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Analysis of retinal images for retinal projection type super multi-view 3D head-mounted display

Takashi Emoto, Tadayuki Konda, Kayo Yoshimoto, and Hideya Takahashi
Dept. of Electrical and Information Engineering, Graduate School of Engineering, Osaka City University; Osaka, Osaka/Japan; hideya@elec.eng.osaka-cu.ac.jp

Abstract

In the augmented reality technology, what a viewer sees needs to be augmented by 3D information in accordance with the real object. Thus, we have previously proposed a retinal projection type super multi-view HMD which provides a viewer with natural 3D images. However, the proposed HMD has two problems. One is whether the blurred retinal image of the real 3D object is equal to the superimposed parallax images of the virtual 3D image. The other one is the restricted depth range of 3D images. When the parallax difference is large and corresponding pixels of parallax images do not overlap each other, we cannot use the superimposed parallax images instead of the blurred image. In this paper, we theoretically consider above problems and verify the effectiveness of the super multi-view HMD. By simulation the light intensity distributions of retinal images, we confirmed that the superimposed parallax images was equal to the blurred image. Moreover, from the range of the suitable parallax difference, we verified the depth range of the 3D image by the proposed HMD was more than 113 mm in front of the pupil.

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, a viewer 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, for a viewer it is hard to understand that it is related with a real-world object. What a viewer 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 a human eye is reproduced naturally by the super multi-view technique. Therefore, although the previously proposed HMD is a monocular HMD, it provides a viewer 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, the proposed HMD has two problems. One is whether the blurred retinal image of the real 3D object is equal to the superimposed parallax images of the virtual 3D image. The other one is the restricted depth range of 3D images. In the previous approach, when the gap between corresponding pixels of the retinal image is too large, we cannot use the superimposed parallax images instead of the blurred image. Then, a viewer cannot see the 3D image since stimulus of accommodation of an eye isn't produced. In the latter, if the proposed HMD cannot display the 3D image at the distance within the focus adjustment range of an eye, a viewer cannot see the 3D image. In order to consider theoretically above these problems and verify the effectiveness of the proposed HMD, we analyze the light intensity distribution of retinal images.

This paper describes the result of the analysis of the light intensity distribution of retinal images in order to verify the effectiveness and the depth range of the 3D image by the proposed retinal projection type super multi-view HMD. In Section 2, the principle of the proposed HMD is described. In Section 3, we describe the method which analyzes the light intensity distribution of retinal images projected by the proposed HMD. In Section 4, we describe the simulation result and verify the effectiveness of the proposed HMD. Finally, we give some conclusions in Section 5.

2. 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 analysis of the retinal images and verify the effectiveness of the super multi-view HMD, the previously proposed see-through retinal projection type 3D HMD are described here again.

2.1 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 1 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 a 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 seen. By using this principle for a retinal projection display, it can provide an extremely long focal depth image without causing ocular accommodation.

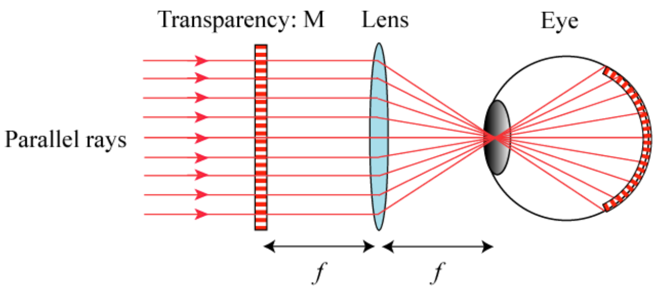

Figure 1. Principle of the Maxwellian view.

2.2 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 an eye, as shown in Figure 2(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 2(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 a human eye is reproduced naturally. Therefore, the retinal projection HMD provides a viewer with natural 3D virtual images so long as the super multi-view condition is satisfied.

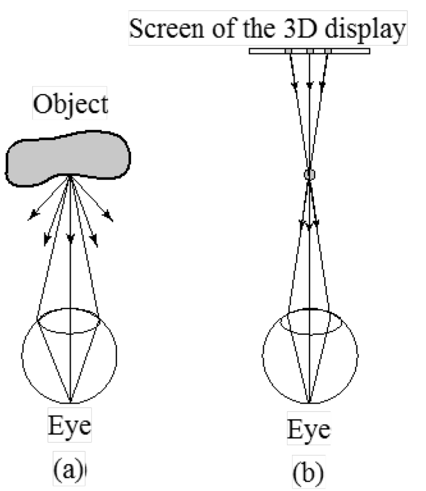

Figure 2. Schematic diagram of the stimulus of accommodation: (a) real world, (b) super multi-view.

