https://doi.org/10.2352/ISSN.2470-1173.2017.5.SD&A-361

Integral three-dimensional display with high image quality using multiple flat-panel displays

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Abstract

We have developed a method for combining the images of multiple flat-panel displays to improve the quality of integral three-dimensional (3D) images. A multi-image combining optical system (MICOS) is used to magnify and combine the images of multiple displays without gaps between multiple active display areas. However, in the previous prototype, the image quality of the 3D images deteriorated due to the use of a MICOS that had a complicated structure and a diffuser plate. This paper describes an optical system for combining multiple images while suppressing the deterioration of 3D image quality. The improved method can suppress the deterioration of the image quality because it uses a simple structure as a MICOS and does not require a diffuser plate. Furthermore, the thickness of the entire equipment was increased because parallel light was required for the backlight of the LCD panel in the previous design. The thickness of the entire equipment could be reduced to 1/5 or less because diffused light can be used in the improved design.

Introduction

We are currently conducting research on integral 3D imaging systems based on integral photography (IP) technology to capture and display 3D photographs proposed by Lippmann [1] in 1908. A viewer can see 3D images without wearing special glasses, and the 3D images are changed according to the viewing position because they have motion parallax in both horizontal and vertical directions. Various studies have reported about systems for capturing and displaying 3D images related to the IP technique [2]–[7]. We have been advancing the research and development of the integral 3D television based on the IP principle so that viewers can see 3D images naturally and easily [8][9].

The principle of capturing and displaying integral 3D images is described as follows. First, the object is captured through a lens array placed in front of it, as shown in Fig. 1 (a). The lens array has a large number of small lenses in the horizontal and vertical directions, and the information on the light ray from various directions can be collectively captured using this lens array. Next, as shown in Fig. 1 (b), the captured image (elemental images) is shown on the display device, and the lens array is placed in front of it. By reconstructing the light ray emitted by the original object, the 3D image is optically reconstructed on the space. However, as shown in Fig. 1, a problem arises wherein the depth of the 3D image is reversed because the capturing direction and the viewing direction are reversed. This problem can be solved by rotating each elemental image 180 degrees with respect to the center of the elemental image [4]. Flat-panel devices such as liquid crystal display (LCD) panels and organic light-emitting diode (OLED) panels or projectors are used as devices for displaying elemental images.

