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Evaluation of eye response using a wearable display with automatic interpupillary distance adjustment

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Abstract: In this study, we introduce a design for a near-eye, wearable display (HMD: head mounted display) that can automatically control the user's interpupillary distance (IPD). In addition, we demonstrate a test-bed module for the wearable AR display based on proposed design. Both the adjustment accuracy and the viewing effect through distance matching between the user's eyes are evaluated by the user's experience in actual wearing of the module. We demonstrate that the distance between the left and right eye pupils can be measured and adjusted using a set of IR camera sensors and a micro-actuator module that we proposed. A half-mirror unit to be mechanically controlled for each eye is designed to combine the image displayed from the projector and an image taken by the IR camera, leading to fine adjustment of the user's IPD. A set of images taken by the IR camera sensors is image-processed in real time to determine each pupil's position with high accuracy under infrared light illumination. Based on the measured information, a micro-actuator module we fabricated for the test bed can automatically adjust the binocular distance to fit each viewer's IPD. The maximum movement distance of each micro-actuator motor is ±10 mm with precision control of at least 0.5 mm. It takes about 18 seconds to calculate the user's IPD from two IR photographs and then to accurately adjust the actual binocular distance of the module that the participant wears. Using the demonstrated test bed, a total of 50 subjects participated to confirm the accuracy in the automatic IPD adjustment with an error of 0.25% as well as the improvement of the displayed image quality and 3D immersive experience.

1. Introduction

Head mounted displays (HMDs) recently have been garnering more attention and support in the AR/VR display market as display devices for the metaverse are becoming increasingly popular according to increased demand for metaverse content. They were mainly developed for gaming environments and military training, but recently their scope has been expanded to include medical diagnosis, education, and training [1–3]. With the trend of Augmented Reality (AR) technologies being applied to HMD devices, HMDs are being transformed from a heavy, inconvenient form to a lightweight form that allow the wearer to focus on watching realistic images with an immersive experience [3–6]. HMD displays can be divided into see-closed and see-through types. The see-closed type has the advantage of increasing the user's level of immersion in the viewing content because the user can only watch the content uploaded through the display in a limited manner, i.e. a completely isolated environment from the outside world.

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However, it has disadvantages such as the bulky physical size of the device and causing motion sickness. On the other hand, the see-through type allows users to simultaneously view the real world along with the content to be displayed. Night vision goggles are a representative example specialized for augmented reality [7]. Although the level of immersion in viewing content using the AR device is lower than that of the see-closed HMD, there are advantages such as user's operational safety in wearing the device and experiencing the augmented reality world.

In order for HMDs to be widely used by general customers, it is necessary to create a multi-user-customized HMD that is capable of automatically adapting the distance between the left and right eyes according to each user. The binocular distance of each person can be defined as the distance between the eye pupil centers [8]. However, most of the currently commercialized HMD devices are designed to be suitable only for users with an eye-to-eye distance of 65 mm. Because general users of the HMD device have various inter-pupillary distances (IPDs) with a range from 51mm to 77mm, inconsistency of 3D content (stereo images) viewed with both eyes causes inconvenience such as dizziness, nausea, vomiting, and eye fatigue. To solve this problem, conventional HMD models allow manual adjustment of the IPD using a knob or wheel [9–11]. There are three well-known methods of manual adjustment of the IPD using a knob or wheel. The first method is for the user to measure the IPD directly using a tape measure while looking at his or her face through a mirror. However, this passive method is not only inaccurate but also inconvenient [12]. Another method is to use the built-in camera of the user's mobile phone with special software [13]. This way uses the technique of eye-position tracking to find the viewer's observation direction on 3-D displays. For instance, the phone's built-in camera takes a picture of the user's face at a known distance to find the IPD distance through self-made tracking software. This way to use the built-in camera, however, is not an accurate method; because of the strong color similarity between the iris and pupil, it is difficult to identify eye positions in detection through the built-in camera. The third method is a measurement approach using reflected infrared pattern recognition [14]. This reflected light pattern changes as the inter-eye distance changes. Although technology with a measurement accuracy of up to 0.2 mm has been developed, the modules and algorithms that implement eye tracking technology are expensive.

In section 2 of this study, the concept and design of an integrated wearable display (HMD) device that can automatically measure and adjustment the IPD is explained. In section 3, the IPD measurement method using the fabricated test bed is explained. In addition, the accuracy of IPD detection and adjustment is experimentally verified through 50 subjects. In section 4, image sharpness, comfortability of observation, sensation of immersion, and perception of the 3-dimensional stereoscopic effect were evaluated by directly observing actual stereoscopic content according to IPD adjustment.

2. Conceptual design of an all-in-one head mounted display

A schematic diagram of the conceptual design of the see-through type, all-in-one HMD device proposed in this study is shown in Fig. 1. The integrated wearable AR display device consists of a micro-display for image projection, a micro-camera, and an infrared LED light to find the pupil center value of both eyes. The micro-camera and micro-display are respectively installed in the same direction, and the camera is mounted on the side of the projector. A micro-actuator motor moves to adjust the distance between the eyes.

