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Wide viewing angle projection-type integral 3D display system with multiple UHD projectors

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Abstract

We developed a novel projection-type integral three-dimensional (3D) display method using multiple projectors and displayed a 3D image with a wide viewing angle. In the proposed method, the viewing angle and positions of light spots that become pixels of a 3D image are controlled by projecting elemental images onto a lens array at a predetermined angle as collimated light beams. By projecting elemental images at different angles from multiple projectors installed at optimal positions, the viewing angle is enlarged, and the resolution is enhanced. We prototyped a projection-type integral 3D display system consisting of five ultra high definition (UHD) projectors with a viewing angle of 40 degrees in the horizontal and vertical directions while having a resolution of 114 thousand dots in the center view. We experimentally verified the display performance of the prototype display system and confirmed the validity of the proposed method.

Introduction

An integral three-dimensional (3D) display is an autostereoscopic display based on integral photography [1]. In general, as shown in Fig. 1, an integral 3D display reproduces a 3D image by disposing a lens array in front of a display screen and displaying elemental images corresponding to the lens array. The lens array consists of many micro lenses. A flat panel display or a projector [2] is used as a display device. An integral 3D display is expected to be applied for 3D television systems because it can provide full parallax and smooth motion parallax without special glasses. It is possible to use a pinhole array or a spot light array instead of a lens array. Various approaches related to methods for displaying and capturing are studied [3, 4].

Fundamentally, to improve the quality of an integral 3D image, a display device that has a large amount of pixels is required. However, it is difficult to improve the image quality with a single display device because very few of them have the number of pixels more than 8K resolution. Therefore, methods for improving image quality by using multiple display devices are studied. For example, in the case of using flat panel display as display device, methods for enhancing the depth range of a 3D image [5] and methods for enlarging the display size [6] are reported. The former overlaps 3D images reconstructed at different depth ranges with overlaid liquid-crystal displays (LCDs), and the latter combines elemental images by a magnifying optical system with parallel LCDs. However, these methods do not enlarge the viewing angle. In the case of using flat panel displays, in general, the crosstalk occurs due to adjacent elemental images because they are displayed as diffused lights. When the desired viewing area is defined as a main-lobe, and viewing areas occurred by crosstalk are defined as side-lobes, the area where all main-lobes reproduced by all flat panel displays are overlapped becomes an overall viewing area. To enlarge the viewing angle, it is necessary to change characteristics of the lens array [7] or to apply a time division method with a mask layer [8].

On the other hand, in the case of using a projector as a display device, it is possible to display an integral 3D image with only a main-lobe by projecting elemental images directly onto the lens array without a diffuser screen. Projection light beams are concentrated at predetermined positions so that concentrated light spots that become pixels of the 3D image are observed on the display surface. By using multiple projectors based on these principles, methods for enhancing the resolution [9] and methods for enlarging the viewing angle [10, 11] are reported. The former multiplies the number of concentrated light spots by installing projectors closely as shown in Fig. 2(a). The latter controls viewing angles and combines viewing areas continuously by installing projectors at predetermined positions and collimating light beams incident to the lens array, as shown in Fig. 2(b). Thus, if multiple projectors are used, it is possible to not only enhance the resolution but also enlarge the viewing angle. However, as discussed above, the purposes with conventional methods are

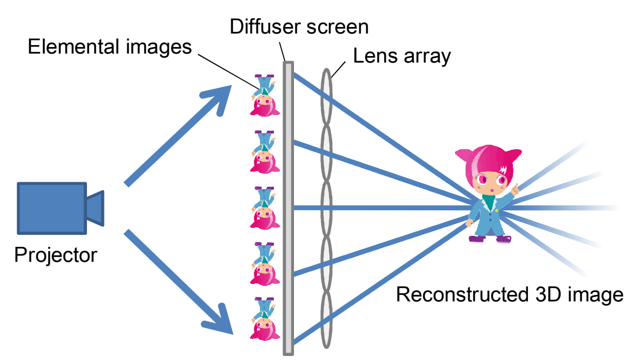

Figure 1. Principle of integral 3D display.

