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Immersive autostereoscopic display based on curved screen and parallax barrier

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In this Letter, we present a display system based on a curved screen and parallax barrier, which provides stereo images with a horizontal field of view of 360° without wearing any eyewear, to achieve an immersive autostereoscopic effect. The display principle and characteristics of this display system are studied theoretically in detail. Three consecutive pixels on a curved screen and parallax barrier form a display unit, which can generate separate viewing zones for the left and right eyes, respectively. Simulation and experimental results show that the non-crosstalk effect can be obtained in the viewing zones, which proves the effectiveness of this display system. This study provides some new ideas for the improvement of the autostereoscopic display and to enable envisioned applications in virtual reality technology.

Keywords: autostereoscopic display; parallax barrier; curved screen.
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1. Introduction

Nowadays, virtual reality (VR) technology has attracted a great deal of interest by virtue of its imagination, immersion, and interaction characteristics[1]. To build a virtual scene that enables people to feel almost like they are in the real world, the VR display is required to provide immersive and stereoscopic images. Previous reports on VR display are mainly about head-mounted displays (HMDs) and curved projection screens[2,3]. For HMD[4,5], the display panel is placed very close to the eyes and generates an immersive stereoscopic effect by sending stereo images to each eye from separate optical paths. The main problem for HMD is that the accommodation-convergence mismatch would become more serious than common stereoscopic television[5]. For curved projection screens[6,7], multiple projectors are usually used in pairs so as to illuminate the entire cylindrical screen, and polarizing filters are utilized to separate the left/right eye channels. So, people can receive immersive stereoscopic images by wearing polarizer glasses when they stand inside the cylinder. However, the de-polarizing effect[7] would appear at the top or bottom of the screen because of the large incident angle of projecting light, so some stereoscopic effect will be lost. Besides the mentioned problems, both HMD and curved projection screens need special eyewear, which is not suitable for people with myopia and for prolonged use[8].

To solve these problems, autostereoscopy may be a good solution, which does not need any form of special glasses or other user-mounted devices[9–11]. The traditional way for autostereoscopic display is based on the parallax barrier[12,13], which is composed of vertical apertures separated by black masks. Left and right eye image columns are placed alternately on the display panel, and the parallax barrier can control light passing only to the desired zone and forming multiple discrete viewpoints. The viewpoints are strictly fixed, so people cannot freely rotate or move their heads, which leads to a non-immersive viewing experience. The low degree of freedom is the major reason why there have been few reports about autostereoscopic display for application in the VR field. In 2004, Tanaka *et al.* proposed an immersive autostereoscopic display named telexistence wide-angle immersive stereoscope (TWISTER)[14], which is composed of 30 display units. The display unit consists of one parallax barrier and two LED arrays, which correspond to two eyes. People can receive immersive autostereoscopic images by rotating display units around him and presenting time-varying patterns. The rotating method is inspiring; however, it would also lead to a bulky configuration, optical instability, and difficulty for image generation. Therefore, an immersive autostereoscopic display based on a static and fixed structure needs to be developed.

In this Letter, we will present an immersive autostereoscopic display based on a curved screen and parallax barrier. Three consecutive pixels on the curved screen and parallax barrier make up a stereoscopic display unit. The pixels on both sides provide images for the left and right eyes, respectively, under the action of the curved parallax barrier. The middle pixel is set to be black to work as the second parallax barrier to prevent the crosstalk between the left and right images. The structure parameters and display characteristics of this proposed display system are investigated theoretically. The simulation and experimental results show that no crosstalk exists in the viewing zones. Moreover, the viewing direction can be freely rotated around the cylindrical center in this centrosymmetric display structure, so an immersive stereoscopic vision is achieved. This work provides an impetus towards the development of the autostereoscopic display in VR applications.

