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360° see-through full-parallax light-field display using Holographic Optical Elements

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Abstract

We propose a see-through cylindrical full-parallax light-field display which is viewable from all around 360 degrees. A rotating cylindrical screen created by the Holographic Optical Elements (HOEs) provides a see-through image that enables multiple observers to view it with the real background scene without using any specific glasses.

A high-speed projector is employed to realize this time-division projection system. It is set on the bottom of the display and directed towards a hyperboloid mirror which is placed on the top of the display. The rays projected from the projector is reflected by the hyperboloid mirror and the rays are incident on the rotating HOE surface. Then, as the cylindrical screen rotates, the rays are scanned horizontally and vertically by the HOE screen.

Since the HOE has angular and wavelength selectivity, only the rays from the projector is diffracted strongly. Otherwise, the rays from the real scene will not be diffracted by the HOE. Therefore, the proposed display achieves see-through, full-parallax and wide viewing zone. Furthermore, we performed computer simulation to verify the principle.

Introduction

In recent years, various 3D displays have been contemplated and constructed. The one of the purposes of the displays is advertisement because 3D image attracts people's attention strongly. For the usage of advertising, characteristics that are wide viewing zone and observable by multiple viewers are desirable. Several displays that achieve these characteristics have been constructed [1-3]. These displays have wide viewing zone that enables observers to see the image while the observers walk around the display and multiple observers can view it at the same time. Also, these displays don't require any specific glasses, thus the observers can see with naked-eyes.

However, these 3D displays can only realize horizontal parallax and they are not suitable for digital signage because the image becomes incorrect when the observers move vertically or view the image from inappropriate height. To solve this problem, Yano et al. developed Spherical full-parallax light-field display using ball of fly-eye mirror[4]. This study realizes a full-parallax light-field display and it has wide viewing zone. Then, observers can see the 3D image correctly when moving not only in horizontal direction, but also in vertical direction.

Recently, transparent display is likely to be used as digital signage. This is another effective way to attract people's attention. Nakamura et al. developed 360-degree transparent holographic screen display[5]. The display is able to be observed 360-degree around. In this display, the 2D image is displayed on the cylindrical screen and it is syncronized by tracking the observer. Holographic optical elements (HOEs) are employed in this display. HOE has characteristics which include wavelength selectivity and angular selectivity. Because of the characteristics, rays from the projector are diffracted on the holographic screen. Moreover, rays from the background just pass through the screen and thus, this display achieves transparency. The image appears to be floating in the air in real scene. However, only one tracked observer is able to see the image correctly. Therefore, the display cannot be applied as a digital signage, which is expected to be observed by multiple viewers at the same time.

We propose a novel full-parallax light-field display using cylindrical HOE screen. A specific projection system that consists of a hyperboloid mirror and a high-speed projector is employed in the proposed display. The HOE screen rotates and realizes the horizontal and vertical scan in time multiplexing manner. The light-field on the cylindrical screen provides wide viewing zone so that the observers can walk around the display and see the 3D image without using any specific glasses. Also, because of the characteristics of HOE, transparency is achieved. Therefore, our proposed 3D display achieves full-parallax, wide viewing zone and transparency that are expected to provide high effectiveness as a digital signage.

Proposed method

The proposed display consists of a high-speed projector, a hyperboloid mirror and see-through cylindrical HOE screen that rotates. The high-speed projector is set on the bottom of the display and directed towards the hyperboloid mirror which is placed on the top of the display. The rays projected from the projector are reflected by the hyperboloid mirror and the rays are incident on the rotating HOE screen. The image from the projector is projected onto the cylindrical screen entirely. Then, the rays are diffracted by the HOE and directed outside of the display. Fig.1 shows the schematic of the design of the proposed display.

