Implementation of EOG-based Gaze Estimation in HMD with Head-tracker

Hiromu Miyashita, Masaki Hayashi, Ken-ichi Okada
Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan
miyashita,hayamasa,okada@mos.ics.keio.ac.jp

Abstract

Head-mounted displays (HMDs) are effective devices for creating immersive virtual environments. Intuitive movement field-of view (FOV) is possible in virtual reality (VR) space with a HMD equipped with a head-tracker. However, gaze targets are not accurately detectable by the measurement of head movements alone. An eye-tracker is needed to determine gaze positions; however, such trackers currently negatively influence the experience of immersion in VR.

In this study, EOG-based gaze estimation was implemented by mounting EOG equipment on a HMD equipped with a head-tracker. This method of gaze estimation ensured that the HMD screen was not hindered and head movements were possible. Disk electrodes attached to swimming goggles and a gyro-sensor were attached to the HMD in order to evaluate performance of this system. Additionally, digital filters were used as denoising algorithms.

Accuracy of gaze estimation was experimentally determined to be 68.9% for a HMD screen which was partitioned into eight target areas. Head-tracking with the gyro-sensor showed 99.4% accuracy. Time until input by the detection of eye movements was 0.37 seconds. These findings suggest that rough gaze positions are detectable by combining gaze estimation and head-tracking.

1. Introduction

Head-mounted displays (HMD) are devices widely used to immerse users in virtual reality (VR). HMDs may also be used with head-tracking sensors, which enables the user to move the head to look around in the virtual world. For example, a 3-axis gyro sensor on the HMD measures head angle and correspondingly moves the field-of-view (FOV) in the same direction in real time. This intuitive interaction contributes to improve the quality of VR [1]. However, HMDs having only a head-tracker cannot accurately and rapidly determine the user's area of gaze since FOV movements consist of not only head movements but also eye movements. Large FOV movements often cause head movements and eye movements, where the eyes are directed to the gaze target before the head moves. However, short FOV movements require only the eyes, and not the head, to move, and the eyes can gaze in a direction different from the direction of the head. Therefore, accurate measurement of the user's area of gaze requires the use of eye-tracking sensors. Figure 1 shows an example of the difference between head direction and actual gaze direction when the FOV moves from lower left to upper right; the FOV from the head direction does not capture the gaze target in the center.

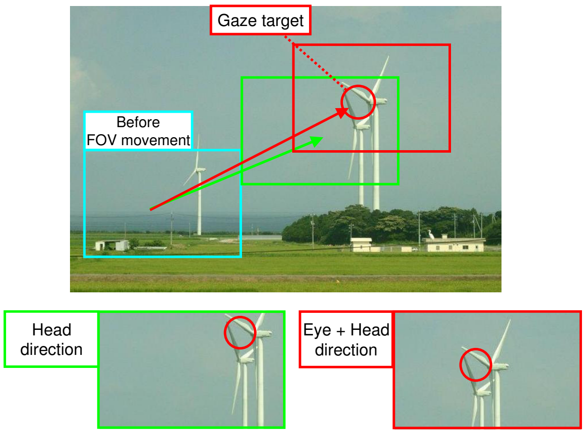

Figure 1. Difference in FOV between head direction and actual gaze direction

Well-known eye-tracking devices are video-based eye-trackers which utilize sclera reflections or corneal reflections [2]. These eye-trackers use contrast to locate the center of the pupil and infrared light to create corneal reflections. Such a process requires fixing the relative position between the device and the eyes, and as such the user must keep the head still. HMDs worn on head blocks that irradiate infrared light to the eyes and measure corneal reflections mean there is a device in the user's FOV, disturbing immersion in VR. Due to such problems, eye-tracking devices have not been implemented on HMDs equipped with head-trackers.

In this study, we adopted the technique of electrooculography (EOG) which is widely applied in clinical medicine. EOG is a method for sensing eye movement and is based on recording the standing corneal-retinal electric potential [2]. We refer to eye-tracking by EOG as EOG-based gaze estimation since EOG cannot track eye movements with absolute precision. For EOG-based gaze estimation, disc electrodes are placed around the eyes and an electrooculogram is measured. By using this method, the user can move his head and no eye-tracker devices block the HMD FOV [3]. Therefore, we have implemented a HMD to which disc electrodes for the EOG and a gyro-sensor for head-tracking are attached. In this study, the accuracy of EOG-based gaze estimation with the HMD was investigated.