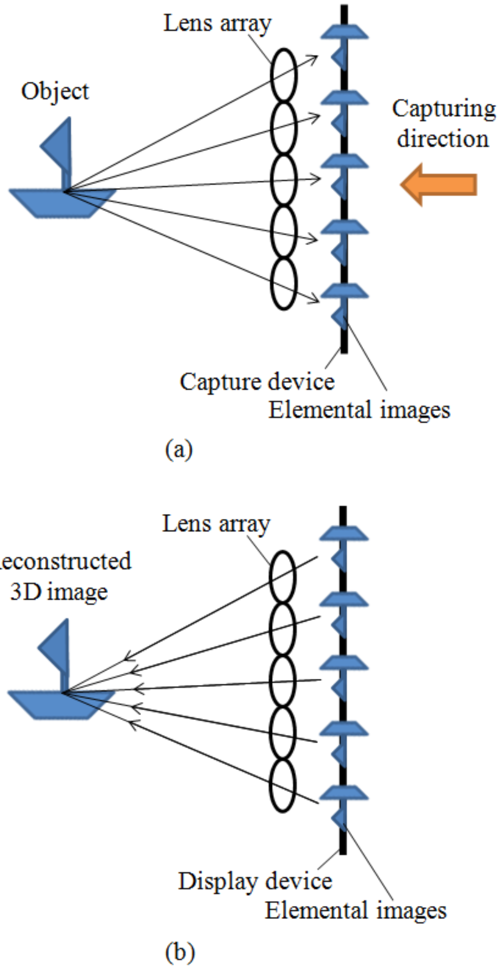


***Figure 1**. Principle of integral photography. (a) Capturing. (b) Displaying.*

The integral 3D images reconstruct the same light ray as the light emitted by the actual object. Therefore, a lot of pixels are needed to improve the 3D image quality [10]. We have reconstructed 3D images of approximately 100,000 pixels using a projector that made the resolution equivalent to 16K images (15,360 × 8,640 pixels) using wobbling technology with display elements of 8K Super Hi-Vision (SHV) [11][12]. However, the number of pixels that can be displayed is limited with the conventional method using a single display device and a lens array. Improving the image quality of the integral 3D images is difficult because images cannot be displayed with a resolution significantly exceeding 8K with a single display device. Therefore, we are advancing research to improve the image quality of integral 3D images using multiple display devices.

Several methods have been proposed for improving the quality of 3D images using multiple projectors as a display device [13]–[17]. A method using a projector is suitable for high definition of images and for enlarging the screen size. However, a problem occurs with the depth of the entire apparatus increasing because using a projector requires a certain projection distance. We are conducting research aiming at a 3D television that can be used in people's homes in the future and aiming to create a thin device. Therefore, we are studying the construction of a thin integral 3D imaging device using multiple flat-panel displays.

So far, 3D images could be displayed while increasing the number of pixels by magnifying the images using multiple LCD panels and a multi-image combining optical system (MICOS) and seeing the image combined continuously without a gap through the lens array [18]. However, the image quality of the 3D images deteriorated due to the MICOS used in the prototype, and their quality could not be sufficiently improved. Therefore, we designed an optical system for combining multiple images while suppressing degradation in image quality and have built prototype equipment for it.

Integral 3D display system using multiple LCD panels

Previous design

This section describes the integral 3D display system with multiple LCD panels constructed previously [18]. Figure 2 shows the design. First, a MICOS is placed on the front surface of the active display area of each of the LCD panels arranged side by side. Each display image is magnified and formed in the space away from the LCD panels. Next, a diffuser plate is placed at the imaging position, and multiple magnified images are continuously combined without a gap between the active display areas. Because the magnified image is distorted due to the positional displacement of the optical device and the aberration of the lens, image processing is applied to the input image to correct the distortion and to combine multiple magnified images precisely. Finally, a lens array is placed in front of the diffuser plate to reconstruct integral 3D images of which the number of elemental images has been increased.

In the previous design, the image quality of the magnified image greatly deteriorates due to a minute displacement of the lens arrangement because the MICOS has a complicated design using a concave lens and an erect unmagnified optical system composed of multiple lens arrays as shown in Fig. 3. Therefore, there was a problem that sufficient image quality cannot be obtained when an integral 3D image is displayed. In addition, a diffuser plate having a large diffusion angle of about 60 to 100 degrees (FWHM) is necessary to use to suppress the luminance unevenness of the 3D image. Because the light ray is strongly scattered on the diffuser plate, the contrast of the image is reduced, and the image quality deteriorates. Furthermore, in the previous design, a stray light is generated in the MICOS, and the magnified image is formed as multiple images when a diffused light is used as the backlight of the LCD panel. Therefore, parallel light is needed for the backlight of LCD panels. A configuration using a point light source and a convex lens is required to generate parallel light irradiating the entire LCD panel. This has a problem of increasing the depth of the entire apparatus.

