laser light source is continuous in Fig. 6(b), the mirror movement has a strong influence on the image quality as image blurring. Reconstructed scene can be no longer recognized. One approach to solve this image blurring is the pulse illumination control of the laser light source. The short pulse illumination can reduce image blurring by reducing the illumination time of the individual holograms. The reconstructed scene obtained by the pulse illumination is shown in Fig. 6(c). The influence of image blurring is quite suppressed, and a Japanese-style tower is reconstructed unlike Fig. 6(b). The ununiformity of the intensity distribution in Fig. 6(c) is, however, not negligible. Especially lower-left parts are reconstructed more strongly than other parts. This ununiformity stems from the difference of diffraction efficiencies of the individual HOEs. It is very difficult to make diffraction efficiencies constant in multiple exposures for the large HOE. To relief this ununiformity, we propose amplitude modulation of the laser light source every hologram in addition to the pulse illumination. The result is shown in Fig. 6(d). The intensity ununiformity is reduced and detailed parts of the 3D scene are recognizable compared with Fig. 6(b). Figure 7 shows the reconstructed image where the camera focus is set to the front parts (yellow parts).
Instead of the Japanese-style tower, leaves of a tree are clearly reconstructed. Moreover, the practical FOV was measured from the reconstructed image, and it was 34° and 25° in the vertical and horizontal directions, respectively. This FOV is quite larger than that of other conventional holographic 3D displays. From these results, 3D reconstruction of a 3D scene with a very wide FOV has been successfully demonstrated.

4.3 Demonstration of AR Representation

In the experiment shown in Sec. 4.2, only the 3D scenes generated by the holograms are reconstructed. Because the HOE used in this study is fundamentally transparent, AR representation with real-existing objects has been demonstrated here. The real-existing objects are a soccer ball and a check pattern, as shown in Fig. 3. Virtual 3D objects are butterflies, as shown in Fig. 8(a). The AR reconstructed images are shown in Fig. 8(b) and (c), where the camera focus is set to the different depth. From these figures, virtual objects are successfully reconstructed three-dimensionally with real-existing objects.

5 Conclusions

In this study, we have demonstrated holographic AR 3D display with a very wide FOV based on the time division method. To enlarge the FOV, the key point is the fabrication of a very large HOE. We developed original recording optical system enabling the area segmentation and multiple exposures. The large HOE of 35 cm × 25 cm was fabricated. The construction of synchronization system including pulse laser control is also an important feature. To verify the effect of the large HOE, some optical experiments including AR representation have been performed, and a very wide FOV of 34° × 25° has been successfully demonstrated.

Because our approach has a high futuristic potential, we believe that it can contribute to early practical realization of holographic 3D displays.

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References