This paper is organized as follows. Features of eye movements and some eye-trackers are explained in section 2. Our proposal and the implementation process are explained in section 3, and experiments to evaluate its performance are described in section 4. Finally, we present the conclusions of our study and discuss future work in section 5.

2. Eye Tracking

Eye tracking is a process of measuring either the point of gaze (i.e. where we are looking) or the motion of the eye relative to the head. Eye movements provide very important information for estimating the thoughts and intentions of persons [4]; the eyes unconsciously turn to objects of attention in the FOV. In addition, eye muscles can move rapidly and untiringly, and eye. movements are generally categorized into saccadic eye movement (saccade) and smooth pursuit eye movement (smooth pursuit) [5].

Saccades are quick, simultaneous movements of both eyes in the same direction and are used when changing gaze targets and staring at speeding objects. In contrast, smooth pursuits are used to maintain gaze on slow objects. Whether to use saccade or smooth pursuit is an unconscious decision and requires no concentration. All of these features has meant that eye tracking has been the topic of study for a long time [6]. The measurement device most often used for measuring eye movements is the eye-tracker, and there are generally six types of eye-trackers [2] [7].

2.1. Electrooculography

EOG is a technique for measuring eye movement that is based on the electric potential of eyes [2]. The cornea of the eyeball has positive electric potential with respect to the retina. This electric potential is measured using disk electrodes placed on the skin around eyes and the data obtained is displayed on an electrooculogram.

Transitions on electrooculograms are essentially proportional to the rotation angle of the eyes. Figure 2 shows an outline of the concept of EOG. One of the advantages of EOG is that the burden placed on users is small since the only equipment required for EOG is the small disk electrodes that are placed on the user's face. Additionally, utilizing the concept of EOG can make the FOV comfortable when using a HMD with the eye-tracker because no camera and no light for measurement is required. However, variability of the electrooculogram reading depends on many factors that are difficult to determine [10]. These perturbations are caused by other biopotentials such as those captured by electroencephalography (EEG) and electromiography (EMG) or are affected by the positioning of the electrodes, skin-electrode contacts, lighting conditions, head movements, blinking, and so on. Consequently, EOG is inferior to other eye-trackers in terms of accuracy, and is often used only for the measurement of saccades.

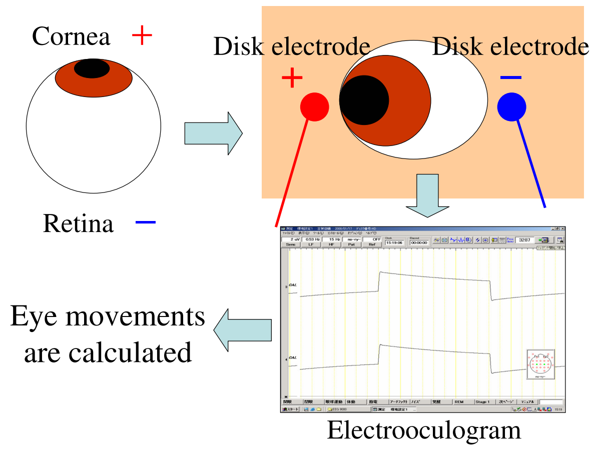

Figure 2. Process of electrooculography

2.2. Optical lever

The optical lever is a method for sensing eye movement using a light and a contact lens which has a small mirror fixed on the edge [2]. The reflected light from the mirror is measured by image analysis or photoelectric conversion. This method can track vertical and horizontal eye rotations of less than 1 degree, and is more accurate than other eye-trackers. Accordingly, the optical lever is often used for research on small involuntary eye movements. However, this method may need negative pressure to prevent the contact lens from floating and moving, but such negative pressure may injure the cornea and eye cells. Moreover, measurements of the reflected light are limited in scope by the eyelid. Thus, the optical lever is not suited to measurements over the long term or for large eye movements.