The whole HOE screen on the cylindrical surface is divided into several sections along the circumferential direction and each of them is recorded to have a lens-like function. When a ray from the projector is incident on the HOE, the ray is diffracted. As shown in Fig.2(a), since the HOE screen rotates around the vertical axis, the diffracted ray is scanned from right to left as one section of the HOE passes. While the ray is scanned horizontally, the projected image is refreshed synchronously with the rotation so that the rays with different colors, which depend on the horizontal angle of the rays, are emitted from the cylindrical screen, as shown in Fig.2(b). Therefore, horizontal parallax is achieved. Each HOE has a lens-like function but the height of the focal points are different among the lenses, as shown in Fig.3(a). Then, the rays are scanned vertically among these lenses during the rotation as shown in Fig.3(c). Also, since the projected image is refreshed synchronously with the rotation, the rays with different colors, that depend on the vertical angle of the rays, are emitted from the cylindrical screen as shown in Fig3(b), which means vertical parallax is achieved. Therefore, full-parallax is achieved in time multiplexing manner.

Due to the angular selectivity and wavelength selectivity of the HOE, the lights passing through the HOE except the lights from the projector are not diffracted by the HOE. Only the rays from the projector are diffracted. Therefore, the lights from the background pass through the HOE and see-through is achieved.

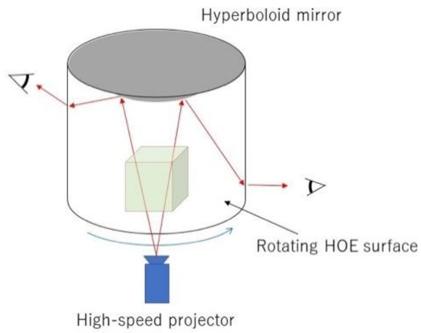
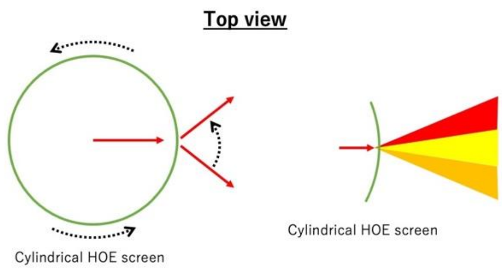
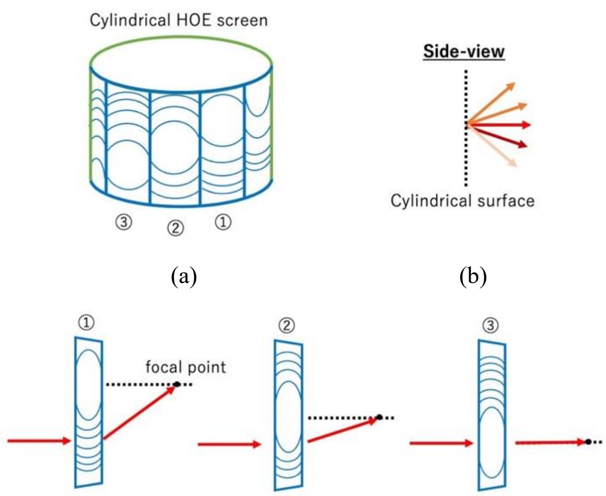


Fig.1 Schematic of the design of the proposed display



(a) (b)

Fig.2 Horizontal scan



(c)

Fig.3 Vertical scan

Design

The projection system in the proposed display consists of the hyperboloid mirror on the top of the display and the high-speed projector on the bottom of the display. Due to the characteristics of the projection system, the pixel pitch on the cylindrical screen differs depending on its height. The pixel pitch is small on the top of the cylindrical screen and large on the bottom. This is affected by the mirror shape. If the mirror shape is inappropriate, the pixel pitch can be singinifantly biased depending on its height on the cylindrical screen. Therefore, the parameters of the mirror shape were calculated so that the difference of the pixel pitch can be reduced to the least possible extent.

The mirror shape is defined by:

$$\frac{\mathrm{r}^2}{a^2} - \frac{y^2}{b^2} = -1 \quad (1)$$

where r is radial direction of the cylindrical surface, y is height, a and b are the parameters to define the mirror shape. The parameters, a and b were calculated under the same conditions as shown in Table 1.

The results of a and b are 94.3 and 77.8 respectively. The mirror shape with the calculated parameters is shown in Fig.4. The blue line represents the calculated mirror shape whereas the red line indicates the rays from the projector. The rays are reflected by the mirror and are incident on the HOE screen as represented by the green line in Fig.4. The pixel pitch that was calculated horizontally and vertically is represented by the green line in Fig.5. In the result, the pixel pitch is still small on the top of the cylindrical screen and large on the bottom but the difference of the pixel pitch was reduced.

