DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452

Retinal projection type 3D head-mounted display using an HOE lens array

Yasuhiro Takatsuka, Kayo Yoshimoto, and Hideya Takahashi
Dept. of Electric and Information Engineering, Graduate School of Engineering, Osaka City University; Osaka, Osaka/Japan; takatsuka@ec.elec.eng.osaka-cu.ac.jp, hideya@elec.eng.osaka-cu.ac.jp

Abstract

We propose a retinal projection type super multi-view (SMV) HMD using a 2D microlens array. The smooth motion parallax is provided by SMV technique. Moreover, if a viewer focuses his or her eyes on the displayed 3D image, the stimulus of accommodation of the human eye is reproduced naturally by SMV technique. Therefore, although the proposed HMD is a monocular HMD, it provides observers with natural 3D images. To verify the effectiveness of the proposed HMD by using camera, we constructed the prototype holographic optical element (HOE). The number of microlenses is 9, and the focal length and the size of each microlens of the prototype HOE were 11.1 mm and 20 mm × 20 mm, respectively. The distance between each convergence point was 6.67 mm. We displayed 3D images at the distance from 200mm to 2000mm in front of the camera, and confirmed the accommodation by the prototype HMD.

1. Introduction

Mixed Reality technology [1] has recently been proposed as an approach for practical use of Virtual Reality technology [2]. See-through head-mounted displays (HMD) provide an effective capability for Mixed Reality. By using a see-through HMD, an observer can see both real world and virtual world at the same time. Some conventional see-through HMDs have been developed. They can display two-dimensional virtual information. However, when two-dimensional virtual information is displayed by a HMD, an observer is hard to understand that it is related with a real-world object. What an observer sees needs to be augmented by three-dimensional (3D) virtual information image in accordance with the real object. In order to overcome this problem, we have previously proposed a retinal projection type super multi-view HMD [3]. The smooth motion parallax provided by the super multi-view technique [4] enables a precise superposition of virtual 3D images on real objects. Moreover, if a viewer focuses his or her eyes on the displayed 3D image, the stimulus for the accommodation of the human eye is reproduced naturally by the super multi-view technique. Therefore, although the previously proposed HMD is a monocular HMD, it provides observers with natural 3D images. In addition, the previously proposed retinal projection type super multi-view HMD use the principle of the Maxwellian view [5]. In the Maxwellian view, parallel rays are converged directly at the center of the pupil, and projected onto the retina directly. Thus, previously proposed HMD can provide an extreme long focal depth image, and a provided 3D image by the proposed HMD is clear and high contrast. However, since our previously super multi-view HMD uses a complicated structured holographic optical element (HOE), it is difficult to improve the HOE to increase the number of rays. In order to overcome this problem, we propose the improved super multi-view HMD by using simple structured HOE.

This paper describes the principle of the improved retinal projection type super multi-view HMD. In Section 2, we describe the principle of the Maxwellian view, the principle of the previously proposed retinal projection type super multi-view HMD and its drawback. In Section 3, the principle of the proposed improved retinal projection type super multi-view HMD is described. In Section 4, to verify the effectiveness of the improved HMD, we describe experimental result. Finally, we give some conclusions in Section 5.

2. Previously Proposed Retinal Projection Type Super Multi-View HMD

We have previously proposed a see-through retinal projection type 3D HMD [6]-[8]. In this paper, since we describe improvement of the previously proposed HMD, the previously proposed see-through retinal projection type 3D HMD is described here again.

2.1 Holographic Combiner

The fundamental role of an HMD is to produce a distinguishable image of the Spatial Light Modulator (SLM) and enable the outside world to be seen through the see-through HMD. In our previous HMD, we used an HOE as a combiner which superimposes the virtual image on the real scene [6]-[8]. Figure 1 shows the principle of a holographic combiner. The HOE is a diffraction grating which is made by using the holography technique. In our previous HMD, the HOE has two functions. One is a half mirror to combine the real world and a virtual image, and the other is a lens to achieve the Maxwellian view. And this HOE has sufficient transparency to see the outside world because it has superior optical characteristics such as wavelength selectivity and angular selectivity. Moreover, since the HOE consists of a thin layer of emulsion, it contributes to compact mobility and lightweight of an HMD.