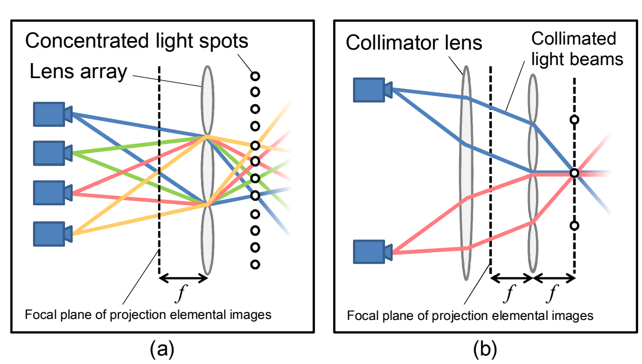

Figure 2. Conventional projection-type integral 3D display with multiple projectors: (a) for enhancing resolution [9], (b) for enlarging viewing angle [10,11].

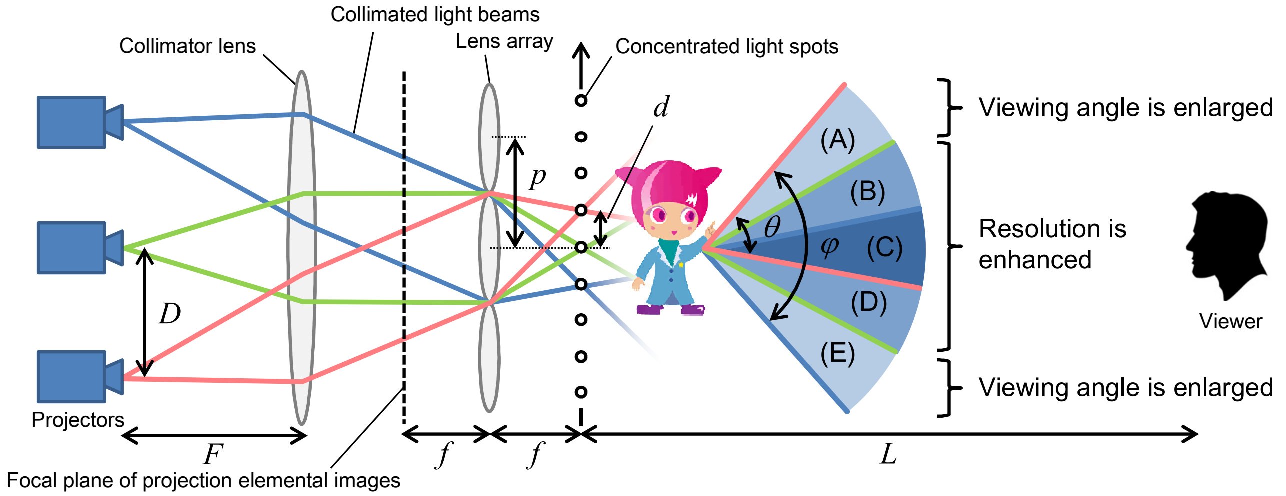

Figure 3. Proposed projection-type integral 3D display with multiple projectors.

either an enhancement of the resolution or an enlargement of the viewing angle. Balancing both enhancements has not been considered. In addition, the resolution of the 3D image is low and the display size is small, because the resolutions of the installed projectors are low. Therefore, in this study we propose a method for displaying an integral 3D image with a wide viewing angle while having a high resolution by using multiple ultra high definition (UHD) projectors. With the proposed method, the balance between enhancements of the viewing angle and resolution is controlled by installing multiple projectors at optimal positions and projecting elemental images onto a lens array at predetermined angles as collimated light beams. We developed the prototype display system consisting of five UHD projectors based on the proposed method and displayed an integral 3D image with a wide viewing angle of 40 degrees in the horizontal and vertical directions. In addition, for the prototype display system, we also developed methods for generating elemental images and a method for compensating distortions of the projection position of elemental images with a high accuracy. Principles of these methods and experimental results concerning the display performance of the prototype display system are presented.