2.3. Search coil

The search coil is a magnetic sensor that measures eye movement [2] by using a contact lens which has a coil embedded in it and magnets positioned around the eye that generate alternating magnetic fields. Electric currents are generated in the search coils through electromagnetic induction. The polarity and amplitude of the current generated varies with the direction and angular displacement of the eye. By measuring these values, the position of the eye can be determined. The search coil has similar attributes to the optical lever; it is highly accuracy but places great burden on users. In comparison with the optical lever, the search coil can trim weight off the contact lenses, making it lighter. This method also measures eye position relative to the head, and is not generally suitable for point-of-regard measurement.

2.4. Scleral reflection

Scleral reflection utilizes the difference between reflectances of the cornea (the black of the eye) and the sclera (the white of the eye) [2]. The boundary between them is irradiated with infrared light, and a camera in front of the eye captures the light reflected from the eye. The intensity of the reflected light varies with the angle of the eye because the reflectance of the sclera is stronger than that of the cornea. However, irradiating eyes with infrared light has the potential to cause eye diseases [8], such as glassblower' s cataracts and eclipse retinopathy.

2.5. Corneal reflection

The method of corneal reflection determines gaze direction by comparing the pupillary position with the reflection of incident light from the cornea [2] [9]. Typically, this eye-tracking system consists of a single eye-tracker box with an infrared light source to illuminate the eye, an infrared camera to capture video of the eye which has automated camera focus and FOV lens and steering mirrors to track head movements. Gaze position is calculated by measuring the position of the Purkinje image which is visible when the cornea is irradiated with a point light source. However, since movement of the head produces a large measurement error, eye tracking by corneal reflection requires the head to be kept immobile or measuring devices must be fixed to a helmet. Additionally, corneal reflection is a risk factor for eye diseases [8].

2.6. Image processing

A technique to measure eye movement by image processing has been proposed [5]. The measurement consists of deriving the pupil or the iris from images of eyes filmed with a video camera. This technique is easily affected by noise such as that generated by the eyelashes and eyelids. However, high-precision eye-tracking is achievable with image denoising. The transaction speed of this technique depends on the frame rate of the video camera. Therefore, video cameras whose frame rate is low cannot measure high-speed eye movements such as the saccade.

3. Implementation

In this paper, we propose the implementation of EOG-based gaze estimation using a HMD equipped with a head-tracker. The HMD collects measurements of FOV movements by using gaze estimation. We adopted EOG for use as an eye-tracker on the HMD since this eye-tracking system does not obstruct the frame of the HMD, and it allows the head to move without burdening the user with mounting devices for measurements. Our aims are accurate estimation of the user's gaze position and speedy descriptions of the FOV in VR when using this device.

We attached a gyro-sensor and disk electrodes to a pair of swimming goggles on the HMD (Figure 3), enabling the user to easily wear all the necessary devices at one time. We used SONY's HMD Glasstron as the base device. Glasstron's screen provides a physical FOV that is 28 degrees in the horizontal and 21 degrees in the vertical directions. For the gyro sensor to measure head angle, we used INTERSENSE's InterTrax2USB. InterTrax2USB captures data of the degrees of its triaxial rotation. The use of this gyro sensor on the HMD allows for the direction of the user's face to be determined. InterTrax2USB can relate the head movements to FOV movements in VR in real time since it runs a description language for VR applications that can connect directly with a PC. Swimming goggles and NIHON KOHDEN's disk electrodes were attached to the HMD for EOG-based gaze estimation (Figure 4). The disk electrodes are firmly glued using NIHON KOHDEN's Elefix electrolyte paste to the swimming goggles in four locations (outer corner of both eyes, and above and below the right eye), making contact (moderate pressure) with the skin around the eyes. The edges of swimming goggles touch around eyes and press disk electrodes in moderation. Horizontal gaze positions are derived from disk electrodes at the outer corner of the eyes and vertical gaze positions are derived from the disk electrodes above and below the right eye. With the combined use of EOG with this HMD, we could accurately determine from the data gathered for both horizontal and vertical eye movements where the eyes were looking. In addition, a disk electrode was placed at the glabella and on both earlobes as ground terminals. Figure 5 shows the positions of the disk electrodes. Before use of the device, the skin around the eyes was cleaned using antiseptic cotton.

