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Fixation Distance Estimation using Vergence Eye Movement for Automatic Focusing Glasses

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Abstract— **In this study, we propose a method for estimating fixation distance on the basis of measurements of vergence eye movements. The aim of this approach is to control the lens focus of automatic focusing glasses. To reduce user effort at the time of calibration, the calibration was performed at infinite distance gazing, and the parameters were determined from the premeasured pupillary distance at infinity and iris diameters. To clarify the effectiveness of the proposed method, we conducted evaluation experiments using prototype glasses. The results showed that even participants requiring myopic correction could perform accurate motion vergence movements. Fixation distance estimation showed that, with the eye calibrated at infinite distance gazing, shorter distances could be estimated with an average accuracy exceeding 90%.**

I. Introduction

As the population ages, incidences of myopia and presbyopia have become increasingly common. Once these conditions occur, close objects appear unfocused when viewed through the single-focus lens used for correcting myopia, and separate reading glasses are required. Rather than wearing different glasses for different purposes, which is inconvenient, many users have opted for glasses with multifocal lenses. Although these glasses enable focusing of both distant and close objects, the multiple focusing regions in a single lens may cause discomfort at the border areas between these regions, and the field of view of proper focus is reduced.

The inherent problems in multifocal lenses have inspired recent development of glasses with adjustable focus lenses. Superfocu Glasses [1] from Superfocus Inc. use a liquid lens with a changeable focal point. emPower! [2] from PixelOptics uses a liquid crystal lens in which electrical signals can switch between different focuses. However, procedures that must be performed to change focus increase the effort on the user.

Conversely, if the glasses can adjust their focus according to the distance between object and user, they can change the focus without the user effort. Therefore, in this paper, we propose a method for estimating the fixation distance from measurements of vergence eye movements. We emphasize that even if the accommodation capability is lowered causing vision loss, vergence movements remain properly executed. Moreover, the effectiveness of the proposed method is tested on five participants using experimental glasses equipped with a camera for photographing the eyeball.

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II. Method for Estimating Fixation Distance

A. Experimental Glasses with Camera

To estimate the fixation distance from the vergence eye movement, rather than the simple eye measurements of previous studies [3][4], our experimental glasses are supplemented with an infrared camera for photographing both eyes. Fig. 1 shows the prototype glasses. It should be noted that these glasses were designed only to evaluate the proposed technique, and are not equipped with a focus-changing lens function.

The resolution and sampling rate of the camera are 640 × 480 pixels and 60 Hz, respectively, and the camera outputs a 1280 × 480 pixel image to the PC. Images are combined by the control board. Following previous study [5], we used a half mirror to photograph the front of the eye; therefore, the prototype glasses are developed using a half mirror. However, since the half mirror fits between the eye and the lens, we not only found that the field of view through the lens was narrowed, but the weight of the glasses increased as the center of gravity of the glasses shifted forward under the weight of the half mirror. Therefore, the camera was positioned under the glass frame, as shown in Fig. 1. In this position, it can photograph the eye directly. The distance between the cameras was set at 65 mm, the average pupillary distance of a Japanese individual [6].

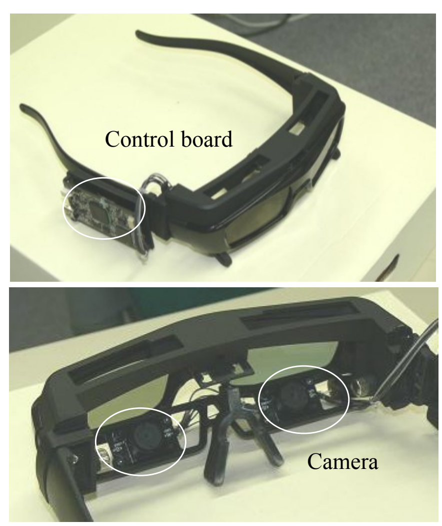

Figure 1. Prototype Glasses with Camera

B. Model for Estimating Fixation Distance using Pupillary distance

The eyes adduct (perform convergence movements) when approaching a fixation point and abduct (perform divergence movements) when retreating from it. Fig. 2 shows the relationship between the eye and the fixation point on the central axis between the two eyes at distance l from the eyes. In Figure 2, D_F and D_I are the distances between the pupil centers at fixation and at infinite distance gazing of the target, respectively, and r is the eyeball radius.