2.3 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 3. For the sake of simplicity, here we limit the number of parallax images to three.

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 4(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 perceives 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 perceives this image as blurred. Similarly, when the viewer adjusts the focal length of eyes to match with the spatial position Q naturally, then the 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 4(b). Thus, the viewer perceives the image of Q as inside the focus and the image of P is out of focus. Therefore, the monocular 3D display is realized by the monocular parallax in an eye.

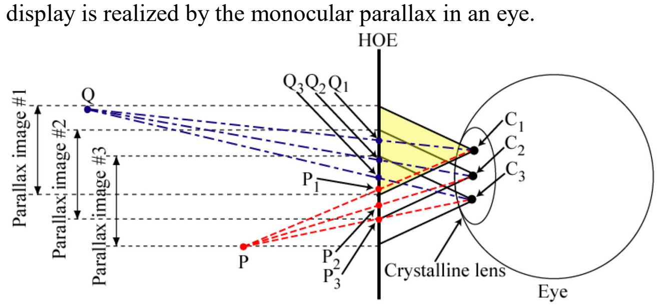

Figure 3. Schematic diagram of the proposed HMD. The super multi-view condition is realized by some projected parallax images which converge on the different positions on the pupil.

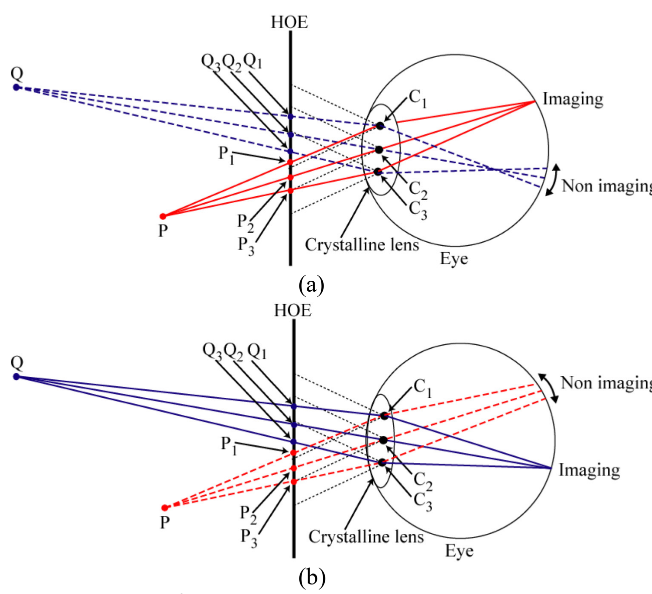

Figure 4. Principle of the monocular 3D HMD by using the super multi-view technique: (a) focusing on nearby point P, (b) focusing on far-off point Q.

3. Analysis of Retinal Image

3.1 Conditions for Recognizing Superimposed Corresponding Points of Parallax Images as a Blurred Point

In the proposed HMD, the super multi-view condition is realized by some parallax images which are projected on the retina. When a viewer focuses his eye on the displayed 3D image, he sees the in-focus image since multiple parallax images are superimposed at same position on the retina. On the other hand, when a viewer doesn't focus his eye on the 3D image, he sees the blurred image (out-of-focus image) since each parallax image is superimposed which is slightly displaced each other. Therefore, the stimulus for the accommodation of a human eye is produced naturally, and a viewer sees 3D images.

We consider a retinal image projected by the proposed HMD. For the sake of simplicity, we consider the superimposing to the case of two parallax images (parallax image #1 and #2). Figure 5 and Figure 6 show retinal images, when two virtual 3D points is displayed by the proposed HMD and a viewer focuses his eye on the left virtual 3D point. When the distance between left virtual 3D point and his eye is equal to the distance between right virtual 3D point and his eye, two parallax images of left virtual 3D point are superimposed completely on the retina, as shown in Figure 5(c). Similarly, two parallax images of right virtual 3D point are superimposed completely on the retina, as shown in Figure 5(c). When the distance between left virtual 3D point and his eye is different from the distance between right virtual 3D point and his eye, two parallax images of left virtual 3D point are superimposed completely but the images of right virtual 3D point are projected at different position on the retina, as shown in Figure 6. When the gap *d* between corresponding parallax images of the retinal image is small, the retinal image is recognized as a blurred point image. When *d* is large, the retinal image is recognized as two point images.

