# PAPER Eyegaze Detection from Monocular Camera Image for Eyegaze Communication System

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SUMMARY An eyegaze interface is one of the key technologies as an input device in the ubiquitous-computing society. In particular, an eyegaze communication system is very important and useful for severely handicapped users such as quadriplegic patients. Most of the conventional eyegaze tracking algorithms require specific light sources, equipment and devices. In this study, a simple eyegaze detection algorithm is proposed using a single monocular video camera. The proposed algorithm works under the condition of fixed head pose, but slight movement of the face is accepted. In our system, we assume that all users have the same eyeball size based on physiological eyeball models. However, we succeed to calibrate the physiologic movement of the eyeball center depending on the gazing direction by approximating it as a change in the eyeball radius. In the gaze detection stage, the iris is extracted from a captured face frame by using the Hough transform. Then, the eyegaze angle is derived by calculating the Euclidean distance of the iris centers between the extracted frame and a reference frame captured in the calibration process. We apply our system to an eyegaze communication interface, and verified the performance through key typing experiments with a visual keyboard on display.

key words: eyegaze detection, Hough transform, eyeball model, eyegaze keyboard

#### 1. Introduction

Human eyes always chase an object of interest to the viewer. An eyegaze determines a user's current line of sight or point of fixation. Therefore, the direction of the eyegaze can express the interests of the user, and the gaze may be used to interpret the user's intention for non-command interactions. The potential benefits of incorporating eye movements into the interaction between humans and computers are numerous. Eyegaze tracking is important for human computer interaction (HCI), and promises to be an effective basic function of the interface in the future. Moreover, the eyegaze communication interface is very important for not only users in normal health but also severely handicapped users such as quadriplegic patients.

Many applications including some commercial eyegaze trackers have been reported. Reference [1] presented an eyegaze tracking system for selecting a menu and an icon on the display. A fast manipulation system was also proposed by combining a mouse device with the eyegaze in Ref. [2]. In these studies, the eyegaze detection is used for an interface with the computer. In a coming

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ubiquitous-computing society, the scene of the interaction with the computer may increase. Thus, the eyegaze detection may be one of the most important technologies for HCI.

There are two approaches for the eyegaze detection problem. The first approach is device-based approach [3]-[7]. Gips et al. proposed a detection algorithm based on EOG (Electro-oculo-graph) method [3], in which the myoelectric potential following the motion of the eyeball can be measured by electrode on the face. However, the influence of the electric noise embedded in miniature potential is not negligible. Cornea-reflex-based systems have also been proposed in Refs. [4]–[7]. Those systems require the infrared illumination. Thus, the device-based approach requires the specific instruments for the measurements. The systems may be expensive and give a heavy load to the users. The second approach is video-based approach [8]–[14]. This approach uses video images captured from a video camera without using any specific instruments. Wang et al. presented a method for estimating the eyegaze by measuring the change of the contour of the iris [8]. Matsumoto et al. estimated the eyeball center by detecting the iris edges and the offset vector using the stereo camera [9]. Methods in Refs. [8]-[10] based on the precise measurements of the eveball are expensive, because of requiring a pan-tilt/zoomin camera or a stereo-camera. Methods having no dependence on camera systems have also been proposed. In these approaches, the eye gaze was detected by connecting an estimated eyeball center with the captured iris center [11], [12]. In those methods, the eyeball center is assumed to be fixed in the head. The rotation of the eyeball is assumed as an ideal rotation with sphericity. These assumptions heighten the dependency to the calibration. The methods without any information of the eyeball center under fixed head pose are described in Refs. [13] and [14]. These methods used a luminance gradient for extract the iris semicircle and the eye corners. Therefore, it is necessary to specify rough position of the eyes beforehand.