The micro-display has a panel size of 6.7 mm × 9 mm (11 mm in diagonal), a resolution of 1280×720, and a 23° angle of view. The infrared LED (wavelength of 850 nm) is mounted on the side of the camera to avoid direct irradiation into each eye. The reason for using infrared illumination is to increase accuracy by obtaining higher reflectance from the iris. Increasing this reflectivity has the effect of increasing the contrast between the pupil and the surrounding iris, as shown in Fig. 2. Figure 2 presents a comparison of iris images taken with visible and infrared light illumination. As shown in Fig. 2, when comparing the boundary area between the pupil and

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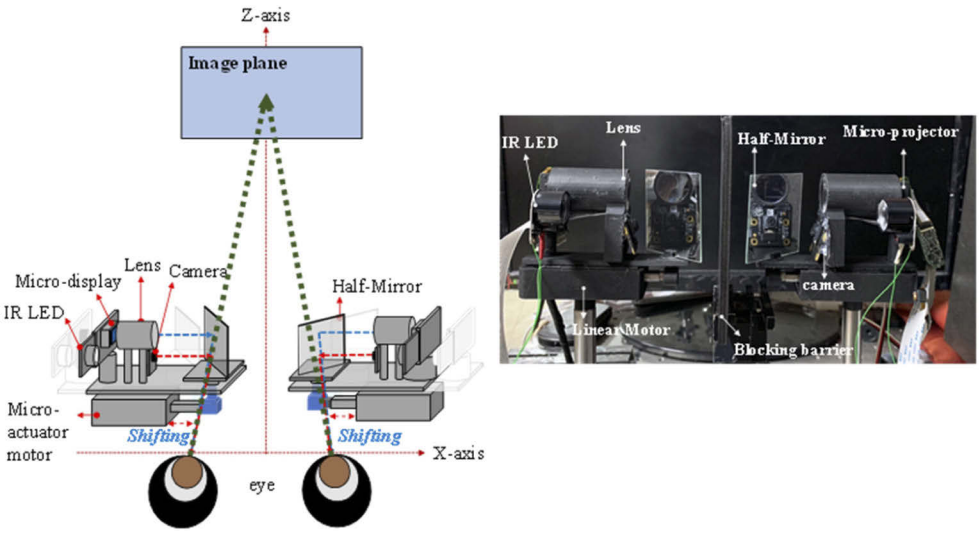

Fig. 1. The basic conceptual diagram and test bed production of the HMD that can adjust the distance between eyes.

the lens in the image using visible light, we can confirm that the boundary region between the pupil and the lens is more clearly distinguished in the image using infrared light.

Fig. 2. Comparison of iris images taken with visible light illumination (a) and infrared light illumination (b) for the same subject.

Figure 3 shows the geometric ray tracing of the image projection part of the HMD device. It is designed to display a virtual image projected from a distance of 500 mm from the eye. The size of the image is 400 mm × 300 mm (500 mm diagonal). The combined focal length of the lens is 22 mm. Since the panel is within the focal length, this lens creates a virtual image of 500 mm. The distance between the micro-display/micro-camera and the half-mirror is 40 mm, as shown in Fig. 3. As shown in Fig. 3, we designed the optical path and the lens unit using ZEMAX, a commercial optical design S/W. When designing this lens part, considering the miniaturization and thinness of the fabricated test-bed, the minimum length for focusing of this lens was derived to be 22 mm from the S/W tool. So, we chose this value as the focal length of the actual compound lens.

A half-mirror is placed at a distance of 12 mm from each pupil and the projector's image is focused on the pupil. The size of the light spot reaching the pupil is equal to 3 mm, which corresponds to the diameter of the pupil. Under room lighting conditions, the pupil diameter becomes larger than 3 mm. These components are combined as a set and loaded by a miniature actuator motor for automatic adjustment of the intraocular distance. The micro-actuator motor is fixed to the goggles frame so that the optical components frame section can move unobstructed.

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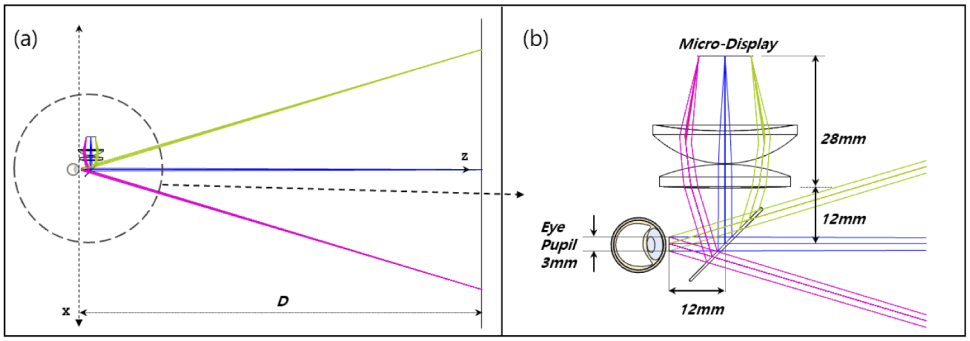

Fig. 3. Ray diagram of the image projection part of the HMD: (a) Overall optical path schematic, (b) magnification of lens part.

The compact actuator motor is a type of stepper motor with a size of 57.5 (L) × 29.9 (W) × 15 (H) mm and a distance resolution of 50 um. This compact actuator motor can travel up to 13 mm with a force of 40 N and a speed of 28 mm/s and can carry tens of kilograms. In order to move the center of each half mirror to match the monitored distance between the user's eyes, one plate (a moving stage) connected to the moving part of this actuator motor is moved (Fig. 1). The actual moving distance of this plate was set to be adjustable ±10 mm with a reference value of 65 mm. And, a value of 4 to 6 mm was considered as the average pupil size of a person [15]. During binocular spacing adjustment by this motor, it is important to provide a positional precision of less than 0.5 mm (less than about 10% of the average pupil size) while at the same time allowing it to move at a constant speed through a constant force (40 N). Otherwise, the process of adjusting the distance between the eyes may cause discomfort, dizziness, embarrassment, and the like to the user. This device, selected as the actuator motor in this study, has a small size, satisfies the above requirements, and is suitable for test bed demonstration. In order to maintain the shape of the projected image at the same location, it is necessary to rotate the half-mirror according to the eye distances of different users. When half of the user' IPD and the projected image distance are expressed by A and L as shown in Fig. 4, the diagonal angle of the half mirror (θ_E) is given by Eq. (1):