Electrical potentials measured with the HMD were recorded as an electrooculogram using NIHON KOHDEN's electroencephalograph Neurofax, and the electrooculogram

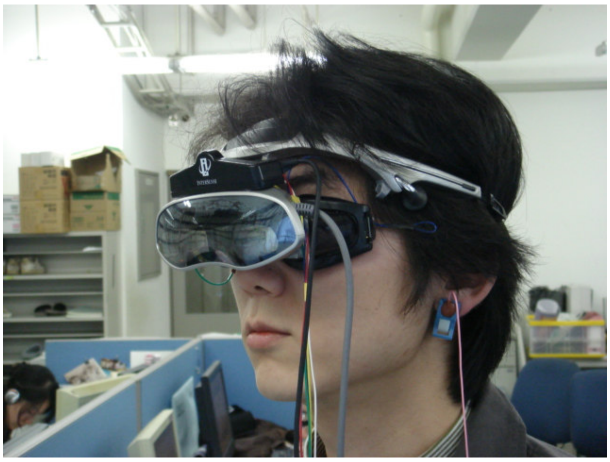

Figure 3. Appearance of the HMD used in this study

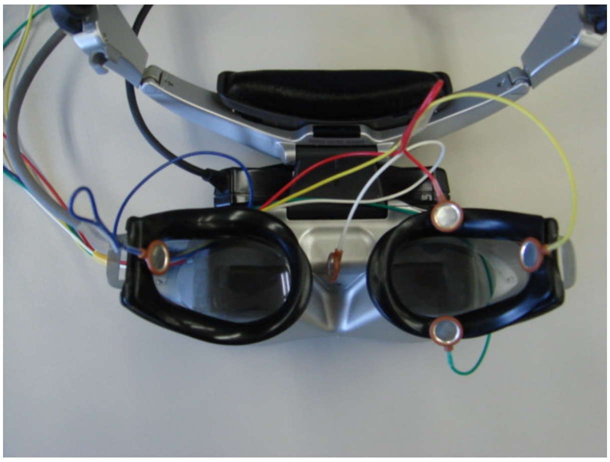

Figure 4. Disk electrodes and swimming goggles attached to the HMD

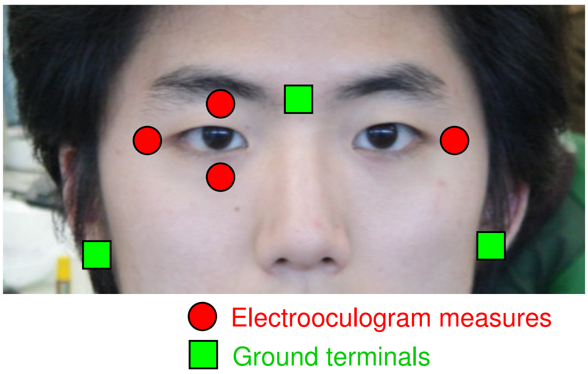

Figure 5. Positions of disk electrodes contacting the skin

was then converted into an estimation of eye movements. A recording of the electrooculogram was saved as binary data, and since the data contained noise specific to EOG, a procedure was required in which the electrooculogram recording was moved using flash memory from the Neurofax to the PC running the gyro sensor and the VR application. Eye gaze information was estimated by synchronizing EOG output and the gyro sensor data recording in time. Therefore, measurements of this precision were performed, but a real time interface with eye movements as triggers was not implemented.

To increase the precision of our system, this estimation was corrected by the use of the filtering algorithms described. Additionally, calibration was required because the electrooculograms did not directly describe gaze position.

Firstly, electrooculograms contain noise from the measurement environment such as electric current source. Neurofax, an electroencephalograph, is equipped with a low-cut filter (LCF) and a high-cut filter (HCF) to reject such noise. In this study, the low-cut off frequency was set to 0.05 Hz (time constant was 0.008 seconds) and the high-cutoff frequency was set to 15 Hz.