We will concentrate on the latter video-based approach, and develop a simple eyegaze detection system using only single monocular video camera. In this study, the algorithm will be developed based on the independency of the head pose (global gaze) and the eyegaze (local gaze). The proposed method focuses on the local gaze under fixed head pose. The rotation model for eyeball is constructed through traditional physiological models which are Emsley's eyeball model [15] and Gullstrand's model No.2 [16]. It is known physiologically that the axis and the eyeball center may shift

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with the rotation of the eyeball [17]. In the schematic eyeball model, the gaze angle shifts by 0.6 degrees for only 0.1 mm shift of the eyeball center. Conventional models did not consider the physiologic characteristic. However, we take care not to disregard this point.

The remaining sections are organized as follows. In Sect. 2, eyeball modeling is introduced and the proposed algorithm is described. In Sects. 3 and 4, experimental results showing the useful and acceptable performance of the proposed system are described.

#### 2. Eyegaze Detection

#### 2.1 Eyeball Modeling and Eyegaze Determination

In the detection process of the eyegaze, the eyeball is often represented by the model that is composed of the eccentric big and small spheres as shown in Fig. 1. Here, it is assumed that the optical axis passes on the centers of their two spheres, *i.e.*, the rotation centers of each sphere are on the optical axis. The eyegaze has a given angle to the optical axis, and is represented by the line that passes over the vicinity of the iris center. In general, the eyegaze does not pass the rotation centers of the model as shown in Fig. 1. However it can be assumed that the rotation center exists on the eyegaze, because the rotation center is in the vicinity of the eyegaze. The eyegaze is defined as a line that connects the eyegaze point and a nodal point of the eyes. The nodal point, for considering the eyeball to a lens, is the point at which the incident angle is equal to the emission angle. Another definition for the eyegaze is a line which passes on the node of the eyes, the central fovea and the gaze-point. However, the identification of the central fovea and the determination of the nodal point are extremely difficult and the measurement is impossible in general.

In this study, the eyegaze is simply defined as a position vector from an iris center to the eyeball rotation center. This position vector is vertical to the surface of the cornea, and agrees roughly with the optical axis and the pupil centerline. However, a physiological knowledge indicates that the rotation center in Fig. 1 can be changed according to the gazing direction [17]. So it is major work in this paper to estimate the distance into the iris center depending on the eyegaze direction. We construct the model utilizing the knowledge of the clinical data described in Sect. 2.3. Moreover, the Gullstrand's reduced schematic eye (No.2) and the Emsley's reduced schematic eye in the next subsection are employed for the other numerical values of the eyeballs.

# 2.2 Gullstrand's Schematic Eye No.2 and Emsley's Reduced Schematic Eye

In order to estimate the eyegaze, we have to determine some parameters of the eyeball. In this paper, we use two kinds of physiological eyeball models. Schematic eye is a standard model in the eye optics of which the parameters are



Fig. 1 Lateral section of right eye model.

provided on the basis of the observed values or its approximated values for the optical parameters in dioptrics. Several schematic eyes have been proposed so far. Examples include LeGrand's schematic eye, Donders' reduced eye, Lawrence's reduced eye and Listing's reduced eye.

In this study, we use Gullstrand's No.2 schematic eye and Emsley's schematic eye, which can simple express the size of eyeball. Gullstrand's model, which consists of the precise model (No.1) and the non-precise one (No.2), and Emeley's model are well-known eyeball models. Gullstrand (No.2)-Emsley's reduced eye consists of one-surface cornea, two-surface lens, spherical, rotationally symmetric surfaces. In these schematic eyes, the values for the accommodation-stop and the super-accommodation of the eyes are presented. Both models are shown in Fig. 2.