The focus of the projector is normally adjusted according to the distance between the projector and a flat screen surface. However, the projection system in the proposed display projects the image onto the cylindrical screen. Therefore, the projection image cannot be focused on the cylindrical screen as it is adjusted normally on a flat surface. Then it causes unique blur, which differs depending on its height on the cylindrical screen. In order to analyze the blur on the cylindrical screen, rays from the projector were simulated. Then, the blur was calculated. It is described as a function of height on the cylindrical screen and the function depends on the focus of the projector. Therefore, the appropriate focus of the projector was calculated so that the blur becomes smaller than the pixel pitch at any height on the cylindrical screen.

The result of the focus is 245.2mm and the blur with the focus is represented by the blue line Fig.5. The aperture size of the projector is 10mm in the simulation. As the result, the blur becomes smaller than the pixel pitch at any height on the cylindrical screen. Therefore, when the focus of the projector is 245.2mm, the blur don't deteriorate the image quality.

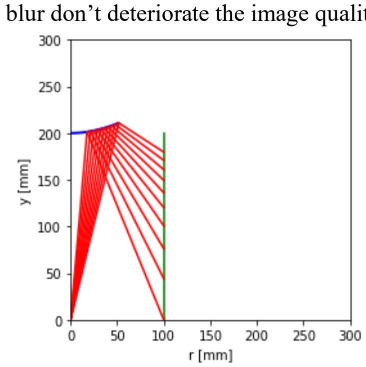


Fig.4 The calculated mirror shape

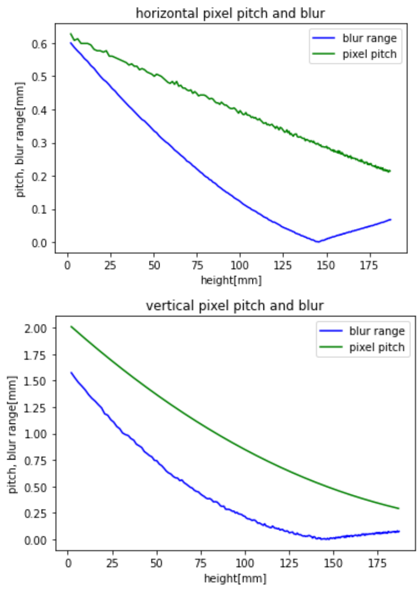


Fig.5 comparison of blur and pixel pitch

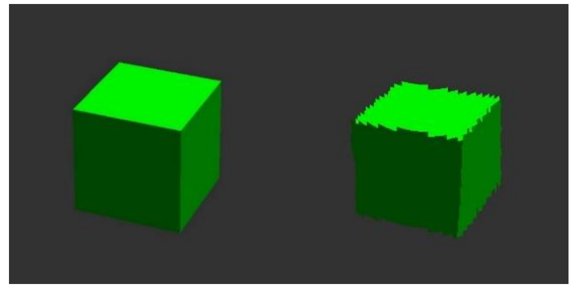
Simulation

We conducted computer simulation to confirm that the 3D image can be observed properly, considering the pixel pitch using ray tracing method. The condition of the simulation is shown in Table 1. In this simulation, Pin-hole model projector is used. Hence, the effect of the aperture of the projector is not considered as it is proven that the aperture will not cause deterioration on the image quality. Also, the diffraction efficiency of the HOEs is not taken into account in this simulation. The simulation was performed with a total of five viewpoints. The center viewpoint is 500mm away from the display, with a height of 100mm which is the same as half of the cylinder's height. Also, four viewpoints at 60mm up, down, left, and right from the center viewpoint are defined.

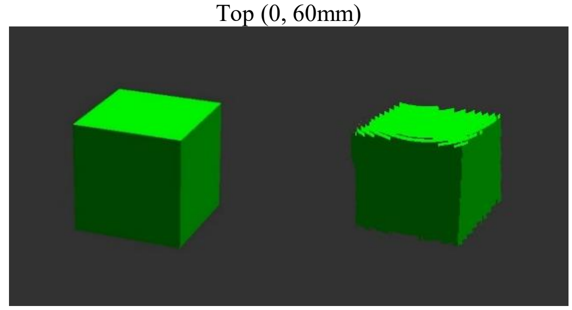
The ideal images and simulation results from each viewpoint are shown in Fig.6. As shown in the results, we confirmed that appropriate parallax is achieved. However, there are jagged pattern on the result images. The lack of the number of horizontal direction caused this pattern and the pattern can be improved with high angular resolution.

