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Projection-type dual-view holographic three-dimensional display and its augmented reality applications

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ABSTRACT

In this paper, a projection-type dual-view holographic three-dimensional (3D) display consisting of a single spatial light modulator (SLM) and a grating light-guide plate is proposed and implemented. A synthetic phase-only hologram of two different 3D objects is calculated by the layer-based Fresnel diffraction method and uploaded onto the SLM for 3D reconstruction. A grating with special design and fabrication is used as the light-guide plate to re-direct the two reconstructed 3D images into the two separated viewing zones simultaneously. Optical experiments demonstrate that the proposed system can realize the function of dual-view holographic 3D display, and it can present 3D images to the human eye with sufficient depth cues, which enables the observers free of the accommodation-vergence conflict and visual fatigue problem. Furthermore, the proposed dual-view holographic 3D display system is applied to the see-through display for augmented reality (AR) applications, and the performance of this system is also tested in the experiments and the results show that the system can provide the dual-view AR 3D sensation successfully.

1. Introduction

Dual-view display technique can present two distinct images or video contents in different viewing directions, which could satisfy different observers' requirements on the same display simultaneously, and it would contribute to a considerable saving in cost and space. This new observation experience allows the dual-view display technique being used in widespread applications. For example, in an automobile, the driver can see the global positioning system satellite navigation while the front seat passenger can view a movie. In medical applications, the dual-view display system can provide the live situation of a patient for a doctor and the next required medical tools for an assistant during a surgical operation.

To date, several beneficial approaches have been performed to achieve this function. The common way to direct the light from different images into each independent viewing zone is using a parallax barrier [1,2] or a lenticular lens array [3,4]. Besides, some dual-view liquid crystal displays have also been proposed [5–10]. However, these dual-view displays cannot present three-dimensional (3D) images, but only deliver ordinary two-dimensional (2D) images to the human eyes, which greatly limits its applications. Recently, several studies have been reported about dual-view display system supporting 3D images [11–15]. These studies combine the dual-view display with the integral imaging display because the integral imaging display can reconstruct quasi-continuous viewpoints and full-parallax 3D images by use of a lens array. But the depth range of 3D reconstruction is seriously restricted by the lateral resolution according to the limitation of the integral imaging theory. Therefore, the true 3D display with sufficient depth cues is needed for the next generation dual-view display.

Holographic display, especially electronic holography, is a promising true 3D display technology that can reconstruct both amplitude and phase information from a natural 3D object [16–19], which can provide sufficient depth cues to prevent the visual fatigue problem caused by accommodation-vergence conflict [20,21]. Here in this paper, we propose and investigate a projection-type dual-view 3D display based on computer-generated holography (CGH) technique. Our display system is achieved by a combination of SLM-based holographic 3D projection and a grating light-guide plate. In the proposed dual-view holographic 3D display, a synthetic phase-only hologram of two 3D objects is generated

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by using the layer-based Fresnel diffraction method and then uploaded onto a single spatial light modulator (SLM) for 3D reconstruction without accommodation-vergence conflict. Furthermore, a grating adopted in the reconstructed configuration performs as a light-guide plate in order to control the propagation directions of two reconstructed 3D images, and its function is to split the reconstructed 3D images for two view zones. To our best knowledge, this is the first time that the CGH technique is introduced to the dual-view 3D display. Moreover, the proposed dual-view holographic 3D display is applied in see-through display for augmented reality (AR) applications, and two different 3D realistic augmentations with sufficient depth cues would be observed from different viewing directions simultaneously. This combination can bring several advantages: (1) observers can see different holographic 3D images in different viewing zones at the same time; (2) the reconstructed 3D images to the human eyes contains sufficient depth cues, which enables the observers free of visual fatigue problem; (3) the proposed see-through display system can realize dual-view augmented reality true 3D display, thus it brings stronger practicability, better realistic fusion, and more comfortable observation experience; (4) the used synthetic phase-only hologram is calculated without iterations, which provides the possibility of real-time true 3D display; (5) the proposed system is simple and compact in optical structure, and the adopted grating has advantages of low cost, simple fabricated procedure, and easy to be copied.

