High-Density Directional Display for Natural Three-Dimensional Images

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Abstract
High-density directional display provides natural three-dimensional images. A large number of directional images are displayed in different horizontal directions with directional rays. There are two different types of display configurations. One is the projection-type and the other is the thin-type. The 64-directional and 128-directional displays using the projection-type configuration and the 72-directional display using the thin-type configuration are presented. The human responses are also shown.

1. Introduction
Recently the developments of three-dimensional displays have been accelerated. The conventional three-dimensional displays have two problems. One is the visual fatigue and the other is the lack of motion parallax. These two facts contradict to the human three-dimensional perception so that their three-dimensional images are unnatural. The next-generation three-dimensional display should offer natural three-dimensional images. The high-density directional display is one of the promising candidates for a natural three-dimensional display.[1-2] This technique has following features: (a) simultaneous observation by multiple persons, (b) not restricted observing position, (c) no need of wearing special three-dimensional glasses, (d) providing high presence (having smooth motion parallax), and (e) compatible with human three-dimensional perception (without fatigue.)

In this paper three prototypes of high-density directional displays developed in Tokyo University of Agriculture & Technology are presented.

2. Natural 3D displays
2.1 Problems of conventional 3D displays
The visual fatigue of conventional three-dimensional display is brought about by the discrepancy between the accommodation function and the convergence function of the human three-dimensional perception. For conventional three-dimensional displays, the convergence function correctly percepts the depth position of a three-dimensional image from the rotating angles of left and right eyes. The accommodation function, however, makes eyes to focus on the display screen, not on the three-dimensional image position, because two images for left and right eyes are displayed just on the display screen. The incorrect responses of the accommodation function caused the visual fatigue.

For conventional three-dimensional displays, the left and right images never change while observers move their head. This lack of the motion parallax is said to decrease the presence of three-dimensional images.

2.2 3D images with high-density directional rays
The high-density directional display presented in this paper is a new three-dimensional display technique which projects a large number of directional images in different directions with directional rays. [1-2] The directional rays are nearly parallel rays having a very small diverging angle. The directional images are orthographic projections of a three-dimensional scene into specific directions. When the number of directional rays becomes large and the proceeding angle pitch of directional rays becomes small, rays from three-dimensional objects are virtually reconstructed as shown in Fig. 1. When the ray proceeding angle pitch becomes small enough, more than two directional rays which pass through an

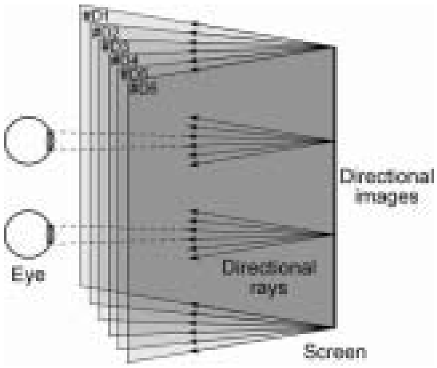


Figure 1 Three-dimensional image displayed by high-density directional rays.

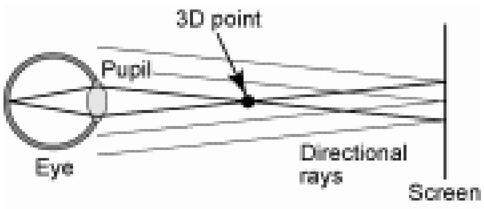


Figure 2 Evoking accommodation responses by high-density directional rays.

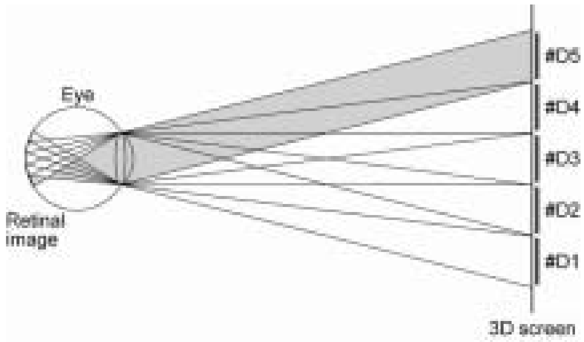


Figure 3 Retinal image formation by high-density directional display.

