Relationship between 3D Eye-Gaze and the TrueDepth Measured by Vive Pro Eye

Kenta Kato and Oky Dicky Ardiansyah Prima
Graduate School of Software and Information Science
Iwate Prefectural University
152-52, Sugo, Takizawa, Iwate, Japan
e-mail: g236s002@s.iwate-pu.ac.jp, prima@iwate-pu.ac.jp

***Abstract*—The widespread availability of eye tracking devices has led to the active application of eye-gaze information, such as input interfaces, eye-gaze-based interaction with computers, and understanding of human visual information. More recently, various Head-Mounted Displays (HMDs) for Virtual Reality (VR) with built-in eye trackers have become commercially available. The Vive Pro Eye has been used for in-depth analysis of saccadic eye movements and in clinical ophthalmology. Unlike any other HMD-type eye tracker, the advanced slippage compensation in this device allows to maintain gaze accuracy and provides stable gaze measurement over a long period. We believe that this advantage may help in estimating accurate Three-Dimensional (3D) eye-gaze, and therefore it is necessary to investigate the accuracy of 3D gaze with the Vive Pro Eye. This study attempts to evaluate the accuracy of eye-gaze in two- and three-dimensions by measuring 3D eye-gaze when gazing at targets placed at different spatial positions with the Vive Pro Eye. Results showed that the relative position of the 3D eye-gaze to the 3D targets placed radially in 40-cm increments from 40 to 200 cm was confirmed. The accuracy of 2D eye-gaze measurements tends to decrease as the viewing angle increases, and consequently the accuracy of the corresponding 3D eye-gaze measurements also decreases. The 3D eye-gaze to the centrally located visual targets increases linearly, while the rest of the eye-gaze increases logarithmically.**

Keywords-3D eye-gaze; eye vergence; eye tracking; 3D perception; computer vision.

I. INTRODUCTION

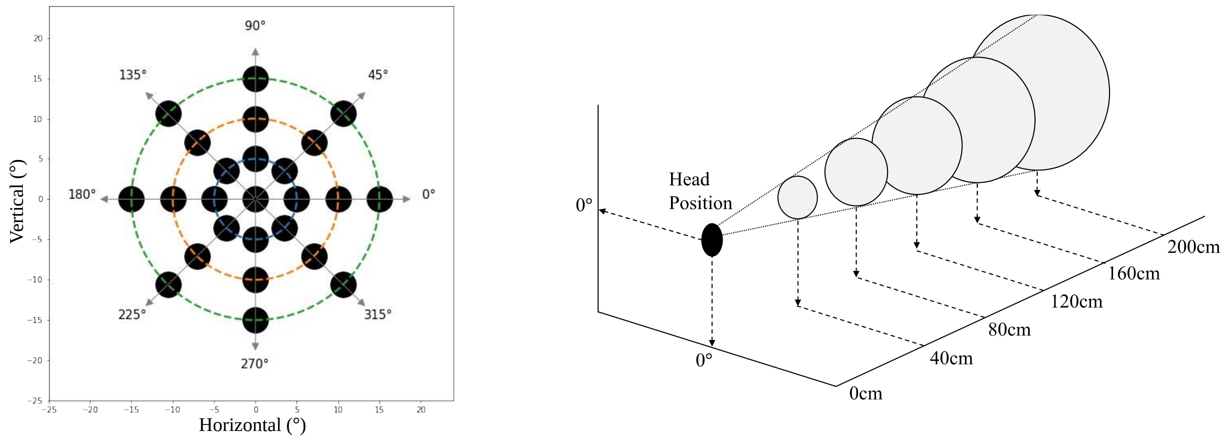
Two-Dimensional (2D) and Three-Dimensional (3D) contents are now accessible to consumers as Head-Mounted Display (HMD)-type Virtual Reality (VR) devices become available to the general consumers. Since these contents can be easily and cost-effectively created using VR, HMD-type VR is being used for applications that are difficult to reproduce in a real environment, such as product design and new training methods for sports [1]-[3]. Users can manipulate 3D contents in VR mostly by using controllers or hand gestures. Recently, HMDs with an eye-tracking function has been introduced as an alternative method to control the contents. Since then, interactions based on eye tracking in VR have been actively developed [4]-[6]. In addition, with the commercialization of HMD-type eye trackers, the use of eye-gaze information in VR environments is being explored in brain science, psychology, disease assessment, and behavioral analysis [7]-[9]. These eye trackers are expected to provide more accurate eye-gaze measurements because they block out ambient light.

