Pixel-Density Enhanced Integral Three-Dimensional Display by Time-Division Multiplexing of Two-Dimensional Image

Hayato Watanabe, Naoto Okaichi, Masanori Kano, Hisayuki Sasaki, Jun Arai

watanabe.h-fe@nhk.or.jp
NHK Science & Technology Research Laboratories, 1-10-11 Kinuta, Setagaya, Tokyo 1578510, Japan
Keywords: integral three-dimensional display, two-dimensional image synthesis, thinner optical system, time-division multiplexing

ABSTRACT

We propose a method for displaying three-dimensional (3D) images with high maximum pixel density by synthesizing a two-dimensional image with an integral 3D image using time-division multiplexing. We developed a prototype display system and verified its display performance through display experiments.

1 Introduction

Integral three-dimensional (3D) displays can display naturally viewable 3D images with smooth motion parallax without the use of special glasses. Owing to this advantage, integral 3D displays are expected to be applied in various fields such as television, medicine, education, advertisement, and entertainment. However, it is difficult to display 3D images with a high pixel density because their pixel density is generally restricted by the lens density of the lens array, which constitutes an integral 3D display [1].

To solve this problem, we are researching and developing two-dimensional (2D) image synthetic integral 3D displays [2,3] that can display 3D images with enhanced resolution characteristics based on layered 3D displays [4,5]. In 2D image synthetic integral 3D displays, elemental images and a 2D image are generated by optimization calculations in advance. A 3D image whose maximum pixel density is enhanced to the pixel density of the 2D image can be displayed by displaying the generated images on an integral 3D display and a 2D display, and by optically synthesizing the images displayed on these displays. Our previous methods used a half-mirror to synthesize an integral 3D display and a 2D image. As a result, the size of the display system increased.

Therefore, we propose a display method that uses a time-division multiplexing (TDM) technique to make the display optics thinner than those used in our previous research. In the proposed method, a polarization-dependent lens array that can switch its operation states between a lens array and a glass plate for light transmission, depending on the polarization state of the incident light, is used. We developed a prototype display system and verified its performance in displaying 3D images.

2 Proposed Display Method

2.1 Basic Configuration

The basic configuration of the proposed 3D display method is shown in Fig. 1(a). The display system consists of a liquid crystal display (LCD), a polarization switching element, a lens/transparent mode switchable lens array (LTMSLA), and a sync signal generator. As shown in Fig. 1(b), the LTMSLA functions as a convex lens array when horizontally polarized light is incident, and as a glass plate for light transmission when vertically polarized light is incident. The LTMSLA is placed at a distance of f, the focal length of the LTMSLA, from the LCD surface.

In a certain frame, the elemental images are displayed on the LCD, and the light emitted from the polarization switching element is switched to horizontal polarization. At this time, an integral 3D display is displayed on the

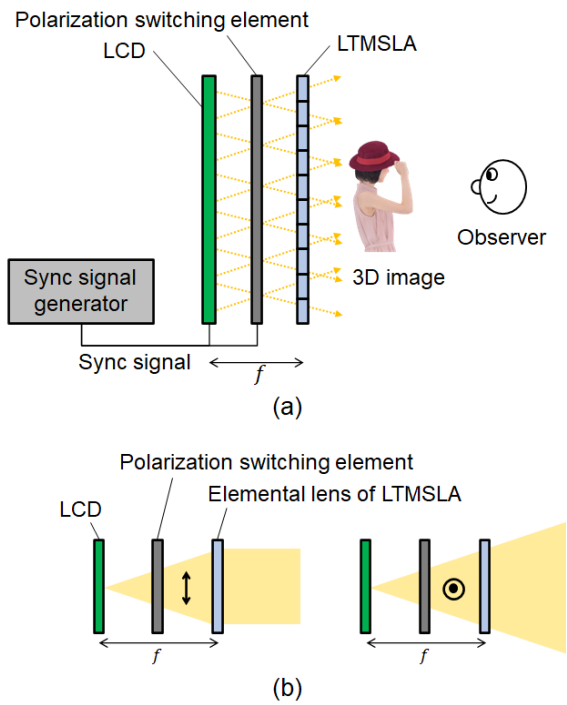

Fig. 1 Pixel density enhanced integral 3D display by time-division multiplexing of 2D image. (a) Basic configuration of the display system. (b) Operation principle of LTMSLA.

display system. In the next frame, the 2D image is displayed on the LCD, and the light emitted from the polarization switching element is switched to vertical polarization. At this time, a 2D image is displayed on the display system. Multiplexing of the integral 3D image and the 2D image can be achieved by switching the image displayed on the LCD and the polarization state of the light emitted from the polarization switching element at a high speed and in synchronization.

