3-4 Three-Dimensional Image System without Special Glasses

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We wanted to realize even more worthwhile interpersonal communication by presenting highly realistic three-dimensional (3-D) video that allows people to feel as if they were actually there. To fulfill that goal, we have developed a large 3-D display, a tabletop 3-D display, a box-type 3-D display, and other equipments as 3-D image systems not needing special glasses for various applications. At the same time, we are conducting research on 3-D model technology, technology for capturing real 3-D images, and other technologies necessary for these 3-D displays. This paper presents the autostereoscopic image technology being developed by this research group, with special attention given to "the large 3-D display without special glasses." The paper then describes the basic principles and gives details of its prototype. Last but not least, the paper discusses future prospects.

Keywords
Ultra-realistic communication, Three-dimensional image, Autostereoscopic image

1 Introduction

Realizing a highly realistic communication system will let us talk to people in remote locations as if we were actually there with them, and to present, appreciate and learn from valuable cultural assets as if in front of our eyes, thereby making our lives even more worthwhile. To make this highly realistic communication a reality, NICT is conducting research on ultra-realistic systems based on 3-D images, extremely high resolution video, a 3-D sound field, haptic sense, sense of smell, and various other kinds of information. Among the technical challenges posed by system development are 3-D video, image technology for large screens with extremely high resolution, immersed-type, space-reconstructing technology, and technology for analyzing the psychological and physiological factors for images.

Recent market trends in the filmmaking and other industries show a growing demand for technologies and products related to stereoscopic video. At the same time, proactive moves are also being made at home and abroad, including the development of technologies for capturing and displaying 3-D images, standardization intended to spread 3-D video, and considering how to produce safe content. Studies are also under way regarding next-generation 3-D images not needing special glasses for reproducing many parallax images and groups of light ray, in an attempt to achieve even more ideal 3-D image displays other than stereoscopic systems designed for practical use in good time.

This research group is developing three kinds of 3-D image systems without special glasses by assuming various forms of utilization, in order to realize ultra-realistic systems based on natural 3-D video[1]. These systems include "large 3-D system without special glasses" (making it possible to display 3-D images on large screens tens to hundreds of inches diagonally by using many projectors)[2], "fVisiOn" tabletop 3-D display (showing 3-D images that appear as if floating in air above a flat desk[3][4], and "gCubik" box-type display (allowing people to observe 3-D images on a handheld box-type display)[5][6].

In this paper, Chapter **2** presents the background and trends regarding 3-D image studies. Chapter **3** gives an overview of various 3-D technologies without special glasses developed by NICT. Chapter **4** describes the technology for "large 3-D system without special glasses" in detail, and Chapter **5** gives the conclusions.

2 Trends in 3-D image technology

In the past few years, stereoscopic video system has spread throughout the moviemaking industry, while new cameras, displays, and other equipment for general consumer use now being commercialized. Thus, 3-D video is beginning to quickly attract attention. In addition to the technology for displaying high-quality 3-D images, comprehensive efforts are now under way to proceed with content production technology, the standardization of image formats, compression coding, package media and interfaces, and considering the guidelines for safe content production and evaluation methods[7].

At the same time, 3-D image technology without special glasses—considered a technology for the future—is also undergoing steady progress. Among the technologies available are a lenticular-based system for reproducing parallax images from several to dozens of viewpoints, and a system consisting of several microscopic displays equipped with lenticular lenses arranged in an array-like pattern to reconstruct a dense group of light ray[8]. The integral 3-D system (classified as a 3-D system of the spatial image reconstruction type) also features horizontal as well as vertical parallax, and is being developed for future household uses[9]. In recent years, Super Hi-Vision with high-precision full resolution (33 million pixels) is used to take and display integral 3-D images of about 100,000 pixels[10]. This integral system requires many pixels to achieve high image quality. Methods of projecting images in a superimposed manner by using many small projectors, and special-purpose high-precision adjustment technologies are being developed as well[11]. Conversely, in holography (having different principles from other systems), strict conditions are required for the display devices. Holography has therefore not yet reached a practical level, but expectations run high for it to become the ultimate method of ideal 3-D display. As a method for capturing and displaying motion pictures, this method is being studied by using the latest high-precision image devices, and color motion picture display has become a reality[12]. Stereoscopic video is now entering a practical stage, while 3-D images for the naked eye entails many research challenges, including the consideration of 3-D display systems and development of constituent technologies for making such systems a reality, high-precision adjustment, and ideal image processing technology.