$$\theta_V = tan^{-1}\left(\frac{a}{l}\right) \tag{1}$$

$$\theta_E = \frac{\pi}{4} + \frac{\theta_V}{2}$$

Figure 4 is a schematic diagram showing the actually implemented geometric shape of the HMD and the arrangement of the user's eyes. Here, each eye is directed toward the center of the output image on the image plane. If the projected image distance is designed by $L = 500$ mm, when the user's IPD is measured as $A = 32.5$ mm, the angle of the half mirror (θ_E) is equal to 46.86°, which is calculated by output from the software we programmed on the basis of Eq. (1). This calculated value is the rotation adjustment in each half-mirror with 46.86° and it leads the eye-to-eye distance on the HMD module to be 65 mm. If ±10 mm is adjusted from the average binocular distance (65 mm), the range of θ_E becomes between 46.5° and 47.15°. That is, when A is 37.5 mm and 27.5 mm, the rotation angle in each half-mirror becomes 0.36° and 0.29°, respectively. Because these angle values are too small for accurate mechanical operation, this angle adjustment method requires precise angle control techniques for fine adjustment.

Therefore, as an alternative approach, we proposed a novel method where the center of the projected image directly moves in parallel on the image plane with the movement of the user's eyes. For a demonstration in the study, the projected image was located at $L = 500$ mm from the user in wearing the test bed. The convergence angle (θ_E) between both eyes is then supposed

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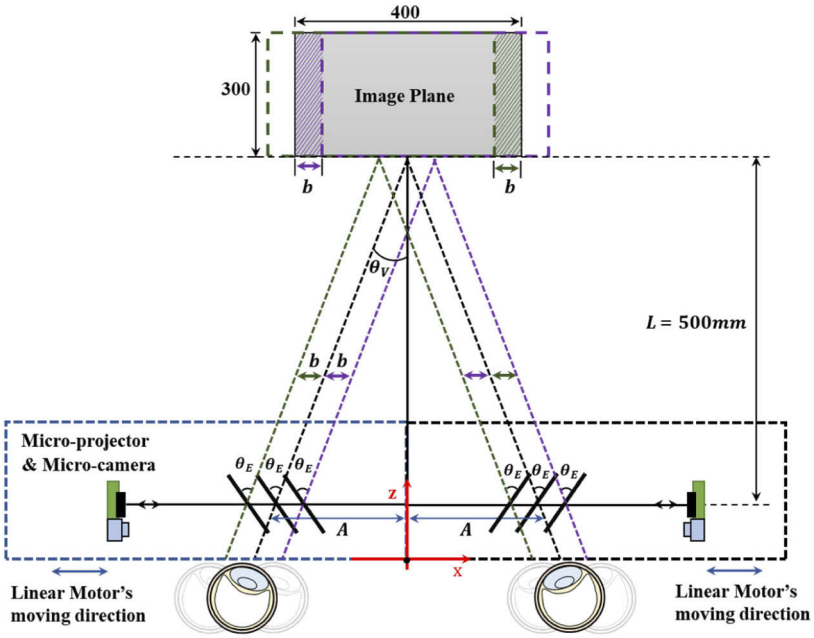

Fig. 4. Geometry of the proposed HMD architecture.

to be unchanged regardless of each half mirror's movement if IPD is constant. In addition, the size of the image projected on the image plane must be changed in response to the variation of the distance between the pupils. Therefore, in the case of $A = 37.5$ mm ($A = 27.5$ mm), it is necessary for each half mirror to move 5 mm away from (5 mm towards) the coordinate origin. As a result, the movement of the half mirror causes an effect in which the width of 5 mm of the original projected image is cut off from both the left and right image, respectively. However, this loss is very small compared to the full image size (400×300 mm); the blocked size totaling 10 mm corresponds to a loss of 2.5% in the full image, and thus the loss becomes almost negligible. The values of $A = 37.5$ mm and $A = 27.5$ mm correspond to inter-ocular distances of 75 mm and 55 mm, respectively. This range of eye-to-eye distance was considered when we designed the geometric size of the HMD device illustrated in Fig. 1. Therefore, we embodied the information so that each micro-actuator motor can travel at least 10 mm. The total weight of the HMD device that we fabricated, including two micro-actuator motors, is less than 400 g, much lighter than most AR devices that are commercially available.

3. Method to measure and adjust the inter-pupillary distance (IPD) for HMD

The information required to measure the distance between the eyes is as follows: convergence angle (θ), the pupil center change amount (Δ_x), and the gazed distance (L). The pupil center change amount (Δ_x) is defined as the horizontal movement amount of the pupil center position compared to the visual axis when the gaze object is gazed upon. The gazed distance (L) is the distance from the center of the eye-to-eye distance to the gazed object. Through the functions of accommodation and convergence, a person can sense the distance and three-dimensional effect of a gazed object. The eyeball is rotated in the sagittal plane around the center of the eyeball by the six muscles around the eye [16]. Figure 5 is a conceptual diagram showing the correlation between the gaze distance (L) and the rotation angle (θ) of the eyeball. The inter-pupillary

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distance (IPD) can be defined by Eq. (2):

$$\begin{aligned} \mathrm{IPD} &= \frac{\overline{P_1'P_1} \cdot \overline{P_2'P_2}(L_2 - L_1)}{L_2 \cdot \overline{P_1'P_1} - L_1 \cdot \overline{P_2'P_2}} \\ &= \frac{2(L_2 - L_1)}{[\tan(\theta_2) - \tan(\theta_1)]} \end{aligned} \tag{2}$$