2.2 Image Generation Method

This section describes the generation of elemental images and a 2D image. In the proposed method, these images are generated based on the principle of additive layered 3D displays [5]. Figure 2 depicts the positional relationship between elemental images, a 2D image, an integral 3D image, and a target light field image. The position of the display plane of the elemental images and the 2D image is the same as that of the LCD, and the number of pixels is also the same as that of the LCD. The 2D image and its luminance values at pixel positions (i, j) are denoted as L and $L(i, j)$, respectively. The position of the display plane of the integral 3D image is the same as that of the lens array plane, and the number of pixels in the 3D image is the same as the number of lenses. The integral 3D image and its luminance values at pixel positions (m, n) and viewpoints s, t are denoted as $I_{s,t}$ and $I_{s,t}(m, n)$, respectively. The target light field image is the desired 3D image to be displayed. The position of the display plane of the target light field image is the same as that of the lens array plane, and the number of pixels is the same as that of the LCD. The target light field image and its luminance values at pixel positions $(i - ds, j - dt)$ and viewpoints s, t are denoted as $V_{s,t}$ and $V_{s,t}(i - ds, j - dt)$, respectively. d is the amount of disparity proportional to the focal length f. Based on the above configuration, the elemental images and the 2D image are generated according to the following equation:

$$\underset{L(i,j),I_{s,t}(m,n)}{\operatorname{argmin}} \left[\sum_{s,t,i,j} \left\{ L(i,j) + I_{s,t}(m,n) - V_{s,t}(i - ds, j - dt) \right\}^2 \right]. \quad (1)$$

A 3D image with luminance values that approximate the target light field image can be displayed by multiplexing the integral 3D image and the 2D image by time division using the generated elemental images and the 2D image.

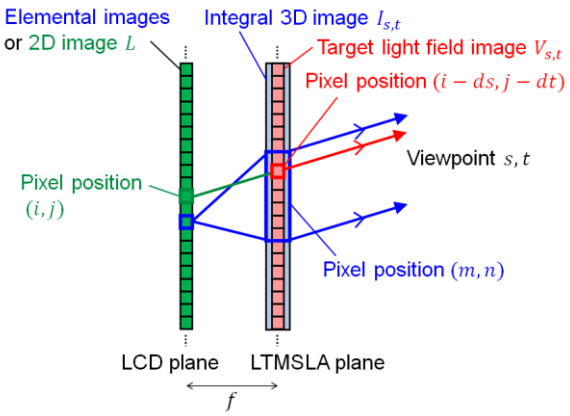

Fig. 2 Positional relationship between display planes of the elemental images, 2D image, integral 3D image, and target light field image.

3 Prototype Display System

A prototype display system was developed to verify the effectiveness of the proposed method. Table 1 lists the specification of the prototype display system, and Fig. 3 shows its appearance. Each optical component was stacked perpendicular to the optical table. Although the displayed image could be observed directly from above, we placed a mirror so that it could be observed from the front. The prototype display system used the LTMSLA developed in our previous study [6]. The LTMSLA consists of two layers of geometric phase optical elements [7]. The focal length was 3.0 mm at a wavelength of 532 nm. A diffusing film with a diffusion angle of 2.0° was placed above the LTMSLA to reduce the color moiré.

The refresh rate of the LCD was 120 Hz. The prototype display system switches between an integral

Table 1 Specifications of the prototype display system.