Stein et al. [10] evaluated several HMDs with built-in eye trackers, including Fove-0, Varjo VR-1, and the Vive Pro Eye. Their results showed that the Vive Pro Eye had the highest latency, even though it was the best in terms of field of view and tracking sampling rate. However, the results also indicated possibly due to data filtering within the Software Development Kit (SDK). To our knowledge, Vive Pro Eye is the only HMD with advanced slip compensation that handles headset motion to maintain accuracy and calibration. This solution allows users to move naturally throughout the experience without losing eye tracking performance. The Vive Pro Eye has been reported to be effective in performing saccadic eye movement assessment [11] and clinical ophthalmology [12].

The Vive Pro Eye outputs eye-gaze information in 3D coordinates, which could enable 3D eye-gaze estimation by crossing both extensions of the left and right eye-gaze raycasts without triangulation. This will allow for a simpler calculation for obtaining 3D eye-gaze than that based on vergence eye movements and is expected to lead to the analysis of various types of visual information using 3D eye-gaze. However, there is currently a lack of rigorous research investigating the accuracy of 3D eye-gaze with the Vive Pro Eye and the impact of gazing distance and direction on the accuracy.

In this study, we use the Vive Pro Eye to collect eye-gaze information while gazing at targets placed at different spatial locations and analyze their distribution in two 2D and 3D. To characterize the eye-gaze at any given direction and distance, we place the visual targets radially on a plane at a given distance. Here, three seconds of fixation was performed to analyze the representative eye-gaze information during the fixation task, since small involuntary eye movements continuously change the eye-gaze position during the fixation. At the end, we will compare the characteristics of 3D eye-gaze measured with the Vive Pro Eye with those obtained with our previous experiments based on vergence eye movements to explore new insights.

The rest of this paper is organized as follows. Section II describes related works on 3D eye-gaze measurements. Section III describes our experiments to characterize the 3D eye-gaze derived by Vive Pro Eye. Section IV summarizes our results. Finally, Section V concludes our study and discusses prospects.



(a) Visual targets placed radially in eight directions.

(b) Arrangement of planes containing the visual targets.

Figure 1. Visual targets and their arrangement in this study.

II. RELATED WORKS

The 3D eye-gaze measurement relies on the relative position of the two eyes with respect to a given visual target. Vergence angle (the angle in the direction of the line of sight of both eyes) changes when the visual target moves to a certain distance from the viewer. Since our eyes never remain completely still as we try to align our eye-gaze with the object [13], 3D eye-gaze measurement is less stable than that of 2D eye-gaze. Small eye movements can cause changes in the position of both eyes, reducing the measurement accuracy. Kato & Prima [14] performed 3D eye-gaze measurements in an MR environment and confirmed that the relative size of the 3D visual target and the surrounding physical environment do not affect the accuracy of 3D eye-gaze.

Some studies have attempted to measure 3D eye-gaze without calibration in order to make such measurement easier. Palmero et al. [15] used recurrent Convolutional Neural Network (CNN) to automatically estimate 3D eye-gaze from still images using information from faces, eye regions, and facial landmarks. Liu et al. [16] proposed automatic 3D eye-gaze estimation using an automatic calibration method that combines 3D salient pixels from RGB-D images and eye-gaze vectors. These attempts yielded plausible results, but their accuracies were not sufficient for the analysis of eye-gaze characteristics.

Vive Pro Eye enables 3D eye-gaze estimation without the need for 3D calibration. It can record 3D eye-gaze origin and eye-gaze direction data estimated by constructing cones passing through the camera's focal point and pupil ellipses on the image plane and finding the circular intersection of these cones at a given distance.

III. 3D EYE-GAZE MEASUREMENT USING VIVE PRO EYE

In this study, we evaluate 3D eye-gaze measured with the Vive Pro Eye, which is currently the most popular eye tracking system for VR HMDs. Because the effect of vergence eye movements is not significant beyond 2m, many studies on vergence eye movements have conducted experiments on visual targets up to 2m [17][18]. For these reasons, our

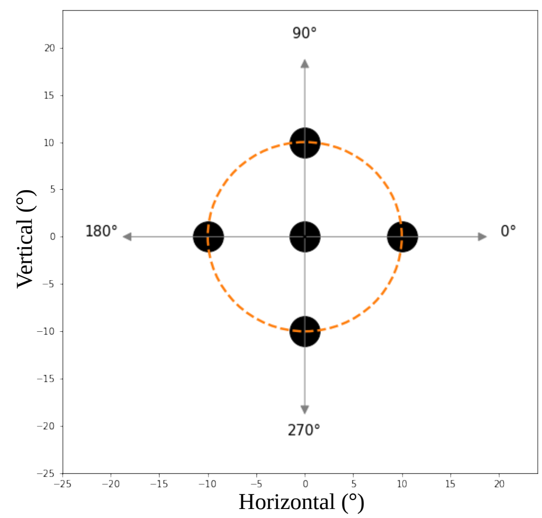


Figure 2. Visual targets for the eye-gaze validation.