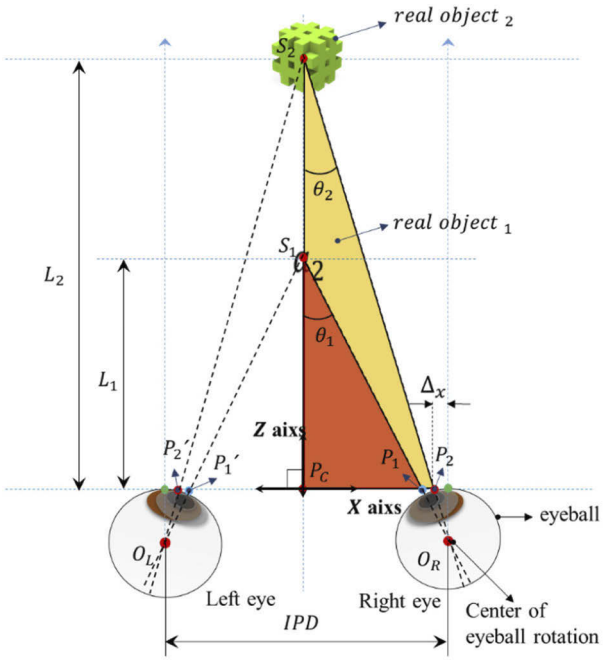

Fig. 5. Schematic diagram of the correlation of eye rotation angle according to the gazed distance.

Considerations related to binocular distance measurement are as follows: First, when the distance of the gazed object is infinitely far, the visual axes of both eyes are parallel to each other. Next, when the gazed object is placed at a finite distance, as each eye rotates, the binocular convergence angle (θ) is determined corresponding to the distance (L) of the gaze object. In order to make an all-in-one HMD device suitable for the general public with different binocular distances, an automatic IPD control method based on accurate inter-eye distance measurement should be devised. In order to acquire clearly separated images of the pupil and iris, images must be captured at a very close distance in consideration of the camera's field of view. However, it is difficult to install cameras and light sources around them. It is difficult to find a space to install while avoiding interfering with image acquisition of these components. However, it is relatively easy to install a camera on a see-through type HMD device because the image is projected on the eye from the side, as shown in Fig. 1. In order to obtain an image that can be clearly distinguished between the pupil and the iris, it is appropriate to acquire an image by IR light illumination, as mentioned in the introduction (see Fig. 2). Considering the angle of view of the IR camera, it is possible to obtain a clearer image by taking pictures at a very close distance (for example, 5.5 cm) from the eye. However, it is not easy to install the IR light source and its camera around the user's eyes because of the spatial limitation according to the physical size occupied by these elements installed onto the HMDs in general. In this study, to solve these problems, we devised

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an approach to select a goggle-type HMD device that projects an image from the side into the eye, as shown in Fig. 1, and to install IR camera sets suitable for this device. A Raspberry Pi camera (v.2 board) with a resolution of 3280×2464 and a pixel size of 1.12 μm [17] was used for this demonstration. Also, considering the position where the half-mirror exists, each camera is located about 55 mm from each eye pupil. Although the camera's field of view is more than 62°, the camera can very sharp photographs of the pupil, as shown in Fig. 2 (b). To set the initialization condition for this experiment, the camera for each eye is aligned so that the pupil center of the subject is located near the center of the image captured by the camera. To achieve the aforementioned alignment, the images captured by each camera are displayed on each monitor in real time. As shown in Fig. 6, while checking the monitor, the position and orientation of each camera mounted within the HMD module worn on the participant's face were adjusted. To facilitate this initialization process, we added a guide line that was displayed on the monitor to help the IR camera aligned, and used a head band by which the user's swaying head can be firmly fixed on the HMD device. These subsidiary tools were allowed to establish the initial condition that accurately monitors the position of the pupil.

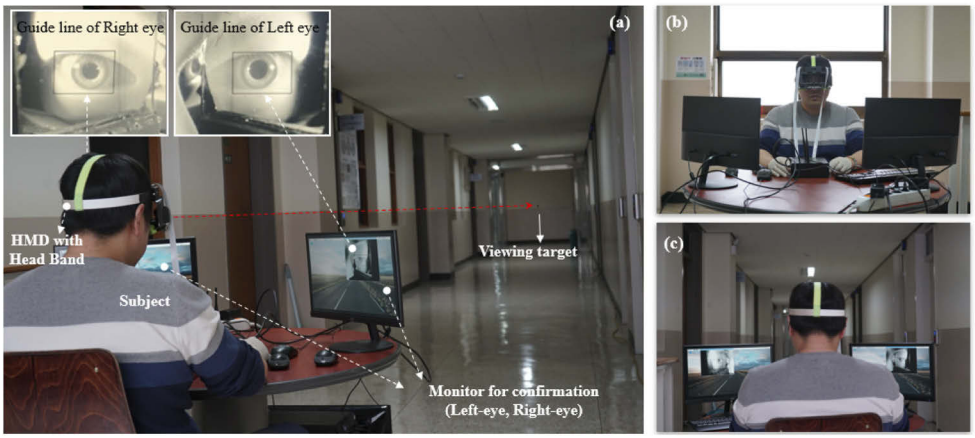

Fig. 6. Initialization set-up for each IR camera mounted within the HMD module; (a) perspective view, (b) front view, (c) rear view.

The left and right pupil images from IR cameras are prepared so that they are located at the same height through the two monitors. Figure 7 shows the images of both eyes of the user looking at an object at an infinite distance. In order to obtain IR images, a see-through typed test bed for the HMD was fabricated, as shown in Fig. 8.

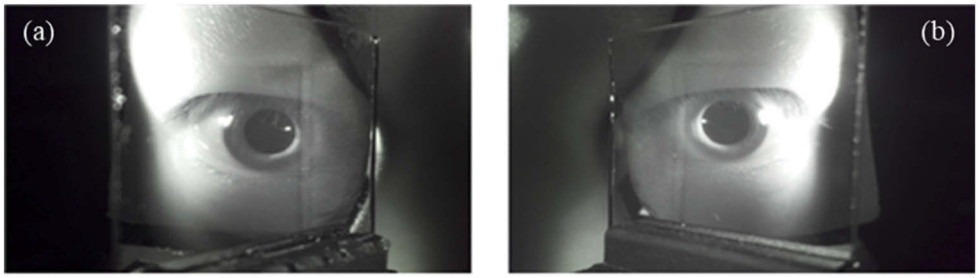

Fig. 7. Images of the left eye (b) and right eye (a), which are taken by the IR cameras, respectively.