### 2.3 Eyegaze Detection Algorithm

Based on the discussion in Sect. 2.1, the eyegaze can be defined as the vector directed from the iris center to the eyeball rotation center. In this study, the amount of the shift at the iris center is detected from a midpoint between both sides of the iris boundary. Figure 3 shows the proposed eye rotation model. The gonioscope width, which is the distance from the cornea to the iris, is set as 3.4 mm on averaging the Gullstrand's No.2 model as shown in Figs. 2(b) and (c) (3.2-3.6 mm). The length from the cornea to the eye ground is provided by 23.9 mm with the Emsley's reduced schematic eye in Fig. 2(a). The measurement of the eyeball rotation center is difficult. In the ophthalmology opinion, the eyeball rotation center lies at the distance 13.0 mm behind the cornea [18]. The length from the eyeball rotation center to the bottom of the iris becomes 9.6 mm (13.0 mm - 3.4 mm). This value is used as the standard radius S of the eyeball. In this study, we define a reference gaze as a vector from the eyeball center to an arbitrary iris center in three dimensions. The angle between a reference gaze captured in the calibration process and the target gaze is detected. So, the output eyegaze angle  $\theta$  is always determined by the reference line O-E and the eyegaze O-E' in Fig. 3 (b). The eyegaze angle is 0 degree when gazing at the reference point.

The shape of the iris can be transformed into the ellipse as the eyeball rotates. Therefore, the center of the actual iris



Fig. 2 Schematic eyes used in this paper: (a) Emsley's model. (b) Gullstrand's No.2 model (accommodation-stop). (c) Gullstrand's No.2 model (super-accommodation).

projected on the two dimensional image may shift. Figure 3 shows the eyeball which we looked at from the top. The points  $A_c$  and  $B_c$  in Fig. 3 (a) shows the boundary of the iris when the camera is gazed. Let O be the center of the eyeball. Then  $A_c$  and  $B_c$  can be expressed as  $\left(-I, -\sqrt{S^2 - I^2}\right)$  and  $(I, -\sqrt{S^2 - I^2})$ , respectively. Let S = 9.6 mm be the radius of the rotation locus. Here, I is radius of the iris and is set as 5.75 mm based on physiological value [18]. In general, *I* includes a personal variation. The range of the variation is 0.5 mm based on a physiological knowledge. In our simulation, this variation hardly influenced the eyegaze detection. Therefore, we fix the radius *I* as 5.75 mm in our study.

In Fig. 3 (b), the line A-B shows a radius of an iris when the reference point is seen. The line A'-B' shows a radius of the iris rotated from the reference gaze. The iris is transformed into the ellipse according to the angle from the optical axis of the camera. Symbol  $\alpha$  is the angle between





(b) The arbitrary reference iris (solid line) and the target iris to be detected (dotted line).



the reference eyegaze O-E and the optical axis of the camera. The points C and C' are extracted midpoint of A-B and A'-B' in the image, respectively. However, actual center points of those irises are E and E'. Then A-B and A'-B' can be rotational-transformed as follows:

$$A: \begin{bmatrix} A_x \\ A_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} -I \\ -\sqrt{S^2 - I^2} \end{bmatrix}$$
(1)

$$B: \begin{bmatrix} B_x \\ B_y \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} I \\ -\sqrt{S^2 - I^2} \end{bmatrix}$$
(2)

$$A': \begin{bmatrix} A'_{x} \\ A'_{y} \end{bmatrix} = \begin{bmatrix} \cos(\alpha + \theta) & -\sin(\alpha + \theta) \\ \sin(\alpha + \theta) & \cos(\alpha + \theta) \end{bmatrix} \begin{bmatrix} -I \\ -\sqrt{S^{2} - I^{2}} \end{bmatrix}$$
(3)  
$$B': \begin{bmatrix} B'_{x} \\ B'_{y} \end{bmatrix} = \begin{bmatrix} \cos(\alpha + \theta) & -\sin(\alpha + \theta) \\ \sin(\alpha + \theta) & \cos(\alpha + \theta) \end{bmatrix} \begin{bmatrix} I \\ -\sqrt{S^{2} - I^{2}} \end{bmatrix}$$

(4)

In Fig. 3 (b), the length f of D-D' can be obtained as

$$f = \frac{A'_{x} + B'_{x}}{2} - \frac{A_{x} + B_{x}}{2}$$
  
=  $\sin(\alpha + \theta) \sqrt{S^{2} - I^{2}} - \sin \alpha \sqrt{S^{2} - I^{2}}$  (5)