Table1 Simulation specification

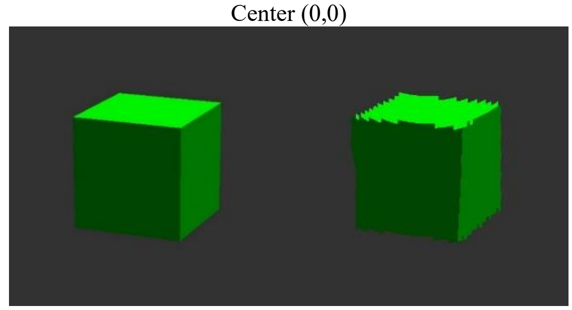
Display height	200 mm
Radius of the display	100 mm
The number of the direction (horizontal × vertical)	60×10
The resolution of the projector	1024×768
Projection angle of the projector	38.6×29.4 degree
Viewing distance	500 mm
Refresh rate	20 Hz
Projection fps	12,000 fps



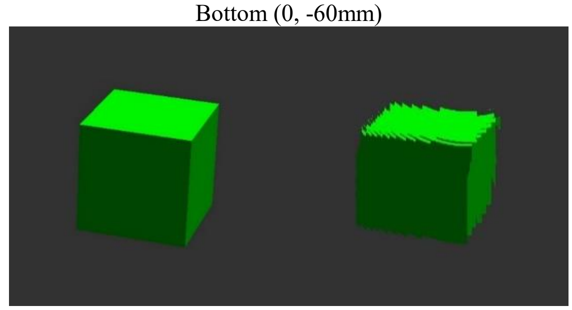
Top (0, 60mm)



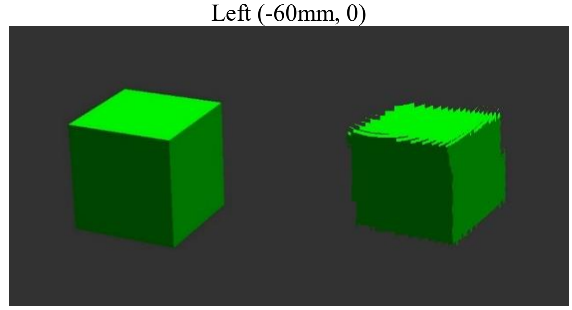
Center (0,0)



Bottom (0, -60mm)



Left (-60mm, 0)



Right (60mm, 0)

Fig.6 Simulation result from each viewpoint

Conclusion

In this paper, we proposed a see-through cylindrical full-parallax light-field display which is viewable from all around 360 degrees.

The proposed display consists of a high-speed projector, a hyperboloid mirror and see-through cylindrical HOE screen that rotates. Rays from the projector are diffracted by the HOE screen and scanned horizontally and vertically. Since the projected image is refreshed synchronously with the rotation, full-parallax is achieved in time multiplexing manner.

In the projection system, the pixel pitch on the cylindrical screen differs depending on its height and it is affected by the mirror shape. Therefore, parameters that define the mirror shape were calculated so that the difference of the pixel pitch on the cylindrical screen is reduced to the least possible extent. As the result, the difference of the pixel pich was reduced.

The focus of the projector is normally adjusted according to the distance between the projector and a flat screen surface. However, the projection system in the proposed display projects the image onto the cylindrical screen. Therefore, the projection image cannot be focused on the cylindrical screen as it is adjusted normally on a flat surface. Then it causes unique blur, which differs depending on its height on the cylindrical screen. The blur was simulated and we confirmed that the blur don't deteriorate the image quality by calculating the appropriate focus of the projector, which is 245.2mm in the result.

Additionally, Computer simulation was performed to confirm the principle of the proposed method. Finally, it was confirmed that appropriate parallax is achieved.

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Author Biography

Reiji Nakashima received the B.Eng from the Nagaoka University of Technology in Niigata, Japan in 2020. He is now in master course of Department of Electrical, Electronics and Information Engineering in the same university.