3 Communication system based on 3-D image

As shown in Fig. 1, one can consider various forms of communication based on 3-D images. One is "large 3-D images without special glasses," where several people can observe large 3-D images and share a 3-D space and environment (Fig. 1 (a)). By reproducing persons, vehicles, and other familiar objects and environments in life-size dimensions, the observer can feel a high degree of realism. As its prototype, we have developed a 3-D display that uses several Hi-Vision projectors to project images from different points as superimposed on a special screen[2]. The system is characterized by being able to reproduce 3-D images on a large screen (about 70 inches diagonally) depending on location of the observer, thereby

(a) Large 3-D display without special glasses (b) Tabletop type 3-D display (c) Box type 3-D display

Fig.1 *Communication system based on 3-D display*

making it possible to reproduce natural 3-D images without needing special glasses. A large-screen 3-D display without special glasses has also been developed for conventional systems[13], but the current version is the first system to enable the display of high-precision, 3-D images of the Hi-Vision class. Since the resolution and color reproducibility of 3-D images displayed are of Hi-Vision image quality, such images are highly applicable. These images are expected to find, for example, many applications in the verification of industrial designs, publicity, exhibitions of cultural heritage, works of art, and other objects, as well as being shown in films. Chapter **4** describes the technology concerning this 3-D image system in detail.

As shown in Fig. 1 (b), there is "3-D display of the tabletop type," where people around a table can observe from all directions 3-D images that appear as if floating above a flat table. We have developed "fVisiOn"[3][4], which combined a micro-projector array built into the table and a specially shaped screen with diffusion characteristics. In terms of principle, people can observe a 3-D image depending on their location from all directions (360 degrees) around the table, and many people can observe the same 3-D image at the same time. Conventional all-direction 3-D image systems[14] and similar means require a spherical or a cylindrical display section. In this system, however, the tabletop is flat and requires no equipment that may become an obstacle to work. People can therefore communicate with one another while comparing a real thing with its 3-D image. Another article in this special issue describes the contents of this study[15].

"3-D images of the box type" (Fig. 1 (c)), where people can experience 3-D images that change interactively according to the movement of fingers and boxes, allows each person to hold a small cube-like display and observe the 3-D images inside the box from all directions. NICT has developed "gCubik," which is a 3-D system based on integral photography as its principle[5][6]. The box is equipped with various internal sensors to display 3-D images interactively according to movement of the observer. The system is optically designed so that people can observe a 3-D image according to the particular direction taken by the observer from any side of the box-like shape. People can therefore feel as if they were actually holding the 3-D image in their hands. Another article in this special issue describes the contents of this study[16].

Among the images to be displayed on these displays are computer graphics and real images. We are also addressing such study areas as 3-D model technology for display on various 3-D displays[17][18], and technologies for taking real 3-D images and image processing[19][20].

