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360-degree three-dimensional display with virtual display surface

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Abstract

We propose the omnidirectional 3D display system which displays directly touchable 3D images. The display surface of the proposed display is cylindrical, and displayed 3D images are observed around the cylindrical display surface. The proposed system composed of multiple basic display units. Each basic display unit consists of an LCD and a holographic optical element which works as a microlens array. The display surface of the proposed system is the virtual screen which is composed of multiple light focusing points (3D pixels) equally spaced in a cylindrical shape. Therefore, the display surface is not the physical obstruction when observers touch 3D images directly. In order to verify the effectiveness of the proposed system, we constructed the 144-degree prototype system. The virtual cylindrical display surface was composed of 8 basic display units. The angle of view of each 3D pixel which formed the virtual cylindrical display surface was 15°, and each 3D pixel irradiated 6 light rays at 3° intervals. The diameter and the height of the virtual cylindrical display surface were 42.6 mm and 50 mm, respectively. A displayed 3D image was directly touchable and was observed from 144° directions.

1. Introduction

People working in the fields of medical science, product design and development, and so on need omnidirectional 3D display systems to enable efficient communication. Previously, many 3D display systems which use a lot of projectors or rotating mechanisms have been proposed to extend the viewing angle of the 3D display. The Seelinder display [1] is the system using rotating mechanisms. This system rotates multiple 1D vertical arrays of LEDs and a cylindrical parallax barrier. But there is a problem that the system has complex mechanism because they use two rotating mechanisms. 360-degree three-dimensional table-screen display [2] combined with multiple high speed projectors and a special screen which passed light rays from projectors to the particular direction. Many viewing points are produced around the system by the rotating screen. In this system, it is necessary to synchronize the rotating screen and multiple high-speed projectors. Interactive 360° light field display [3] and Color three-dimensional display with omnidirectional view [4] used a single high speed projector and a rotating mirror. They display omnidirectional 3D images by changing the projected image which is corresponded to the direction of the mirror. This system can display high quality image, but observer cannot touch directly 3D images because the rotating mirror is the physical obstruction. In order to overcome this problem, we propose an omnidirectional 3D display system which controls light rays by using the combination of a holographic microlense array and an LCD instead of the rotating mirror. Since the angle of view of each holographic microlens is narrow, the proposed display system is composed of multiple basic display units to extend the viewing angle of the 3D display. Each basic display unit consists of an LCD and a holographic microlens array. With the proposed 3D display system, multiple basic 3D display units are aligned in a circle and are imaged at the center of the circle in impeller form by the relay optics. Thus, the display surface of the proposed system is the virtual screen which is composed of multiple light focusing points (3D pixels) equally spaced in a cylindrical shape. Therefore, the virtual display surface is not the physical obstruction and observed 3D images are directly touchable.

This paper describes the principle of the 360-degree three-dimensional display with virtual display surface. In Section 2, we describe the configuration of the proposed system, and explain that the basic display unit has equivalent effect to the rotating mirror system. Moreover, we describe that observed 3D images are directly touchable. In Section 3, to verify the effectiveness of the proposed system, we describe the experimental result. Finally, we give some conclusion in Section 4.

2. 360-degree Three-Dimensional Display

2.1 Basic 3D Display Unit

The proposed display system is composed of multiple basic display units instead of a rotating mirror. Each basic display unit consists of an LCD and a holographic microlens array. Each microlens of the basic display unit irradiates light rays to the desirable directions which are controlled by pixel information of the LCD like a light field display. Since the proposed display uses a cylindrical microlens array, observed 3D images have parallax only in horizontal direction. As shown in Figure 1, the irradiation angle of the light ray from each microlens corresponds to the rotation angle of the rotating mirror system. In other words, when n light rays are irradiated from each microlens at $\theta/(n-1)$-degree intervals, one basic display unit is equivalent to the rotating mirror having rotation angle $\theta+(\theta/(n-1))$ degrees.

Figure 2 shows the diffraction characteristics of the holographic microlens array. Every holographic microlens works as a cylindrical lens with angle of view θ horizontally. And also, it diffracts the optical axis at the elevation angle 40° and diffuses the illumination light vertically. For the sake of simplicity, here we limit the number of directions of irradiated light rays within each microlens to six. The density of microlenses is equal to the density of 3D pixels on the virtual cylindrical display surface. In order to increase the resolution of observed 3D images, horizontal microlens arrays are shifted with respect to each other by one pixel.