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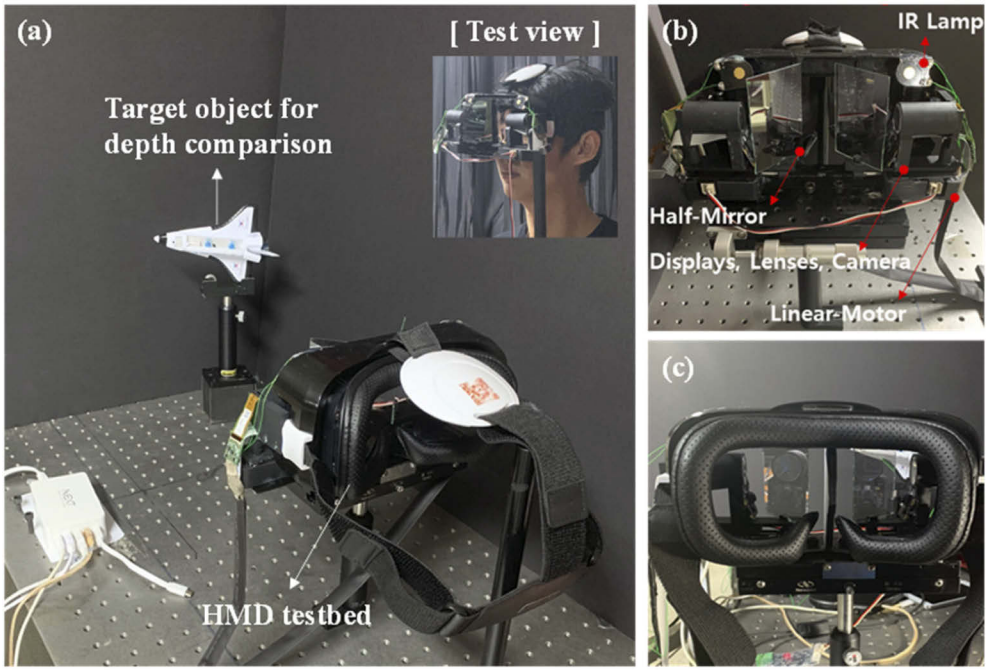

Fig. 8. HMD display test bed which can adjust the distance between the user 's eyes; (a) perspective view, (b) front view, (c) rear view.

In the IR image acquisition process, we found that the IR image's size of 1mm corresponds to 50.46 pixels on the basis of the actual scaling measurements. From the identified reference of 50.46 pixel/mm, the IPD can be estimated through the following steps: First, each image of both eyes is photographed with each IR camera under IR illumination. Second, through the process of identifying the captured binocular images, the center position of each pupil is confirmed. Third, in order to determine the participant's IPD, it is necessary to calculate the distance value in pixels between the left and right pupils of the subject, using the average IPD value (65 mm) as a reference value. Here, the reference value of 65 mm between the two pupils corresponds to 3280 pixels. We therefore obtain the difference value in pixels by subtracting the calculated distance in pixels from the reference value (3280 pixels). Then, when this difference value is divided by 50.46, the difference between the distance between the eyes of the subject and the reference value of 65 mm is derived with units of millimeters. The calculated value is added or subtracted from the initially set binocular distance of 65 mm through the proposed algorithm to derive the value to be adjusted. Finally, based on the adjustment value, the distance between both eyes is adjusted through the actuator motor.

An algorithm was built using Open CV to perform the overall process described above. Open CV is an open library that helps computer vision related programs. In particular, various functions support the functions of image processing, 3D construction, tracking, machine learning, recognition, and deep learning [18]. Figure 9 shows the proposed overall inter-eye distance measurement algorithm and flowchart.

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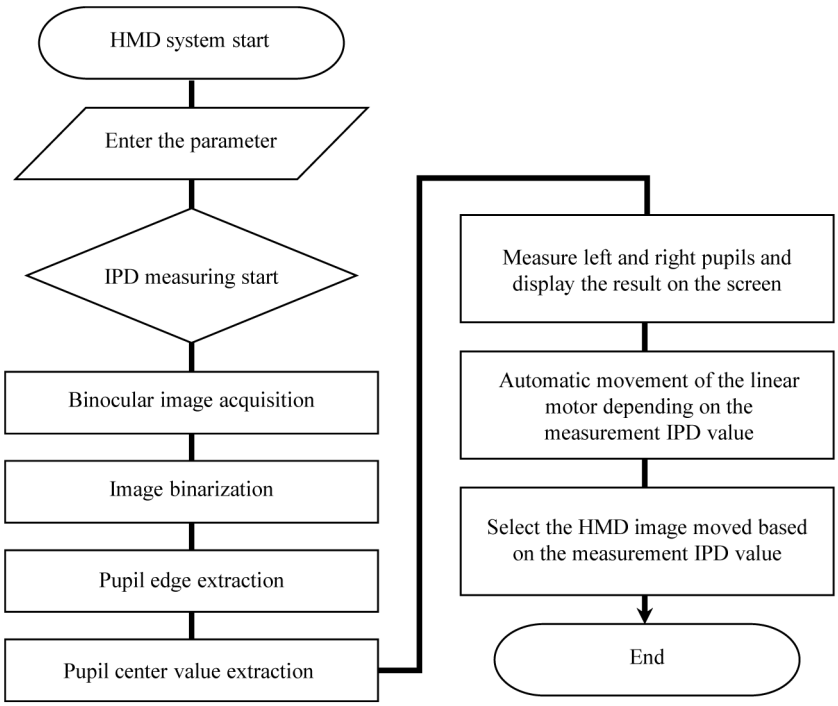

Fig. 9. Flow diagram of the algorithm for our proposed IPD measurement process.