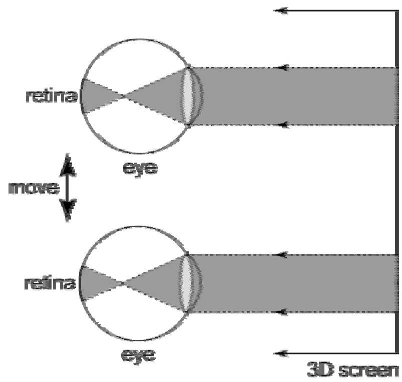


Figure 4 Smooth motion parallax provided by high-density directional display.

identical three-dimensional point enter into a pupil of an eye simultaneously so that an eye can focus on a three-dimensional point as shown in Fig.2. Therefore, observers may be free from the visual fatigue. This can be done under the condition that the ray angle pitch becomes as small as 0.2°~0.4° and the number of directional rays becomes larger than ~50 for the normal observation condition.

Because a directional image is displayed with nearly parallel rays, a part of a directional image can enter into a pupil of an eye and is imaged on a retina as shown in Fig. 3. When a number of directional images are simultaneously displayed, a number of partial images are imaged on the retina to form a retinal image. As illustrated in Fig. 4, the part of a directional image which enters the pupil changes depending on the observing position so that the motion parallax, which is as smooth as the resolution of the directional image, is obtained.

3. High-Density Directional Display

3.1 Display Configurations

In order to display a large number of directional images with directional rays, two different types of display systems have been proposed. [1-2] One is the projection-type, and the other is the thin-type. In both systems, the high-density directional images are displayed in different horizontal directions.

3.2 Projection-Type System

The projection-type three-dimensional display system is illustrated in Fig. 5. The system consists of an array of two-dimensional displays, an array of micro lenses, an array of apertures, a common lens, and a vertical diffuser. A number of imaging systems are multiplexed. One imaging system consists of an LCD panel, a micro lens, an aperture, a common lens, and a vertical diffuser. The horizontal positions of all imaging systems are different. Each directional image is displayed on each LCD panel, and all directional images displayed on the LCD array are imaged on the vertical diffuser and are projected in different horizontal directions.

The horizontal sectional view of the projection-type system is shown in Fig. 6(a). All directional images are superimposed on the vertical diffuser. Because all imaging systems have different horizontal positions, all directional images are displayed in different horizontal directions. The aperture array limits the ray proceeding directions so that all directional images are displayed with nearly parallel rays. The transparent parts of all apertures are made continuous horizontally in order not to give rise to horizontal directions in which no rays proceed. Figure 6(b) shows the vertical sectional view. The difference in the vertical display direction due to the vertical position of the imaging system is canceled by the vertical diffuser. The vertical diffuser expands the ray proceeding direction vertically.

The imaging systems are arranged two-dimensionally so that a large number of imaging systems can be used. The modified two-dimensional arrangement enables images to be displayed in different horizontal directions. The directional images are displayed with directional rays in the horizontal direction.

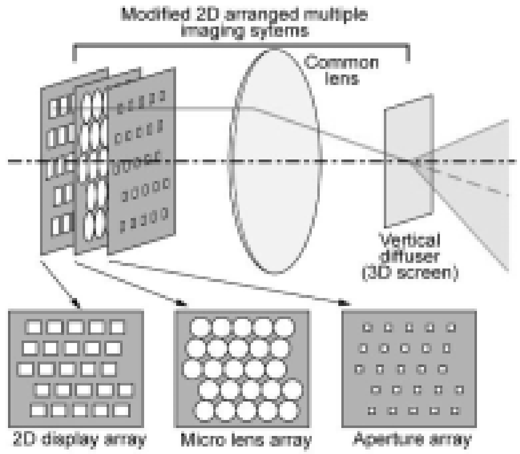


Figure 5 Projection-type high-density directional display.