Expressing the fixation distance l in terms of D_F, D_I, and r yields

$$l = \frac{1}{2} \times D_I \tan\left(\cos^{-1}\left(\frac{D_I - D_F}{2r}\right)\right) - r \cdot \tag{1}$$

From equation (1), because r and D_I are constants, fixation distance l can be determined by measuring the distance between the pupil centers D_F, provided that the two constants are known. In this study, D_I of each individual was measured by an Auto Refract–Keratometer (NIDEC ARK-560), and r was at 12 mm, the average eyeball radius [7].

C. Calculating the Distance between Pupil Centers

The pupil center distance is determined from the pupil center coordinates in eye images captured by the infrared camera, as shown in Fig. 3. The x and y axes are defined as shown in the figure. The pupils of both eyes are detected as ellipses from which the center coordinates of the left pupil (L_x, L_y) and right pupil (R_x, R_y) are determined. We use the technique proposed Sakashita et al. to detect ellipses [8].

However, since the captured output image is obtained by connecting the captured images of each camera, missing regions appear in the image, as shown in Fig. 4. Thus, the detected distance between the center coordinates of the pupils is not the true pupillary distance. The true distance is determined from the estimated distance as follows. If the resolutions in the right and left camera images are S_R and S_L, respectively (pixel/mm), and the horizontal length of the missing region is D_M (mm), the true pupillary distance D_F (mm) is expressed as (see Fig. 4):

$$D_F = \frac{640 - R_x}{S_R} + D_M + \frac{L_x - 640}{S_L} \tag{2}$$

Here, the resolutions S_R and S_L and horizontal length of the missing region D_M are determined by calibration when wearing the glasses, since these values can change depending on how the glasses are worn.

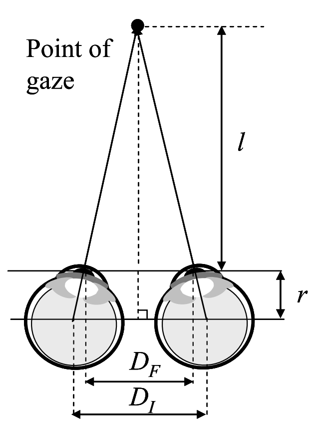

Figure 2. Relationship between a pair of eyeballs and the distance of gaze point

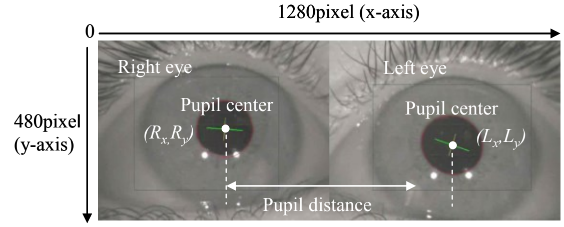

Figure 3. Photograph of a participant's eyes

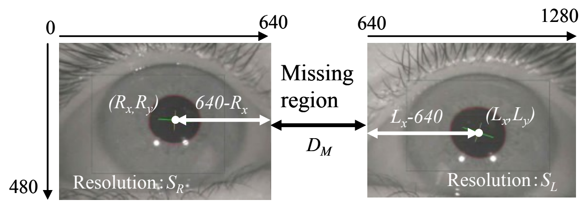

Figure 4. Missing region in captured images

D. Calibration Method using Iris Diameter

When calibrating previous eye tracking system, a number of eye-direction detectors require watching a set of markers whose positions have been determined by the user position [9][10]. However, performing such calibrations each time the glasses are worn is impractical. Here, a single calibration was performed at infinite distance gazing. This calibration method exploits the fact that, unlike the pupil diameter, the iris diameter is robust to external influences such as surrounding illumination.

Prior to using the glasses, the user should be measured the pupillary distance at infinite distance gazing, together with the iris diameter. In this study, these values are obtained by the Auto Refract–Keratometer. This is a once-only measurement and does not require repeating even if the glasses are changed. During calibration, performed by mounting the glasses, eye imaging is performed at the time of infinite distance gazing. The resolutions S_R, S_L, and the horizontal length of the missing region D_M, are determined from the pupil center coordinates and the iris diameter extracted from the captured images.

Here, the resolutions of the right and left cameras S_R and S_L are calculated by comparing the iris diameter from the captured image with the premeasured iris diameter. The horizontal length of the missing region D_M is calculated by substituting the image-determined pupil center coordinates, the resolutions, and the pupil center distance at infinite distance gazing, into Equation (2).