evaluation will be conducted by measuring eye-gaze up to 2m from the subject. The eye tracking accuracy of the Vive Pro Eye is 0.5° to 1.1° within a 20° Field of View (FoV). To evaluate the quality of 3D eye-gaze within and outside this FoV, we will measure the eye-gaze at broader FoV.

A. *Equipments*

Our experiment will be performed using Unity3D 2019.4.31f1 and SteamVR 1.21.12 software to drive the Vive Pro Eye. Eye-gaze data will be acquired using SRanipal Runtime 1.3.2.0. The computer for the experiment features a Ryzen 9 3900 3.1Ghz, DDR4 64GB RAM, and a NVIDIA GeForce RTX 2060 Super graphics card.

B. *Visual Targets*

Visual targets are placed radially from 40 cm to 200 cm to the subject in 40 cm increments. Visual targets and their arrangement are illustrated in Figure 1.

TABLE I. 2D EYE-GAZE ACCURACIES (PRECISIONS) AT VARIOUS DISTANCES.

UNITS: °

Subject	40cm	80cm	120cm	160cm	200cm
1	1.34 (0.09)	**0.84 (0.10)**	**0.91 (0.10)**	**0.95 (0.10)**	**0.83 (0.10)**
2	**0.63 (0.08)**	**0.55 (0.08)**	**0.56 (0.08)**	**0.61 (0.09)**	**0.53 (0.08)**
3	**0.47 (0.06)**	**0.48 (0.06)**	**0.45 (0.05)**	**0.49 (0.06)**	**0.74 (0.82)**
4	**0.49 (0.05)**	**0.48 (0.05)**	**0.57 (0.06)**	**0.59 (0.04)**	**0.60 (0.06)**
5	**0.78 (0.06)**	**0.56 (0.06)**	**0.85 (0.08)**	**0.68 (0.09)**	**0.75 (0.82)**
6	1.25 (0.09)	**1.00 (0.10)**	1.20 (0.10)	1.06 (0.09)	**0.90 (0.09)**
7	1.61 (0.09)	1.09 (0.07)	1.04 (0.06)	1.08 (0.08)	1.11 (0.07)
8	1.60 (1.04)	1.64 (0.83)	1.05 (0.16)	1.08 (0.08)	1.00 (0.13)
Mean	1.02 (0.20)	0.83 (0.18)	0.83 (0.09)	0.82 (0.10)	0.81 (0.18)
Std. Dev.	0.451 (0.321)	0.380 (0.270)	0.254 (0.031)	0.231 (0.054)	0.182 (0.244)

TABLE II. 2D EYE-GAZE ACCURACIES (PRECISIONS) AT VARIOUS ANGLES.

UNITS: °

Subject	0°	10°	20°	30°
1	1.17 (0.11)	**0.95 (0.12)**	**0.99 (0.09)**	1.01 (0.08)
2	**0.51 (0.06)**	**0.51 (0.10)**	**0.63 (0.08)**	**0.60 (0.07)**
3	**0.28 (0.06)**	**0.36 (0.06)**	**0.52 (0.06)**	**0.70 (0.65)**
4	**0.46 (0.03)**	**0.45 (0.04)**	**0.54 (0.07)**	**0.65 (0.05)**
5	**0.40 (0.06)**	**0.67 (0.10)**	**0.62 (0.06)**	**0.91 (0.05)**
6	**0.55 (0.07)**	**0.65 (0.08)**	**0.95 (0.11)**	1.53 (0.09)
7	**0.83 (0.09)**	**0.79 (0.07)**	1.06 (0.08)	1.65 (0.07)
8	**0.92 (0.13)**	**1.03 (0.15)**	**0.81 (0.12)**	1.87 (1.10)
Mean	0.64 (0.08)	0.68 (0.09)	0.76 (0.08)	1.11 (0.27)
Std. Dev.	0.283 (0.030)	0.222 (0.031)	0.201 (0.021)	0.467 (0.367)

C. *Procedure*

Subjects are provided with information about the experiment and then are asked to give informed consent to participate in the experiment. The subjects are then asked to answer an eye health questionnaire, and their visual acuity is measured using a Landolt ring placed three meters away from them. In addition, we give training on how to operate the Vive Pro Eye to ensure that the subject does not make any mistakes during the experiment. The subject is seated on a chair, wearing the Vive Pro Eye and its controller. The camera pose in the virtual space is fixed so that changes in the subject's head pose do not affect the measurement. Our experiment is performed according to the following procedure.