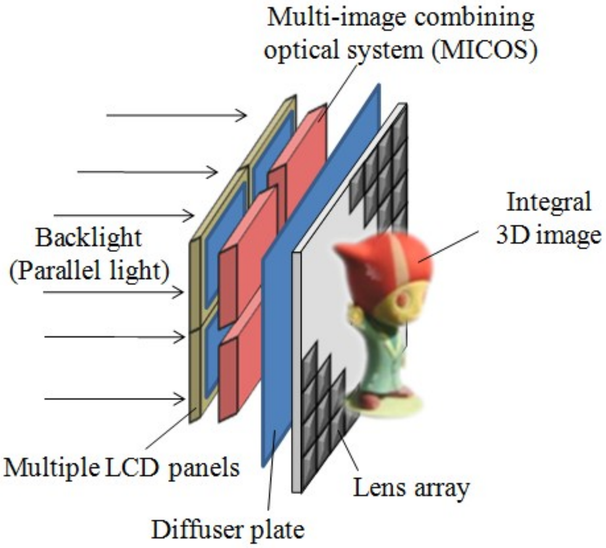


***Figure 2**. Previous design of integral 3D display device using multiple LCD panels and previous MICOS.*

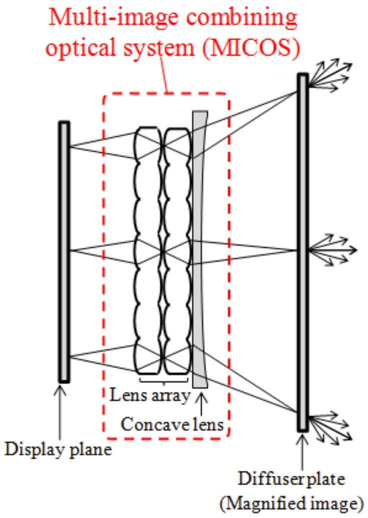


***Figure 3**. Previous design of MICOS.*

Improved design

A new design of the optical system was created to solve the problem described in the previous section. First, LCD panels are arranged side by side, and lens arrays are placed in front of each active display area. Integral 3D images divided on each display are reconstructed, as shown in Fig. 4, by inputting elemental images to each LCD panel. Next, the improved MICOS is placed in front of the lens array. Figure 5 shows the design. As shown in Fig. 6, the MICOS uses a combination of a concave lens and a convex lens. As a result, the integral 3D images in each panel are magnified. Finally, integral 3D images with a higher number of elemental images are reconstructed by combining multiple magnified integral 3D images continuously without a gap between active display areas.

Table 1 summarizes the differences between the previous design and the improved one. In the improved design, the image quality of the integral 3D images has been improved because the

MICOS is designed simply and because the diffuser plate is not used. Furthermore, in the improved design, diffused light can be used for the backlight of LCD panels. Therefore, the depth of the entire apparatus can be reduced.

The functions of the convex lens and the concave lens of MICOS are described as follows. The convex lens magnifies the image of the display plane and generates a virtual image. If the distance between the display plane and the convex lens is a, the distance between the convex lens and the virtual image plane is b, and the focal length of the convex lens is f_+; as shown in Fig. 6, the virtual image can be expressed in the following equation from the formula of the lens,

$$\frac{1}{a}-\frac{1}{b}=\frac{1}{f_+}. \tag{1}$$

Furthermore, the magnification ratio m of the image can be expressed in the following equation,

$$m=\frac{b}{a}. \tag{2}$$

The concave lens has a function of controlling the directionality of light traveling. Using a concave lens enables optimizing the range of the viewing zone in which the 3D image can be continuously viewed on the entire display surface.