III. Evaluation of the Estimation Method

To clarify the effectiveness of the method for estimating the fixation distance from vergence eye movements (as described in Section II), we conducted measurements of the pupil center distance at varying fixation distance. Five individuals (five males) in the 20–40 age (mean age 37), who do not have any history of ophthalmologic disease, participated in the experiments. The participants were named PIN1–PIN5. Three participants (PIN3–PIN5) require myopic correction. All participants were tested with no visual correction even in participants with myopia. Each subject received adequate description of the experiment and submitted a formal consent to participate.

A. Experiment Setup and Schedules

Fig. 5 shows the setup of the experiment. Participants sat in a chair wearing the prototype glasses and gazed at visual targets centered on an 8" display directly ahead. The head position was fixed, with chin resting on the chin support. The display, installed on a robot cylinder (RCS3-SA8C IAI), was placed at a controlled distance from the participants.

In this experiment, an eye movement was filmed as the display was moved pseudo-randomly in 10 cm increments within 20–100 cm of the eyes of the participant. The video was saved on the PC. The number of display movements was 62 (with 6 or 7 stops in each distance). Stopping time was 3 to 5 seconds, Landolt rings were shown on the display as visual targets approximately once per second following movement stop, and were changed pseudo-randomly. Participants were asked to detect the changed locations of the breaks in the rings. If these locations could not be discerned, the participant would indicate "unknown." The diameters of the displayed Landolt rings were between 1.5 mm and 2.1 mm, with a break in either the vertical or horizontal direction.

B. Measurement of Pupillary distance

Using the resolution and horizontal length of the missing region calculated by calibration at infinite distance gazing, the pupillary distance was calculated for each distance of the fixated object.

Incidentally, since infinite distance gazing is difficult to perform in real life, calibration was carried out using a captured eye image fixated approximately 50 m ahead, which was deemed a sufficiently large distance. Table I shows the difference between the theoretical and calculated average pupillary distance (mm) as each participant fixated on the visual targets. Here the theoretical value is calculated from Equation (1), using the measured pupil center distances at infinite distance gazing. Since the theoretical and calculated values differ by less than 0.5 mm for all subjects, we infer that the eyeball moves according to the model.

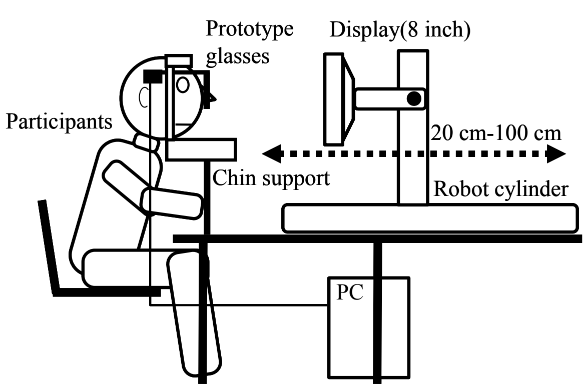

Figure 5. Experiment system configuration

TABLE I. Difference between Theoretical and Calculated Average Pupillary distance

Fixation Distance	Difference of Pupillary distance (mm)				
	PIN1	*PIN2*	*PIN3*	*PIN4*	*PIN5*
20cm	0.22	0.37	0.27	0.05	0.11
30cm	0.20	0.28	0.20	0.04	0.02
40cm	0.22	0.25	0.18	0.16	0.05
50cm	0.29	0.25	0.16	0.19	0.09
60cm	0.17	0.11	0.10	0.16	0.05
70cm	0.19	0.09	0.10	0.19	0.10
80cm	0.24	0.10	0.06	0.23	0.12
90cm	0.17	0.04	0.01	0.17	0.09
100cm	0.16	0.02	0.02	0.20	0.10

In addition, myopic participants (PIN3–PIN5) correctly indicated break directions in Landolt rings less than 20% of the time, at target distances 70 cm or further. Nevertheless, the eye movements of such participants could correctly follow reference marks placed at distances of 70 cm or more. This result shows that fixation distance can be estimated from eye movements even at fixation points that cannot be focused, confirming that eye movements can be used to alter the lens focus in automatic focusing glasses.