2. Theoretical principles and system configurations

2.1. System configuration of the proposed dual-view holographic 3D display

Fig. 1 schematically illustrates the principle and structure of the proposed dual-view holographic 3D display, where the dual-view 3D display system and corresponding AR 3D display system are shown in Fig. 1(a) and (b), respectively. The proposed dual-view holographic 3D display system is mainly composed of a single SLM and a grating light-guide plate. The SLM is used to load the synthetic phase-only hologram of two 3D objects for optical holographic reconstruction. When the parallel light is projected onto the SLM, two different 3D images will be reconstructed in different propagation directions, with the directional information of propagation paths expressed by the digital gratings encoded on the SLM. However, the separated angle between two reconstructed 3D images is strictly limited by the overlarge pixel pitch of the current available SLM so that the dual-view property of the reconstructed images is difficult to produce completely. In order to increase the separated angle for meeting the dual-view requirement, a grating with special design is adopted as the light-guide plate in the reconstructed configuration, which can re-direct the two reconstructed 3D images to two predefined viewing zones, respectively. In other words, the function of the grating is to split the incident beam for obtaining two completely separated view zones. Furthermore, in the system configuration shown in Fig. 1(a), an ocular lens closed to the grating is employed to generate two convergent viewpoints, whose function is that the viewing distance can be preset according to the requirement of observers. In such a way, the observers at different viewing zones can see different reconstructed 3D images at the same time. Moreover, the proposed dual-view holographic 3D display also could be applied in see-through display. As shown in Fig. 1(b), an optical combiner (such as a beam splitter or a half mirror), as the critical optical see-through element in the dual-view AR 3D system, is set behind the grating light-guide plate and the ocular lens, and then the two separated reconstructed 3D images will pass through the optical combiner. Thus, the observers can see the combination of virtual 3D images and real 3D scenes through the optical combiner. That is to say, two different 3D holographic realistic augmentation effects could be observed from different viewing directions simultaneously.

2.2. Generation of the synthetic phase-only hologram for dual-view 3D display

Fig. 2(a) shows the generation process of the synthetic phase-only hologram for the proposed dual-view 3D display. Two different 3D objects are used as the information source for hologram calculation, which can be obtained by real models or 3D computer graphic. In order to calculate the computer-generated hologram (CGH) of each 3D object with the layer-based Fresnel diffraction method [22,23], the object is sliced into multiple parallel layers according to the depth information, and each layer contains the amplitude information of the corresponding depth range. For simplicity, we take a 3D object composed of two layers as an example to demonstrate the calculation process of the CGH, and the calculation model for layer-based CGH generation of the 3D object is illustrated in Fig. 2(b).

In the rectangular coordinate system shown in Fig. 2(b), the object plane and the hologram plane are located in the $\xi-\eta$ plane and $x-y$ plane, respectively. The z–axles of two coordinate systems are coincident, and two characters, ‘a’ and ‘b’, are placed at different object planes, with the distances from the hologram plane of d_1 and d_2, respectively. According to the Fresnel diffraction theory, we can obtain the complex amplitude distribution $U_i(x,y)$ on the hologram plane contributed by the wavefront of the object plane i can be expressed as [24]:

$$\begin{aligned} U_i(x,y) &= Frt[O(\xi_i,\eta_i)]_{\lambda d_i} \\ &= \frac{1}{j\lambda d_i}\exp(jkd_i)\iint A(\xi_i,\eta_i)\exp[j\varphi(\xi_i,\eta_i)] \\ &\quad\times \exp\left\{j\frac{k}{2d_i}[(x-\xi_i)^2+(y-\eta_i)^2]\right\} d\xi_i d\eta_i \end{aligned} \tag{1}$$

where Frt stands for the Fresnel diffraction, $O(\xi_i,\eta_i)$ denotes the complex amplitude distribution of the object plane i, j represents the imaginary unit, $k=2\pi/\lambda$ is the wave number, λ is the wavelength, d_i is the propagation distance from the object plane i to the hologram plane, $i=1,2,\ldots,I$ (I represents the total number of the sliced layers), $A(\xi_i,\eta_i)$ denotes the amplitude distribution of the object plane i, and $\varphi(\xi_i,\eta_i)$ represents the random phase distribution, which is used to smoothen the spatial spectrum of the object information and simulate the diffusive effect of the object surface.

After the diffracted calculations from the slice layers to the hologram plane, the whole complex amplitude distribution on the hologram plane can be obtained by superposing the complex amplitude distributions contributed by all the sliced layers. Subsequently, the whole complex amplitude distribution $U(x,y)$ of the 3D object on the hologram plane can be expressed as

$$U(x,y)=\sum_{i=1}^{I}U_i(x,y) \tag{2}$$

By discarding the amplitude of the whole complex amplitude distribution on the hologram plane and keeping its phase only, we can obtain the phase-only hologram of the 3D object as follows

$$\varphi(x,y)=\arg U(x,y) \tag{3}$$

where arg represents the argument of the complex amplitude distribution. In such a way, the layer-based phase-only CGH of a 3D object is generated. Note that the calculation method could be extended easily to generate the layer-based phase-only CGHs of complex 3D objects composed of more than two layers.

In the generation process of the synthetic phase-only hologram shown in Fig. 2(a), we firstly calculate the original layer-based phase-only holograms (Hologram 1 and 2) of two 3D objects by using the layer-based Fresnel diffraction method mentioned above, whose phase distributions are assumed as φ_1 and φ_2, respectively. Secondly, in order to synthesize each hologram with a directional function, the digital