Full-parallax three-dimensional display using new directional diffuser

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A full-parallax three-dimensional (3D) display using a new directional diffuser is demonstrated. The display could present 3D images with 45 views comprising 9 horizontal views by 5 vertical views. The resolution and size of the 3D images displayed are 226×226 pixels and 300×300 (mm). The new directional diffuser consisting of two perpendicular lenticular sheets can be widely used in the display domain owing to its low cost and simple process.

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The development of three-dimensional (3D) displays has drawn increasing attention[1−10]. All 3D displays can be divided into two broad categories: PIC information reproduction and DIC information reproduction. PIC information stands for the position, intensity, and color information of the points of a 3D object. DIC information stands for the direction, intensity, and color information of the light beams that originate from a 3D object. After recording the PIC information of 3D objects, 3D images can be represented realistically by reproducing the same PIC information of the 3D objects. The PIC information reproduction has no hidden effects because the lighting points reproduced are nondirectional. However, the DIC information reproduction can overcome this shortcoming. All volumetric 3D displays belong to the PIC information reproduction, while all other 3D displays such as holographic and stereoscopic can be classified into the DIC information reproduction.

Recently in DIC information reproduction, a series of super multi-view (SMV) displays and high-density directional displays were proposed by Takaki *et al.*[11−14]. These 3D displays, consisting of a projector array and a vertical diffuser, can display natural 3D images with a large number of horizontal-only parallax views and a small angle pitch. In these systems, each directional image is displayed on one liquid crystal display (LCD) panel. A common lens and an aperture are used to make the imaging rays nearly parallel. The small-size aperture blocks a lot of light from arriving at the screen. In 2010, Takaki *et al.* also published another 3D display combining a multi-projection system and a flat panel auto-stereoscopic display, which can display 256 horizontal views[15]. A real-time horizontal-only parallax 3D display was demonstrated by Sang *et al.* in 2009, which contains a projector array and a holographic functional screen[16].

Compared with these horizontal-only parallax 3D display systems, the full-parallax 3D displaying with both horizontal and vertical parallax are more realistic and natural to represent 3D images.

In full-parallax 3D display, the integral imaging has drawn much attention for its ability to display large images in full parallax using a simple optical system; its small viewing angle and low resolution, however, have become obstacles to its development[17]. Sang *et al.* thus suggested a full-parallax method using a special holographic functional screen[16]. The holographic functional screen is graphically printed with speckle patterns exposed on proper sensitive material point by point[18].

In this letter, a full-parallax 3D display system using a projector array and a specially designed directional diffusion screen is proposed. The viewing angle of this system is much larger than that of an integral imaging display and could be enlarged easily by adding more projectors. The new directional diffusion screen consists of two perpendicular lenticular sheets, which are inexpensive and simple to manufacture. The function of the directional diffuser is similar to that of the holographic functional screen: the diffusion angle is easy to control in either the horizontal or vertical direction. Moreover, the new directional diffusion screen is commercially available.

A projector array consisting of M×N projectors (P11, P12, . . . , Pmn) and a directional diffuser is used to reproduce the DIC information. Figure 1 shows the system schematic diagram. The diagram shows all the projectors converging at the center of the directional diffuser, with each projecting a recombined image onto the directional diffuser along different directions simultaneously. The directional diffuser consists of two perpendicular lenticular sheets, with each one controlling the horizontal and

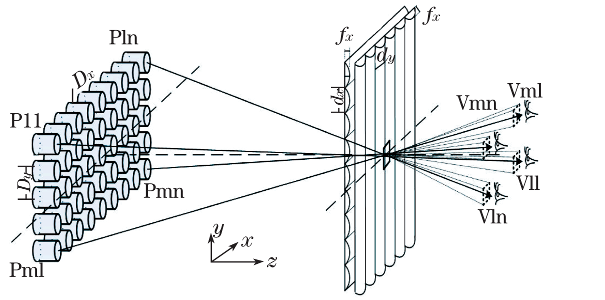

Fig. 1. Full-parallax 3D display system using new directional diffuser.

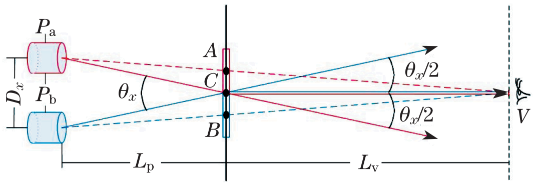

Fig. 2. Relationship between the projectors and the diffusion angle.

vertical diffusion angles, respectively. On the directional diffuser, each image pixel is composed of M×N overlapped pixels which come from different projectors. These overlapped pixels emit light in different directions separately. Thus, along different directions, V11, V12,. . . , Vmn, different kinds of information on this pixel induce different views of a 3D scene in front of the directional diffuser. In addition, each view of the 3D scene is constituted by M×N pieces of images from different projectors.