3.3 Thin-Type System

The thin-type three-dimensional display is illustrated in Fig. 7. The three-dimensional screen consists of 3D pixels. The 3D pixel is constructed from a modified two-dimensionally arranged light source array and an optical system that includes a single micro-lens and a vertical diffuser. The light source array and the vertical diffuser are located at opposite focal planes of the micro lens. Figure 8(a) shows the horizontal sectional view of the 3D pixel. Because the horizontal positions of all light sources are different, the rays from different light sources proceed in different horizontal directions after passing through the micro-lens. Figure 8(b) shows the vertical sectional view of the 3D pixel. The difference in the vertical ray proceeding directions is canceled by the vertical diffuser. A large number of light sources are arranged two-dimensionally and rays are emitted in different horizontal directions so that high-density directional rays are obtained in the horizontal direction. Because the three-dimensional screen consists of a two-dimensional arrangement of the 3D pixels, a large number of directional images are displayed with directional rays in different horizontal directions.

In both systems, the ray direction can be controlled only in the horizontal direction. In order to control rays both horizontally and vertically, the number of LCD panels must be squared for the projection-type system and the number of light sources must be squared for the thin-type system. However, for human visual perception, it is much more important to have the ray direction change in the horizontal direction than in the vertical direction.

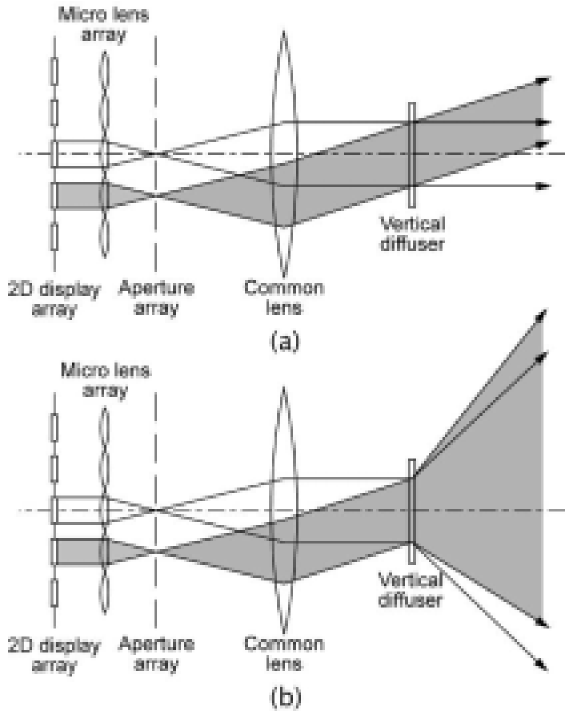


Figure 6 Rays in the projection-type system: (a) horizontal sectional view, and (b) vertical sectional view.

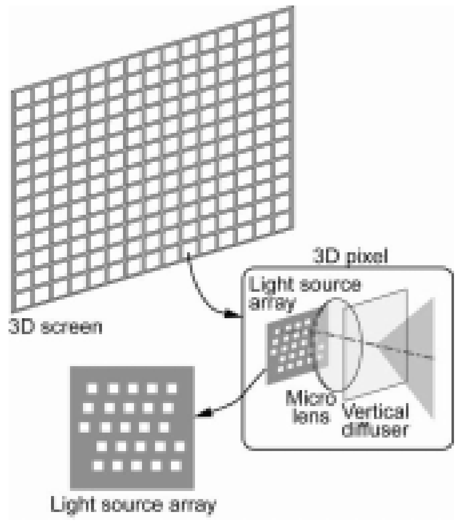


Figure 7 Thin-type high-density directional display.