Secondly, the electrooculograms are affected by brain waves and potentials from face muscles. Compared with potential changes of eye movements, such noise is smaller and higher frequency. We removed the noise using a first-order infinite impulse response (IIR) filter as a low-pass filter (LPF). The behavior of this digital filter is calculated using a simple algorithm.

Thirdly, the electrooculograms converged to zero when gaze was maintained on one point for longer than 3 seconds. The convergence was attributed to the LCF of an electroencephalograph. Stability of the electric potential by stopping eye movements reduced the frequency to zero, and it was rejected by the LCF. Thus, the electrooculogram needs to be adjusted because the convergence causes slippage of gaze estimation. We differentiated the electrooculograms and removed derivative values less than a certain value in order to eliminate convergence. Using this algorithm, potential variations associated with eye movements were extracted. However, this algorithm could not handle the more constant movements of smooth pursuits, so we limited the eye movements determined experimentally to saccades. Figure 6 shows the processes and the effects of the denoising algorithms used.

Eyeblinks induced strong noise on the electrooculograms. This was attributed to automatic eye movements and motion around the eyelid when blinking. The noises were generated only in vertical electrooculograms. These were not rejected by the IIR filter and the elimination of convergence since eyeblinks have potential variations as large as normal eye movements. Thus, vertical saccades were difficult to differentiate from eyeblinks. In this study, we avoided this issue by setting blinking times at a fixed time interval and potential changes were ignored during the

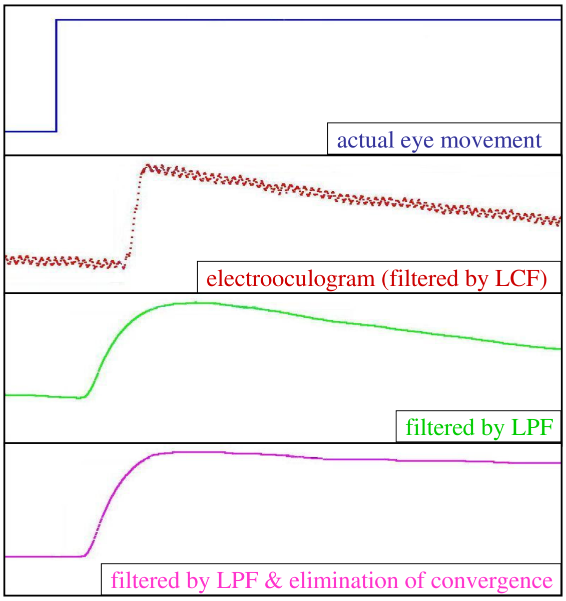

Figure 6. Process and effect of filters used

blinking times which were set to avoid drying of the eyes.

In addition, electrooculograms were calibrated with regards to the amplitude of the potential to the angle of the eyes. Before using the HMD, the users gazed at four side edges of the HMD's frame (leftmost, rightmost, topmost and bottommost) for the calibration. The ratio of the amplitude and the angle was determined on the basis of the calibration. All gaze positions were obtained by multiplying the ratio obtained from the electrooculograms because amplitudes are almost proportional to angles.

4. Experiments

In this study, we implemented EOG-based gaze estimation on a HMD with a head-tracker and applied some denoising algorithms to improve the accuracy of estimation. Additionally, we conducted evaluation experiments to evaluate the accuracy of the gaze estimation. In experiment 1, the accuracy of EOG used with the HMD was confirmed. In experiment 2, the HMD was used to immerse a user in VR and the performances of gaze estimation and head-tracking were measured. The experimental period was from December 25, 2007 to January 9, 2008. Both experiments involved 10 participants (9 males, 1 female; mean age 23 years) who were students of Keio University.

4.1. Experiment 1: Precision of EOG-based gaze estimation

4.1.1 Method

In this experiment, the participants tried to look at targets one by one as presented by the HMD. The experimental procedure was as follows.