LCD	Pixel pitch	49.8 μm
	Refresh rate	120 Hz
LTMSLA	Size	120 × 100 mm
	Lens pitch	1.0 mm (square array)
	Focal length	3.0 mm @ 532 nm
Polarization switching element	Liquid crystal mode	Optically compensated bend mode
3D image	Display size	120 × 100 mm
	Maximum number of pixels	2409 × 2008 pixels
	Viewing zone angle	18.9° (H), 18.9° (V)
	Frame rate	60 fps

3D image and a 2D image every 1/120 s for TDM. The frame rate of the 3D images was 60 frames per second (fps), and the theoretical maximum number of pixels in the 3D images was approximately 2400 × 2000.

4 Experimental Results

The results of displaying the 3D image of the wedge chart on the prototype display system are shown in Fig. 4(a). We compared the general integral 3D image obtained without TDM with the integral 3D image obtained using the proposed method with TDM. Visual observation confirmed that the 3D image with TDM had higher resolution characteristics when its depth position was 0 mm or 10 mm. However, when the depth position was 20 mm, the 3D image with TDM was slightly blurrier than that without TDM.

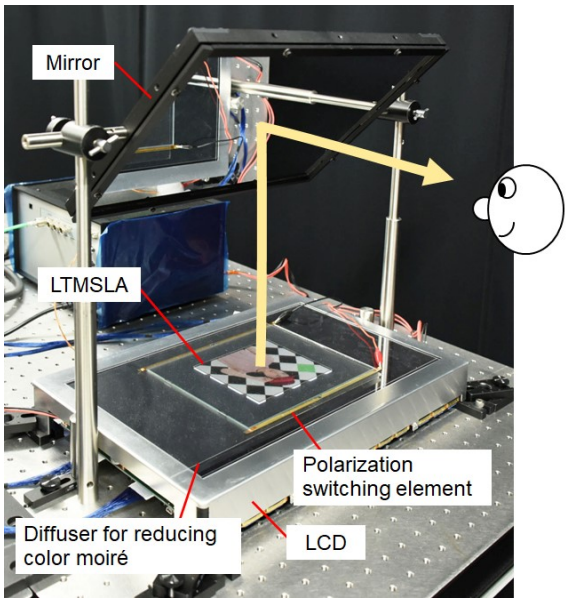

Fig. 3 Appearance of the prototype display system.

The results of displaying the 3D image of 3D models are shown in Fig. 4(b). The 3D model of the woman was placed so that the depth position of her eyes was the same as that of the lens array plane. The background checker pattern was placed 30 mm behind the lens array plane. We confirmed that the resolution characteristics in the area around a woman's face were enhanced by the proposed method using TDM. However, the background checker pattern was slightly blurred compared with that without TDM.

The main cause of the blurring of 3D images when 3D images are displayed at depth positions far from the lens array plane is the low response characteristics of the LCD. Crosstalk is estimated to occur when the image displayed on the LCD is switched between the elemental images and the 2D image. To solve this problem, it is necessary to use a display device with high response characteristics.

5 Conclusions

We propose a method for displaying 3D images with high maximum pixel density by synthesizing a 2D image with an integral 3D image using TDM. In the proposed method, an integral 3D image and a 2D image are switched at high speed using an LCD, polarization switching element, and LTMSLA. We developed a