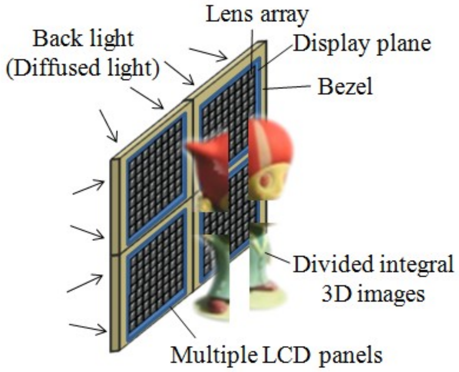


Figure 4*. Display of divided integral 3D images.*

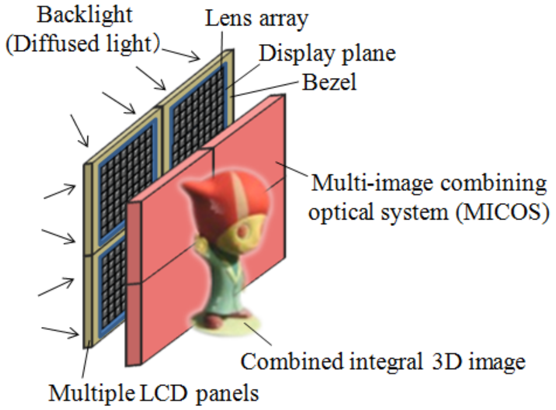


Figure 5*. Improved design of integral 3D display device using multiple LCD panels and improved MICOS.*

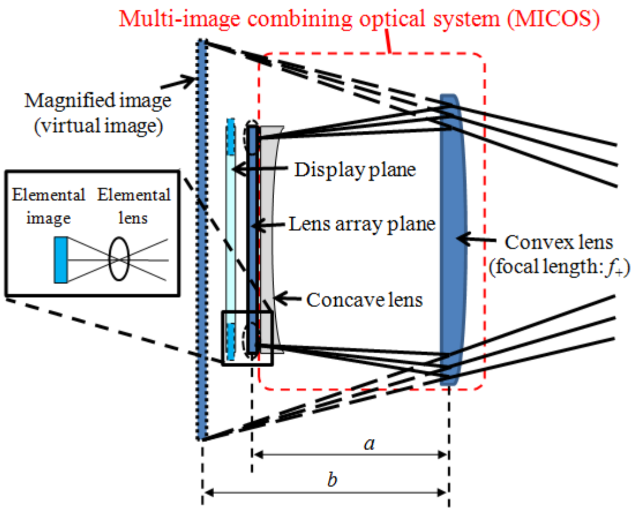


Figure 6*. Improved design of MICOS.*

Table 1. Differences between the previous design and the improved one.

	Previous design	Improved design
MICOS	Multiple lens arrays and a concave lens (complicated)	A concave lens and a convex lens (simple)
Diffuser plate	Necessary	Unnecessary
Backlight of LCD panel	Parallel light is necessary.	Diffused light can be used.

Multi-image combining by using improved MICOS

The previous section described a method of combining the images of multiple displays without gaps between active display areas by applying the improved MICOS. As shown in Fig. 7, multiple displays, lens arrays, and MICOS are arranged side by side. The multiple convex lenses at the foremost part are arranged in close contact so as not to form a gap. As shown in Fig. 7, the combined magnified images partially overlap. When viewing the 3D image from the outside of angle θ formed by this overlapping portion (viewpoint A of Fig. 7), the interval between multiple images appears to be separated, and the gap between multiple images is generated as shown in Fig. 8 (a). Continuous viewing of the image without gaps between multiple images, as shown in Fig. 8 (b), is possible only when viewing the images within angle θ (viewpoint B of Fig. 7). Angle θ can be expressed in the following equation,

$$\theta=2\arctan\left(\frac{bw_1-aw_2}{2ab}\right), \tag{3}$$

where w_1 and w_2 represent the width of the active display area and the width of the entire display including the bezel, respectively. Angle θ is designed to be larger than the viewing angle of the integral 3D image. In addition, elemental images are created in consideration of overlapping portions due to magnification and displayed on each display.