2. Structure and Principle

Figure 1(a) shows the configuration of the proposed display system based on the curved screen and parallax barrier. Display pixels are connected circularly to form a curved screen. Three consecutive pixels make up a display unit: pixels “R” and “L” provide images for right and left eyes, respectively, and pixel “M” is used to prevent crosstalk. Discrete black strips are placed circularly and separated by a slit with a certain width, to obtain a curved parallax barrier. The curved screen and parallax barrier share the same center O, and the distance between them is constant, which makes the whole display structure centrosymmetric. The detailed geometrical relationship between the curved screen and parallax barrier can be described as follows: straight lines are drawn from the center O to the edges of the black strip, and the lines will intersect at the junctions between different pixels.

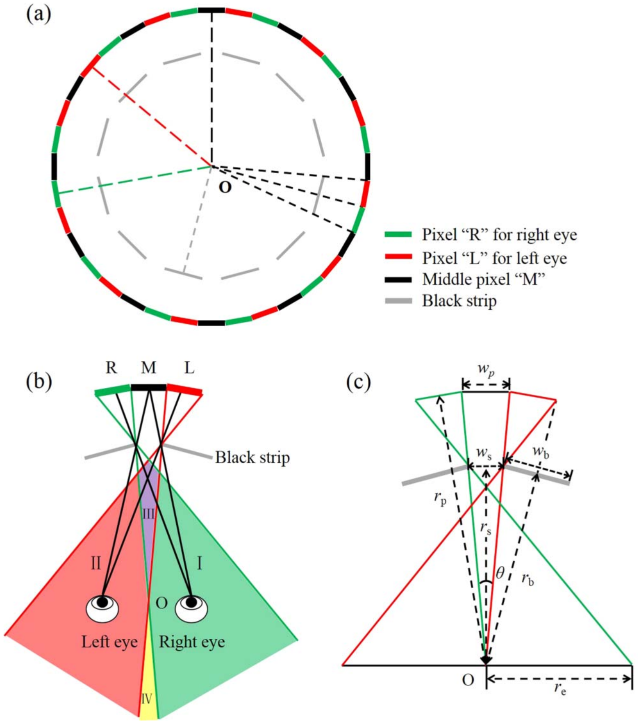

Fig. 1. (a) Configuration of the immersive autostereoscopic display based on a curved screen and parallax barrier; (b) principle and (c) structure parameters of one display unit.

Figure 1(b) shows the display unit and its working principle. A parallax barrier is arranged in front of the three pixels. Under the effect of the parallax barrier, pixels “R” and “L” form four regions. Regions I and II correspond to the viewing zones for the right and left eyes, respectively. Region III is the crosstalk zone where the pixels “R” and “L” are visible simultaneously. In contrast to that, no pixels can be seen in region IV. To prevent the crosstalk, the middle pixel “M” is set to be black to act as the second parallax barrier[12]. When the right eye is located in region I, it will see the pixels “R” and “M” through the slit at the same time. The existence of pixel “M” does not affect the image content of pixel “R” but only decreases its illuminating intensity, so the right eye can receive the right image with lower luminance. Considering that the left eye has a similar display procedure, an autostereoscopic vision can be achieved as long as the eyes stay in their corresponding regions. Moreover, since the whole structure [Fig. 1(a)] is centrosymmetric, people can watch the images by rotating around the center O, thereby an immersive autostereoscopic effect can be obtained.

Figure 1(c) shows the structure parameters of the display unit. The parallax barrier with slit width w_s and black strip width w_b is placed in front of the display pixel with a width of w_p. The distances from the center O to the slit, black strip, and pixel are denoted by r_s, r_b, and r_p, respectively. All of these distances are represented by dotted lines. θ is the angle of the pixel relative to the center O. r_e represents the maximum horizontal movement distance for one eye. Beyond the allowable distance, one of the two eyes will see the wrong images. Considering that the interpupillary distance is usually about 65 mm[15], r_e is set to be 70 mm in this paper. From the geometrical relationships in Fig. 1(c), the following equations are obtained:

$$\frac{w_p}{2} = r_p \times \tan(\theta/2), \tag{1}$$

$$\frac{w_p}{r_e} = \frac{r_p - r_s}{r_s}, \tag{2}$$

$$\frac{w_s}{2} = r_s \times \tan(\theta/2), \tag{3}$$

$$r_b = \frac{r_s}{\cos(\theta/2)} \times \cos\theta, \tag{4}$$

$$\frac{w_b}{2} = r_b \times \tan\theta. \tag{5}$$

On the basis of these equations, we can design an immersive autostereoscopic display and simulate its display characteristics.