4. Prototype Displays

Three prototype displays were constructed. Their specifications are listed in Table 1. The projection-type configuration was used for constructing the 64-directional[1-2] and 128-directional[3] displays, and the

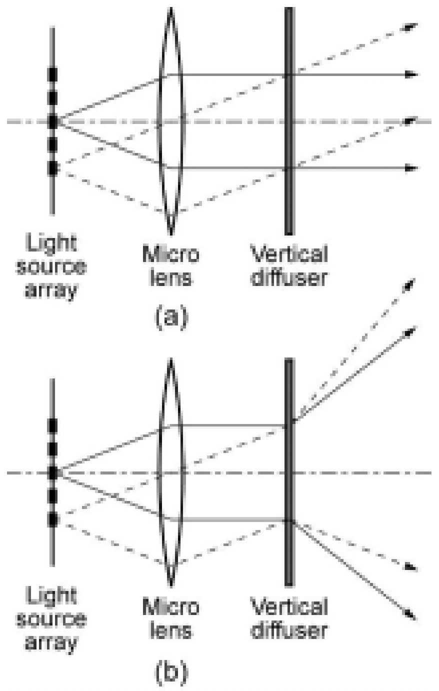


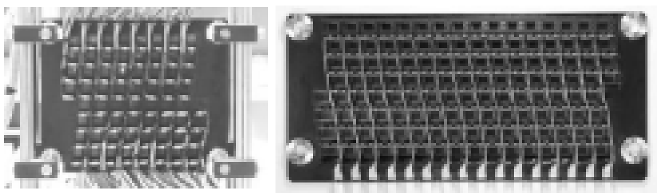
Figure 8 Rays in the thin-type system: (a) horizontal sectional view, and (b) vertical sectional view.

thin-type configuration was used for constructing the 72-directional display. [4]

The LCD arrays constructed for the projection-type systems are shown in Fig. 9. The 0.55'' LCD panels were arranged in a 8×8 array for the 64-directional display (Fig. 9(a)), and 0.44'' LCD panels were arranged in a 16×8 array for the 128-directional display(Fig. 9(b)). The horizontal positions of all LCD panels are different. Figures 10(a) and 10(b) respectively show the 64-directional display and the 128-directional display. They are controlled by specially designed PC clusters. Because the diameter of a common lens should be larger than the screen (vertical diffuser), a Fresnel lens was used. A lenticular sheet was used for a vertical diffuser.

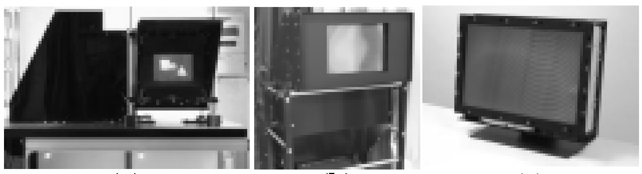
In order to construct the thin-type display, no practical modified two-dimensionally arranged light source array exists. There are two approaches by which to address this shortcoming. The first is to slant an LCD panel, and the second is to slant the optical system. The LCD pixels are used as light sources. The latter method is employed to construct the prototype display. The optical system is simplified by replacing the single micro-lens and the vertical diffuser with a single cylindrical lens. As shown in Fig. 11, the 3D pixel consists of the slanted cylindrical lens and a number of color sub-pixels on the LCD panel. The axis of the cylindrical lens is denoted in the figure. Because the horizontal ray proceeding direction depends on the horizontal distance between the color sub-pixels and the cylindrical lens axis, the cylindrical lens is slanted so as to differentiate the horizontal distances of all of sub-pixels of the same color in each 3D pixel. The rays diverge primarily in the vertical direction because the cylindrical lens has no refraction power. The prototype display consists of an LCD panel and an array of slanted cylindrical lenses, i.e., a slanted lenticular sheet.

An ultra high-resolution LCD panel was used to construct the thin-type display. The resolution was WQUXGA (3,840×2,400), and a single 3D pixel consisted of 36×6 color sub-pixels (M = 12 and N = 6). The prototype display has the three-dimensional resolution of 320×400 and emits directional rays in 72 different horizontal directions with an angle pitch of 0.38°. The 72-directional display is shown in Fig. 10(c).



(a) (b)

Figure 9 Modified two-dimensionally arranged LCD arrays: (a) 8×8 LCD array, and (b) 8×16



(a) (b) (c)

Figure 10 Photographs of prototype high-density directional displays: (a) 64-directiona, (b) 128-directional, and (c) 72-directional displays.

Table 1 Specifications of prototype 3D displays.