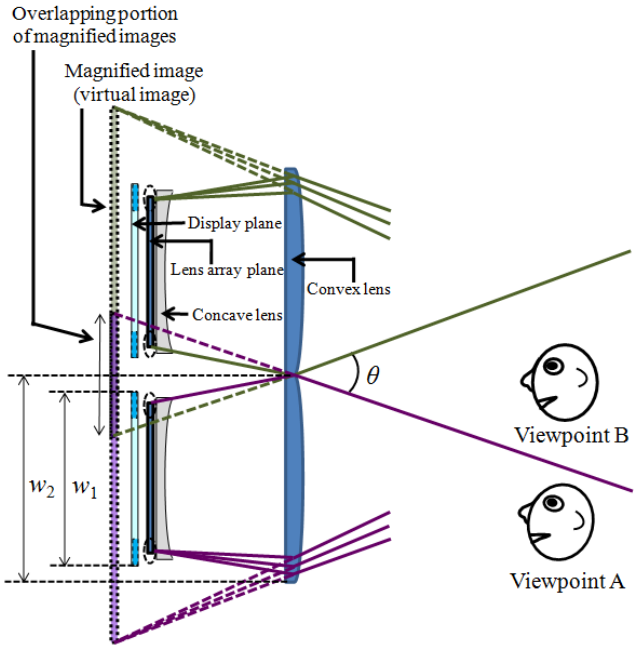


***Figure 7**. Combining the images using multiple LCD panels, lens arrays, and MICOS.*

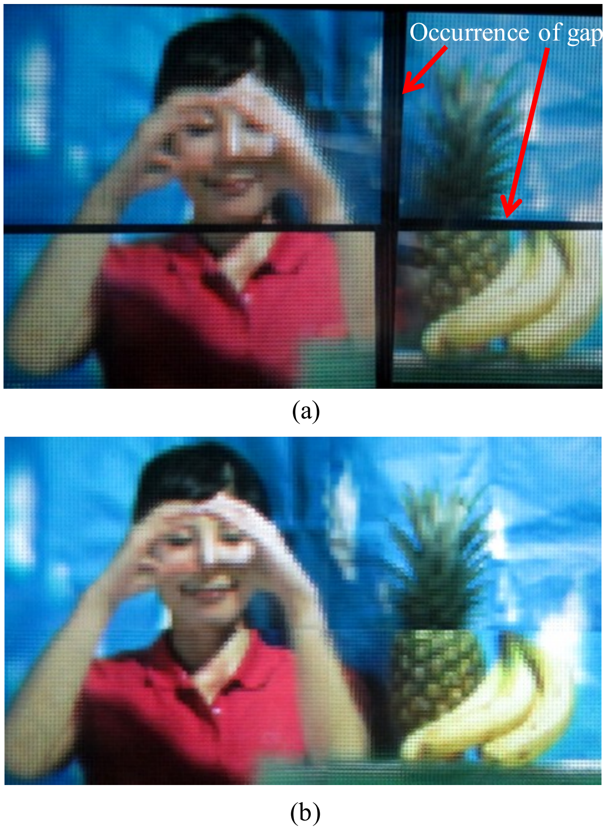


***Figure 8.** Occurrence of gap between multiple images. (a) View from outside of angle θ formed by the overlapping portion of magnified images (viewpoint A of Fig. 7). (b) View within angle θ (viewpoint B of Fig. 7).*

Prototype and reconstruction of integral 3D images

A prototype using an improved MICOS was constructed. Table 2 shows the specifications of the prototype with the improved design. Four LCD panels with HD resolution (number of pixels: 1,920 × 1,080) were used, and integral 3D image reconstruction with the total number of elemental images of 17,248 and viewing angle of 18.7 degrees (design value) was achieved.

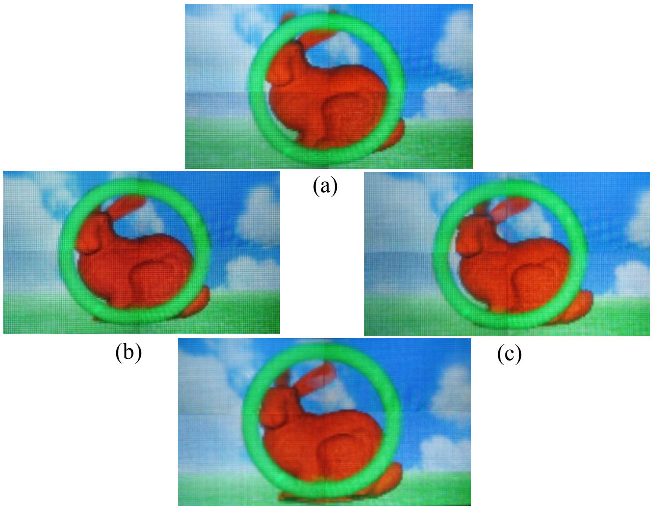
Table 2. Specifications of the prototype with the improved design.