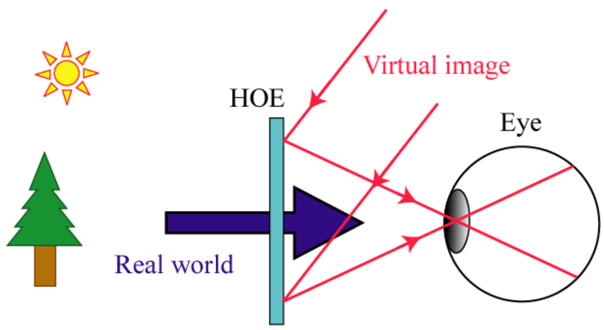


Figure 1. Principle of a holographic combiner.

DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452

2.2 Principle of the Maxwellian View

The Maxwellian view is the key technology of our previous HMD [5]. In the Maxwellian view, parallel rays are converged directly at the center of the pupil, and projected onto the retina directly. This technique is used to measure the sensitivity of the human vision system or in experiments of psychological visual perception. Figure 2 shows the principle of the Maxwellian view. The parallel rays irradiate the transparent object M. The object M is located on the front focus plane of the lens, and the pupil of the human eye is located on the back focus plane of the lens. In this case, object M and the retina are conjugate, and the light stimulus, which has an extremely long focal depth, can be observed. By using this principle for a retinal projection display, it can provide an extremely long focal depth image without causing ocular accommodation.

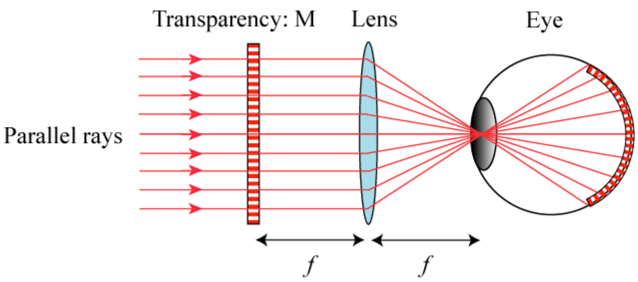


Figure 2. Principle of the Maxwellian view.

2.3 Super Multi-View

In the real world, usually illumination light is diffusely reflected at an object's surface and reflected light causes stimulus of accommodation of the eye, as shown in Figure 3(a). In the ray reconstruction method, several pixels that have been angularly multiplexed can be utilized to give the impression that rays are emanating from a converging point, as shown in Figure 3(b). However, multiple rays of the light diffusing at the object's surface are sampled discretely. If the sampling interval of parallax rays is narrower than the pupil's diameter, two or more rays always pass through the pupil of each eye. This condition is called 'super multi-view' [4]. In the super multi-view condition, reconstructed 3D images have very smooth motion parallax, and if a viewer focuses his or her eyes on the reconstructed object's surface, the stimulus for the accommodation of the human eye is reproduced naturally. Therefore, the retinal projection HMD provides observers with natural 3D virtual images so long as the super multi-view condition is satisfied.

2.4 Principle of Super Multi-View HMD

The proposed retinal projection type super multi-view HMD uses the principle of the Maxwellian view. In the Maxwellian view, parallel rays are converged directly at the center of the pupil. In the proposed HMD, the super multi-view condition is realized by some projected parallax images which converge on the different positions on the pupil, as shown in Figure 4. For the sake of simplicity, here we limit the number of parallax images to three.