1 : Perform calibration

2 : Wait 3 seconds for the next step

3 : Look at a small square displayed in a random position in the HMD for 3 seconds (Figure 7)

4 : Repeat steps 2 and 3 ten times

The accuracy of EOG was derived from the positions of the squares and the estimated gaze positions on each trial. To compare these positions, the HMD screen was partitioned equiangularly into several areas from the center. When the target and the estimated gaze point were in the same area, it was judged that the estimation was correct. Figure 8 shows an example of correct estimation when the screen was partitioned into eight areas. However, the border lines were not displayed so that the participant could concentrate gaze on the targets.

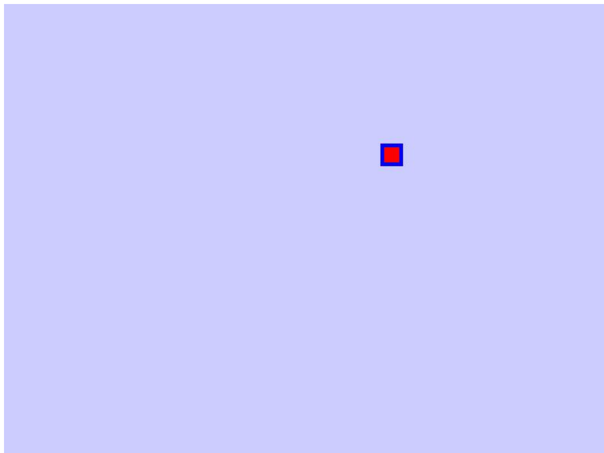

Figure 7. Gaze target displayed on the HMD

4.1.2 Results

Figure 9 shows the result of experiment 1, where accuracy of the EOG-based gaze estimation is shown on the y-axis and the number of the partitions on the x-axis. When there was a higher number of partitions, the resolution of the estimation was high. The graph shows that accuracy decreased as resolution increased. Gaze-based interfaces are required to have around 90% accuracy for ordinary use [11]. If the accuracy of using the HMD as the interface device is limited to above 90This implies that a HMD system can present

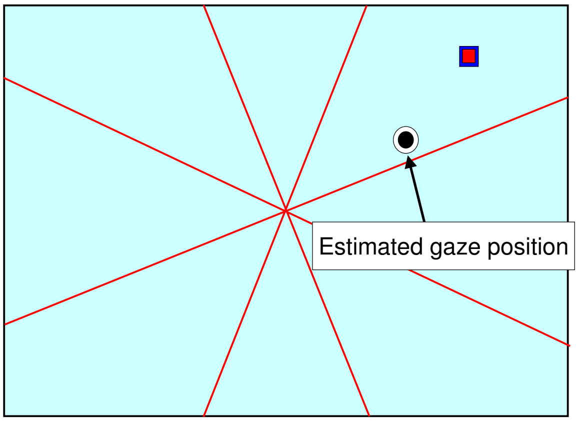

Figure 8. Example of correct estimation upon division of the screen into eight areas

only four choices at the same time. We considered that the reason for such accuracy was the lack of feedback from gaze estimation to the user; the user is not able to check his own gaze position objectively in real time because the estimation is subjected to some filtering by the other PC after measurement, and thus the gaze is not fixed on the target because the user cannot make a clear distinction between the center of FOV and peripheral vision. In addition, too much pressure might have been exerted on the participant's skin around the eyes since the disk electrodes were attached to swimming goggles on the HMD. In this study, we gaze estimation had an accuracy of 68.9Thus, in experiment 2 we implemented gaze estimation in eight directions and provided a VR environment with the HMD.

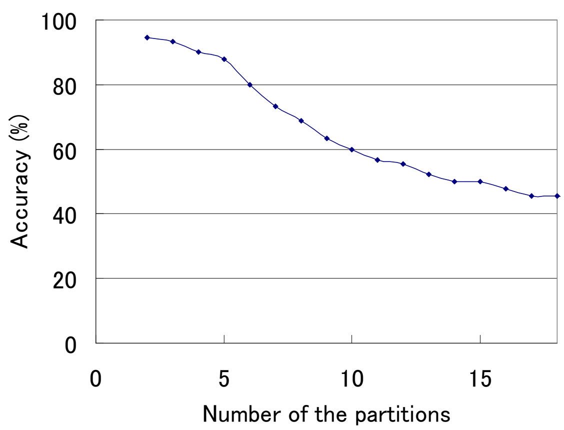

Figure 9. Accuracy of EOG-based gaze estimation in experiment 1

4.2. Experiment 2: Gaze estimation and head-tracking

4.2.1 Method

In experiment 2, the accuracy of EOG-based gaze estimation and head-tracking with the gyro-sensor were measured. Additionally, time until input by eye movements and head movements was measured. We created a VR space with a 360-degree view. The space was similar to the inside of a box where all six faces have geometric designs. The measurements involved moving the user's FOV in the VR space with the gyro-sensor. The procedure of experiment 2 was as follows.