The distance D_x between two horizontal adjacent projectors and the projection length L_p shall be matched with the horizontal diffusion angle θ_x of the directional diffuser. The relationship is given as

$$D_x/L_\mathrm{p} = 2 \times \tan(\theta_x/2), \tag{1}$$

while the relationship in the vertical direction is

$$D_y/L_\mathrm{p} = 2 \times \tan(\theta_y/2). \tag{2}$$

Figure 2 illustrates the relationship directly. If the diffusion angle θ_x of the directional diffuser equals zero, at the viewpoint V, the observers could just see two points, A and B, separately coming from projector P_a and P_b, respectively. Along with the diffusion angle θ_x increasing, the visible area will also expand. When the diffusion angle θ_x equals $2\times\arctan(D_x/2L_\mathrm{p})$, the two areas will meet at point C and a continuous image constituted by many element images is presented.

Finding a directional diffuser with the horizontal diffusion angle θ_x and the vertical diffusion angle θ_y is important. A good choice is the holographic functional screen because it can meet the requirements of two directional diffusion angle controls. Fabrication of the holographic screen is, however, very complicated. Thus, two perpendicular lenticular sheets are adopted to act as the diffusion screen, which is commercially available and cheaper. The diffusion angles θ_x and θ_y are controlled by each lenticular sheet separately (Fig. 3). The relationships between the cylinder width d, focal length f, and diffusion angle θ of the two directional diffusers are expressed as

$$\theta_x = 2 \times \arctan(d_y/2f_y), \tag{3}$$

$$\theta_y = 2 \times \arctan(d_x/2f_x). \tag{4}$$

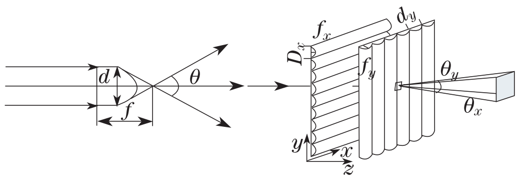

Fig. 3. Diffusion angle of the directional diffuser.

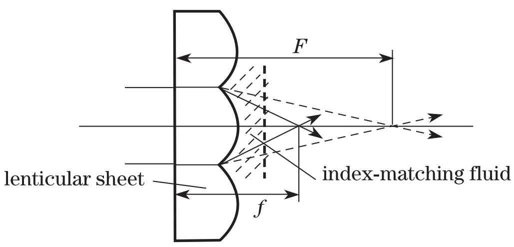

Fig. 4. Adjusting method of the focal length by adding index-matching fluid.

To obtain good images, lenticular sheets with tiny cylinder width (d=0.254 mm) are chosen. When the cylinder width d is decided, the focal length f becomes the determinate factor of the diffusion angle. There are two methods to obtain the desired focal length f. The best method for commercial production is to design a proper optical surface with a certain cylinder radius for the lenticular sheet to get the required diffusion angle. An easy way would be to add an index-matching fluid onto the commercial lenticular sheets. Figure 4 illustrates the method of adjusting the focal length by adding an index-matching fluid, which can be epoxy resin with a suitable index. The resin is used to bond the two directional lenticular sheets together. If the focal length of a lenticular sheet is f, it becomes F after adding the index-matching fluid. From the classic theory of geometrical optics, the accurate relationship between the combined focal length F and the focal length f is

$$F = \frac{N-1}{N-n} f, \tag{5}$$

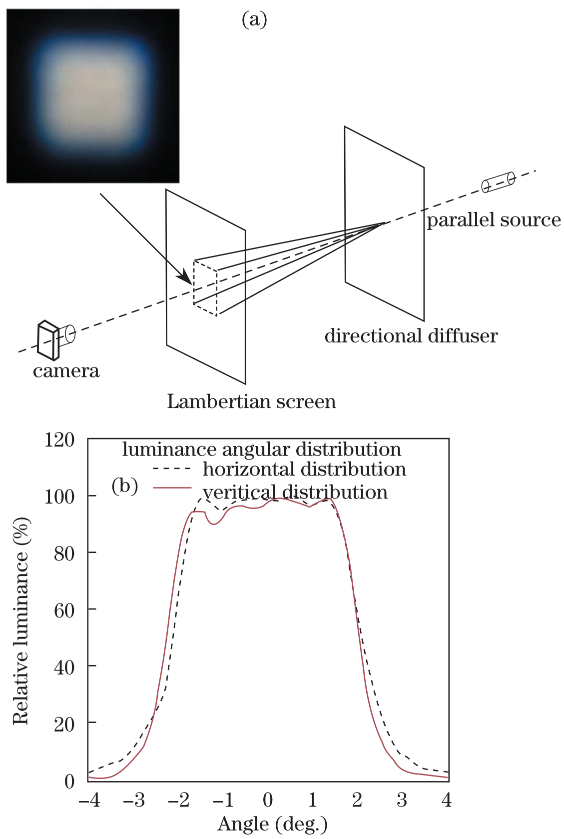

Fig. 5. Uniformity of the luminance angular distribution of the directional diffuser. (a) Measuring setup; (b) horizontal and vertical luminance angular distributions.

