Optics Communications 402 (2017) 41–46

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Wide field of view tabletop light field display based on piece-wise tracking and off-axis pickup

Yanhong Zhu, Xinzhu Sang *, Xunbo Yu, Peng Wang, Shujun Xing, Duo Chen, Binbin Yan, Kuiru Wang, Chongxiu Yu

State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, 100876, China

A R T I C L E   I N F O

Keywords:
Light field display
Piece-wise tracking
Off-axis pickup

A B S T R A C T

A wide field of view (FOV) tabletop light field display (LFD) based on piece-wise tracking and off-axis pickup is presented to display the floating three-dimensional (3D) scene, which is 360°surrounding viewable. The demonstrated LFD is specially designed with an integral imaging display (IID) with 83 × 83 viewpoints and a full-parallax holographic functional screen (HFS). To improve the FOV, a piece-wise tracking based FOV enhancement method is proposed. The relationship between the viewing zone and the elemental images (EIs) is formulated. A ray-tracing based method using off-axis pickup instead of parallel pickup directly is adopted to render the 3D scene to EIs. Then the piece-wise tracking method of varying the viewing zone by placing the EIs according to the position of viewer is analyzed. The floating 3D scene with a FOV of 70°× 70°is experimentally demonstrated with a good 3D perception.

1. Introduction

Three-dimensional (3D) display can transmit 3D image information with the maximum reality to observers. Many researchers have made long term efforts to propose and develop 3D display systems that are capable of expressing 3D images like real objects [1,2]. The 3D display technology which can present 360° surrounding floating 3D scene is one of the most attractive research topics [3–5]. The integral imaging display (IID) shows advantages of full parallax, continuous view-points within the viewing zone and real-time full-color operation, which is one of potential technologies to achieve floating 360° display [6]. However, the integral imaging display also has limitations, such as low spatial resolution, small field of view (FOV), and small depth range [7–15]. To achieve an excellent 360° floating 3D display, a large FOV is essential, and a few of works on enlarging FOV of integral imaging display were presented, such as the display with a curve lens array [14], and the display using two elemental image (EI) masks to increase the incident rays to a lens [15]. Real-time tracking technology was also introduced to increase the FOV of 3D displays and the EIs were rendered and displayed in real-time according the tracked position [16–18]. In IIDs, the EIs are always rendered from multi-view images [19–21], such as the each camera viewpoint independent rendering method. The total rendering time is $\boldsymbol{M}\times\boldsymbol{N}$ times of a single viewpoint assuming a viewpoint number of $\boldsymbol{M}\times\boldsymbol{N}$ with those methods. In normal real-time tracking IID [17,18], only the viewpoint corresponding to the tracked position was rendered from virtual scene and used to generate the EIs displayed on the 3D display to ensure real-time tracking and display, and nothing could be observed in the non-tracked position.

Our designed LFD is implemented with an IID (composing of a lens array, a liquid crystal display (LCD) panel) and a holographic functional screen (HFS). The optical designed FOV of our LFD is from −20°to 20° in both orthogonal directions, which is not large enough for the tabletop 3D display. To improve the FOV, a tracking based FOV enhancement method is introduced. To achieve a visual effect without aliasing, each viewpoint should also be captured with the same resolution with the LCD [22]. Rendering the EIs for our LFD with 6889 (83×83) viewpoint images with the resolution of 3840×2160 in real-time tracking mode is impossible. It often takes several hours to render one frame with the normal each camera viewpoint independent rendering method [19]. A piece-wise tracking method with a fast response time is introduced to our LFD in order to avoid occurring discontinuous display, and the LFD with the proposed method can provide 3D information for multiple viewers. In the proposed method, a series of EIs are pre-generated, instead of generating from multi-viewpoint images in real time. A high efficient ray-tracing based EIs rendering method using off-axis pickup is adopted [23]. The EIs containing multi-directional

* Corresponding author.
E-mail addresses: 1171824310@qq.com (Y. Zhu), xzsang@bupt.edu.cn (X. Sang).

http://dx.doi.org/10.1016/j.optcom.2017.05.056
Received 27 March 2017; Received in revised form 17 May 2017; Accepted 21 May 2017
0030-4018/

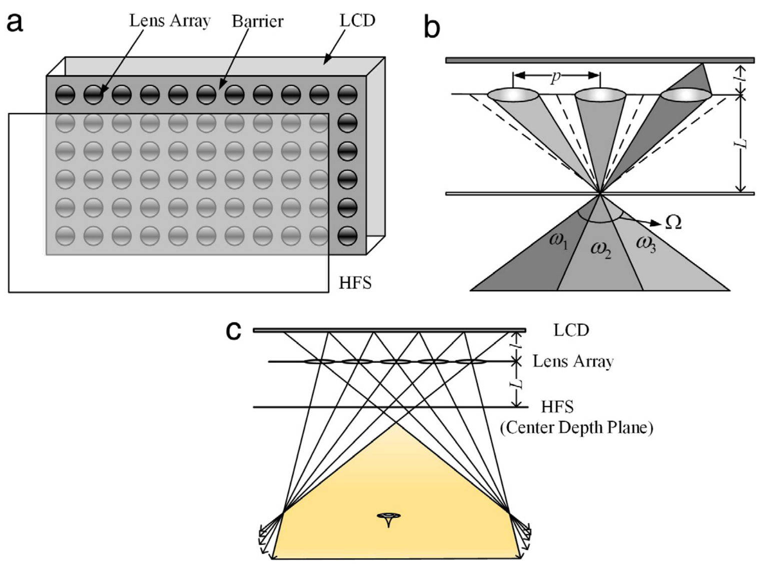

Fig. 1. (a) The structure of the LFD, (b) the diffuse of the HFS, (c) the viewing zone of the display.