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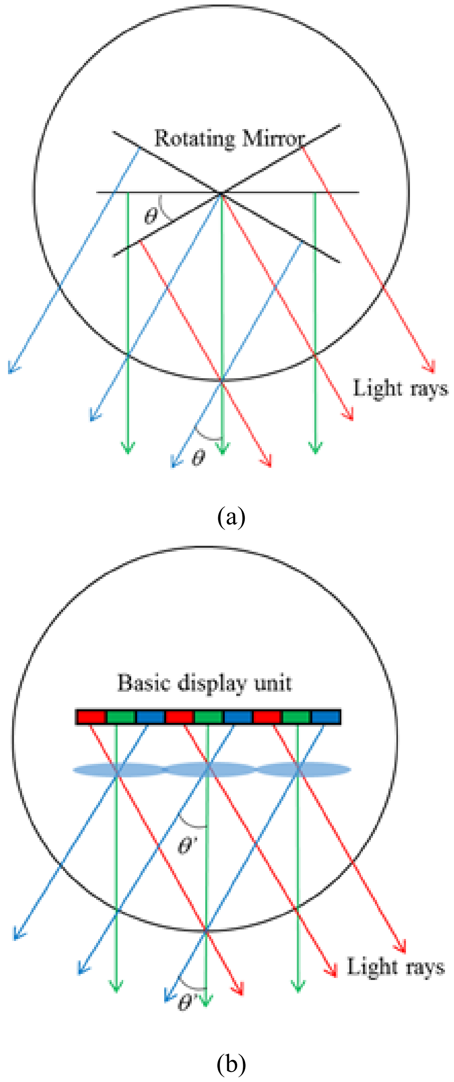

Figure 1. Comparison between the rotating mirror system and the basic display unit: (a) rotating mirror system, (b) microlens array system (basic display unit).

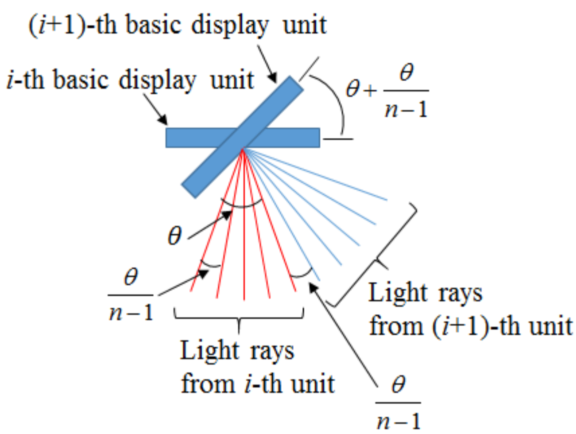

Figure 3.Angular interval between two basic display units.

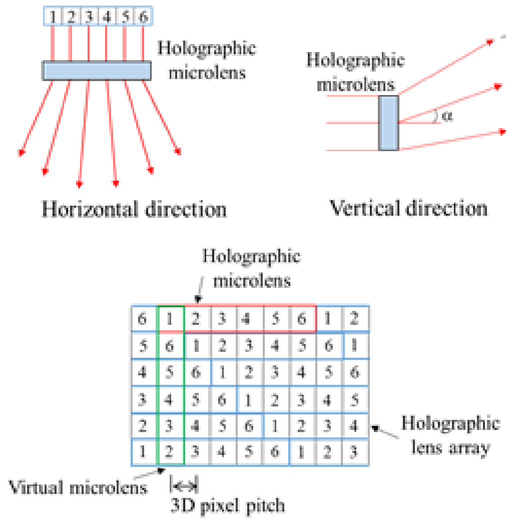

Figure 2. Characteristics of holographic microlens array.

2.2 Proposed 3D Display System

As mentioned in section 2.1, when n light rays are irradiated from each microlens at $\theta/(n-1)$-degree intervals, one basic display unit is equivalent to the rotating mirror having rotation angle $\theta+(\theta/(n-1))$ degrees. Therefore, as shown in Figure3, let n_{bdu} be the required number of basic display units to realize the virtual cylindrical display surface which is observed from 360° directions, n_{bdu} is given by

$$n_{\text{bdu}} = \frac{360}{\theta + \dfrac{\theta}{n-1}} \quad . \tag{1}$$

Figure 4 shows the schematic diagram of basic 3D display unit and the relay optical system. Each microlens is capable of emitting light rays in emergence directions corresponding to the number of LCD pixels like as a light field display. In the proposed 3D display system, multiple basic 3D display units are aligned in a circle and are imaged at the center of the circle in impeller form by the relay optics as shown in Figure 5. Since multiple basic display units are imaged at the center of the cylinder in impeller form by the relay optics, the display surface of the proposed system is the virtual screen which is composed of multiple light focusing points (3D pixels) equally spaced in a cylindrical shape. Therefore, the virtual display surface is not the physical obstruction and observed 3D images are directly touchable as shown in Figure 5.