Number of rays	64	128	72
Display type	projection		thin
Display angle pitch	0.34°	0.23°	0.38°
Horizontal view angle	21.6°	29.6°	27.4°
Screen size	9.25"	13.2"	22.2"

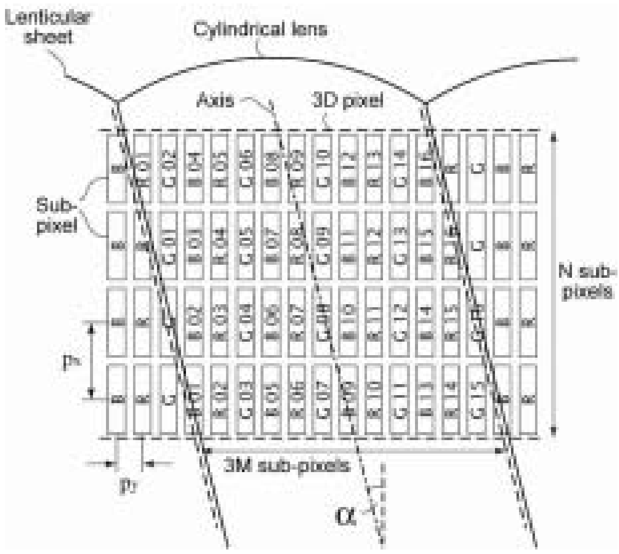


Figure 11 Slanting lenticular sheet to realize modified two-dimensionally arranged light source array.

Figure 12 shows the three-dimensional images displayed by the 64-directional display. The three-dimensional images can be displayed in front of the display screen. Observers can perceive the absolute depth position of thee-dimensional images because rays actually converge at three-dimensional images. Therefore observers can examine the position of three-dimensional images by their hands. Figure 13 shows the photographs of three-dimensional images generated by the 128-directional display captured from different horizontal directions. The images change very smoothly as the view point moves horizontally. Figure 14 shows the three-dimensional images generated by the 72-directional display. The medical three-dimensional images were produced from actual DICOM data using a volume rendering software.

5. Human responses

The accommodation responses to the three-dimensional images produced by the high-density directional displays were measured using the optometer.[5] Figure 15 shows the results measured for 5 observers. In Fig. 15(a) the horizontal axis shows the measured accommodation responses to a real target, and the vertical axis shows those to the 64-directional display. In Fig. 15(b) the vertical axis shows the measured responses to a conventional binocular display. The accommodation responses to the prototype display were similar to those obtained or a real object. More natural accommodation responses were obtained for the prototype display.

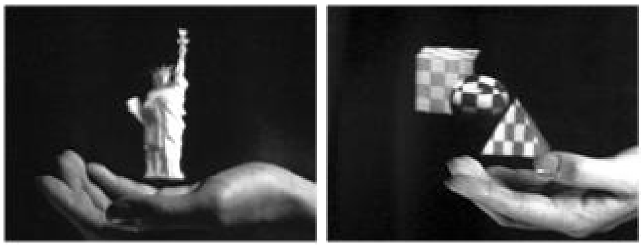


Figure 12 Photographs of 3D images generated by 64-directional display.

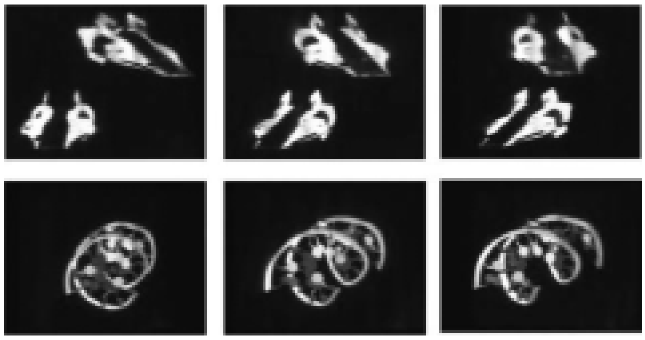


Figure 13 Photographs of 3D images generated by 128-directional display.