3. Results and Discussion

An immersive autostereoscopic display model is developed, with the structure parameters as shown in Table 1. Considering that the angular resolution of human eye is about 1′ (0.017°), the

Table 1. Structure Parameters of the Immersive Autostereoscopic Display.

Parameter	Value (mm)
r_p	1000
w_p	0.279
w_s	0.278
w_b	0.556
r_s	996.03
r_b	996.03

pixel angle θ is set to be 0.016° to fulfill the viewing requirements. r_p is set to be 1000 mm, which means that the viewing distance from center O to the screen is 1 m. Based on Eq. (1), w_p is calculated to be 0.279 mm. Moreover, on the basis of the Eqs. (2)–(5), w_s and w_b are calculated to be 0.278 mm and 0.556 mm, respectively, which indicates that the aperture ratio of the parallax barrier is about 33.3%. r_s and r_b have the same value of 996.03 mm because θ is too small.

As shown in Fig. 1(b), the display unit has three pixels, so the angle of the display unit relative to center O is 0.048°. When the eyes focus on the image content, the effective horizontal field of view (FOV) is about 50°[15,16], which means that there will be thousands of display units that can be received in the eyes at the same time, as shown in Fig. 2(a). To prevent the crosstalk, the viewing zone for each eye is changed to a specific shape compared to region I or II shown in Fig. 1(b). The detailed mathematical expression of this specific shape can be found elsewhere[16]. The viewing zones for the right and left eyes are repainted in Fig. 2(b), and a coordinate system is established for the convenience of the following description. The origin locates at the center O. Futher, the y axis splits the two viewing zones equally, and the x axis is perpendicular to the y axis and passes through the center O. Therefore, the viewing zones for the right and left eyes are located in the positive and negative directions, respectively, of the x axis.

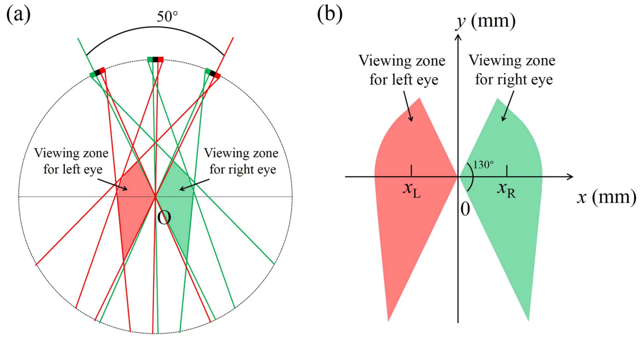

Fig. 2. (a) Viewing zones for numerous display units; (b) viewing zones with a coordinate system.

The software LightTools is used to build up the theoretical model of the immersive autostereoscopic display and investigate its crosstalk characteristics. The structure parameters of the theoretical model are set according to Table 1. The number of light sources is 1042 in the horizontal direction corresponding to the effective horizontal FOV. A surface receiver with a size of 130 mm × 10 mm is used to measure the illumination distribution along the x axis. To achieve the simulation results as accurately as possible, the number of tracing rays is set to 500 million. Firstly, the pixels "M" and "R" are set to be non-illuminated, where only pixel "L" is set to be illuminated, and the ray tracing simulation result is shown in Fig. 3(a). It can be seen that all the received light converges in the region on the left side of center O, which is the viewing zone for the left eye. A more intuitive and accurate light distribution result is also shown in Fig. 3(b). It can be clearly seen that the light illumination keeps zero in the region on the right side of center O, that is, there is no light from pixel "L" that can enter the viewing zone for the right eye, which shows a non-crosstalk characteristic. Further, the pixels "M" and "L" are set to be non-illuminated, and only pixel "R" is illuminated; then similar but opposite results are obtained in Figs. 3(c) and 3(d). It can be seen that there is no light from pixel "R" in the viewing zone for the left eye. The simulation results shown in Fig. 3 provide a good basis to prove that the combination of the parallax barrier and pixel "M" can effectively prevent the crosstalk between the two viewing zones, which ensures a good autostereoscopic quality.