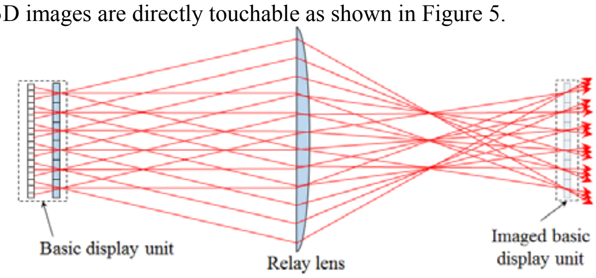

Figure 4. Schematic diagram of the basic 3D display unit and the relay optical system.

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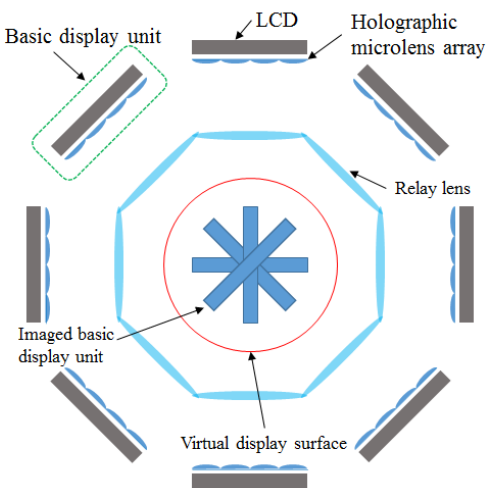
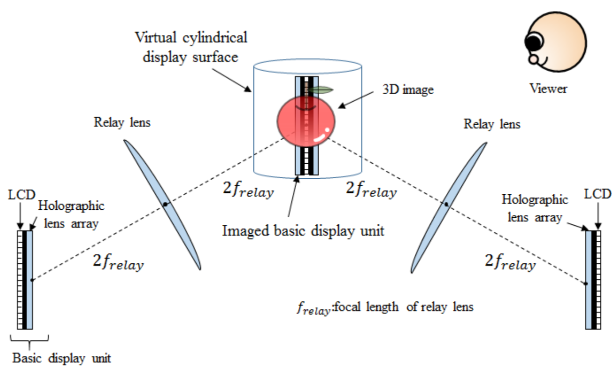


(a)



(b)

Figure 5. Schematic diagram of the proposed display system: (a) top view, (b) side view.

Figure 6 illustrates the relationship between the radius of the virtual display screen and reflected light rays with the rotating mirror system. We assume that each 3D pixel on the virtual display irradiates n light rays, the rotation angle of the mirror is ω deg/sec, and the frame rate of the projector is m fps. Then, the angle of view of each 3D pixel is given by

$$\theta = \frac{\omega(n-1)}{m} \quad (2)$$

Let w be the pixel size on the mirror, the radius of the virtual display screen R is given by

$$R = \frac{\frac{n-1}{2}\cdot w}{\sin\left(\frac{\theta}{2}\right)} \quad (3)$$

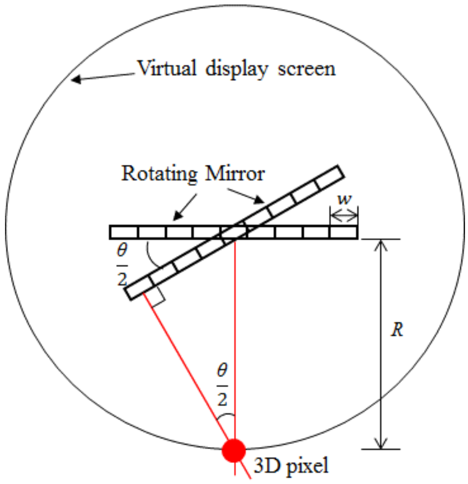


Figure 6. Relationship between the radius of the virtual display screen and reflected light rays with the rotating mirror system.

Figure 7 shows the relationship between the radius of the virtual display screen and reflected light rays with the microlens array system. Figure 8 illustrates the comparison between the rotating mirror system and the microlens array system. When the rotating angle θ is equal to the irradiation angle θ', the microlens array system has equivalent effect to the rotating mirror system.

