Optik 157 (2018) 190–196

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Full length article

A multi-plane optical see-through holographic three-dimensional display for augmented reality applications

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ARTICLE INFO

Article history:
Received 23 September 2017
Accepted 13 November 2017

Keywords:
Three-dimensional display
Holographic display
Augmented reality
Spatial light modulators
Programmable zoom lenses

ABSTRACT

In this paper, a multi-plane optical see-through holographic three-dimensional (3D) display system for augmented reality (AR) applications is proposed and implemented. This system is composed of a holographic projection module and an optical see-through display module. The holographic projection module manages to reconstruct the multi-plane 3D scene by using a spatial light modulator (SLM), and the correct depth information can be expressed by programmable zoom lenses encoded on the SLM. The reconstructed 3D scene and the real physical world will fuse together through the optical see-through display module. An experimental verification system for the proposed multi-plane optical see-through holographic 3D display is demonstrated. The experimental results prove that the proposed system can achieve the multi-plane AR holographic 3D display effect without any image bearing structure, and can solve the accommodation-vergence conflict problem effectively. This system has the advantages of large depth range, continuous expression capacity of depth information and no visual fatigue.

1. Introduction

Augmented reality (AR) technology combines the real world with computer-generated virtual information to enhance the sense of reality by superimposing virtual objects and cues upon the real physical world in real time [1–3]. Nowadays, AR technology is undergoing rapid progress, and many relevant methods have been proposed [4–7]. AR has already been applied in a lot of applications, such as medical treatment [8], cultural protection [9] and entertainment [10]. For example, in the monument restoration, the famous Chinese ancient ruins Yuanmingyuan can be reconstructed by AR technology to provide vivid scenes for the visitors; in the surgical navigation, the overlay of true tooth and virtual tooth nerve channel could be seen for surgeon to perform operations safely with the help of the AR display system.

Head-mounted display (HMD) is one of the most mainstream products of AR display technology, including Google glass [11] and Microsoft Hololens [12], etc. Although many significant developments and advancements have been achieved, there still exist several key technical problems to be solved. For the conventional stereoscopic AR products, in which the three-

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https://doi.org/10.1016/j.ijleo.2017.11.081
0030-4026/

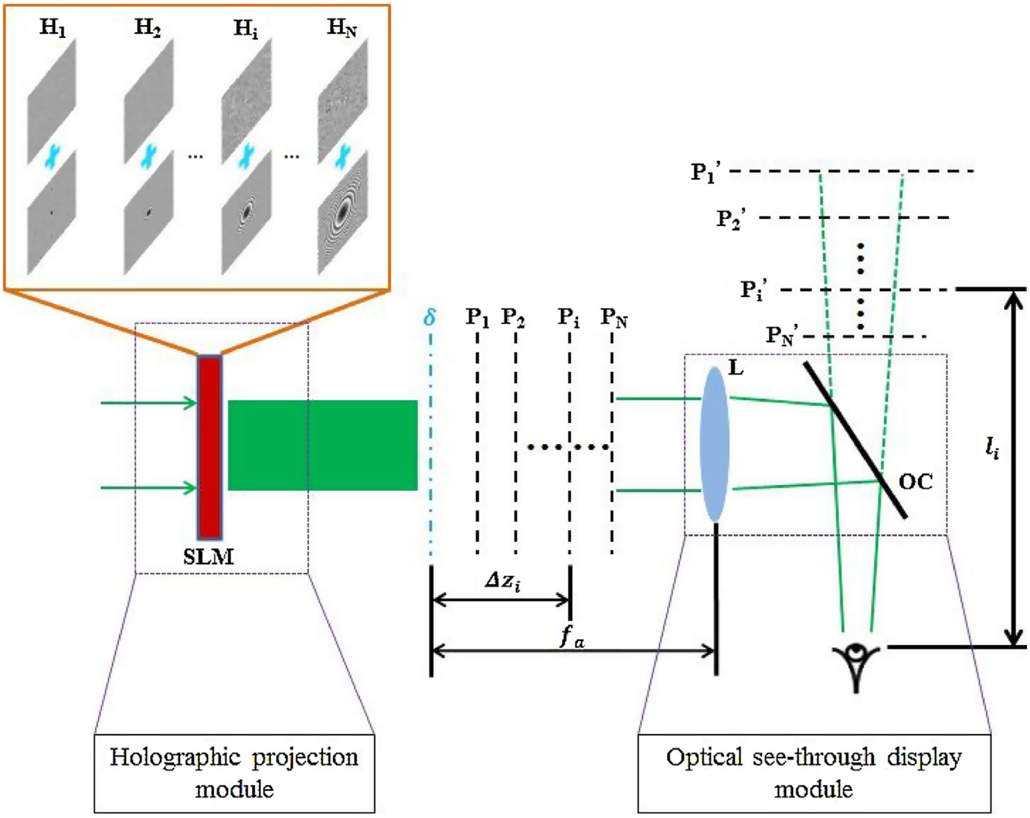

Fig. 1. Schematic diagram of the proposed optical see-through holographic 3D display system, where L is the ocular lens with a focal length of f_a, and OC represents optical combiner.

dimensional (3D) scene is generated by a pair of two-dimensional (2D) perspective images with binocular parallax, one main problem is the visual discomfort and fatigue caused by the accommodation-vergence conflict [13]. To solve this problem, many approaches have been proposed [14–16]. The multi-plane 3D display, as one of important realization approaches, can perceive a real 3D scene volume rendered with nearly-correct focus cues [17]. Recently, Liu et al. proposed a multi-plane optical see-through head-mounted display design for AR applications [18]. It manages to provide correct depth information and solves the accommodation-vergence conflict problem by using a stack of polymer-stabilized liquid crystal (PSLC) scattering shutters in time sequence. However, the multiple 2D slices for 3D reconstruction need to be projected onto the PSLC stacks, and switching the PSLC shutter requires an alternating voltage signal. In this case, the positions of imaging planes are relatively fixed and discrete, which increases the inconvenience of adjustment. Moreover, the time-multiplexing way adopted by this method puts forward higher requirement to the refresh rate of image projector. All factors mentioned above contribute to the increase of cost and complexity.

In this paper, we propose a multi-plane optical see-through holographic 3D display system for AR applications, where the virtual 3D scene is generated by means of holographic projection, the locations of multi-plane 2D slices are controlled by programmable zoom lenses with different focal lengths, and the realistic augmentation can be realized without using any image bearing structure. This system is able to perceive a real 3D scene volume, and present the correct depth information accurately, thus to solve the accommodation-vergence conflict problem effectively, and it has the advantages of large depth range and no visual fatigue. Compared with the 2D slices projection system developed in Ref. [18], our system adopted a spatial light modulator (SLM) to implement holographic projection. Therefore, correct depth information can be obtained by programmable zoom lenses encoded on the SLM, and it is convenient to express the depth information of virtual scene continuously. In addition, time-multiplexing method is replaced by space-division method to lower down the requirement for the refresh rate of projector in the experiment. In the next sections, the theoretical principle and system configuration will be described in detail, and the verification experiment results will be presented and analyzed.

2. Theoretical principle and system configuration

Fig. 1 is the schematic diagram of the proposed multi-plane optical see-through holographic 3D display system. The system is composed of two modules: the holographic projection module and the optical see-through display module. The 2D slices (P_1, P_2, . . ., P_i, . . ., P_N) from the virtual 3D scene will be projected by the holographic projection module, in which