Here D' is the center of the rotated iris in the camera image. Therefore, the actual angle can be derived as

$$\theta = \sin^{-1} \frac{f + \sin \alpha \sqrt{S^2 - I^2}}{\sqrt{S^2 - I^2}} - \alpha.$$
 (6)

Then the accurate eyegaze vector O-E' can be detected. In order to solve the equation in Eq. (6), we have to know the angle  $\alpha$  between the optical axis of the camera and the reference eyegaze. In the calibration process in Sect. 2.4, variables  $\theta$  and f are known and fixed. So, the angle  $\alpha$  can be estimated, and the amount of the rotation  $\theta$  from the reference eyegaze can be detected.

Under the condition of fixed head pose, the size of the eyeball in the image can be assumed to be constant. However, it is known that the axis and the rotation center may shift according to the rotation of the eyeball [17]. In the schematic eyeball model, the gaze angle shifts by 0.6 degrees for only 0.1 mm shift of the eyeball center. Conventional models did not consider the physiology. However, we paid attention to no disregard of it. In this study, the shift of the eyeball rotation center is modeled by adjusting the radius *S* depending on the gazing direction. The precise calibration algorithm will be described in Sect. 2.4.

Our model is constructed assuming the adult's schematic eye. Therefore, the error increases for junior subjects whose size of the eyeball is too smaller than adults. In that case, we have to determine the eyeball radius S and the iris radius I based on other physiological knowledge. Since we have not considered the tracking between frames, the eyegaze detection is performed independently for each frame. In this study, we don't take into account of the changes in the position resolution by the lens aberrations.

#### 2.4 Calibration

Before the eyegaze will be detected, two kinds of individual calibrations for each subject are performed by gazing two or more markers, 5–20 markers in general on the display.

At first, as described in Sect. 2.3, a reference angle  $\alpha$  in Eq. (6) are estimated. Figure 4 shows 34 indices and 9 calibration points. In our study, the gaze for the center calibration point in Fig.4 is assumed as a reference gaze. In the following calibration process, the subject gazes some calibration points. We know the angle  $\theta$  for each calibration point beforehand, and the length f is obtained from the frame. The eyeball radius S and the iris radius I are set as 9.6 mm and 5.75 mm, respectively based on the physiological model. By substituting those parameters in Eq. (6), Then, the estimated reference angle  $\alpha'$  is decided as mean of the estimated results for all reference points.

The purpose of the next calibration is to approximate

· A				·С				В·
	٠	•	•	٠	•	•		
	٠	•	•	٠	•	٠	•	
·С	٠	•	٠	٠	٠	٠	٠	С·
	٠	•	٠	٠	٠	٠	•	
	٠	•	٠	٠	٠	٠	٠	
·В				· C				Α·

Fig. 4 Indices and calibration points.

the movement of the eyeball rotation center depending on the eyegaze direction. The rotation control of the human eyeball by the extraocular muscle is different depending on the direction. In addition, for the eyeball rotation to vertical direction, the involution movement is also appended to that. As mentioned in Sect. 2.3, the movement of the eyeball rotation center depending on the eyegaze direction is realized by adjusting the eyeball radius S in Eq. (6). The eyegaze angle is calculated by considering the eyeball center movement using the calibrated eyeball radius S' as follows:

$$\theta = \sin^{-1} \frac{f + \sin \alpha' \sqrt{S'^2 - I^2}}{\sqrt{S'^2 - I^2}} - \alpha'.$$
(7)

In this study, we divide the display into some blocks based on the direction of the eyegaze. The radius S is calibrated for vertical and horizontal directions separately in each block. First, the display is divided into four blocks around the reference point. In the case of 8-points calibration, right and left-hand calibration points C in Fig. 4, are used for the horizontal rotation when the vertical rotation is a small. Top and bottom calibration points C, are used for the vertical rotation when the horizontal rotation is small. Then the eyeball radius has to be decided in 9 directions, so the target display is divided into each 6 blocks with different forms in the horizontal and vertical directions, respectively. A user gazes a calibration point of the upper left, and the shift value f in Eq. (7) is calculated. Then, the personalized radius S' is calculated so that the amount of the rotation of the eyeball may become to -20 degrees for horizontal direction and -15 degrees for vertical directions. The same adjustment procedure proceeds to the other calibration point. In the case of 4-points calibration, each block has one calibration point. Then, calibrated length  $S'_h$  for a horizontal rotation and  $S'_{\nu}$  for a vertical rotation are obtained from one calibration point.