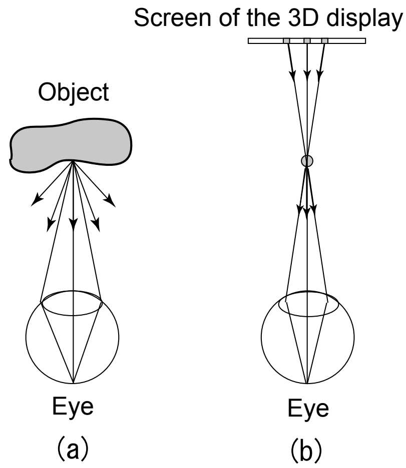


Figure 3. Schematic diagram of the stimulus of accommodation: (a) real world, (b) super multi-view.

The parallax image #i converges on the convergent point Ci. Pi and Qi denote pixels of the parallax image #i which correspond to virtual 3D points P and Q, respectively. In Figure 5(a), when the viewer adjusts the focal length of eyes to match with the spatial position P naturally then projected image of pixels P1, P2 and P3 are focused to same position on the retina. The viewer feels this image as the 3D point. On the other hand, when the viewer adjusts the focal length of eyes to match with the spatial position P then projected image of pixels Q1, Q2 and Q3 are focused to different positions on the retina. The viewer feels this image is blurred. Similarly, when the viewer adjusts the focal length of eyes to match with the spatial position Q naturally then projected image of pixels Q1, Q2 and Q3 are focused to same position on the retina, and projected image of pixels P1, P2 and P3 are focused to different positions on the retina as shown in Figure 5(b). Thus, the viewer feels that the image of Q is in focus and the image of P is out of focus. Therefore, the monocular 3D display is realized by the monocular parallax in an eye. Since the stimulus of accommodation of the human eye is naturally by the super multi-view technique, the proposed HMD displays the virtual image at the distance within the ability for focusing on the eye.

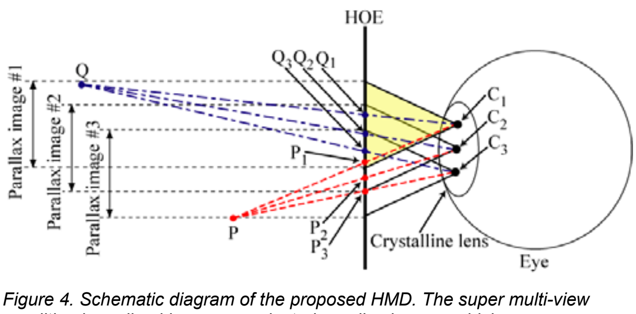


Figure 4. Schematic diagram of the proposed HMD. The super multi-view condition is realized by some projected parallax images which converge on the different positions on the pupil.

©2016 Society for Imaging Science and Technology
DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452

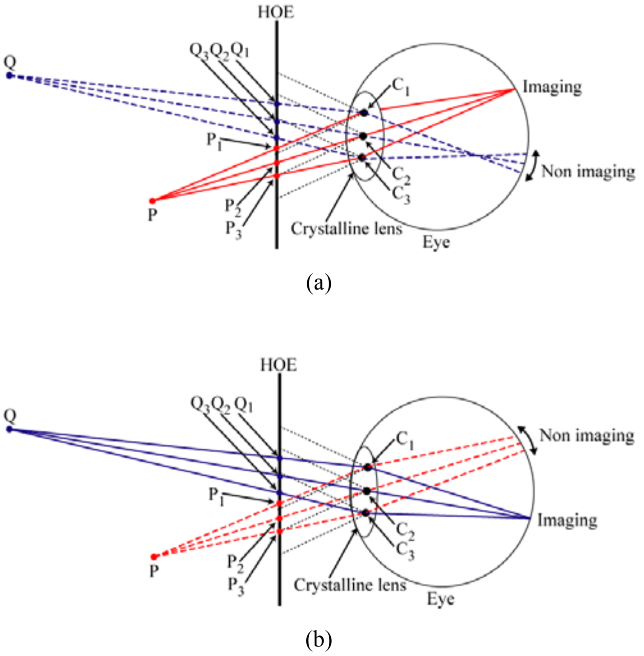


Figure 5. Principle of the monocular 3D HMD by using the super multi-view technique: (a) focusing on nearby point P, (b) focusing on far-off point Q.