C. Evaluation of Estimation Method

Fixation distance was estimated using the pupillary distance calculated from the captured eye images. Table II shows the mean of estimation errors in the fixation point distances for each participant. The estimation error tends to increase at longer fixation distance. The rotation angle of the eye reduces when viewing more distant objects (as evident from equation (1)), thereby enlarging the proportional error in the pupillary distance measurement. The most likely cause of the error in fixation distance estimation is the use of infinite distance gazing for calibration. In this study, we considered that precise distance marks are impractical for everyday-use calibration, whereas infinite distance gazing requires a single calibration. However, the pupillary distance when gazing 50 m ahead (deemed a sufficient distance) becomes inevitably shorter than that measured with the Auto Refract–Keratometer. Furthermore, as described above, the effect of this difference is magnified at large viewing distances, when the amount of eye movement is reduced.

TABLE II. ESTIMATION ERROR IN THE FIXATION POINT DISTANCES

Setting Distance	Average Error [%]*)				
	PIN1	***PIN2***	***PIN3***	***PIN4***	***PIN5***
5m	8.04	7.66	6.39	6.71	6.99
10m	12.94	7.95	5.43	11.52	5.90
20m	16.86	9.46	6.33	15.17	6.81
50m	19.63	10.98	7.52	17.63	8.00
100m	20.58	11.55	8.02	18.49	8.51
infinite	21.56	12.13	8.58	19.39	9.09

Therefore, to determine the parameters during calibration (S_R, S_L, D_M), we use the theoretical pupillary distance gazing at 5–100 m as a substitute for gazing at infinity. Table III shows the average error of the estimating fixation distance at all distances of the visual target using the substituted parameters. For all participants, the error reduces relative to that obtained using infinite gazing parameters. Although the optimum calibration distance depends on the participant, by setting the distance at 5 m (for example), the fixation distance could be estimated within ±10% for all subjects.

IV. DISCUSSION

The proposed method uses a model to estimate the fixation distance on the pupil center axis, thus the fixation distance can be estimated from measurements of pupillary distance alone. When the user looks at an object which exists in the diagonal direction, the relations between the pupillary distance and the fixation distance are different from the relations of the model of proposed method. As a result, the estimating fixation distance may make distortion problems.

TABLE III. ERROR OF ESTIMATING FIXATION DISTANCE

Fixation Distance	Mean Error of Fixation Distance Estimation [cm]				
	PIN1	***PIN2***	***PIN3***	***PIN4***	***PIN5***
20cm	1.49	2.23	1.74	-0.30	-0.62
30cm	2.94	3.68	2.65	0.57	0.30
40cm	5.88	5.71	4.25	3.89	1.02
50cm	12.82	9.26	6.16	7.71	3.27
60cm	10.35	6.03	5.34	9.42	2.55
70cm	16.42	6.00	7.13	15.90	6.93
80cm	30.91	9.34	5.46	26.75	1179
90cm	25.99	4.56	0.98	24.98	13.37
100cm	30.68	3.63	3.05	39.74	15.87

$$^{*)}\ \text{Error}[\%] = \frac{\left|\text{Estimated Distance} - \text{Fixation Distance}\right|}{\text{Fixation Distance}}$$

Using this method, we now aim at designing prototypes for real-time automatic focusing glasses that control their own focus, and evaluate them in a real environment. Toward this goal, we will further investigate the effectiveness of the proposed method as well as the magnitude of the abovementioned problems.

V. CONCLUSION

In this study, we proposed a method for estimating fixation distance on the basis of measurements of vergence eye movements. The evaluation experiment suggests that the method can be used to control the lens focus of automatic focusing glasses. We evaluated the method on five participants using the prototype glasses. In the proposed method, the fixation distance is estimated from the pupillary distance calculated from captured eye images. To reduce user effort at the time of calibration, the calibration was performed at infinite distance gazing, and the parameters were determined from premeasured pupillary distance at infinite distance gazing and iris diameters measured with the Auto Refract–Keratometer.

In the evaluation experiment, we took eye images of participants gazing at targets spaced at 10 cm increments from 20 cm to 100 cm. Even though the accommodation ability was reduced in myopic participants, vergence movement was performed correctly at fixation points that cannot be focused. These results confirmed that eye movement can be used to change the lens focus of automatic focusing glasses. Furthermore, when we applied shorter distance to the pupil of the calibration at infinite distance gazing, proposed method for estimating fixation distance showed more than 90% accuracy.

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