perspective information in the FOV are changed only if the viewer exceeds a certain viewing angle threshold. In this way, the LFD can provide 3D information for a viewing zone instead of a tracked viewing position for multiple viewers only if the viewers stay in the tracked viewing zone. The FOV can be wider as far as the aberration of the lens array can be tolerant.

2. Principle of the proposed LFD

2.1. The structure of the designed LFD

The LFD is implemented with an IID (composing of a LCD panel with the resolution of 3840×2160 and a lens array) and a HFS as shown in Fig. 1(a). The lens array is composed of lenses arranged on the barrier. The focal length of the lens array is f, the gap between the LCD panel and lens array is denoted as l. The distance between the lens array and the HFS is L. HFS is placed at the focused image plane, which is also called as center depth plane. The relationship among f, l and L satisfies the Gaussian imaging law, as shown in Eq. (1).

$$\frac{1}{l}+\frac{1}{L}=\frac{1}{f}. \tag{1}$$

HFS is an optical element which is holographically printed with speckle patterns exposed on the proper sensitive material [2], which redistributes the incident light beams with a diffused angle of ω alone the incident direction as shown in Fig. 1(b). There always exist gaps between the displayed pixels in normal integral imaging displays, which decreases the visual performance [11–14,17,18]. The HFS is introduced to eliminate the gaps and achieve a 3D light field with uniform light distribution as shown in Fig. 1(b). The ω is designed as Eq. (2) in our LFD, and p is the pitch of the lens array. To achieve a large viewing zone, the EIs are arranged according to the viewer's position, and the generated viewing zone of the display is shown in Fig. 1(c). The LFD is designed in real mode with the gap l larger than the focal length of the lens array f ($l > f$) [7]. It displays the floating three-dimensional (3D) scene, which is 360° surrounding viewable. The designed LFD in real mode shows a large FOV and high 3D image resolution. The display of floating real image upon the lens array satisfies our demand of displaying floating 3D scene.

$$\omega = \arctan(p/L). \tag{2}$$

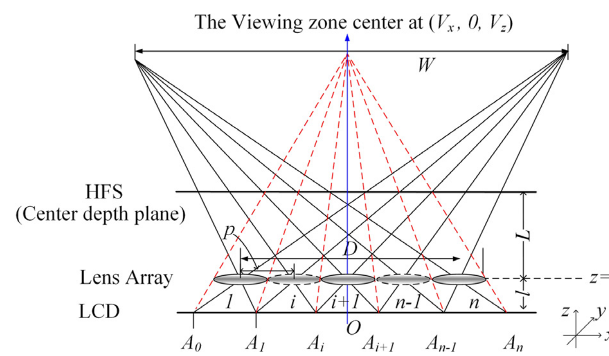

Fig. 2. The relationship between the viewing zone and the elemental images.

2.2. The proposed piece-wise tracking method

To enlarge the FOV to satisfy the demand of displaying tabletop 3D scene with a surrounding viewing area, a piece-wise tracking method is proposed. To realize the tracking method, the relationship between the EIs and the center position of the viewing zone is formulated, and a high efficient ray-tracing based EIs rendering method with off-axis pickup is adopted.

The relationship between the EIs and the viewing zone is shown as Fig. 2. The original point of the x–y plane locates at the center of the LCD panel, the z plane with $z = 0$ locates at the lens array plane. A_i means the x coordinate of the boundary area of the ith EI, which is the position where the ray from the central position of the viewing zone through each boundary of the elemental lens meets the EI plane. All the following formulas consider EI plane as one-dimensional line on x axis for analysis simplification, but they can be expanded to two-dimensional x–y plane. The A_i can be calculated as Eq. (3), and p is the pitch of the lens. The position at $(V_x, 0, V_z)$ represents the center of viewing zone, and n is the number of the lens in x-direction. The width of an EI in the x-direction is defined as $A_{i-1}A_i$, which is also the distance between the A_{i-1} and A_i , and it can be represented by Eq. (4). The width of the viewing zone can be defined as W by Eq. (5).

$$A_i = -\frac{V_x}{V_z} l + \left(i - \frac{n}{2}\right)\left(1 + \frac{l}{V_z}\right) p \tag{3}$$

$$A_{i-1}A_i = \left(\frac{l}{V_z} + 1\right) p \tag{4}$$