LCD panel	Resolution	HD (1,920 × 1,080 pixels)
	Number of panels	4 units
	Pixel pitch	55.5 μm
MICOS	Focal length of concave lens	-145 mm
	Focal length of convex lens	175 mm
Lens array	Arrangement / Shape	Square / Square
	Pitch / Focal length	1.21 mm / 2.42 mm
	Lens number (per LCD panel)	88 (H) × 49 (V)
3D image	Number of elemental images	176 (H) × 98 (V) (Total: 17,248)
	Viewing angle	18.7 degrees (design value)
	Screen size	289 mm (H) × 162 mm (V)

Figure 9 shows integral 3D images from four viewpoints using the improved prototype device. The green ring was reconstructed about 38 mm in front of the virtual image plane, the red bunny was reconstructed on the virtual image plane, and the background was reconstructed about 38 mm behind the virtual image plane. Motion parallax corresponding to various viewing positions can be confirmed.

Figure 10 (a) and (b) show the integral 3D images reconstructed by the previous prototype device and the improved one, respectively. In the integral 3D image displayed using the previous design, the whole image is blurry, and the contrast is low. The integral 3D image displayed using the improved design had higher contrast and improved image quality.

Photographs of the previous prototype and the improved prototype are shown in Fig. 10 (c) and (d). The depth of the prototype—including the whole backlight—was about 600 mm for the previous prototype, whereas in the improved design it was about 110 mm, which was considerably smaller.



(a) (b) (c) (d)

Figure 9. *Integral 3D images from four viewpoints using the improved prototype device. (a) View from upper position. (b) View from left position. (c) View from right position. (d) View from lower position.*

Conclusion

This paper proposed an optical system with a new design for an integral 3D display device using multiple LCD panels. We also reported on a prototype device we constructed. Previously, the image quality of reconstructed integral 3D images greatly deteriorated when using a MICOS with a complicated design and a diffuser plate. Our improved design enabled improving the image quality of integral 3D images by using a MICOS of a simple design and by eliminating a diffuser plate. Furthermore, as a backlight of LCD panels, parallel light has to be used in the previous design, but the depth of the entire apparatus can be reduced because the diffused light can be used in the improved design.

In the future, we will study a distortion correction method for integral 3D images using image processing for elemental images and an optical system in which the connecting part is inconspicuous when combining multiple images. We also plan to apply this method to a panel with higher definition and to evaluate image quality in the reconstructed integral 3D images in more detail.

References

[1] M. G. Lippmann, “Épreuves, réversibles donnant la sensation du relief,” J. Phys., vol. 7, pp. 821–825, 1908.

[2] Y. Igarashi, H. Murata, and M. Ueda, “3-D display system using a computer generated integral photograph,” Jpn. J. Appl. Phys., vol. 17, no. 9, pp. 1683–1684, 1978.

[3] N. Davies, M. McCormick, and L. Yang, “Three-dimensional imaging systems: a new development,” Appl. Opt., vol. 27, issue 21, pp. 4520–4528, 1988.

[4] F. Okano, H. Hoshino, J. Arai, and I. Yuyama, “Real-time pickup method for a three-dimensional image based on integral photography,” Appl. Opt., vol. 36, issue 7, pp. 1598–1603, 1997.