1 : Perform calibration

2 : Wait 2 seconds for the next step

3 : Within 5 seconds face a white sphere in a random position in VR space for one second (Figure 10)

4 : Check the new color of the sphere which is changed randomly from white

5 : Within 5 seconds look at a square which is the same color as the sphere (Figure 11)

6 : Repeat steps 2 to 5 ten times

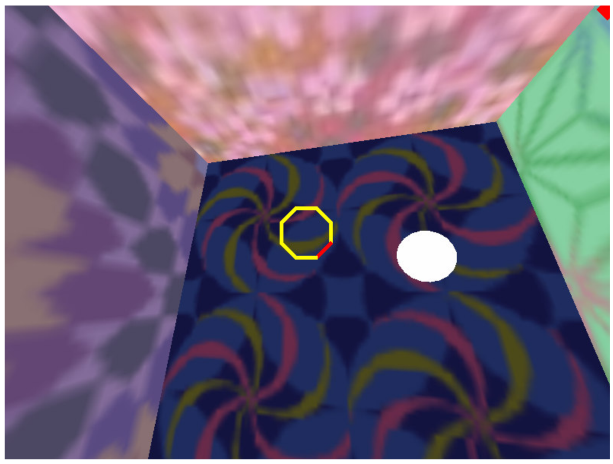

Figure 10. Target of head movement and guide ring at the center of the screen

Eight differently colored squares were designed as gaze targets (Figure 11) and were displayed at four sides and four corners of the screen. The screen was partitioned radially into eight equal areas as in experiment 1. If the estimated gaze point was in the same area as the target, it was judged to be correct. The spheres colored in one of eight colors which were same as the colors of the gaze targets. In step 3, the participant had to move his head to position the sphere in a guide ring at the center of the screen. The margin for error was two degrees or less of the view angle because the

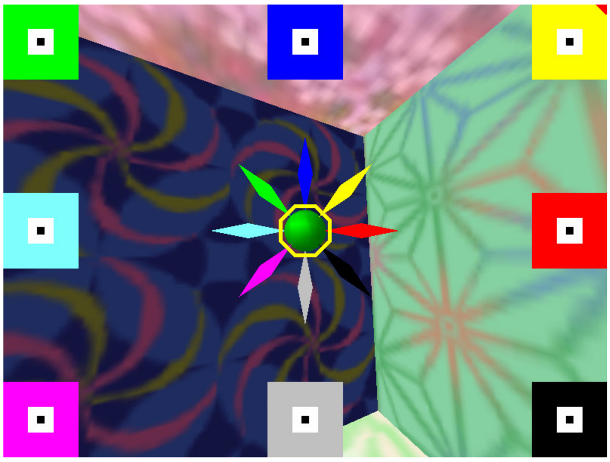

Figure 11. Eight differently colored targets of eye movement

participant was able to face the spheres at the center of FOV with this margin. In step 5, the participant had to gaze at the center of a square which was the same color as the sphere in the VR space. To help eye movements in the act of gazing, colored arrows were displayed around the guide ring. We 1
assumed that participants would not gaze at the wrong target because the procedure was designed to be simple and the participants had completed some practice trials. At the end of experiment 2, the usability of the HMD was then assessed by questionnaire.

4.2.2 Results

Table 1 shows the performances of EOG-based gaze estimation and head-tracking. The accuracy of gaze estimation was 48.7%, which was lower than the 68.9% accuracy obtained in experiment 1.