4. Evaluation of eye response according to IPD distance measurement technique

In this study, the distance between the two eyes of the HMD device was measured for 50 subjects. The full range of the measured IPD is between 54 mm and 69 mm. By using the fabricated test bed for the see-through typed HMD, accuracy and reliability tests are carried out by measuring the IPDs with various subjects. For an objective evaluation, 50 people were selected for this experiment, with the viewing target set to 25 m, as indicated in Fig. 6 (a). The subjects consist of males and females in their twenties with corrected visual acuity of 1.0 or higher. From the binocular images (see Fig. 7) obtained through IR cameras, the position of each pupil is detected so that the center position value of the pupil is extracted to measure the distance between the eyes. Hough Circle Transform function, Sobel edge, and Canny edge detection functions were used as centroid value extraction algorithms. The Hough Circle Transform function is used to define the center and diameter of the pupil under the assumption that the pupil has a perfect circle shape, and the Sobel edge and Canny edge detection function were used to separate the pupil's profile from the iris [19–21]. As we show in Code 1, Ref. [22], the entire algorithm was created using the OpenCV function. Figure 10 shows the original IR images (3280✕2464) obtained from the subject, and the pupil detection results (green circle), and the center value extraction results (red script).

Infrared images of both eyes are automatically obtained by the values of the minimum distance from the center of the detected circle (miniDist), the parameters of the Canny edge detector (param1), the minimum radius of the circle (minRadius), and the maximum radius of the circle (maxRadius). In most cases of the subjects who participated in the measurement experiment, pupil detection and central value extraction were performed automatically in the binocular infrared images. However, it may be difficult to analyze the IR captured image when the captured

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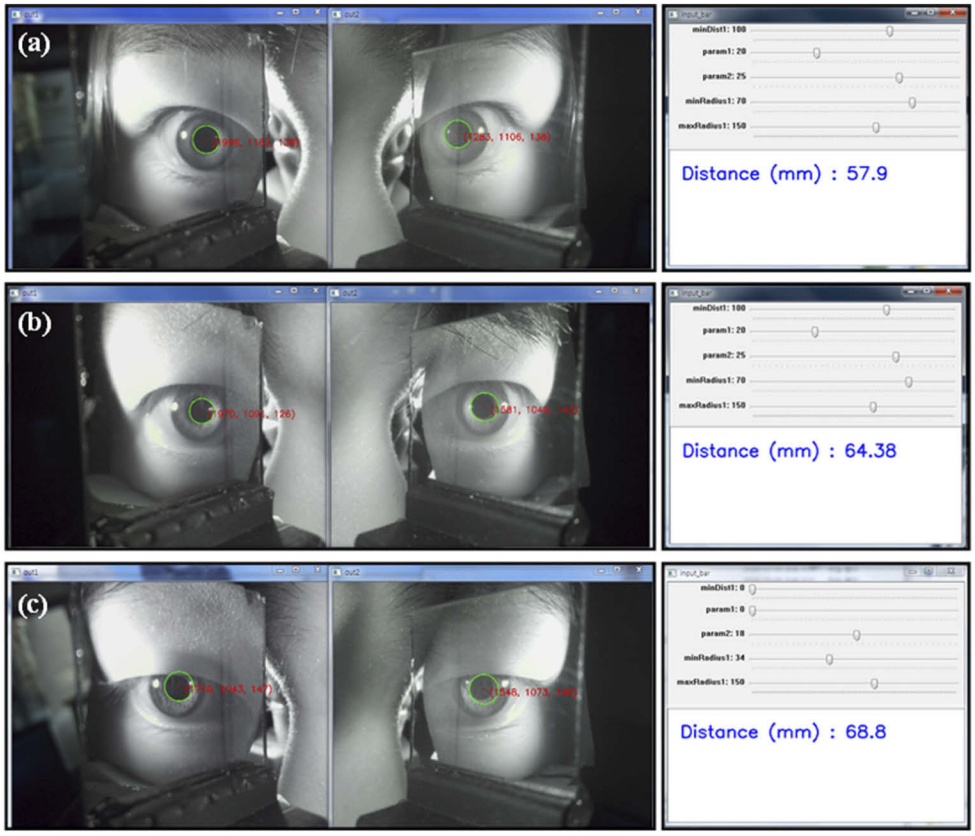

Fig. 10. Results of pupil position location detection and IPD measurement from 3 different persons; (a) result with IPD = 57.9 mm, (b) result with IPD = 64.38 mm, and (c) result with IPD = 68.8 mm (see Visualization 1, Visualization 2, Visualization 3, Visualization 4 and Visualization 5).

IR image is blurred or when the shadows around the eyes are weighted due to the influence of lighting. In this case, each extraction parameter is adjusted to perform pupil detection and centroid value extraction. Figure 11 shows the results of pupil size measurement of the subject's left and right eyes, respectively. As a result of the measurement test, the pupil size measured from the proposed algorithm was from a minimum of 9.51 mm to a maximum of 17.74 mm.