Furthermore, to validate the reliability of simulation results, an experimental model of the immersive autostereoscopic display is built up, and the schematic structure is shown in Fig. 4(a). A pixels film, which is a transparent film with pixels printed on it, combined with an ambient light source is used as the curved screen. In the pixels film, pixels "R" and "M" are set to be opaque, and pixel "L" is set to be transparent. So, under

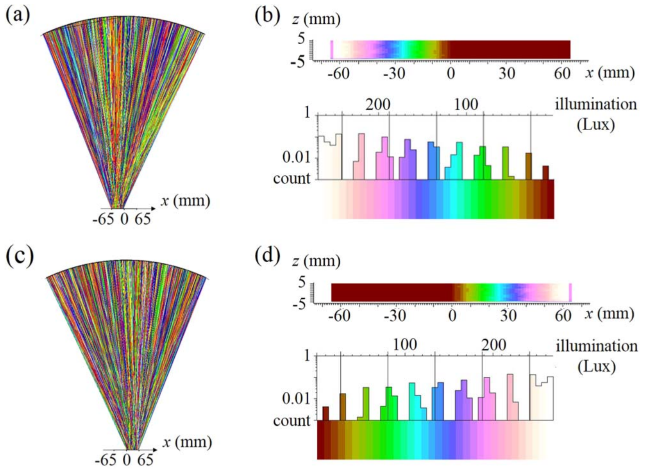

Fig. 3. Simulation results when only pixel "L" is set to be illuminated: (a) ray tracing result and (b) illumination distribution on the surface of receiver. Simulation results when only pixel "R" is set to be illuminated: (c) ray tracing result and (d) illumination distribution on the surface of receiver.

the ambient light illumination, pixels “R” and “M” are non-illuminated, and pixel “L” is illuminated, which is the same as the simulation condition described above. The parallax barrier is composed of parallel, periodic opaque, and transparent parts. The pixels film and the parallax barrier film are attached to the outside and inside surface, respectively, of a piece of curved glass, so the distance between the two films and the curvature radius of the two films can be easily determined by the thickness and curvature radius of the curved glass. A camera with a horizontal FOV of 50° is used to capture the light from the pixels film. Two locations are selected for the camera, and their coordinates are (−32.5, 0) and (32.5, 0), which are used to match the usual interpupillary distance.

According to the schematic structure shown in Fig. 4(a), and the structure parameters shown in Table 1, the experimental setups are developed, as shown in Fig. 4(b). The curved glass is fabricated by the hot melt technique, and its height and thickness are 0.8 m and 4 mm, respectively. The curvature radius and the arc length of the outside surface of the curved glass are both 1 m. The pixels film and parallax barrier film are attached to the outside and inside surface of the curved glass, and the microscope images of the two films are also shown in Fig. 4(b). The horizontal lengths of the two films are both 0.9 m, so the two films can provide an effective horizontal FOV of 50° for the digital camera, which can move along the x axis.