Proposed Projection-type Integral 3D Display

Basic System

Figure 3 shows a basic configuration of the proposed method. A display system consists of multiple projectors, a collimator lens, and a lens array. Elemental images are projected at a different predetermined angle from each projector. By setting the distance between the projectors and collimator lens to the focal length of the collimator lens F, the projection elemental images enter the lens array as collimated light beams and are concentrated at the focal length of the elemental lenses f. These concentration points are observed as light spots on the display surface and become pixels of a 3D image. The viewing angle with a single projector θ and the pitch of the light spots d are expressed by the following equations:

$$\tan^{-1}\left(\frac{d}{f}-\frac{p}{2f}\right)\leq\theta\leq\tan^{-1}\left(\frac{d}{f}+\frac{p}{2f}\right), \tag{1}$$

$$d=\left|\frac{f}{F}D\right|, \tag{2}$$

where p is the pitch of lens and D is the pitch of the projectors. With the proposed method, the viewing angle and the positions of concentrated light spots can be controlled by arranging the optical characteristics of the display system and the installation positions of the projector based on Eqs. (1, 2). For example, as shown in Fig. 3, when three projectors are installed so that the position of the concentrated light spot d becomes one-third of the pitch of lens p, the overall viewing angle φ is enlarged approximately 1.6 times compared to the case of displaying with a single projector. In this case, at viewing area (C) in the figure, the resolution is enhanced by overlapping 3D images reproduced by three projectors and multiplying the number of concentrated light spots comprising the 3D image by a factor of three. At viewing area (B, D), the resolution is enhanced by overlapping 3D images reproduced by two projectors and multiplying the number of concentrated light spots by a factor of two. At viewing area (A, E), the 3D image reproduced by a side projector is observed. Thus, the 3D image with a different resolution that depends on the viewing area is observed. With the proposed method, it is possible to easily adjust display characteristics by arranging the number of projectors and installation positions. For example, a wide motion parallax can be realized by extending the viewing area at both ends while maintaining a high resolution in the center view.

Considering a spatial frequency of an integral 3D display that depends on the pixel pitch and lens characteristics [12], we note that multiplying the number of concentrated light spots is equivalent to increasing the density of lenses. For this reason, the Nyquist frequency β_n that depends on the pitch of the lens p is enhanced as follows:

$$\beta_n=\frac{L}{2p}, \tag{3}$$

where L is the viewing distance. When the depth distance of the 3D image becomes larger, the restrictions imposed by the viewing spatial frequency β that depends on the pixel pitch become tighter than those by the Nyquist frequency β_n. As an example, the spatial

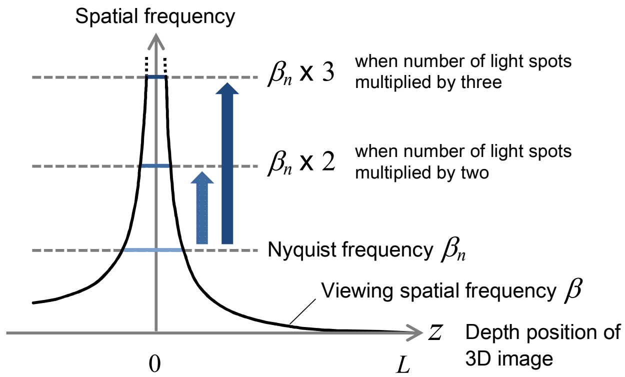

Figure 4. Enhancement of spatial frequency.

frequencies for the densities of the concentrated light spots equally multiplied by two and three are shown in Fig. 4. The Nyquist frequency β_n, which is the upper limit of the spatial frequency, is enhanced proportionally. The viewing angle frequency β does not change if the pixel pitches of all projectors are the same and pixel aperture ratios are 100%. Thus, the Nyquist frequency β_n can be enhanced by multiplying the number of concentrated light spots with the proposed method.

Generation of Elemental Images

To display a 3D image with the proposed method, methods for generating elemental images depending on the viewing angle and positions of concentrated light spots of each projector are required. We developed two types of methods for generating elemental images. One is for 3D computer graphics (3D-CG) objects and the other is for real objects.