Initial value S = 9.6 mm obtained by Gullstrand's No.2 schematic eye and Emsley's schematic eye. The average of S' and S is adopted as calibrated radius if |S' - S| < 1.0 mm. If  $|S' - S| \ge 1.0$  mm, it is judged that the subject's



Fig. 5 Actual images in the vicinity of eyes.

eyeball size was far from the size of the schematic eyeball models or the eyeball didn't rotate ideally. In this case, S' is used directly as a personalized radius. By using the calibrated eyeball radius S', the optimum reference angle  $\alpha'$ might be changed. However, in our experiment, repeatedly optimizing  $\alpha$  did not influence the detection result. As mentioned in Sect. 2.3, our model is constructed assuming the adult's schematic eye. Therefore, the error increases for junior subjects whose size of the eyeball is too smaller than adults. In that case, we have to determine the eyeball radius S and the iris radius I based on other physiological knowledge.

In the conventional algorithms, calibrated parameters have been optimized with the constant values for all directions. A main advantage in this study is the controllable calibration parameters according to the eyegaze directions.

#### 2.5 Iris Detection

Figure 5 shows actual images in the vicinity of the eyes. The proposed technique does not require any optical condition unlike techniques based on the pupil image. We use the iris as a feature for gaze estimation. Concretely, we detect the eyegaze from the amount of the shift at the iris center. Therefore, it is necessary to extract the position of the iris from captured face images.

In the proposed algorithm, edges in a captured frame are firstly detected by using the well-known Sobel filter after the binarization. The Hough transform is applied to the detected edges, and the position of the iris is extracted. The condition of light sources and camera resolution may influence to steady iris extraction. In our experiment, there is enough luminance difference for separating the iris and white eye under general illuminations. The iris hiding by the eyelid and the eyelash may occur to the false iris detection. However, the Hough transform is a comparatively robust method for the hiding problem. In our experiment, the steady iris extraction can be realized from half data of the iris boundary. The required resolution for steady iris extraction will be discussed by the angle resolution in Sect. 3.1. Details of the camera condition necessary to capture the eve movement will be also described in Sect. 3.1.



**Fig.6** Iris detection process. (a) a binarized image, (b) edge detected image, and (c) estimated iris image by the Hough transform.

Figures 6 (a), (b) and (c) show a binarized image, the extracted edges and the iris image extracted by the Hough transform, respectively. The coordinates of the iris center can be obtained from the iris image, and the amount of the shift at the iris center can be also extracted by comparing with the coordinates of a reference iris captured in the calibration stage in Sect. 2.4. The opposite eye to the gaze direction may be blinded widely by the eyelid and the eyelashes. Therefore, we use the left or right iris according to the direction of eyegaze. Then the amount of the shift at the iris center can be used to the eyegaze detection in the next subsection.

#### 3. Experimental Results of Eyegaze Detection

#### 3.1 Experimental Environment

The proposed method is here demonstrated for the display interface. Subjects are six males and two females. In the experiment, a reference point is set on the center of display, and that the subject with the naked-eyes sits in front of the reference point. The subject fixates his eye to the front, thus the effect of the direction of his face can be suppressed. Each subject tested by two times. As a subject sits in front of the eyegaze display, a monocular video camera mounted below the monitor observes one of the subject's eyes. The distance from the display to the eyeball of the subject sitting on the chair is set with 400 mm, which is a widely usable distance.