4 Large 3-D display system without special glasses

4.1 Basic principles

The large-screen 3-D display allows sever-

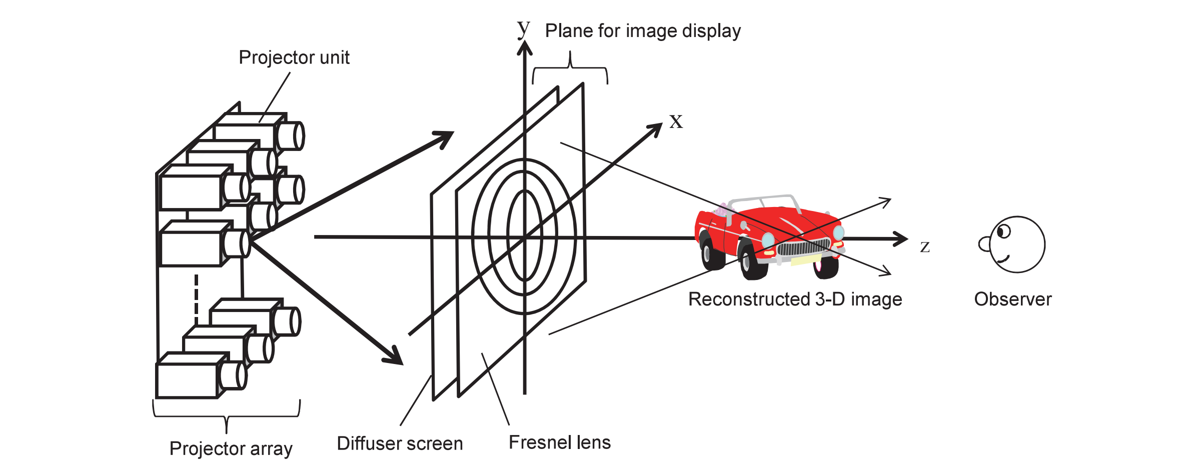

Fig.2 *Basic configuration of a large 3-D system without special glasses based on a projector array*

al people to observe a natural 3-D image at the same time according to each person's particular viewing position without needing special glasses (Fig. 2). A projector array is used as an image display unit and consists of several small projectors (called "projector units") arranged horizontally and vertically. From each projector unit, images with horizontal parallax (called "parallax images") are projected as superimposed on the plane for image display that combines a screen having special diffusion characteristics with a fresnel lens. The diffuser screen is a rear screen having diffusion angle characteristics with a small angle in the horizontal direction relative to the incident light, and a wide diffusion angle in the perpendicular direction. These diffusion characteristics enable the system to produce different images at various horizontal angles, thereby allowing the observer to observe parallax images according to the horizontal position. Conversely, in the vertical direction, the incident light becomes widely diffused, thereby eliminating the effects of the projection angle in that direction. One can therefore arrange the projector units vertically as well (in the y-axis direction), so that increasing the number of units increases the image density that is horizontal number of parallax images per unit viewing angle. In this system, one can approximate the system to a 3-D display of the spatial image reconstruction type, which reproduces light ray of an object in terms of principle, according to the positional relation of the projector array and plane for image display. Increasing the parallax image density is expected to produce a high-quality, 3-D display at high resolution with a smooth kinematic parallax and a wide viewing zone.

In this system, the arrangement of the projector array, projection method, positional relation with the diffuser screen and fresnel lens, optical characteristics, and other factors can be varied to change the form of display between what is called multi-view 3-D image to light ray reproduction 3-D image, thereby making it possible to adjust balance in the viewing zone, resolution, and various other characteristics of 3-D images. This paper describes the basic performance of this display system clearly, with the system configured so that the distance between the projector array and fresnel lens would be the same as the focal point distance of the fresnel lens. For cases where the beams of parallax images to the observer were regarded as being almost parallel beams, the typical composition and design guidelines are described below.

4.2 Basic composition and design guidelines for the system

Figure 3 is an overhead view of the basic arrangement of this system. In this composition, the number of projector units is almost the same as the number of horizontal parallax im-