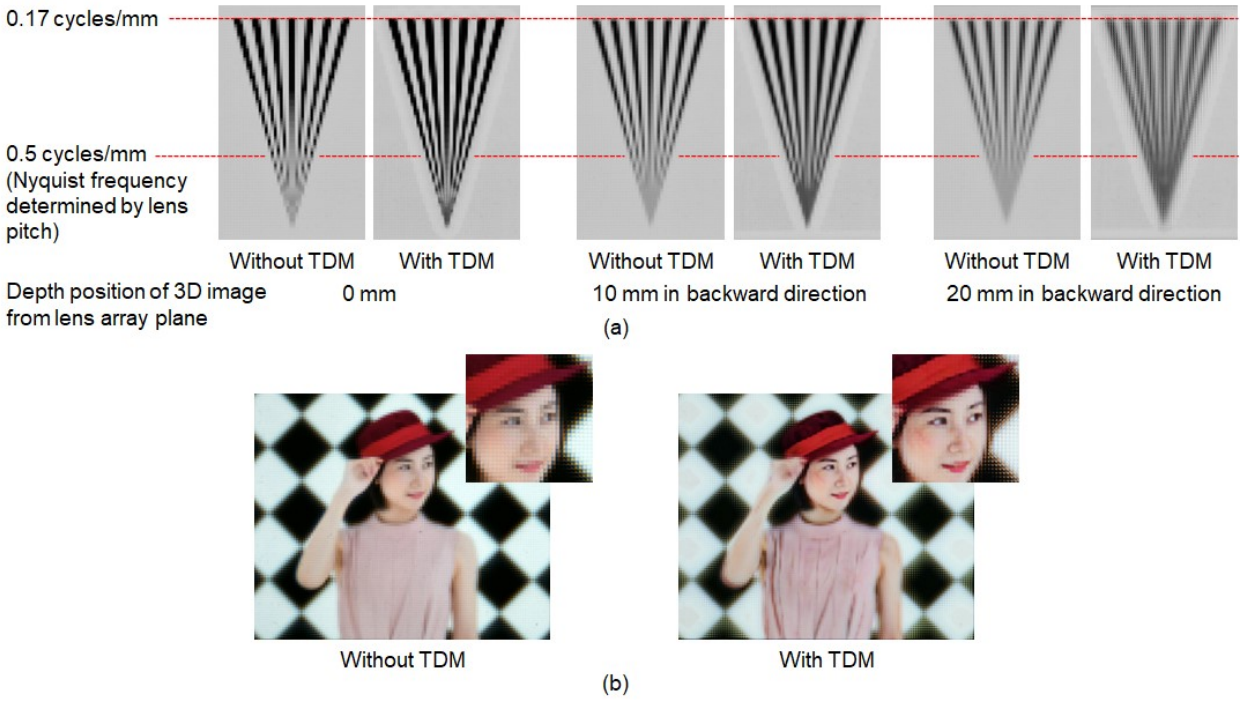

Fig. 4 3D images displayed by the prototype display system. (a) 3D image of the wedge chart. (b) 3D image of the 3D models.

prototype display system and confirmed that the resolution characteristics of 3D images could be enhanced at depth positions close to the lens array plane. The prototype display system has a problem in that the resolution characteristics of 3D images at depth positions far from the lens array plane are low owing to time-division crosstalk. In the future, we intend to improve the display device and evaluate the display performance for 3D images.

References

[1] H. Hoshino, F. Okano, H. Isono, and I. Yuyama, “Analysis of resolution limitation of integral photography,” J. Opt. Soc. Am. A, Vol. 15, No. 8, pp. 2059–2065 (1998).

[2] H. Watanabe, J. Arai, C. Tsutake, K. Takahashi, and T. Fujii, “Pixel-density enhanced integral three-dimensional display with two-dimensional image synthesis,” Opt. Express, Vol. 30, No. 20, pp. 36038–36054 (2022).

[3] H. Watanabe, J. Arai, C. Tsutake, K. Takahashi, and T. Fujii, “Image Generation Method Using Weight Maps for Subjective Quality Improvement in Two-Dimensional Image Synthetic Integral Three-Dimensional Display,” Proc. IDW ‘22, pp. 521–524 (2022).

[4] G. Wetzstein, D. Lanman, M. Hirsch, and R. Raskar, “Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting,” ACM Trans. Graph., Vol. 31, No. 4, pp. 1–11 (2012).

[5] S. Lee, C. Jang, S. Moon, J. Cho, and B. Lee, “Additive light field displays: realization of augmented reality with holographic optical elements,” ACM Trans. Graph., Vol. 35, No. 4, pp. 1–13 (2016).

[6] H. Watanabe, N. Okaichi, M. Kano, H. Sasaki, and J. Arai, “Direct-view integral 3D/2D convertible display using geometric phase lens array,” Proc. 3D Image Conference, 6-3 (2023). (in Japanese)

[7] J. Kim, Y. Li, M. N. Miskiewicz, C. Oh, M. W. Kudenov, and M. J. Escuti, “Fabrication of ideal geometric-phase holograms with arbitrary wavefronts,” Optica, Vol. 2, No. 11, pp. 958–964 (2015).