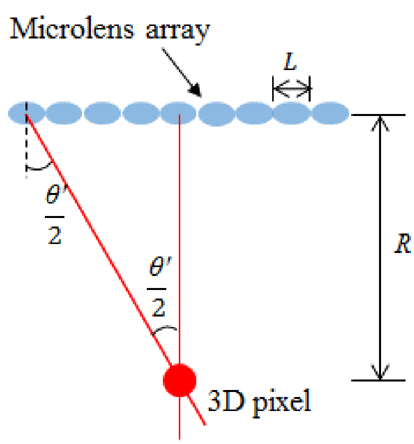


Figure 7. Relationship between the radius of the virtual display screen and reflected light rays with the microlens array system.

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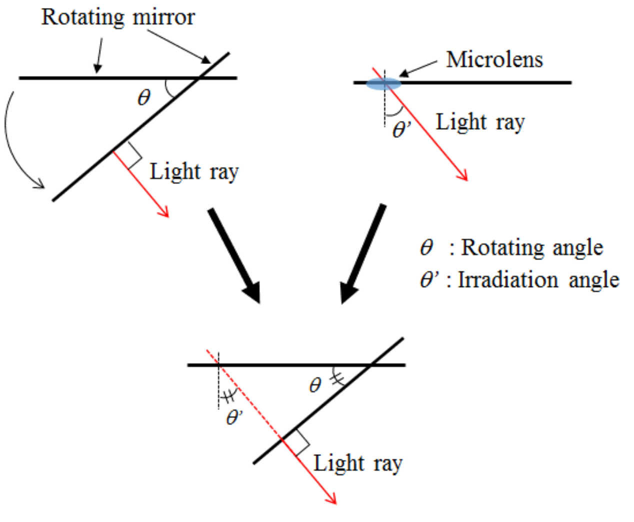

Figure 8. Comparison between the rotating mirror system and the microlens array system.

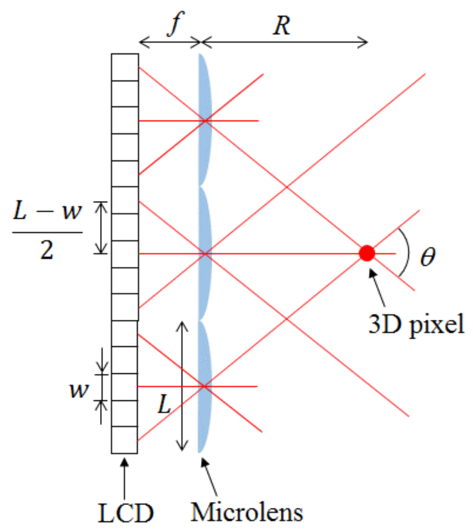

Figure 9. Characteristics of holographic microlens array.

With the microlens array system, let L be the size of each microlens, w be the pixel size of the LCD, the number of light rays emitted by each microlens n is given by

$$n = \frac{L}{w} \quad (4)$$

Thus, the radius of the virtual display screen R is given by

$$R = \frac{\frac{n-1}{2} \cdot L}{\tan\left(\frac{\theta}{2}\right)} \quad (5)$$

In Eq. (5), we suppose that light rays from six consecutive microlenses make a 3D pixel. As shown in Figure 9, let f be the focal length of each microlens and θ be the angle of view of each microlens, then the following equation is derived.

$$\tan\left(\frac{\theta}{2}\right) = \frac{L-w}{2f} \quad (6)$$

Thus, substituting Eq. (6) for Eq. (5), we have Eq. (7).