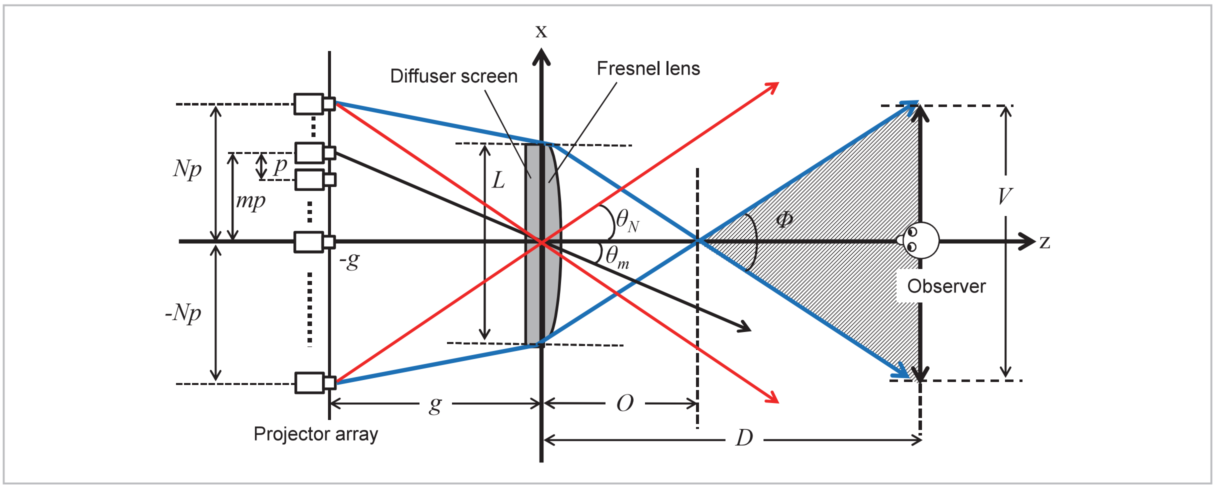

Fig.3 *Basic arrangement of large 3-D system without special glasses*

ages. For that reason, pitch p between the projector units is set to a value that matches the number of parallax images per horizontal unit angle. When distance g between the projector array and fresnel lens is the same as the focal point distance of the fresnel lens, angle θ_m of the light ray projected by the mth projector unit is directed towards the observer via the plane for image display, and is expressed as follows:

$$\theta_m = \arctan\left(-\frac{mp}{g}\right) \tag{1}$$

where, p denotes the pitch (constant) between projector units, with the horizontal location of the mth projector unit expressed as x = mp ($-N < m < N$) where N denotes a natural number, and $2N + 1$ is the total number of projector units).

Moreover, angle difference $\Delta\theta_m$ between the outgoing principal light ray from the mth projector unit and that from the (m+1)th one are as follows:

$$|\Delta\theta_m| = |\theta_{m+1} - \theta_m| \approx \left|\frac{p}{g}\right| \tag{2}$$

Viewing angle ϕ of the 3-D image displayed at the center of the screen will conversely become as follows:

$$\phi = 2|\theta_N| = 2\left|\arctan\left(-\frac{Np}{g}\right)\right| \tag{3}$$

As shown in this equation, the viewing zone of a reconstructed 3-D image depends on width Np of the projector array and distance g between the projector array and the plane for image display (i.e., focal length of the fresnel lens).

The area where the entire display image can be observed, however, is limited to the shaded portion shown in Fig. 3. Distance O from the plane for image display to this viewing area is as follows:

$$O = \frac{L}{2\tan|\theta_N|} = \frac{Lg}{2Np} \tag{4}$$

where, L denotes the size of the display image. The angle where this area is viewed is viewing angle ϕ in Equation (3). When the distance between the fresnel lens and the observer is D, viewing zone V is as follows:

$$V = 2\left|(D-O)\tan\frac{\phi}{2}\right| = \left|\frac{2DNp}{g} - L\right| \tag{5}$$

Equations (1) to (5) above make it possible to consider the number of projector units ($2N + 1$), arrangement pitch p, distance g between the projector array and fresnel lens (i.e., focal length of the fresnel lens), and other parameters based on size L and viewing angle ϕ of the display screen of the 3-D image, angle pitch $\Delta\theta$ of the parallax image, viewing zone V, and other factors as requirements for the 3-D image, and use these parameters as guidelines for system design.

4.3 Arrangement of projector units and screen diffusion characteristics

The key device for this system is a screen having the special diffusion characteristics described above. The arrangement of the projector array is limited by the size of each unit, thereby making it difficult to arrange the projectors densely in proximity of the horizontal direction alone. For that reason, as shown in Fig. 4, the system is composed not only in the horizontal direction but also in the vertical direction as well, in a two-dimensional manner.

The projector units in each row are arranged with horizontal pitch p_h sequentially in the vertical direction. Conversely, in the clearance between lines in the vertical direction, the projector units are arranged with comparatively large vertical pitch p_v due to the limitation on projector unit size. Here, horizontal pitch p_h corresponds to pitch p of the projector unit shown in Fig. 3 and given in Equation (2).