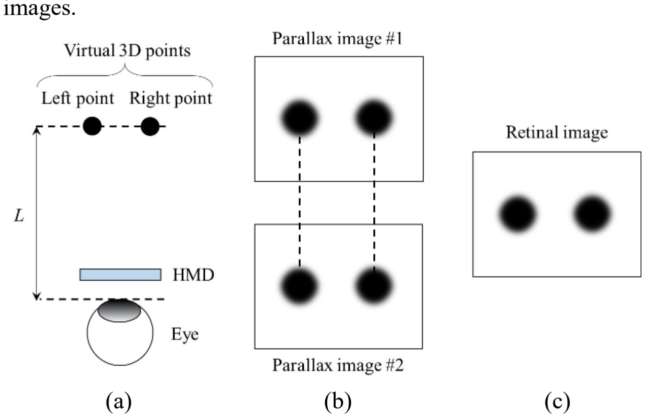

Figure 5. Retinal images when two points is displayed by the proposed HMD and a viewer focuses his eye on left point. The distance between two virtual 3D points and his eye is equal: (a) schematic diagram of the location of virtual 3D points, (b) parallax images projected onto the retina, and (c) retinal image.

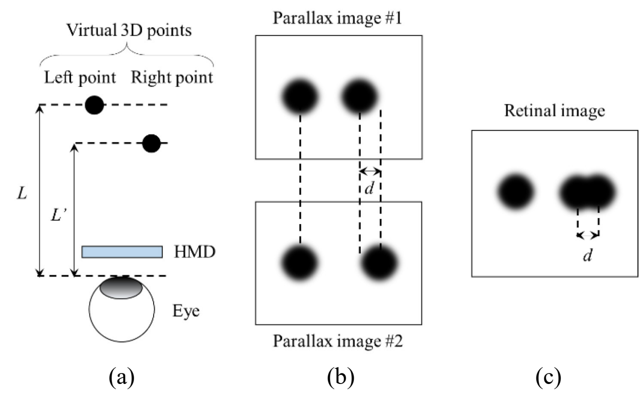

Figure 6. Retinal images when two points is displayed by the proposed HMD and a viewer focuses his eye on left point. The distance between two virtual 3D points and his eye is different: (a) schematic diagram of the location of virtual 3D points, (b) parallax images projected onto the retina, and (c) retinal image.

Figure 7 shows the light intensity distribution on the retina when two point images are projected onto the retina. A viewer sees an in-focus point image when *d* is equal to 0, as shown in Figure 7(a). A viewer sees an out-of-focus blurred point image when *d* is small, as shown in Figure 7(b). A viewer sees two different point images when *d* is large, as shown in Figure 7(c). In order to recognize the images of two points as a blurred point image, it is necessary that the crosstalk between the images of two points is greater than or equal to 50%. When the crosstalk is greater than or equal to 50%, the stimulus of accommodation of an eye is triggered.

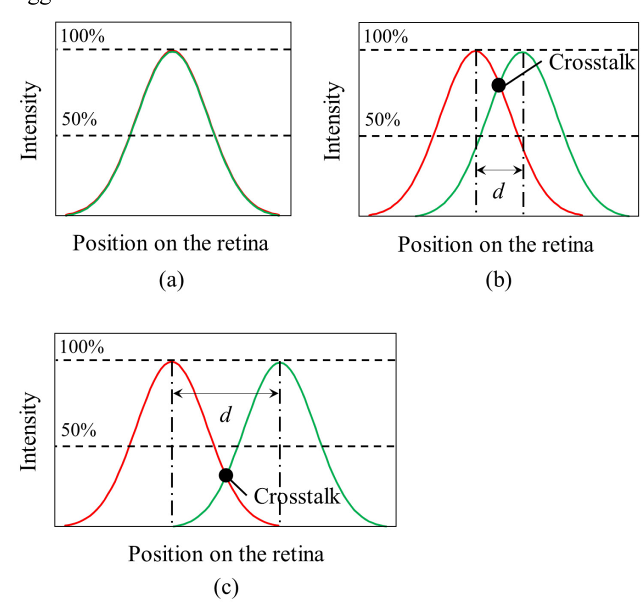

Figure 7. Schematic diagram of the light intensity distribution on the retina when two point images are projected onto the retina: (a) d is equal to 0, (b) d is small, and (c) d is large.