The capture size of the iris is important. In our model, the rotation of the eyeball is converted into the shift of the iris center in the two dimensional image. Because of obtaining the shift of the iris center from Eq. (5), the minimum shift is 0.5 pixels. Here, let introduce "Angle resolution" for defining the eyeball rotation angle according to this minimum shift. The angle resolution is a factor dominating the eyegaze detection, and it depends on the iris image size to be captured. Therefore, we need to decide the required gaze detection accuracy, before setting the experimental system such as the used camera and devices. In Sect. 4, we apply the proposed method for a keyboard interface. The size of each key is 5 deg. in the viewing angle. Therefore, the user often miss-types the key, when the average of gaze detection error over 2.5 deg. Based on this key size, we need to set the average of gaze detection error to be within 2.5 deg.

We calculate pixels of the iris diameter necessary to achieve this accuracy based on the simulation using the actual images. The limit of the angle resolution is 2.5 deg., *i.e.*, the required eyegaze detection error is within 2.5 deg. This angle resolution may not be so practical, because that the obtained eyegaze sifts by 2.5 deg. as the extraction of the iris deviates slightly by 0.5 pixel.

The designed eyegaze detection error and the angle resolution for satisfying it may be related each other, and they need to be well discussed. In this study, we decide the required angle resolution as one fifth of the angle resolution's limit. This angle resolution was enough experimentally. When the angle resolution is required within 0.5 deg., it is desirable that the iris size to be captured is larger than 60 pixels. Therefore,  $520 \times 320$  image size is at least necessary for satisfying this requirement. This camera condition is enough also for steady iris extraction by the Hough transform.

In this study, the face image was taken with the digital video camera, Panasonic NV-GS200K ( $640 \times 480$ ), which is at the distance 120 mm apart from the display. The standard angle  $\alpha$  in Eq. (6), which is actually estimated in the calibration process, is around 27 deg. and the camera resolution is about 165  $\mu$ m/pixel. Therefore, the length of the iris diameter is about 70 pixels, which correspond to  $2I \approx 11.5$  mm. If the standard model S = 9.6 mm is assumed as an observer's eveball radius, the movement of one pixel on the camera corresponds to the viewing angle 1.4 deg. Figure 7 shows example of captured frames. Each subject was irradiated from a little upper behind of him with a fluorescent lamp. The jaw of subject is fixed on the plate. Additionally, since the proposed system works under the fixing head pose, the square patch  $(11.5 \text{ mm} \times 11.5 \text{ mm})$  on the face can be used to correct slight movement of the face by manual operation.

In the experiment, 34 indices without the center index are displayed. The size of each index is 2.45 mm, which is 7 pixels on the display. The center index is used as the reference point. The experimental procedure is as follow:

(1) One index is displayed.

(2) Subjects gaze the displayed index.

(3) Button is pushed by the subject when thinking that he gazes.

(4) When the button is pushed, the face image is captured, and a next index is displayed.

The direction of the eyegaze from the reference point is calculated for each selected indices by using Eq. (6).

# 3.2 Calibration

We test three kinds of calibration points which are 2-points,



(c) Subject C (female)Fig.7 Examples of captured frames.

4-points and 8-points calibration. In order to compare the effectiveness of our multiple eyeball's radius S' with one of a single radius, least mean square (LMS) algorithm is used. In the experiment, the face image was always captured in 8-points calibration. Only the calibration frame was reduced in the 2-points calibration and 4-points calibration to make a fair comparison. More detail is as follow;

(1) Four eyeball radius S' are optimized from 2-points calibration.

(2) Eight eyeball radius S' are optimized from 4-points calibration.

(3) Twelve eyeball radius S' are optimized from 8-points calibration.