The angle pitch of the parallax image, the uniformity of brightness, continuity, and other factors are used to optimize the horizontal diffusion angle of the diffuser screen. As shown in Fig. 5 (a), the incident light from a projector unit is emitted out at angle θ_m relative to the optical axis of the fresnel lens as expressed in

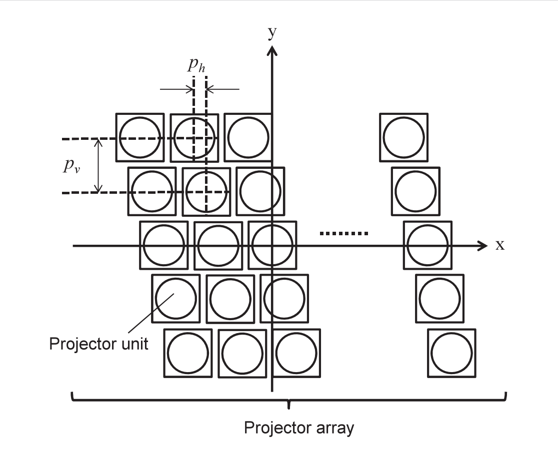

Fig.4 Example of projector array arrangement

Equation (1). Here, let the horizontal diffusion be a Gaussian distribution, and optical distribution i_m of outgoing beams from the mth projector unit will be expressed as follows:

$$i_m = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left[-\frac{(\theta - \theta_m)^2}{2\sigma_x^2} \right] \quad (6)$$

where, σ_x denotes standard deviation of the distribution of optical diffusion angles and represents the size of the diffusion angle. For the purpose of this paper, it will be called the diffusion angle. The incident light from the group of projector units is emitted out as being superimposed as shown in Fig. 5 (b), and its optical distribution $I(\theta)$ is as follows:

$$\begin{aligned} I(\theta) &= \sum_{m=-N}^{N} i_m \\ &= \frac{1}{\sqrt{2\pi}\sigma_x} \sum_{m=-N}^{N} \exp\left[-\frac{(\theta - \theta_m)^2}{2\sigma_x^2} \right] \end{aligned} \quad (7)$$

In a 3-D image synthesized by the parallax images, the flatness and crosstalk in the distribution of brightness between parallax images will be affected by the screen's horizontal diffusion characteristics. A small diffusion angle makes the brightness between parallax images uneven in terms of the brightness value of the synthesized beam indicated by a red line in Fig. 5 (b), resulting in uneven brightness in the image. Conversely, increasing the diffusion angle increases the percentage of the shaded amount of crosstalk shown in Fig. 5 (b).

As a concrete example of numerical calculations, let the parallax number be 50 parallaxes at a viewing angle of 40 degrees, evaluate the degree of modulation in brightness of the synthesized beam with $M = (I_{max} - I_{min})/(I_{max} + I_{min}) \times 100[\%]$ (where, as shown in Fig. 5 (b), I_{max} denotes the maximum brightness and I_{min} the minimum brightness), and then estimate the crosstalk rate with the percentage of the crosstalk portion relative to the entire outgoing beam. As a result, the degree of modulation $M[\%]$ of uneven brightness relative to diffusion angle σ_x and crosstalk rate $R[\%]$ will be as shown in Fig. 6.