Figure 5(a) shows the image captured by the camera when located on the coordinate (−32.5, 0). It can be obtained that the scene under the ambient light can be seen, which indicates that the light from pixel “L” can enter the camera in the viewing zone for the left eye. When the camera is moved to the coordinate (32.5, 0), the image turns out to be all black, as shown in Fig. 5(b). The all black image demonstrates that no light from pixel “L” can enter the camera in the viewing zone for the right eye, which shows a non-crosstalk characteristic. Moreover, considering that the configuration of the experimental setups is bilaterally symmetric, it recognizes that a reversed result can be obtained when pixels “L” and “M” are set to be opaque, and pixel “R” is set to be transparent. The experimental results shown in Fig. 5, which have a good agreement with the simulation results shown in Fig. 3, provide further evidence to prove the effectiveness of the proposed immersive autostereoscopic display system. It should be noted that some black stripes can also be seen in the Fig. 5(a). It is a typical phenomenon in the autostereoscopic display based on parallax barrier[17], which is induced by the barriers and will cause the loss of display brightness[8]. To further decrease the effect of the parallax barrier, it can be achieved by using the slanted barrier[18] or increasing the backlight illumination[19]. We will improve this problem in our future work to get better application prospects.

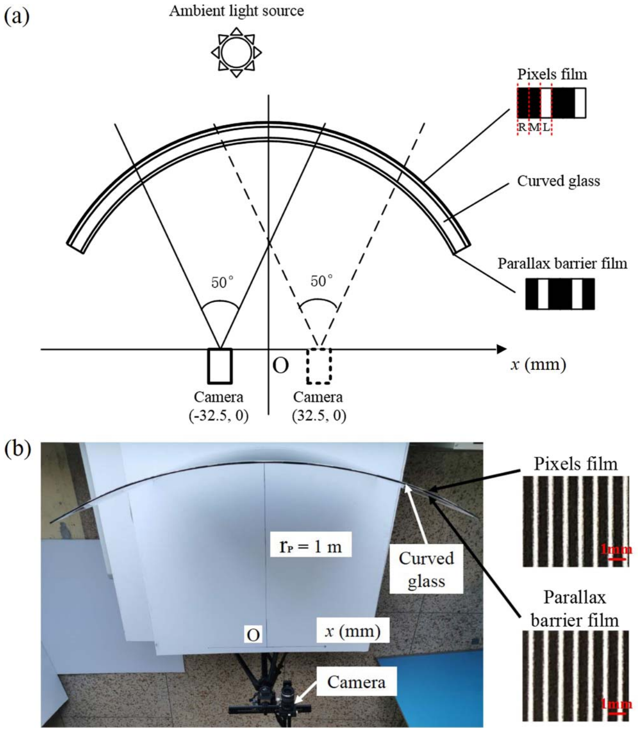

Fig. 4. (a) Schematic structure and (b) experimental setups to test the immersive autostereoscopic display based on a curved screen and parallax barrier.

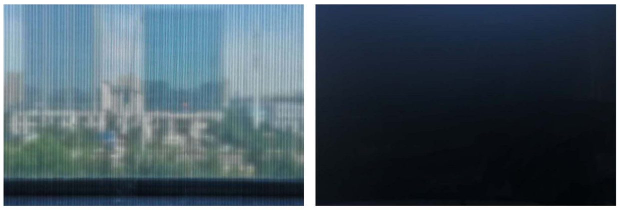
(a) (b)

Fig. 5. Images captured by the camera at different coordinates: (a) (−32.5,0) and (b) (32.5, 0).

4. Conclusion

We have demonstrated an immersive autostereoscopic display based on a curved screen and parallax barrier with a static and fixed structure. The display principle and structure design are investigated in detail. Three consecutive pixels and parallax barriers form a display unit. Under the action of the numerous display units, two separated viewing zones are generated for the left and right eyes. After building up a theoretical model in optical software, the simulation results show that there is no crosstalk between these two viewing zones. Moreover, the viewing direction can be freely rotated around the cylindrical center to achieve an immersive stereoscopic vision. We also build up an experimental model to test the display characteristics of this proposed display system. The results show that the left and right images can be obtained with the non-crosstalk effect, which proves the effectiveness of this display system. Therefore, we believe that this work will open a promising way to design immersive autostereoscopic displays for VR applications.

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