In 2-points calibration, we use calibration points A: one shifts -15 deg. vertically and -20 deg. horizontally out of the reference point, other +15 deg. vertically and +20 deg. In 4-points calibration, we add points A to calibration points B: one shifts -15 deg. vertically and +20 deg. horizontally out of reference point, other +15 deg. vertically and -20 deg. In 8-points calibration, we add points A and B to calibration points C: one shifts  $\pm 15 \text{ deg.}$  vertically and 0 deg. horizontally out of reference point, other 0 deg. vertically and  $\pm 20 \text{ deg.}$ 

#### 3.3 Results of Eyegaze Detection

Tables 1, 2 and 3 show the average of the eyegaze detection error for eight subjects of each number of calibration points. Table 4 shows the average of the eye gaze detection error at all indices. The matrix corresponds to the position of 34 indices on display. As shown in Table 4, we can verify

	(d) Horizontal aneedion error.								
2.03	1.90	1.47	0.87	1.30	1.22	1.40			
3.34	2.95	1.76	2.17	1.38	1.45	1.18			
4.41	4.95	2.95		0.73	0.99	1.04			
0.75	0.88	0.77	0.75	0.71	0.67	1.90			
0.25	0.32	0.59	1.07	2.13	3.75	3.76			

Table 1	Eyegaze detection error of 2-points calibration, (degree	:)
	(a) Horizontal direction error	

(b) Vertical direction error.								
3.92	3.15	3.23	2.60	2.45	1.96	1.36		
2.52	2.12	1.98	2.21	2.11	1.15	1.22		
1.55	1.14	1.44		0.87	0.51	1.32		
0.76	0.43	0.51	0.77	1.75	1.07	1.34		
0.69	0.99	1 23	0.88	2.16	1 78	1.5		

 Table 2
 Eyegaze detection error of 4-points calibration, (degree).

 (a) Horizontal direction error
 (a) Horizontal direction error

	(a) Horizontal direction error.								
0.79	1.86	0.96	0.81	1.30	1.22	1.40			
2.91	2.77	1.25	2.11	1.38	1.45	1.18			
2.85	3.51	2.40		0.73	0.99	1.04			
0.75	0.88	0.77	0.75	1.17	1.05	1.19			
0.25	0.32	0.59	1.07	1.01	1.46	0.66			

(b) Vertical direction error.							
1.70	1.20	1.37	1.48	2.45	1.96	1.36	
1.36	1.35	1.14	1.59	2.11	1.15	1.22	
1.55	1.23	1.56		0.87	0.51	1.32	
0.76	0.43	0.51	0.77	1.47	0.88	1.02	
0.69	0.99	1.23	0.88	0.94	0.96	0.54	

 Table 3
 Eyegaze detection error of 8-points calibration, (degree).

 (a) Horizontal direction error

	(d) Holizolital direction error.							
0.79	1.86	0.96	0.81	1.30	1.22	1.40		
1.37	1.68	0.93	2.11	1.48	0.87	1.25		
2.13	2.38	1.76		0.56	0.68	0.87		
1.30	2.16	0.46	0.75	0.64	0.37	1.41		
0.25	0.32	0.59	1.07	1.01	1.46	0.66		

(b) Vertical direction error.								
1.70	1.20	1.81	1.85	1.59	1.96	1.36		
1.36	1.35	1.34	1.26	1.22	1.15	1.22		
1.55	1.23	1.56		0.87	0.51	1.32		
0.76	0.43	0.31	0.54	1.31	0.88	1.02		
0.69	0.99	1.02	0.83	0.63	0.96	0.54		

 Table 4
 Average of eyegaze detection error (variable).

	Horizontal	Vertical
2-points calibration	1.70	1.61
4-points calibration	1.32	1.19
8-points calibration	1.14	1.13

that the accuracy of eyegaze detection is improved according to increase the calibration point. This means that the error is suppressed by 8.3–11.9 mm at 400 mm apart from the display.

The proposed calibration method is compared with the average of LMS fitting. The average of the eyegaze detection error using LMS is shown in Table 5. As shown in the table, the eyegaze detection accuracy using the optimized radius of the eyeball is lower than using the variable radius

Table 5	Average of	eyegaze	detection error	(fitting	by LM	S)
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	Horizontal	Vertical
2-points calibration	1.78	2.00
4-points calibration	1.75	1.93
8-points calibration	1.69	1.73

 Table 6
 Variance of eyegaze detection error (variable).