We describe the resolution of the retina as another evaluation of the light intensity distribution. Figure 8 shows the light intensity distributions on the retina when two point images are projected onto the retina. In Figure 8, the red curve and the green curve show the light intensity distributions of projected point images on the retina, and the black curve shows the sum of them. Let *Imax* be peak of the black curve and *Imin* be valley of the black curve, *Imin*/*Imax* is greater than 90% when retinal image is recognized as a blurred point image.

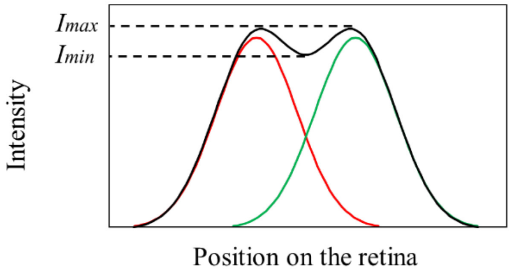

Figure 8. Light intensity distribution on the retina when two point images are projected onto the retina. The red curve and the green curve show the light intensity distribution of projected point images on the retina, and the black curve shows sum of them.

3.2 Amount of Position Gap between corresponding pixels of the retinal image

We estimate the amount of position gap between corresponding pixels of the retinal image by using Gellstrand's schematic eye model [9], as shown in Figure 9. Since the accommodation of an eye is effective in the depth from 25 cm to 2 m, we analyze the amount of position gap between corresponding pixels of the retinal image by the proposed HMD in the range of 25 cm to 2 m. Figure 10 shows the schematic diagram of the amount of position gap between corresponding pixels of the retinal image. The maximum amount of position gap between corresponding pixels of the retinal image is one of the following case (a) or (b).

(a) The amount of position gap between corresponding pixels of the retinal image w_1 of each ray on the retina emitted from the position of 25 cm when a viewer focuses on 2 m.

(b) The amount of position gap between corresponding pixels of the retinal image w_2 of each ray on the retina emitted from the position of 2 m when a viewer focuses on 25 cm.

Let's consider the number of convergent point is three and the interval between each of convergent points is 2 mm. As a result of analysis by using Gellstrand's schematic eye model, the amount of position gap between corresponding pixels of the retinal image w_1 is 133 µm in Figure 10(a), and the amount of position gap between corresponding pixels of the retinal image w_2 is 129 µm in Figure 10(b). Thus, we found the maximum amount of position gap between corresponding pixels of the retinal image is 133 µm.

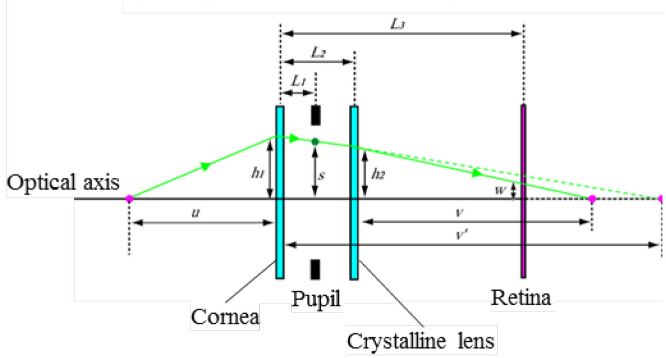

Figure 9. Gellstrand's schematic eye model.

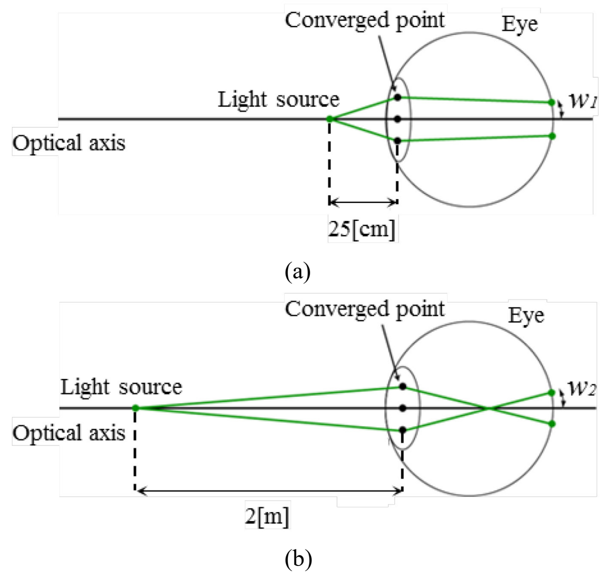

Figure 10. Schematic diagram of the amount of position gap between corresponding pixels of the retinal image: (a) a viewer focuses on infinity, (b) a viewer focuses on 25 cm.