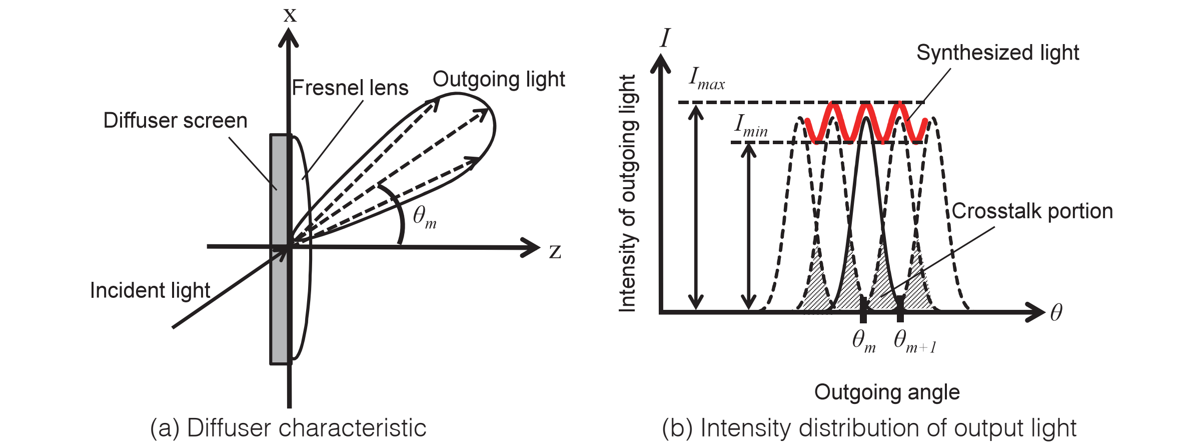

Fig.5 *Characteristics of the diffuser screen*

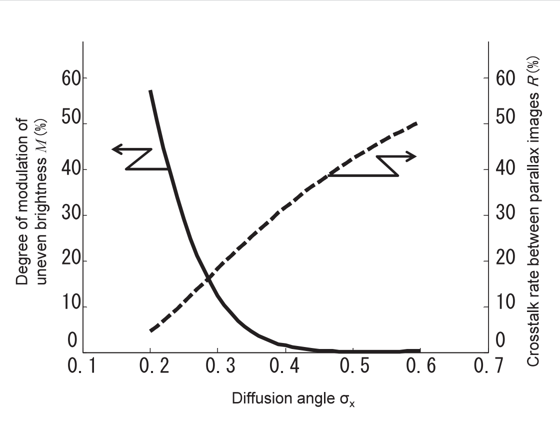

Fig.6 *Diffusion angle of the screen and display image characteristics*

When horizontal diffusion angle σ_x is small, the degree of modulation (M) of the synthesized beam will be larger, resulting in higher uneven brightness. Conversely, when σ_x is high, the crosstalk of the outgoing beam between parallax images will be larger. From Fig. 6, secure the balance between uneven brightness and crosstalk, so that one can project appropriate diffusion angle σ_x as being in the range of about 0.25 to 0.3. This corresponds to a half-value angle of 0.5 to 0.7 degrees in the diffusion angle distribution of beams. Another method involves selecting optimal diffusion characteristics from these relations, and improving the screen material and structure, thereby optimizing the diffusion angle distribution characteristics of the beams.

With regard to the vertical direction as shown in Fig. 7, the angle of the beam that enters the diffuser screen varies depending on which projector unit is involved—the upper or lower one. Consequently, a difference also arises in the diffusion direction of the beam depending on whether the upper or lower projector unit is involved.

When one observes from position y_0 as shown in Fig. 7, distribution $I(y)$ of the brightness values in the y-axis direction of the screen (as viewed by the observer) will be as follows:

$$I(y) = \frac{1}{\sqrt{2\pi}\sigma_y} \sum_{m=-N_V}^{N_V} \exp\left[-\frac{(\theta_{mv}+\theta_o)^2}{2\sigma_y^{\ 2}} \right]$$
$$\approx \frac{1}{\sqrt{2\pi}\sigma_y} \sum_{m=-N_V}^{N_V} \exp\left[-\frac{\left(\frac{mp_v}{g} + \frac{y-y_o}{D} \right)^2}{2\sigma_y^{\ 2}} \right] \quad (8)$$

where, $2N_V + 1$ is the number of lines in the projector array in the vertical direction, θ_{mv} denotes the irradiation angle of the beam in the vertical direction, θ_a the angle of the beam from each image location to the observer as shown in Fig. 7, and σ_y the diffusion angle in the vertical direction. As a concrete example of numerical calculations, assume that $N_V = 3$, $g = 2.5$[m], $p_v = 15$[cm], $D = 3$[m], and $y_0 = 0$[m], and the distribution of brightness values in the y-axis direction of the display image will then be observed as shown in Fig. 8.

As indicated in Equation (8), the image becomes shaded according to location y of the image, location y_0 of the observer, and location