$$R = f \cdot \frac{L}{w} \quad (7)$$

3. Experimental Result

In order to verify the effectiveness of the proposed 3D display, we constructed the prototype system. The basic 3D display unit consisted of an LCD, a holographic microlens array, and a relay optical system. We used the iPod touch ver.5 as an LCD, and its pixel size is 0.078 mm × 0.078 mm. The size of the holographic microlens array is 49.92 mm × 49.92 mm, and it contains 106 × 640 holographic microlenses. The size of each holographic microlens is 0.468 mm × 0.078 mm and its focal length is 1.8 mm. Thus, each holographic microlens emits 6 light rays horizontally. In the vertical direction, all light rays are diffracted to 40° upward and are diffused. The combination of an LCD and a holographic microlens array is imaged at the center of the virtual display surface by the relay optic without magnification. We used a Fresnel lens of the focal length 152 mm as a relay lens. From these conditions, considering the displayed 3D image by this system has parallax only in the horizontal direction, we can derived that the viewing angle of the basic 3D display unit was 15° and each 3D pixel irradiates 6 light rays. The prototype 3D display consisted of 8 basic 3D display units. They were aligned 18-degree apart in a circle. Thus, the prototype system was a part of circle with radius 465.8 mm, and the viewing angle of a 3D image was 144-degree. And then, to satisfy Eq. (7), we decided that the radius R of the virtual screen size was 10.62 mm. In the other hand, the distance that crosstalk of adjacent light rays emitted from a 3D pixel becomes 50% is the maximum radius size of a displayed 3D image. By wave-optics analysis, we estimated that the maximum radius size was 21.3 mm in the prototype display system [5],[6]. Therefore, the maximum size of a displayed 3D image was 42.6 mm in diameter, 50 mm in height, and the viewing angle of a 3D image was 144-degree. Table 1 shows the specifications of the prototype 3D display system. Figure 10 shows the prototype of the proposed display system. Figure 11 shows displayed 3D image taken from left side 63°, left side 45°, left side 27°, left side 9°, right side 9°, right side 27°, right side 45°, and right side 63°.

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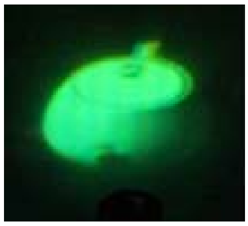
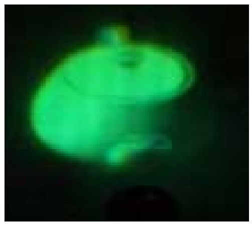
Table 1. Specifications of the prototype display system.

Holographic microlens	Lens size	0.468 × 0.078 mm
	Lens array size	49.92 × 49.92 mm
	Number of holographic microlenses	106 × 640
	Angle of view	15°
	Elevation angle	40°
LCD	Number of pixels	640 × 640
	Pitch of the pixel	0.078 × 0.078 mm
	Size of display panel	49.92 × 49.92 mm
Prototype system	Number of basic display units	8
	Angular interval between two basic display units	18°
	Radius of the system	465.8 mm
	Display area	Diameter:42.6 mm Height:50.0 mm
	Number of 3D pixels	106 × 640
	Number of emitted light rays from each 3D pixel	6
	Viewing angle	144°

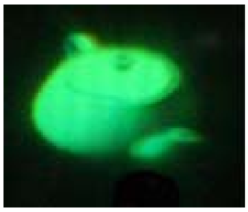
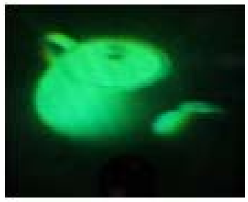
(a)

(b)

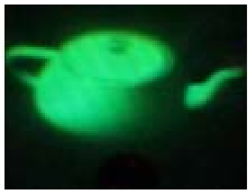
Figure 10. The prototype of the proposed display system: (a) top view, (b) side view.

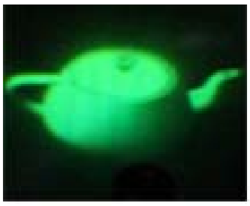
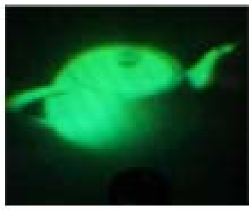
(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 11. Observed 3D image: (a) from left side 63°, (b) left side 45°, (c) left side 27°, (d) left side 9°, (e) right side 9°, (f) right side 27°, (g) right side 45° (h) right side 63°.

4. Conclusion

We proposed a 360-degree three-dimensional display with virtual display surface. The virtual display surface of the proposed display is cylindrical, and displayed 3D images are observed around the cylindrical display surface. The proposed system composed of multiple basic display units. Each basic display unit consists of an LCD and a holographic micolens array. The display surface of the proposed system is the virtual screen which is composed of multiple light focusing points (3D pixels) equally spaced in a cylindrical shape. Therefore, the display surface is not the physical obstruction when observers touch 3D images directly.

The effectiveness of the proposed display was verified experimentally. The prototype 3D display system consists of 8 basic 3D display units. They are aligned 18-degree apart in a circle with radius 465.8 mm. The maximum size of a displayed 3D image was 42.6 mm in diameter, 50 mm in height. The viewing angle of a 3D image was 144-degree, and there are no flipped images.

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Additionally, observed 3D images were directly touchable. The proposed 3D display will be useful for applications in which several people work together to perform tasks or enjoy entertainment with a synergistic effect.

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Author Biography

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