[5] H. Arimoto and B. Javidi, “Integral three-dimensional imaging with digital reconstruction,” Opt. Lett., vol. 26, issue 3, pp. 157–159, 2001.

[6] B. Javidi, I. Moon, and S. Yeom, “Three-dimensional identification of biological microorganism using integral imaging,” Opt. Exp., vol. 14, issue 25, pp. 12096–12108, 2006.

[7] B. Javidi, F. Okano, and J. Son (Eds.), Three-Dimensional Imaging, Visualization, and Display, Springer, New York, 2009.

[8] J. Arai, M. Okui, T. Yamashita, and F. Okano, “Integral three-dimensional television using a 2000-scanning-line video system,” Appl. Opt., vol. 45, issue 8, pp. 1704–1712, 2006.

[9] K. Suehiro, M. Yoshimura, Y. Haino, M. Sato, J. Arai, M. Kawakita, and F. Okano, “Integral 3D TV using ultrahigh-definition D-ILA device,” in *Stereoscopic Displays and Applications XIX*, Proc. SPIE-IS&T Electronic Imaging, SPIE vol. 6803, 680318, 2008. DOI: 10.1117/12.766892.

[10] H. Hoshino, F. Okano, and I. Yuyama, “Analysis of resolution limitation of integral photography,” J. Opt. Soc. Am. A, vol. 15, issue 8, pp. 2059–2065, 1998.

[11] T. Yamashita, M. Kanazawa, K. Oyamada, K. Hamasaki, Y. Shishikui, K. Shogen, K. Arai, M. Sugawara, and K. Mitani, “Progress report on the development of Super-Hi Vision,” SMPTE Motion Imaging J., vol. 119, issue 6, pp. 77–83, 2010.

[12] J. Arai, M. Kawakita, T. Yamashita, H. Sasaki, M. Miura, H. Hiura, M. Okui, and F. Okano, “Integral three-dimensional television with video system using pixel-offset method,” Opt. Exp., vol. 21, issue 3, pp. 3474–3485, 2013.

[13] H. Liao, M. Iwahara, T. Koike, N. Hata, I. Sakuma, and T. Dohi, “Scalable high-resolution integral videography autostereoscopic display with a seamless multiprojection system,” Appl. Opt., vol. 44, issue 3, pp. 305–315, 2005.

[14] Y. Takaki and N. Nago, “Multi-projection of lenticular displays to construct a 256-view super multi-view display,” Opt. Exp., vol. 18, issue 9, pp. 8824–8835, 2010.

[15] M. Kawakita, S. Iwasawa, M. Sakai, Y. Haino, M. Sato, and N. Inoue, “3D image quality of 200-inch glasses-free 3D display system,” in *Stereoscopic Displays and Applications XXIII*, Proc. SPIE-IS&T Electronic Imaging, SPIE vol. 8288, 82880B, 2012. DOI: 10.1117/12.912274.

[16] J.-Y. Jang, D. Shin, B.-G. Lee, and E.-S. Kim, “Multi-projection integral imaging by use of a convex mirror array,” Opt. Lett., vol. 39, issue 10, pp. 2853–2856, 2014.

[17] N. Okaichi, H. Hiura, M. Miura, and J. Arai, “Integral 3D display with multi-projection system using distortion compensation,” ITE Annual Convention 2013, 11-5, 2013. (in Japanese)

[18] N. Okaichi, M. Miura, J. Arai, and T. Mishina, “Integral 3D display using multiple LCDs,” in *Stereoscopic Displays and Applications XXVI*, Proc. SPIE-IS&T Electronic Imaging, SPIE vol. 9391, 939114, 2015. DOI: 10.1117/12.2077514.