Step 1: Perform the Vive Pro Eye 5-point eye-gaze calibration.

Step 2: Validate the eye-gaze accuracy using the 5-point validation target created for this experiment. If binocular eye-gaze accuracy is greater than 1°, return to Step 1.

Step 3: Trigger the controller to perform eye-gaze measurements on each target for 3s. The experiment is terminated after 125 trials.

The Step 2 is performed because the Vive Pro Eye's eye-gaze calibration does not provide the accuracy with numerical values. Figure 2 shows the placement of the visual targets to be used for the validation. Targets are placed 1m away from the subject and at 20° FoV in four directions.

IV. EXPERIMENTS AND RESULTS

Eight subjects (seven males, a female, mean age 23.4) participated in the experiment. They were tested for visual acuity using a Landolt ring to confirm that their vision achieved 1.0 or better. They were also asked to fill out a questionnaire to confirm that they had no health concerns.

A. *Pre-processing*

The Vive Pro Eye detects the opening and closing of the eyes, and the degree of eye opening is defined as 0 (closed) to 1 (open). In this study, to obtain accurate eye-gaze data, we extracted only data in which the degree of eye opening was greater than 0.9 for both eyes of the subject. Eye opening at 0.9 or less may result in false detection as the eyelid falls to hide some portion of the pupil.

B. *Eye-Gaze Accuracies and Precisions*

The accuracy and precision of the 3D eye-gaze depends on that of the 2D eye-gaze. The following equation was used in the calculations.

$$Accuracy_{2D} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_{xi} - G_{xi})^2 + \left(T_{yi} - G_{yi}\right)^2} \quad (1)$$

$$Precision_{2D} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(G_{xi+1} - G_{xi})^2 + \left(G_{yi+1} - G_{yi}\right)^2} \quad (2)$$

Here, n is the number of targets used for the measurement, T_{xi}, T_{yi}, and G_{xi}, G_{yi} are the coordinates of the i-th target and the associated eye-gaze points.

Table I shows the results of the 2D eye-gaze accuracies and precisions for visual targets placed at various distances, as shown in Figure 1. The numbers in bold indicate an accuracy

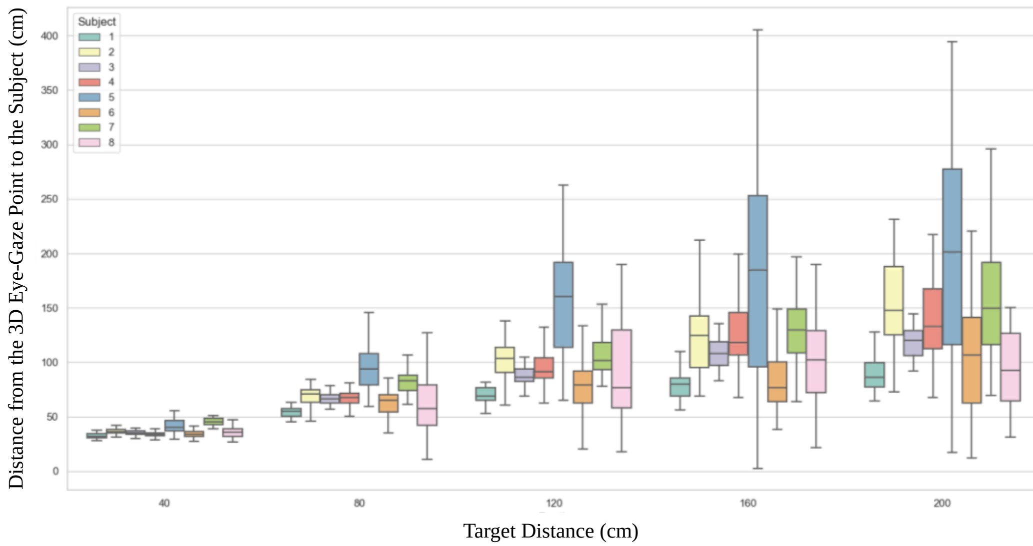


Figure 3. Distribution of distance from 3D eye-gaze point to subject.