In particular, a method for generating elemental images from 3D-CG objects by using an oblique projection with a general integral 3D display system consisting of a flat panel display as a target is reported [13]. With this method, principal points of elemental lenses are regarded as sampling points of light ray information. Elemental images are generated by acquiring rays that pass through the principal points of elemental lenses at predetermined angles collectively by using oblique projection. We improved this method to apply it to our projection-type integral 3D display system method. With our display method, positions of concentrated light spots are regarded as sampling points of light ray information instead of the principal points of elemental lenses. As shown in Fig. 5(a), elemental images can be generated by calculating positions of virtual cameras and matrices for oblique projection from the viewing angle and positions of the

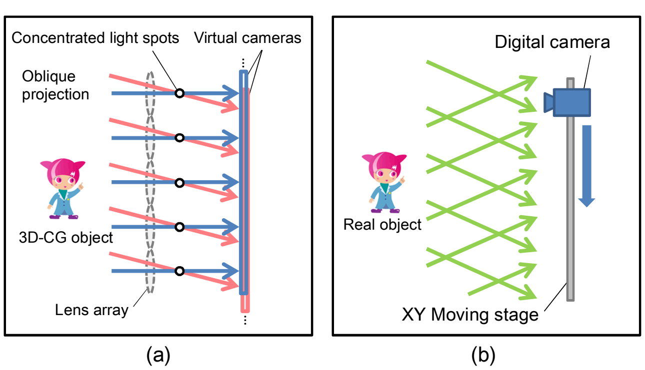

Figure 5. Generation of elemental images: (a) for 3D-CG objects, (b) for real objects.

concentrated light spots of each projector and by acquiring rays that pass through the positions of the concentrated light spots at predetermined angles collectively. This method is used for displaying resolution charts in experiments described below.

For real objects, we developed a method for generating elemental images from perspective projection images from multi-view point. We developed a multi-view point image capture system consisting of a single digital camera and an XY moving stage [14]. Figure 5(b) shows the configuration of this system. Elemental images can be generated by capturing enough wide-area that includes the viewing area and approximately extracting light ray information consisting of the viewing area from captured images. This method is used for displaying real objects in experiments described below.

Distortion Compensation of Elemental Images

This section describes a method for compensating distortions of a reconstructed 3D image. In general, an integral 3D display system has a problem with the degradation of the quality of a 3D image caused by the error of alignment between the position of elemental images and the lens array. Especially in the case of using a projector as a display device, a nonlinear positional error of the 3D image is caused by projection distortions and installation errors [15]. A method for compensating elemental images with an image processing approach is required because physical alignments of projectors and optical compensations of projection distortions have limitations of accuracy. Until now, a method for a manual geometric compensation of elemental images using a diffuser panel with a printing correction pattern [11] and a method for generating

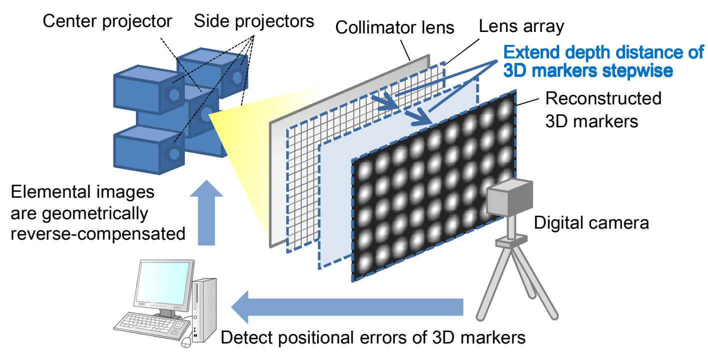

Figure 6. Basic configuration of compensation system.

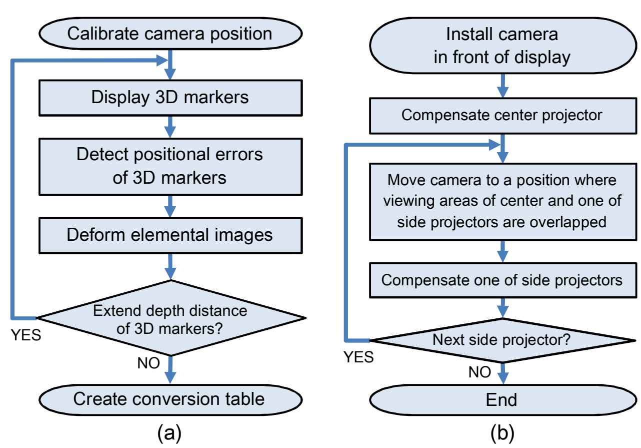

Figure 7. Flow of compensation: (a) for a single projector, (b) for five projectors.

elemental images by measuring a light beam of each pixel with a camera installed on a moving stage [9] are reported. However, these methods are complicated, take a long operation time, and require equipment exclusively for compensation. Though other methods by re-photographing patterns like gray-code are reported [16], the compensation accuracy is not sufficient because they are invalid when an error is over the pitch of the lens.