The difference in pupil size between the left and right eyes of the participant depends on the amount of light incident on the pupil. This difference of size of pupil may vary from person to person and may depend on the distribution of muscles in the iris because each individual's left and right eyes are different [23]. Figure 12 shows that the distance between the participant's eyes was from 54.06 mm (minimum) to 68.74 mm (maximum) according to the calculation through the SW we developed for automatic IPD measurement. The experiment result shown in Fig. 12 indicates that the error of the automatic IPD calculation of the HMD module that the participant wears is 0.25% in comparison with the same subject's IPD measurement directly measured with a manual ruler. The result confirms that the test bed we proposed can automatically measure and adjust the IPD with very high precision. This also means that the proposed algorithm accurately extracts not only the IPD value but also the location information of each pupil. In addition, from the experimental result of measuring the distance between the subject's eyes, we found that 10 participants (20%) had the IPD in the range from 64 mm to 66 mm, 36 participants (72%) had

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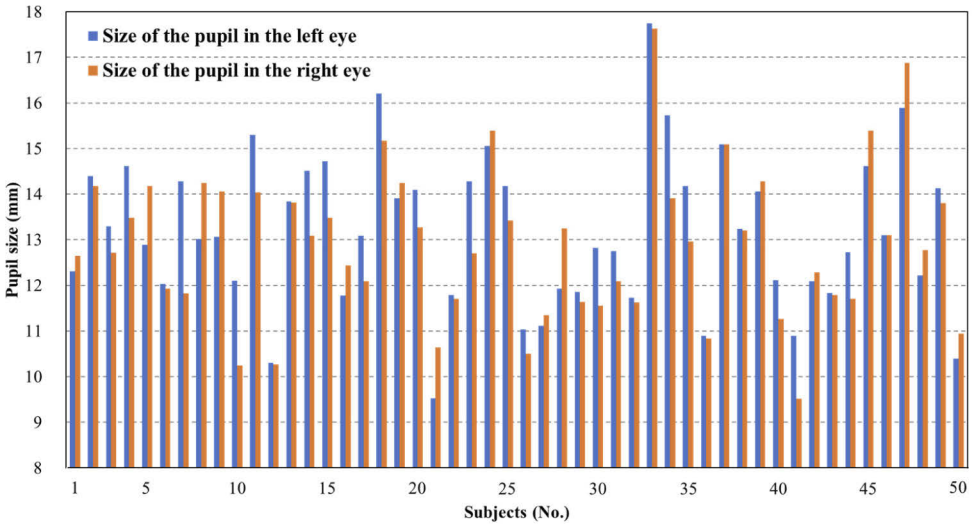

Fig. 11. Results of measuring the pupil size of the subject's left and right eyes from the proposed test bed.

the range less than 64 mm or less. Also, 4 participants (8%) had the range of greater than 66 mm. It takes about 18 seconds from wearing the wearable display module to adjusting the eye-to-eye distance. This test bed enables quicks and accurate IPD measurement for a short period of time (18 sec) and makes a user-customized wearable display with accurate actuator movement.

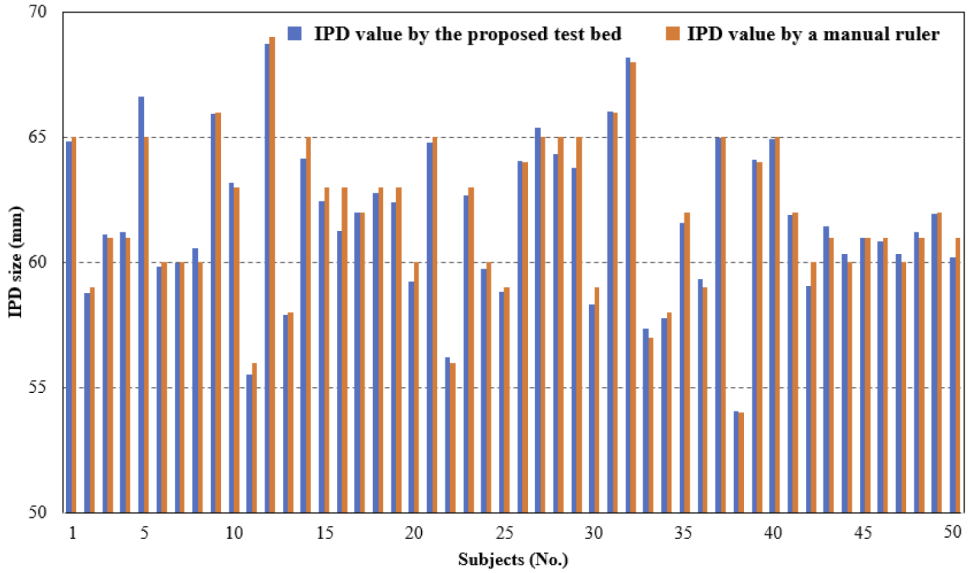

Fig. 12. Comparison of the calculated results of each user's inter-eye distance from the proposed test bed with the manually measured results.

Among 50 subjects, further experiment to evaluate the effect from IPD control was performed by choosing 40 participants within the IPD's movement range operated by the test bed, except people with the IPD between 64 mm and 66 mm. Figure 13-(d), 13-(e), and 13-(f) show the

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projected images, each captured by the DSLR camera monitoring these actual images, while original contents in Fig. 13-(a), 13-(b), and 13-(c) were used as input data to be uploaded onto the proposed HMD's panel.

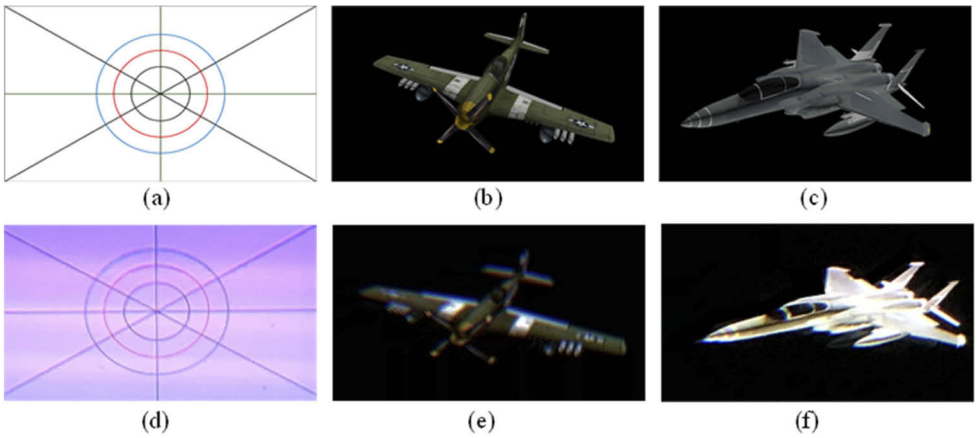

Fig. 13. Examples of original content: (a), (b), and (c) are used as input data to be uploaded onto the proposed HMD's panel. After uploading them onto the proposed HMD's panel, (d), (e), and (f) are camera-captured, real projected images which are gazed by the HMD's user, respectively.