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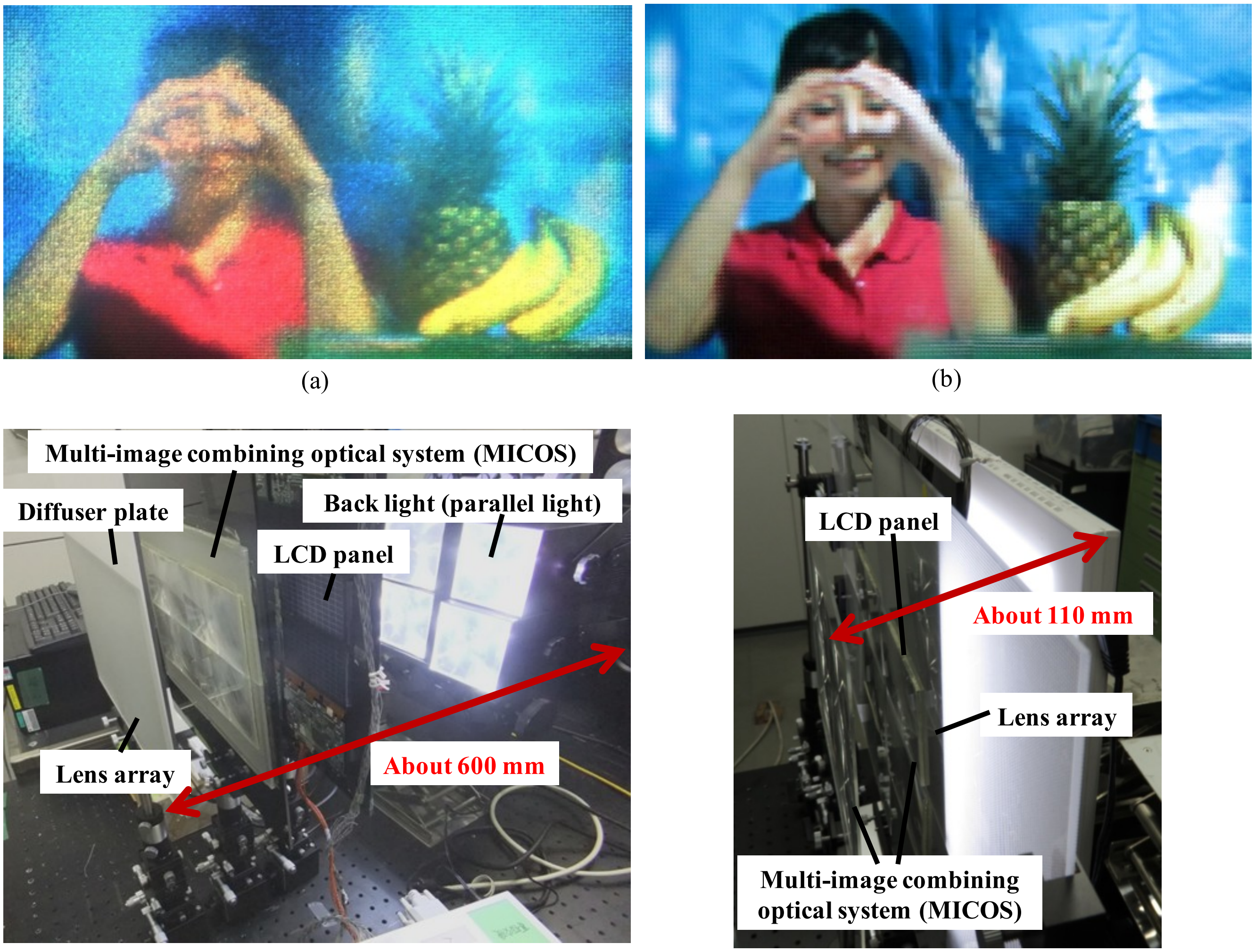

(a) (b)

(c) (d)

Figure 10. *Reconstructed integral 3D images and photographs of prototype. (a) 3D image using previous prototype. (b) 3D image using improved prototype. (c) Previous prototype. (d) Improved prototype.*