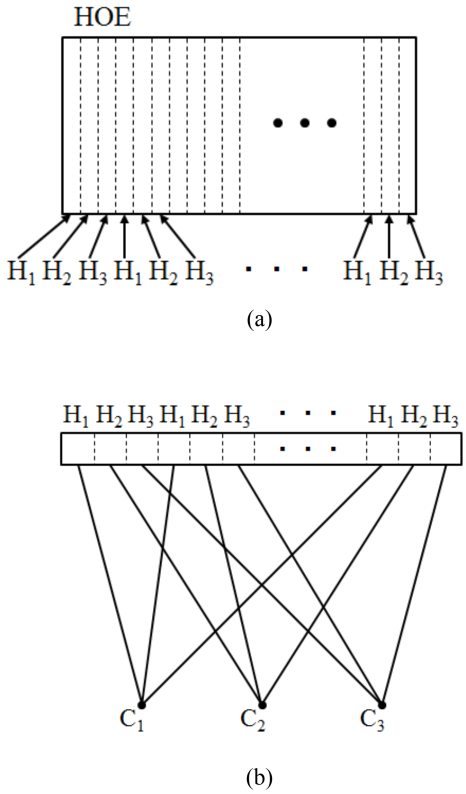


Figure 6. Structure of HOE: (a) side view, (b) top view. The whole HOE consists of thrgee types of HOEs, H_1, H_2 and H_3 that correspond to convergent points C_1, C_2 and C_3, respectively.

2.5 Previous HOE

In the previous HMD, the number of parallax images is three, thus the number of convergent points on the pupil is also three. Figure 6 shows the structure of the previous HOE. The whole HOE consists of three types of sub-HOEs, H_1, H_2 and H_3. Each sub-HOE, H_i, converges the corresponding projected parallax image on the convergent point C_i. The whole HOE is composed of stripe structured three types of HOEs as shown in Figure 6. However, since the previous HOE has complicated structured, it is difficult to improve the HOE to increase the number of rays which realize the super multi-view condition.

3. Improved Retinal Projection Type Super Multi-View HMD

In our previous HMD, we used a vertically-striped HOE lens array that is different for each vertical line of the parallax image as shown in Figure 8. However, since each sub-HOE lens width was narrow (about tens of micrometers), it was difficult to manufacture the lens array. In order to overcome this problem, we propose the new super multi-view HMD using a 2D microlens array (MLA) which is manufactured in a simple way. Like integral photography, the combination of parallax images and microlens array is used. As shown in Figure 7, each parallax image is converged on the pupil. Therefore, as shown in Figures 7 and 8, the super multi-view condition is realized like Figures 4 and 5. In this method, an HOE lens works as a simple 2D microlens array. If an HOE is a reflective HOE, a see-through type HMD is realized. The number of convergent points is equal to the number of combinations of parallax image and microlens. Additionally, with the improved HMD, a 2D microlens array and full parallax images are used. Thus, observed 3D images are full parallax 3D images.

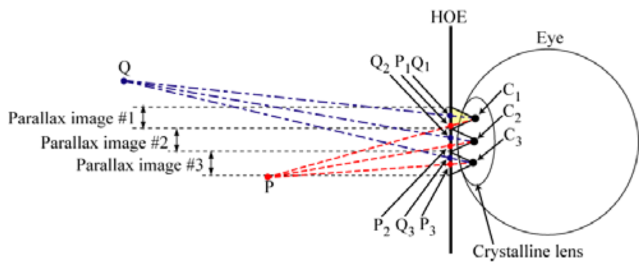


Figure 7. Schematic diagram of the proposed HMD with improved HOE lens array. The super multi-view condition is realized by some projected parallax images which converge on the different positions on the pupil.