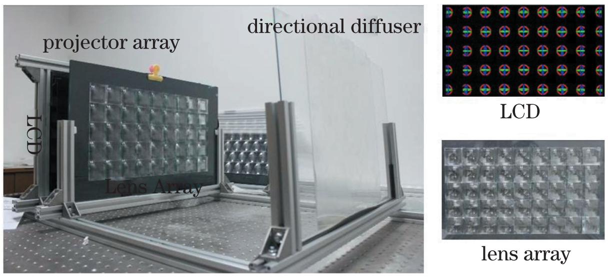

Fig. 6. Photo of the full-parallax 3D display.

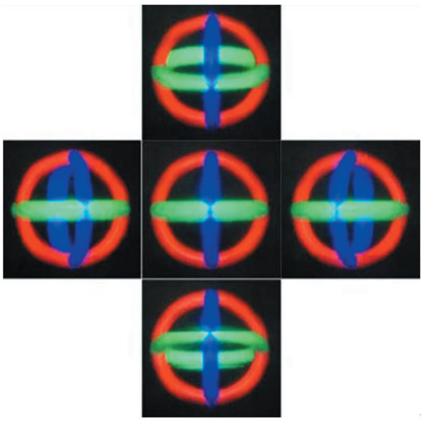

Fig. 7. Photos of a 3D image displayed.

where N denotes the refractive index of the lenticular sheets and n denotes the refractive index of the index-matching fluid. When the refractive index of the index-matching fluid n changes from 1 to N, the combined focal length F changes from f to ∞.

A full-parallax 3D display with 45 views, consisting of 9 horizontal views by 5 vertical views, demonstrates the method mentioned above. A 23-inch LCD display with a 1,920×1,080 pixels resolution and a 45 Fresnel lens with a 100-mm focal length are used as a projector array. The LCD screen is divided into 45 display zones. The size of the Fresnel lens is set as 50×50 (mm) to achieve the resolution of one corresponding zone larger than 200×200 pixels. The projection length is set as 600 mm, so the projection image size could be approximately 300×300 (mm) and the size of one pixel cannot be larger than 1 (mm). According to Eqs. (1) and (2), the diffusion angle is 4.77° both in the horizontal and vertical directions. To match with the projector array, two commercial 100-lines/inch lenticular sheets with the refractive index of 1.575 and the focal length of 0.641 mm are bonded by epoxy resin with the refractive index of 1.454, according to Eqs. (3)–(5).

The luminance angular distribution of the diffused light beam would affect the uniformity of 3D images directly. A measuring setup is thus made to measure the performance of the directional diffuser (Fig. 5(a)). In the setup, a very narrow beam of incoherent light passes through the directional diffuser and illuminates a squared area on a lambertian screen. An image whose uniformity has been corrected is then captured by a camera. After processing the image, the luminance angular distribution of the diffused light beam is obtained (Fig. 5(b)). The horizontal axis of the chart denotes the angle of the diffused beam. The unit is in degrees. The vertical axis denotes the relative luminance. The dotted and solid lines show the horizontal and vertical distributions, respectively. Both the captured diffusion pattern and the curves show that the luminance angular distribution is sufficiently uniform.

A photograph of the demonstration, which contains a LCD screen, a lens array, and a directional diffuser, is shown in Fig. 6. The image on the LCD screen is divided into a series of sub-images on the diffusion screen through a corresponding sub-lens of the lens array.

The parameters of our prototype are listed in Table 1. The prototype can display 3D images with 45 views consisting of 9 horizontal views by 5 vertical views. The resolution of the 3D images is 226×226 pixels within an area of 300×300 (mm) on the screen. We use OpenGL to produce a 3D object: three cross circles. The displayed 3D image is captured from different viewpoints, as shown in Fig. 7.

In conclusion, we demonstrate a new method of making a full-parallax 3D display that can display 3D images with both horizontal and vertical parallax. The directional diffuser composed of commercial lenticular sheets has good performance in the full-parallax 3D display system. This kind of diffusion screen is inexpensive and can be widely used. The projection lens used is Fresnel lens, so the quality of projection images on the directional diffuser is not as perfect as that of a precise lens. Better projection lens or pico-projectors will be used to improve the performance of full-parallax 3D display images in our future work.

Table 1. Parameters of the Prototype

Number of Projectors	45
Number of Views	9 Horizontal Views×5 Vertical Views
3D Image Resolution	226×226×9×5 pixels
3D Image Size	300×300 (mm)
Directional Diffuser	Both Horizontal and Vertical Approximately 4.77°
Lenticular Sheet	Cylindrical Width: 100 lines/inch Focal Length: 0.641 mm Refractive Index: 1.575
Index-Matching Fluid	Epoxy Resin: Refract Index of 1.454
Projection Lens	45 Fresnel Lens: Focal Length of 100 mm Size: 50×50 (mm)
LCD Display	23 Inches, Resolution 1,920×1,080 pixels

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