Therefore, we developed a highly accurate method for auto-compensating elemental images using 3D markers [17]. The configuration and the flow of this method are shown in Figs. 6 and 7, respectively. Multiple 3D markers are displayed and directly captured with a digital camera installed at a viewing area. Elemental images are geometrically reverse-compensated from the detection results of positional errors between the detected and desired positions of the 3D markers. With this method, it is possible to gradually improve the compensation accuracy while extending the depth distance of the 3D markers. It has been experimentally confirmed that the compensation accuracy is less than 0.2 pixels. This compensation method is applied for all projectors one by one. For the prototype display system consisting of five projectors described below, the flow shown in Fig. 7(b) is applied. First, after installing the camera in front of the display and calibrating the camera position based on concentrated light spots of the center projector, the elemental images of the center projector are compensated. Next, after moving the camera to a position where the viewing areas of the center and one of side projectors are overlapped and calibrating the camera position based on the concentrated light spots of the center projector, the elemental images of the side projector are compensated. Positions of five 3D images can be accurately compensated by compensating another side projector in the same process based on the center projector.

Prototype Display System

We developed a prototype display system consisting of five UHD projectors based on the proposed method. Taking into consideration the external sizes and display specifications of our own projectors, we selected one 8K projector and four 4K projectors for the prototype display system. The appearance and specifications are shown in Fig. 8(a) and Table 1, respectively. The prototype display system consists of five projectors, two half mirrors, a collimator lens, and a lens array. As shown in Fig. 8(b), light beams of side 4K projectors are inclined by the lens shift function and the half mirrors so that the light beams enter the lens array at angles of 8.1 degrees in horizontal and vertical directions. As shown in Fig. 8(c), this configuration is equivalent to a configuration having four 4K projectors installed at four corners of an 8K projector with a space of 228 mm in between. The designed value of the viewing angle is approximately 40 degrees in both horizontal and vertical directions and that of the resolution is 114 thousand dots.

Experimental Results

Resolution Characteristics

We displayed a resolution chart to verify the effect of the enhancement of the resolution as shown in Fig. 9. The widths of the upper and lower part of the lines were 5 mm and 1 mm, respectively. The length of a side was 200 mm including the blank space. The capture images were obtained using the center projector and five projectors by switching them in the same center view. When the chart was displayed at the depth of 0 mm, the visible width was made smaller by displaying with five projectors. The

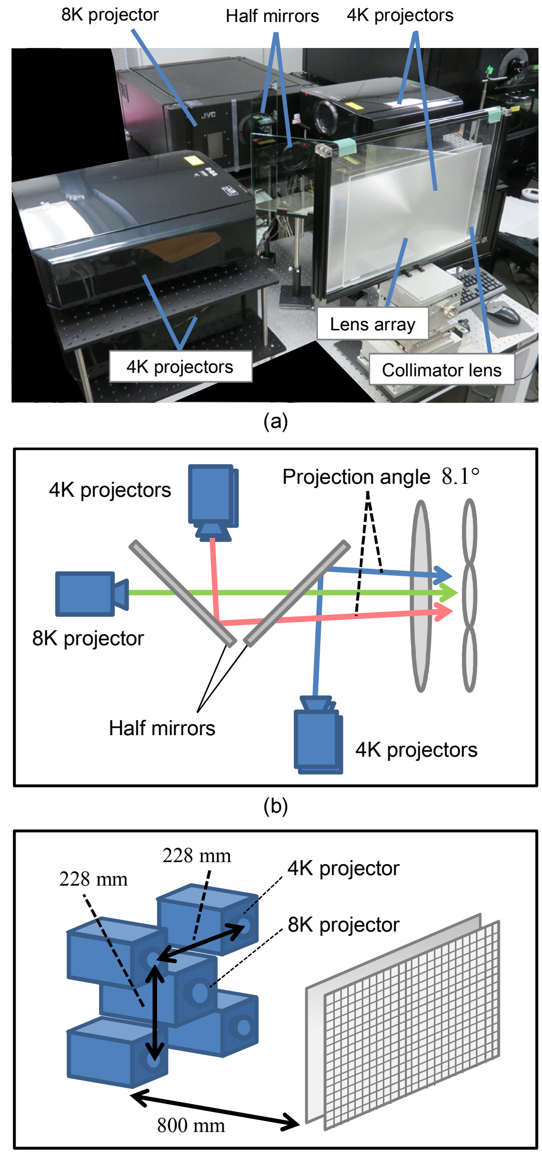

Figure 8. Configuration of prototype display system: (a) appearance, (b) top view, (c) equivalent configuration.