©2016 Society for Imaging Science and Technology
DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452

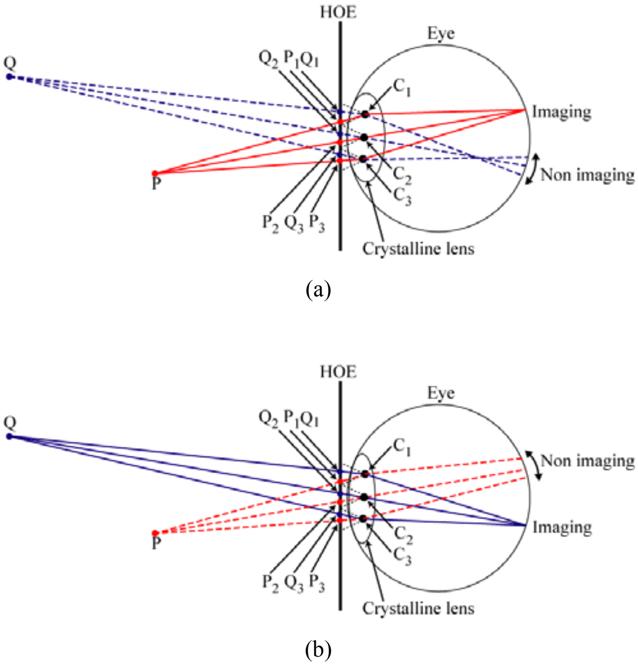


Figure 8. Principle of the monocular 3D HMD by using the super multi-view technique with improved HOE lens array: (a) focusing on nearby point P, (b) focusing on far-off point Q.

4 Experimental Results

In order to verify the effectiveness of the proposed improved HMD, we constructed the prototype HMD. The prototype HMD consists of the image projection optical system and HOE microlens array as shown in Figure 9. The projected parallax images and a microlens array makes multiple convergent points. With the prototype HOE, the number of holographic microlenses is 3 × 3, thus the number of convergent points is nine. For the sake of simplicity, we use the horizontal parallax only. Figure 10 shows the structure of the prototype HOE. The prototype HOE consists of 3 × 3 holographic microlenses. Each holographic microlens converges the corresponding projected parallax image on the convergent point C_i as shown in Figure 7. Figure 11(a) shows the prototype HOE, and Figure 11(b) shows convergent points of the prototype HOE. To verify the effectiveness of the proposed HMD by using camera, the distance between each convergence point was 6.67 mm. And also, the focal length and the size of each holographic microlens of the HOE were 11.1 mm and 20 mm × 20 mm, respectively. The number of projected parallax images is 3. Thus, since 3 light rays pass through the pupil of each eye, the condition of super multi-view is satisfied. To verify the displayed image, we set up the camera at the position of the convergent points, and captured observed images. Since the camera was used instead of the eye, we set the distance between HOE and convergent point to 11.1 mm. Figure 12 shows the schematic diagram of the experimental setup. We displayed virtual images at the distance 20 cm and 200 cm in front of the camera, and confirmed the accommodation. That is, L_1 is 20 cm and L_2 is 200 cm. Figure 13 shows one of the parallax images which was displayed by the prototype HMD. The position of the circular cone was set at 200 cm in front of the camera, and the position of the sphere was set at 20 cm in front of the camera. Figure 14(a) shows the case of focusing on far-off objects correctly and the circular cone image at the distance of 200 cm in front of the camera could be observed clear but the sphere image at 20 cm was blurred. On the other hand, Figure 14(b) shows the case of focusing on nearby objects. The sphere image at 20 cm could be observed clear but the circular cone image at 200 cm was blurred. Therefore, we found that the natural stimulus for the accommodation was produced by the proposed HMD.

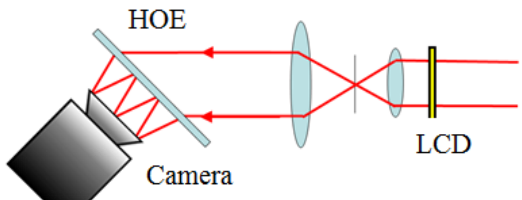


Figure 9. Prototype HMD.