3.3 Light Intensity Distribution of Retinal Image

Here, we consider the diffraction of retinal images. Figure 11 shows the schematic diagram of the proposed HMD. A light ray emitted from a pixel of the proposed HMD converges to the pupil. Since the proposed HMD is a super multi-view system, parallel light rays from three pixels pass through the pupil and are projected onto the retina. *P* is the width of a pixel, *g* is the distance between liquid crystal and lens of the proposed HMD, *f* is focal range, and *r* is distance between pupil and retina.

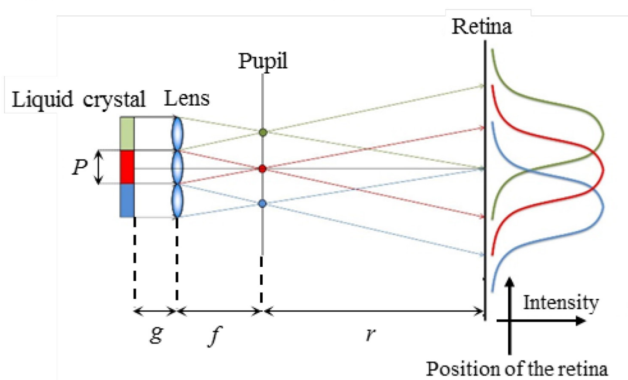

Figure 11. Schematic diagram of the proposed HMD.

From wave optics analysis, we analyzed the light intensity distribution of retinal images [10]. In the prototype HMD, *P* is 240 µm, *g* is 2 mm, *f* is 20 mm, and *r* is 24 mm. We calculated the light intensity distribution of rays from three adjacent convergent points, as shown in Figure 12. The horizontal axis shows the position on retina and the central fovea is located on 0 mm. The vertical axis shows normalized intensity. The amount of position gap between corresponding pixels of the retinal image is 133 µm that the maximum amount of position gap between corresponding pixels of the retinal image estimated in the Section 3.2. Since the crosstalk is over 50%, the retinal image is recognized as a blurred 3D image.

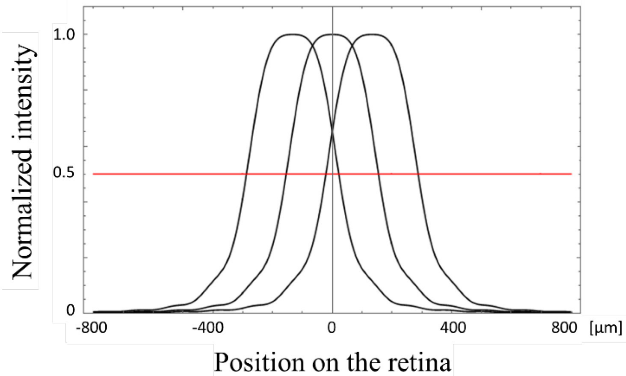

Figure 12. Light intensity distribution on the retina of rays from three adjacent converging points. The amount of position gap between corresponding pixels of the retinal image is 133 μm.

We calculated the light intensity distribution which three pixels are superimposed when the amount of position gap between corresponding pixels of the retinal image is 133 μm in the proposed HMD, as shown in Figure 13. Since the valley of the distribution isn't found, *Imin*/*Imax* is greater than 90%. Therefore, the retinal image is recognized as a blurred 3D image.

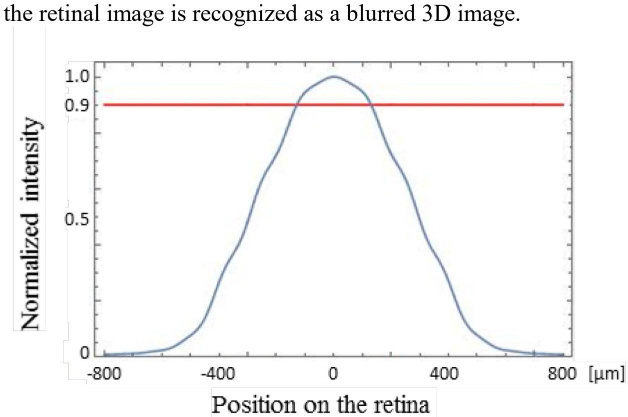

Figure 13. Light intensity distribution which three pixels are superimposed. The amount of position gap between corresponding pixels of the retinal image is 133 μm.