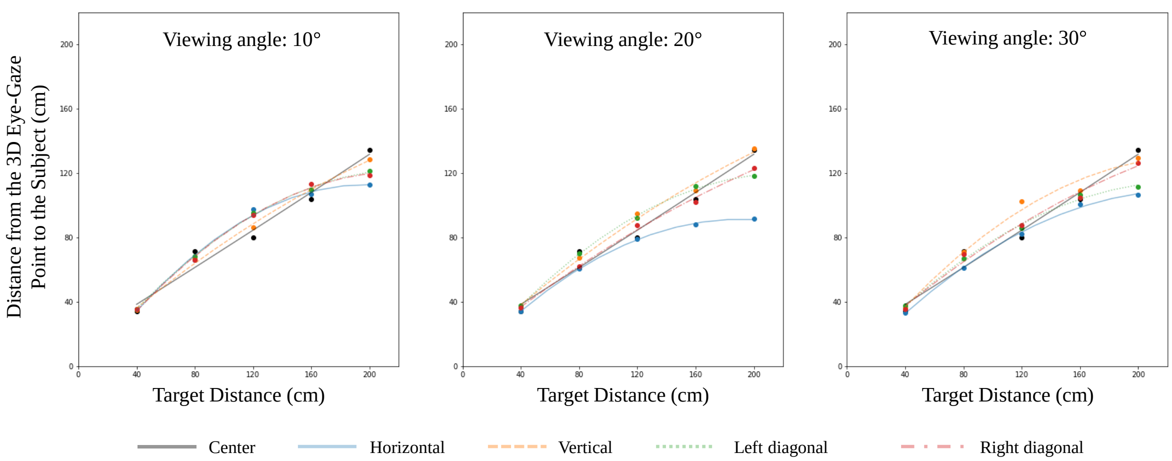


Figure 4. Distribution of distance from 3D eye-gaze point to subject at each viewing angle.

of 1 degree or less, which accounts for 62.5% in total. A one-way Analysis of Variance (ANOVA) revealed that there was not a statistically significant difference in mean accuracy score between at least five groups in distances ($F(4, 35) = 0.572$, $p = 0.685$). The results for accuracies and precisions by angles are shown in Table II. The accuracy of the eye-gaze measurement tends to decrease as the viewing angle increases. ANOVA revealed that there was a statistically significant difference in mean accuracy score between at least four groups in angles ($F(3, 28) = 3.379$, $p = 0.0321$).

C. 3D Eye-Gaze versus TrueDepth

The TrueDepth of 3D eye-gaze is defined by the actual distance from the viewing point to the observer. As shown in Figure 3, the distribution of each subject's 3D eye-gaze increases with gazing distance. This trend was not observed from the accuracy of the 2D eye-gaze in Table I. However, this result is acceptable because, as mentioned earlier, 3D eye-gaze measurement is less stable than 2D eye-gaze measurement because the eye-gaze is not completely still as we attempt to align our eye-gaze with the object. To further investigate the behavior of 3D eye-gaze in detail, we took the median values of all subjects' 3D eye-gaze for each viewing angle, as shown in Figure 4. The 3D eye-gaze to the centrally located visual targets increases linearly, whereas the rest of the eye-gaze shows logarithmic growth. Since the Vive Pro Eye uses a Fresnel lens, the estimated 3D eye-gaze results may be closer to the gazing subject as the viewing angle increases. However, since the scanpaths of the 3D eye-gaze obtained from dynamic visual cues measured in Kato & Prima (2021) also show such a curved trajectory [14], this phenomenon is still open for further study.

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V. CONCLUSIONS

This study evaluated the eye-gaze measurement capability of the Vive Pro Eye in terms of 3D eye-gaze measurement. Although this measurement was performed without triangulation and only by crossing the two extensions of the left and right eye-gaze raycasts, the resulting 3D eye-gaze point was found to be acceptable. The estimated distance from the 3D eye-gaze measurement point to the subject tends to be closer than the actual distance (TrueDepth). However, this can be corrected by using methods such as linear regression analysis.

Small involuntary eye movements were found to affect the stability of the 3D eye-gaze measurement. The distribution of eye-gaze points was found to increase with gazing distance. We also found that 3D eye-gaze to a centrally located visual target increased linearly, while the rest of the eye-gaze increased logarithmically.

From these findings, we can conclude that the Vive Pro Eye is capable of measuring 3D eye-gaze. However, users will need to construct their own measurement methods in order to reveal the accuracy and precision of the eye-gaze, although this type of library is commonly available in commercially available scientific eye trackers.

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