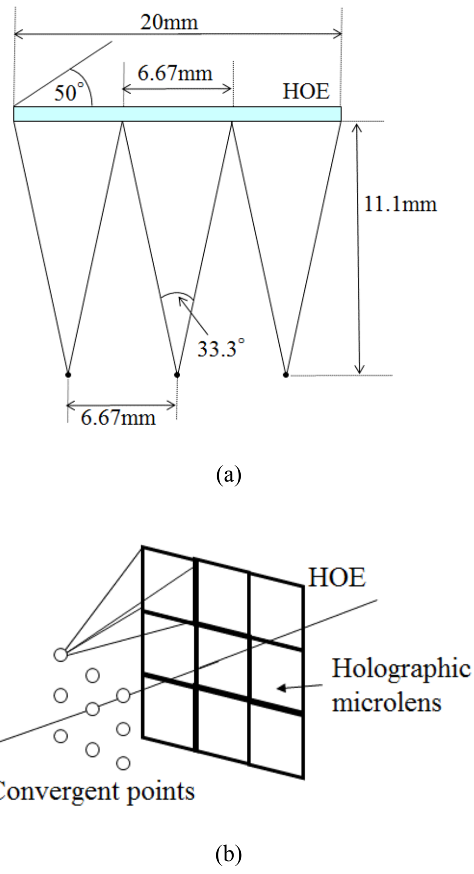
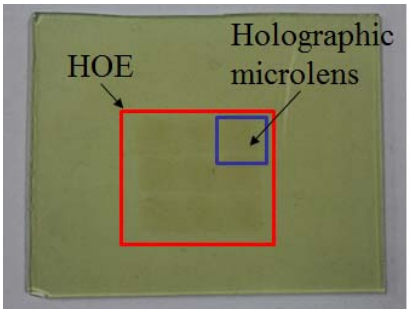
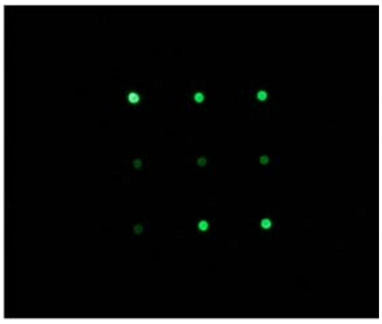


Figure 10. Structure of the prototype HOE.

DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452



(a)



(b)

Figure 11. Prototype HOE: (a) holographic microlens array, (b) convergent points.

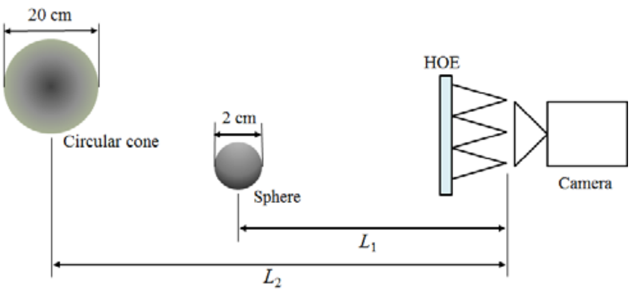


Figure 12. Schematic diagram of the experimental set up.

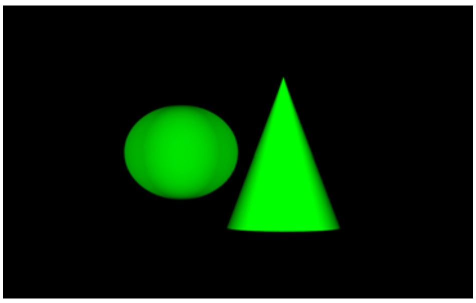
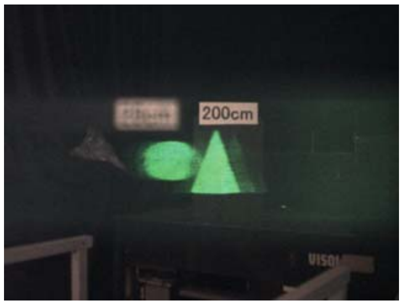
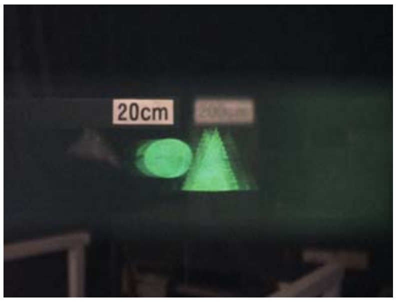