Figure 12 shows higher accuracy of gaze estimation in the experiment 2, calculated by scaling the partitioned area of the screen, and keeping the number of gaze targets at eight. The accuracy of gaze estimation decreased as the resolution increased as in experiment 1. Compared with the result of experiment 1 however, overall the accuracy is low. These results indicate that gaze estimation was adversely affected by head movement or tilt. We surmise that the HMD moved slightly by its own weight and the inertial force of the head movements, thereby shaking impedance between disk electrodes and skin due to changes in pressure of the electrodes attached to the HMD.

The accuracy of the head-tracking with the gyro-sensor was 99.4This extreme precision may be explained by the user receiving feedback of head movements in real time.

Time until input in Table 1 shows that EOG estimated eye movements early. We infer from this result that EOG can detect transition of the user's attention from one object to another ahead of the head-tracker.

Table 1. Performances of gaze estimation and head-tracking

Process	Accuracy(%)	Time until input(sec)
Gaze estimation	48.7	0.37
Head-tracking	99.4	1.74

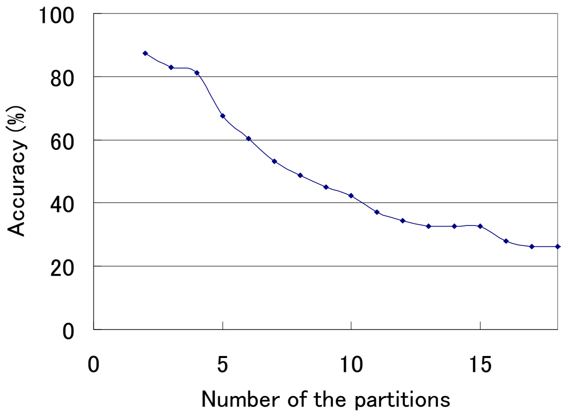

Figure 12. Accuracy of gaze estimation in experiment 2

Table 2 shows the questionnaire results regarding usability of the HMD in experiment 2. The questionnaire items were answered used a 1-7 Likert scale (1 = strongly disagree, 7 = strongly agree). As shown in the table, the intuitive interface of the HMD and immersion in VR are 1
features appreciated by the users. However, the questionnaire found that the participants became fatigued with FOV movements induced by head movements. Questionnaire responses indicated that the fatigue was caused by inclination of the body and twisting of the upper body. From these findings, we can assume that EOG-based gaze estimation does not exert harmful, only tiring, influences on the body when using head-tracking and experiencing VR space.

Table 2. Usability of the HMD with EOG and head-tracking

Question	Value
The interface was easy to use	5.5
The interface was easy to learn	6.4
The interface was felt natural to use	6.3
The interface was intuitive	6.8
The interface did not cause fatigue	2.7
I felt immersed in the virtual reality world	6.3
It was not uncomfortable being in virtual reality space	5.2
Using the HMD was enjoyable	6.2

5. Conclusion

A HMD with a head-tracker is an effective device for provide an immersive VR experience, allowing users to move their FOV intuitively, and thus contributing to advancing the quality of VR. However, such a HMD does not accurately and rapidly show the gaze target in the center of the screen; an eye-tracker is required to detect the gaze object accurately. However, general eye-trackers block the screen of the HMD and restrict head movements.

Against this background, we proposed the implementation of EOG-based gaze estimation using a HMD with a head-tracker. Additionally, we attached a gyro-sensor and disk electrodes to swimming goggles fixed to the HMD.

To evaluate performance of this system, two experiments were conducted. The experiment results revealed that gaze estimation had 68.9% accuracy when the gaze points were estimated at one of eight partitioned areas. In addition, head movements caused detrimental effects on the disk electrodes, thereby decreasing measurement accuracy. Compared to head movements, gaze movements were detected early by EOG. While EOG-based gaze estimation did not impair the usability of the HMD and immersion in VR space, FOV movements with the head-tracker caused user fatigue.

Approximate gaze areas are detectable by combining gaze estimation and head-tracking. However, advancement of this method of gaze estimation is needed in order for the HMD to be used as an interface device. As future work, we will improve the method of affixing the disk electrodes as well as the filtering algorithms used. In addition, we will work toward the estimation of eye movements in real time in efforts to realize gaze interaction between the user and VR.

6. Acknowledgements

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