Next, we consider how much pixels can be shifted. We estimated the amount of position gap between corresponding pixels of the retinal image when the crosstalk is 50%. The light intensity distribution in this case is shown in Figure 14. It was confirmed that the amount of position gap between corresponding pixels of the retinal image is 310 μm. We also simulated the light intensity distribution which three pixels are superimposed when the amount of position gap between corresponding pixels of the retinal image is 310 μm, as shown in Figure 15. Since *Imin*/*Imax* is greater than 90%, the retinal image is recognized as a blurred 3D image.

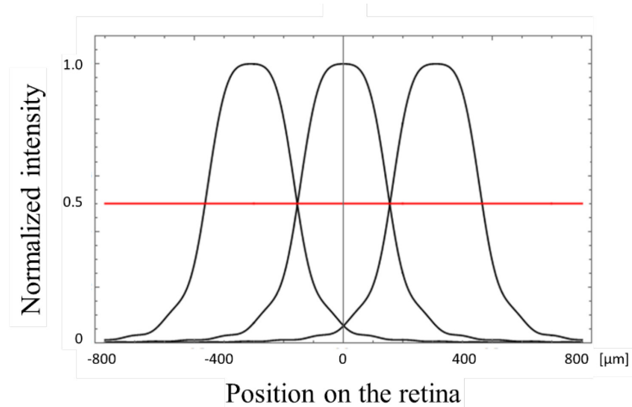

Figure 14. Light intensity distribution on the retina of rays from three adjacent converging points. The amount of position gap between corresponding pixels of the retinal image is 310 μm.

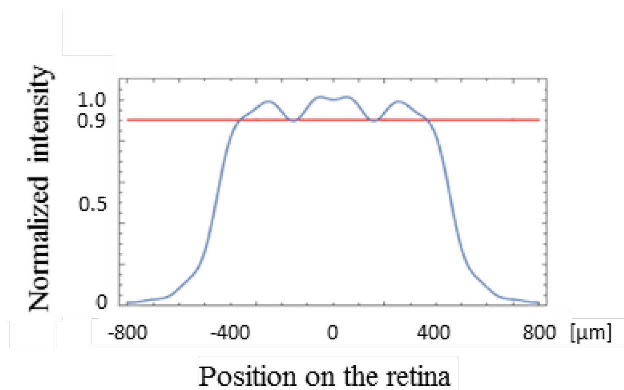

Figure 15. Light intensity distribution which three pixels are superimposed. The amount of position gap between corresponding pixels of the retinal image is 310 μm.

Next, we consider the depth range of the proposed HMD in which it can display a virtual 3D image when the amount of position gap between corresponding pixels of the retinal image is 310 μm. We estimated the depth between a virtual 3D image and an eye by Gellstrand's schematic eye model. As a result, the depth of a virtual 3D image between the nearest position and an eye was 113 mm and the depth of a virtual 3D image between the farthest position and an eye was infinity. Therefore, we verified the depth range of a virtual 3D image provided by the proposed HMD was from 113 mm to infinity in front of an eye. Thus, it was verified the proposed HMD can display the virtual 3D image at the distance within the focus adjustment range of an eye.

4 Conclusion

As a result of analysis, we confirmed that the superimposed parallax images was equal to a blurred image. Moreover, from the amount of position gap between corresponding pixels of the retinal image, we estimated the depth range of a virtual 3D image provided by the proposed HMD was more than 113 mm in front of pupil. Since the accommodation capability of a human eye is the range from 25 cm to 2 m, the proposed HMD displays the virtual image at the distance within the ability for focusing on an eye. We would like to produce the actually available retinal projection type super multi-view 3D HMD by using the proposed method in further research.

Acknowledgement

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Author Biography

Takashi Emoto received his BE in information engineering from Osaka City University in 2015. Currently, he is a graduate student of Dept. of Electrical and Information Engineering. His current research interests include retinal projection display and 3D display.

Tadayuki Konda received his BE in information engineering from Osaka City University in 2016. Currently, he is a graduate student of Dept. of Electrical 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.