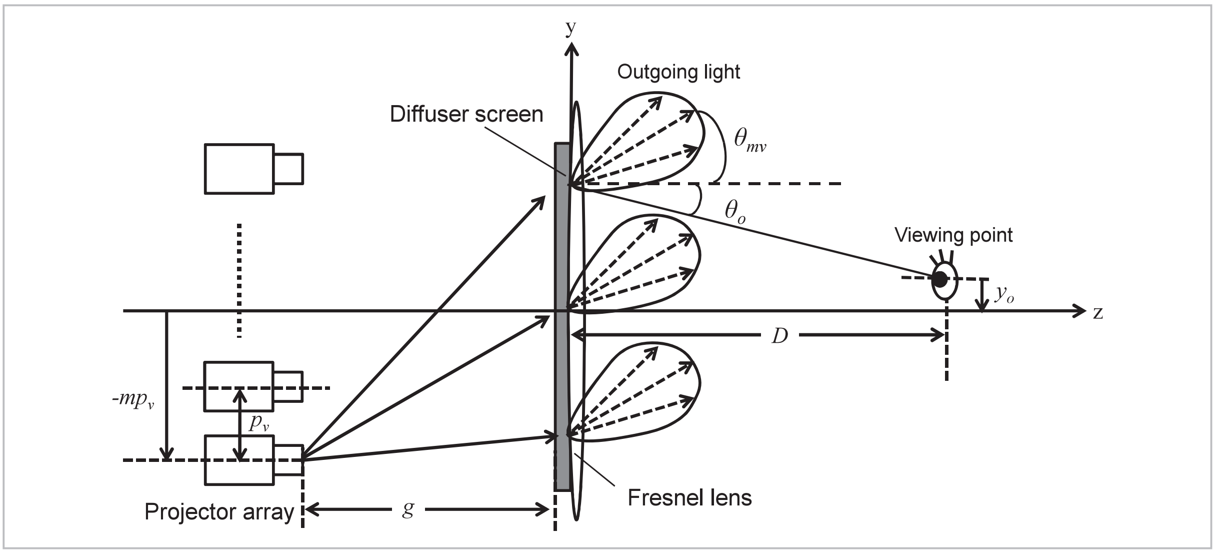

Fig.7 *Vertical diffusion characteristics*

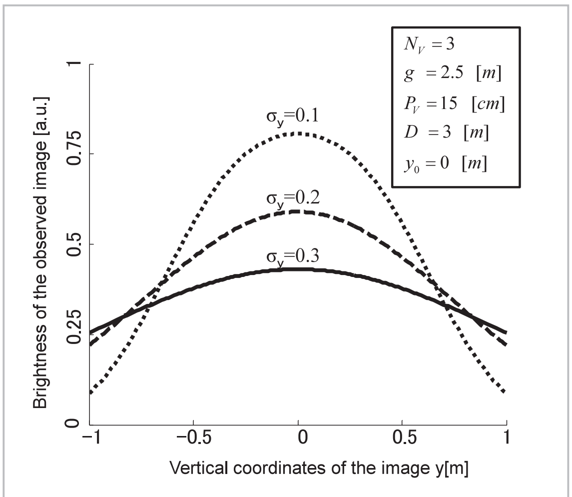

Fig.8 *Distribution of brightness values in y-axis direction of the observed image*

Fig.9 *Prototyped projector array*

Table 1 *Specifications for prototyped equipment*

Projector unit	Number of units	＞50
	Liquid crystal panel	0.7 inch D-ILA
	Panel resolution	1920×1080
	Total number of pixels	＞100 million
Reconstructed 3-D image	Image display size	70 inches (16:9)
	Resolution (when image location z=0)	1920 (H) x 1080 (V)
	Frame rate	60 fps
	Viewing angle	approx. 40 degrees (horizontal parallax)

mp of the projector unit. Note that a comparatively large diffusion angle characteristic is needed to obtain an image having a brightness distribution with a certain degree of uniformity in the vertical direction.

4.4 Prototyped system

Figure 9 shows the prototyped projector array; Table 1 lists the specifications. The prototyped projector array used more than 50 Hi-Vision projector units. The displayed 3-D image measures 70 inches, while the resolution is 1920 pixels horizontally and 1080 pixels vertically for 3-D images on the screen surface. It is also possible to display motion pictures with a frame rate of 60 [fps]. The diffuser screen had a large diffusion characteristic of more than 40 degrees vertically, with a small diffusion char-