Figure 13. One of the original blur-free parallax images.



(a)



(b)

Figure 14. Observed images: (a) focusing on far-off object, (b) focusing on nearby object.

5 Conclusion

In conclusion, a retinal projection type super multi-view HMD using a holographic 2D microlens array was proposed. The HOE which is used the proposed HMD works as a 2D microlens array. Thus, its structure is simple and it is manufactured in a simple way. In the prototype system, since the number of projected parallax images is 1 × 3, the smooth motion parallax provided horizontally. The proposed HMD displays the virtual image at the distance within the ability for focusing on the eye. To verify the effectiveness of the proposed HMD, we displayed virtual images at the distance from 20 cm to 200 cm in front of the camera, and confirmed the accommodation. The proposed HMD enables a precise superposition of virtual 3D images on the real scene.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 15K00281.

References

[1] H. Tamura and Y. Ohta, Mixed Reality, Ohmsha, 1999.

[2] G. Burdea and P. Coiffet, Virtual Reality Technology, John Wiley & Sons, 1994.

[3] H. Takahashi, Y. Ito, S. Nakata, and Y. Yamada, "Retinal Projection Type Super Multi-View Head-Mounted Display," Proc. SPIE-IS&T Electronic Imaging, vol. 9012, pp. 90120L1-9012L6, 2014.

DOI: 10.2352/ISSN.2470-1173.2016.5.SDA-452

[4] Y. Kajiki, H. Yoshikawa, and T. Honda, "Ocular Accommodation by Super Multi-View Stereogram and 45-View Stereoscopic Display," Proc. IDW '96, vol. 2, pp. 489-492, 1996.

[5] G. Westheimer, "The Maxwellian View," Vision Res., vol. 6, pp. 669-682, 1966.

[6] H. Takahashi, S. Hirooka, "Stereoscopic See-Through Retinal Projection Head-Mounted Display," Proc. SPIE, vol. 6803, pp. 68031N1-68031N8, 2008.

[7] K. Takaichi and H. Takahashi, "Multi-Color See-Through Retinal Projection Head-Mounted Display," ICIC Express Letters, vol. 6, no. 5, pp. 1291-1296, 2012.

[8] Y. Ito, K. Takaichi, and H. Takahashi, "See-Through Retinal Projection Head-Mounted Display by using the Extended Maxwellian View," ICIC Express Letters, vol. 7, no. 6, pp. 1755-1760, 2013.

Author Biography

Yasuhiro Takatsuka received his BE in information engineering from Osaka City University (2014). Currently, he is a graduate student of Dept. of Electric and Information Engineering. His current research interests include retinal projection display and 3D display.

Kayo Yoshimoto received her BE and ME degrees in mechanical engineering from Osaka University in 2009 and 2011, respectively, and her PhD in medical and nursing engineering from Osaka University in 2014. Since then she has been a Research Associate of the Dept. of Electric and Information Engineering of Osaka City University. Her current research interests include medical engineering and nursing engineering.

Hideya Takahashi received his BE, his ME, and his Ph.D. in electrical engineering from Osaka City University in 1982, 1984, and 1992, respectively. From 1987, he is a faculty member at Osaka City University, and since 2011, he has been a Professor of the Dept. of Electric and Information Engineering. His current research interests include interactive 3D display, retinal projection display, and wearable computers. He is a member of SPIE and OSA