Each participant evaluated the projected image quality in watching each uploaded content of the initial HMD's condition, i.e. the situation before IPD adjustment and then in watching the same content after IPD adjustment, respectively. As shown in Table 1, three kinds of categories were used to test the quality of these projected images: 1) image sharpness improvement, 2)

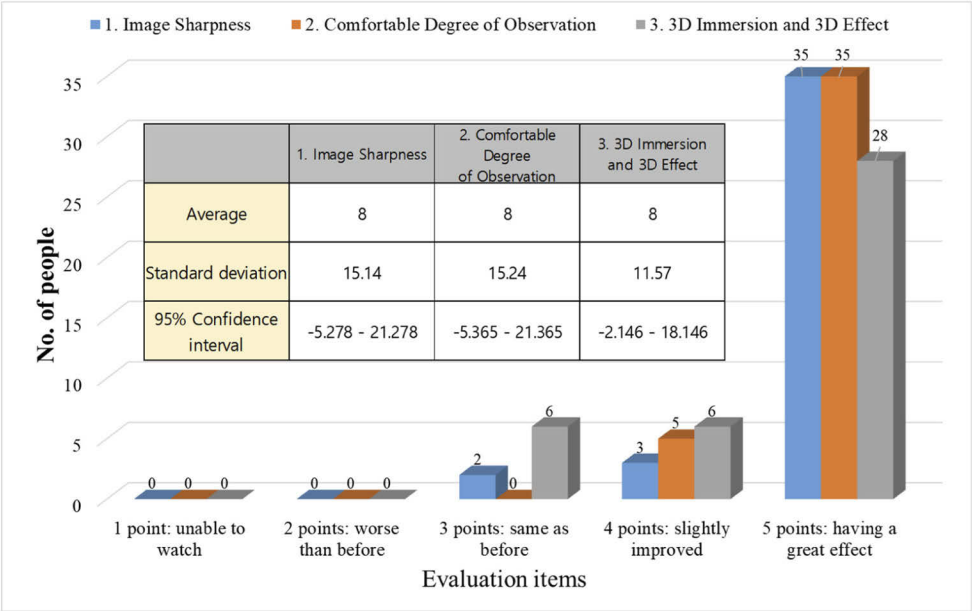

Fig. 14. Evaluation result of displayed image quality before and after IPD adjustment on the test bed.

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comfortable degree of image observation, and 3) 3D immersion and 3D effect. Each category was scored on a scale of 1 to 5 by the participants wearing the HMD device, according to the evaluation score as indicated in Table 1.

Figure 14 shows that 87.5% among the subjects (35 of 40) gave both category I and category II the score of 5 points. This result indicates that the IPD adjustment on the HMD module which we designed had a significant influence in improving both displayed image clearness and comfortability when watching the HMD's content. In addition, we found that the user's precise IPD adjustment in wearing the HMD device is a critical factor to determine 3D immersive experience in the wearable AR display, as shown in the Fig. 14.

5. Conclusion

In this study, we present a wearable AR display (HMD) with a user-customized IPD control module that can automatically match the viewer's binocular distance. Based on the proposed design, a see-through HMD was demonstrated as a test bed. For this purpose, we fabricated a set of IR camera sensors and micro-actuator modules, that can measure and adjust the binocular distance, respectively. The viewer's pupils were clearly photographed and well defined using the IR cameras under infrared illumination. The movement precision of 0.5 mm for IPD modulation was experimentally verified using the micro-actuator motors. Accurate IPD calculations from binocular IR images through an algorithm we programmed were performed and visualized. Using the demonstrated test bed, a total of 50 subjects participated to evaluate the precise operation of eye-to-eye distance adjustment on the test bed. Automatic IPD adjustment accuracy was confirmed within 0.25% of error compared to the direct measurement of each subject's IPD. In addition, it was experimentally confirmed that both clearness and comfort degree in viewing the projected image including 3D immersion of the gazed image were improved, as the user's IPD was automatically adjusted in the HMD we proposed.

The accuracy of binocular distance measurement is affected by the actual user's improper HMD wearing, the user's face (head) contour shape, and lighting conditions. First, in terms of S/W, it is to secure a database in various environments and user conditions for deep learning-based training to minimize the measurement error. By applying the user-customized IPD's prediction AI model implemented through this database into the proposed HMD system, it will be possible to contribute to improving the accuracy performance of binocular distance measurement in the near future. Furthermore, in terms of H/W, in fabrication of the mechanism for fixing the main components, it is necessary to replace it with a kind of materials with light weight and strong characteristics. In addition, it is necessary to improve the accuracy of the measurement value due to the use of a high-resolution micro-display having a smaller pixel size. Finally, if an auxiliary device that can minimize head shake is added, it will be possible to improve accuracy and minimize measurement errors.

For future work, it is necessary to develop technologies for correcting optical aberration and image distortion issues of wearable AR displays, which were not considered in the study. Further studies are also needed to reduce the weight of the optical components and improve the physical comfortability when wearing the HMD devices. In applying the proposed HMD with user-customized IPD function for the metaverse commercialization, the development of wireless communication capable of transmitting large-capacity, high-quality content will support the device to display realistic 3D images in real-time in the near future.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but maybe obtained from the authors upon reasonable request.

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