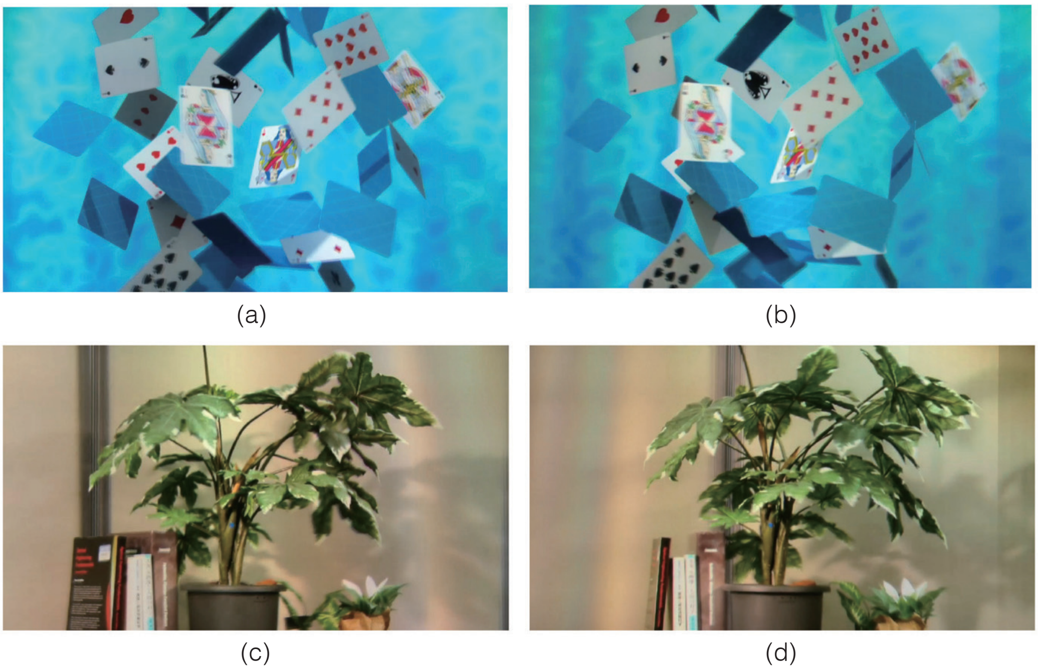

Fig.10 *Example of display image*

3-D computer graphics as (a) observed from the left, (b) observed from the right; real image as (c) observed from the left, and (d) observed from the right.

acteristic of a few degrees horizontally. For the prototype, the projector array and display content were adjusted to improve total image quality of reconstructed 3-D images at the observation location according to the projector array, diffuser screen, fresnel lens characteristics, and other equipment actually used. The viewing area of the prototype can be observed by about five persons in a range of about 1.5 [m] horizontally and 2-3 [m] depthwise.

Figures 10 (a) and (b) show a reconstructed image of 3-D computer graphics as observed from the left and right, respectively. One can see that there is parallax due to a difference in the positional relations of playing cards in the background and foreground according to the observation location. Moreover, Fig. 10 (c) and (d) similarly show real still images displayed. The images were taken as follows: one still camera was mounted on an automatic stage. As the camera moved vertically relative to the object, the images were taken and parallax images obtained. In taking real images, it is necessary to calibrate the camera, and correct the image brightness and coloring for each parallax image. In the future, it will be necessary to develop photographic methods suited for this display, as well as advanced and simple technologies for image processing.

5 Conclusion

This paper presented the development of a highly realistic communication system based on 3-D imagery. Particular attention was paid to large 3-D displays without special glasses; that is, considering a basic system and prototyping the equipment have enabled high-precision, 3-D display.

In the future, we will enhance the performance of the image display function of various display systems and evaluate display images. Particular attention will be paid to large 3-D imagery without special glasses; that is, we intend to make the screens even larger. Among the technical challenges to be addressed for that purpose are optimizing the diffuser screen, developing high-precision screen adjustment technology, and technology for producing computer graphics and obtaining real imagery. In the future, we will also promote research and consider developing functions for image transmission, as well as for interactive, live communication with remote locations.

The large 3-D system without special glasses was jointly developed with JVC Kenwood Holdings, Inc.

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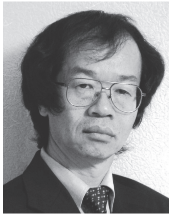

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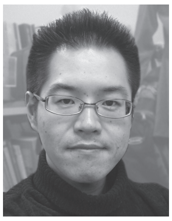
3D Image Media and Display Technology



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3D Image Media and Display Technology

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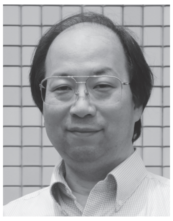

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