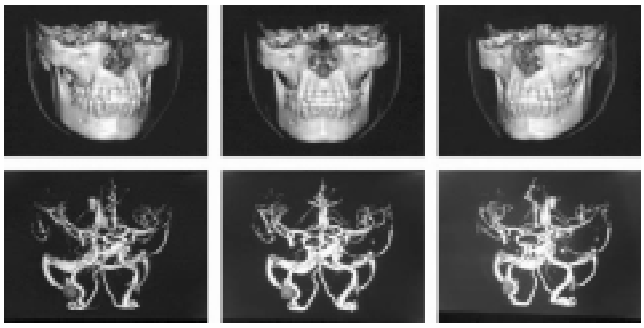


Figure 14 Photographs of 3D images generated by 72-directional display.

The high-density directional display provides very smooth motion parallax. However, the image discontinuity might be perceived when the ray angle pitch is not small enough because the retinal image consists of many partial images. Figure 16 shows the perception of image discontinuity when the display angle pitch and the depth position of three-dimensional images were changed.[6] The number of observers was 10 and the averages are plotted in the figure. When the ray angle pitch becomes smaller, the three-dimensional images without the image discontinuity can be displayed further from the screen.

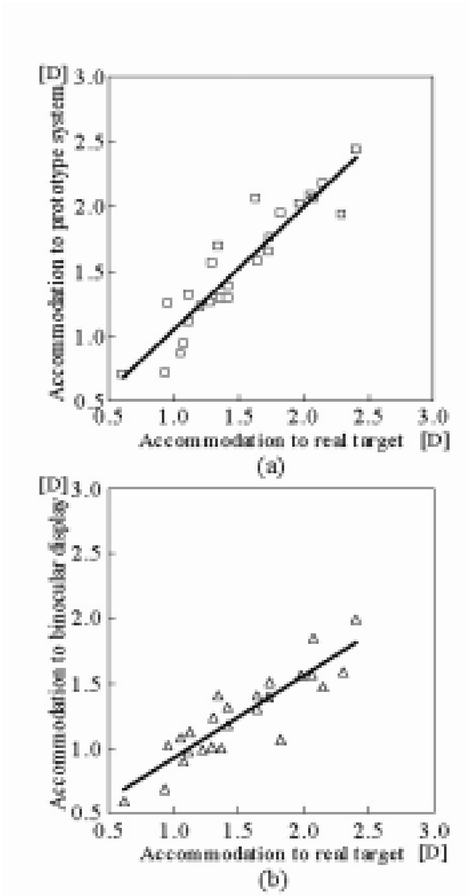


Figure 15 Accommodation responses to (a) 64-directional display, and (b) binocular

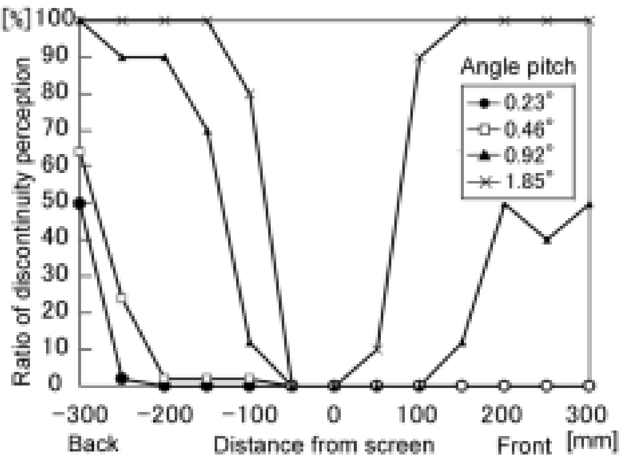


Figure 16 Image discontinuity perception for display angle pitch and image depth position.

6. Summary

In this paper, the high-density directional display which provides natural three-dimensional images is presented. Three prototype displays, such as 64-directional, 72-directional, and 128-directional displays are also presented. The accommodation function correctly works so that the display is free from the visual fatigue. The motion parallax is very smooth and the presence of three-dimensional images is very high.

7. Acknowledgements

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8. References

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