Table 1. Specifications of prototype integral 3D display system

Projector	Number	Full-resolution 8K: 1 Wobbling 4K: 4
Lens array	Pitch	2.64 mm
	Focal length	5.41 mm
	Arrangement	Delta
	Number	180 (H) X 127 (V)
Collimator lens	Focal length	800 mm
3D image	Size	21.9 in
	Resolution	approx. 114 thousand dots (in center view)
	Viewing angle	approx. 40 degrees (H, V)
	Frame rate	60 fps

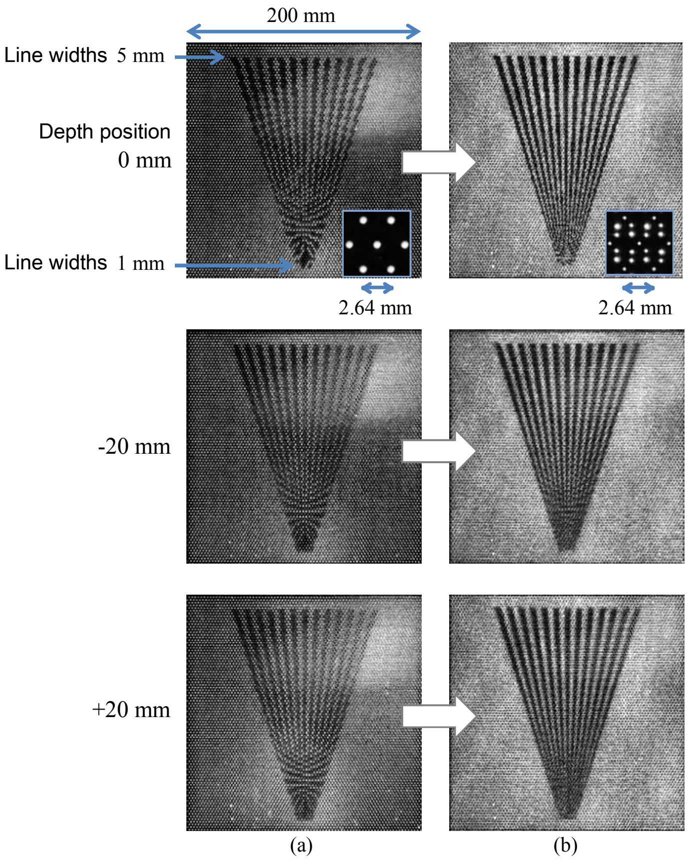

Figure 9. Capture images of the resolution chart obtained using (a) center projector, (b) five projectors.

number of concentrated light spots was multiplied five times as shown in extended images. When the chart was displayed at the depth of -20 mm and +20 mm, the resolution was similarly enhanced, though the reconstructed image was slightly dimmed. Thus, the enhancement of the resolution with the proposed method was verified.

With the prototype display system, the center view had the highest resolution, and the resolution became lower as the view was moving to the periphery. It is assumed that the spatial frequency of each view point is determined depending on the number and specifications of projectors that contribute to the reproduction of the 3D image. A stricter verification requires a consideration of the aperture ratios of pixels. Though the resolution only in the center view is verified in experiments, we will verify the detailed resolution characteristics of the overall viewing area in the future.

Viewing Angle Characteristics

Figure 10 shows the designed viewing area of the prototype display system. The viewing angle is approximately 40 degrees in both horizontal and vertical directions. The shape of the viewing area becomes the union of five cones, because the shape of the elemental lenses is circular. The width and height of the observation area are both 1.5 m at the viewing distance of 2 m. The result of observing the 3D image from five different views is shown in Fig. 11(a-e). Wide motion parallax could be observed, for example, from a change of the positional relation between the body of the mascot and the logo of '3D'. Motion parallax was also

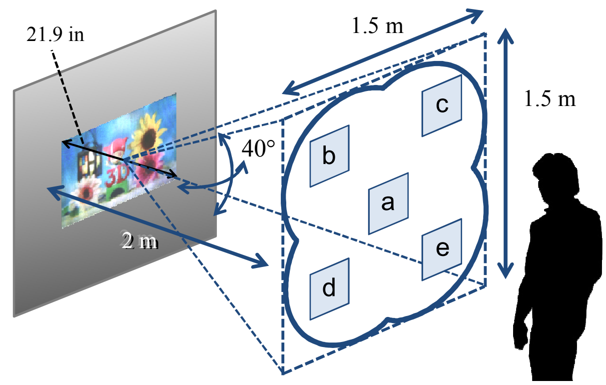

Figure 10. Viewing area of the prototype display system at a viewing distance of 2 m.

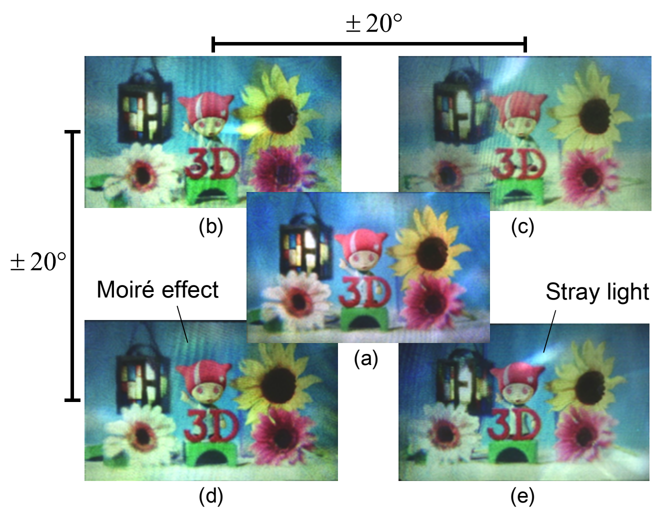

Figure 11. Integral 3D image from different views: (a) center view, (b) upper left view, (c) upper right view, (d) lower left view, (e) lower right view.

smooth at the change points of each viewing area reproduced by each projector. When the 3D image was observed from a non-viewing area, the display surface became dark because the prototype display system could display an integral 3D image without the side-lobe.

As issues with the prototype display system, Moiré effect and stray light were observed in the reproduced image. The Moiré effect was caused by the interference between a Fresnel lens used as a collimator lens and a lens array. It is possible to suppress the Moiré effect by adjusting the distance between the Fresnel lens and the lens array, or to eliminate it by using a convex lens instead of the Fresnel lens. Stray light was caused by light beams incident to gaps between adjacent elemental lenses. It is possible to suppress it by accurately applying mask processing to the elemental images corresponding to the non-lens area, or attaching an aperture mask to the lens array. It is possible to eliminate stray light by using a lens array consisting of hexagonal or square lenses.

Brightness and color balance of 3D images were slightly changed because projectors that contribute to the reproduction of the 3D image were different in each view point. To compensate brightness and color balance, it is assumed that the color compensation for pixels of elemental images is required. For color balance, it is possible to reduce its differences by building the display system with the same model of the projector. We will consider these improvements in the future.

Conclusions

We proposed a novel projection-type integral 3D display method with multiple projectors. With the proposed method, the viewing angle can be enlarged while enhancing the resolution by projecting elemental images onto a lens array at predetermined angles as collimated light beams from multiple projectors installed at optimal positions. We prototyped a projection-type integral 3D display consisting of five projectors with a viewing angle of 40 degrees in both horizontal and vertical directions while having a resolution of 114 thousand dots in the center view. A wide motion parallax is confirmed in the experiments, and the effect of the enhancement of the resolution is verified with the resolution chart.

The proposed method is very useful for developing 3D television systems, because it has a high flexibility of display characteristics design, and display parameters like the viewing angle and the resolution can be changed. Though we prototyped the display system with our own five UHD projectors, we will improve the system to display higher-quality 3D images by enhancing the resolution of projection images and improving the projection method and optics.

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