	Horizontal	Vertical
2-points calibration	2.88	2.08
4-points calibration	1.39	1.37
8-points calibration	1.10	1.21

 Table 7
 Variance of eyegaze detection error (LMS).

	Horizontal	Vertical	
2-points calibration	2.66	3.52	
4-points calibration	2.54	2.97	
8-points calibration	2.51	3.19	

#### of eyeball.

Table 6 and Table 7 show the variance of gaze detection error using the variable radius and using optimized radius. This result has the tendency similar to the result of the gaze detection error. For detecting the steady eyegaze, it is necessary to increase the calibration points. The radius of eyeball should decide according to the eyegaze directions. The number of calibration points can be changed according to the required accuracy of application.

The mean time required for gazing one index is about 1.25 sec. The processing time of eyegaze detection using the eyeball model is under of 0.0001 second. The processing time required for detecting the iris by the Hough transform is about 10 sec. This processing time can be reduced with the hardware. For example, it can be improved about 0.02 sec., when the high speed image processing board for the Hough transform is used. Anyway, the results show that our system has enough accuracy for the application. Therefore, the proposed approach can be used for the support system for the machine interface, rough eyegaze pointer, etc.

The proposed algorithm, which is quite simple eyegaze detection, gives good results. Since we treat the fixed case in this paper, development into a head free condition will be simple. The correction for the errors, except for the personal error of the eyeball shape, may be also required. While, results by video-based method tend to be affected on the shooting condition dependent on the obtained images. For using the low brightness camera, more robust iris detector may be required to attain higher accuracy, because the iris zone on the image is narrower.

#### 4. Application for Eyegaze Keyboard

We also developed an eyegaze communication interface using the proposed method. A user can operate this eyegaze communication system by looking at square keys that are displayed on the control screen. Japanese syllabary is written on the visual keyboards. Then the simple word processing can be realized by looking at each key in turn.



Fig. 8 Japanese syllabary keyboard.

#### 4.1 Experimental Environment

Figure 8 shows two types of keyboards "*normal*" and "*interactive*" on the display. When the distance of sight is 400 mm, the size of each key on the *normal* keyboard is about five degrees as shown in Fig. 8 (a). The key size was determined by constructing an actual application system that efficiently spread Japanese 50 "hiragana" syllabary keys over a 15 inch display device. In the case of an *interactive* keyboard, the size of a gazed key and surrounding six keys were increases by 1.2 times that of "*normal*" as shown in Fig. 8 (b). Figure 9 shows the example of subject under the experiment.

Subjects are five males. Short sentences are input by visual key typing using subject's eyegaze. The experiments on eyegaze detection for full display were described in Sect. 3. Therefore, we focus on the designing of keyboard based on the key typing experiment with short sentences by the subjects. Input sentences used in our experiment are as follows.

こんにちは ありがとう

Sentences are composed of ten characters in all. Only "5" is prepared two sizes of the font in the square of the key: 20 and 45 point to research the relation between the font



Fig. 9 Operation of visual keyboard.

Table 8Correct rate of eyegaze typing.

	A	В	С	D	Ε	Ave.
Normal	95%	85%	90%	90%	100%	92%
Interactive	95%	95%	90%	100%	100%	96%



Fig. 10 Fixation maps of two font-sizes key.

sizes and the concentration of the eyegaze. These font sizes are about one and three degrees in the viewing angle. The sizes of the key are five degrees in the viewing angle. As for the calibration, proposed 2-points calibration is selected. Experimental environment is almost same as the eyegaze detection experiment described in Sect. 3.1. Each subject performs three tests. The direction to the eyegaze from the reference point was calculated for each selected keys by using Eq. (7). The button is pushed by the subject to decide the key with his gazing.

# 4.2 Results of Eyegaze Key Typing

Table 8 shows the correct rate of eyegaze typing for each subject. In this experiment, five subjects perform two tests for gazing ten characters, respectively, that is 100 points in total. Subjects expended about 24 seconds to input two sentences when the first experiment without the practice.

The average correct typing rates for the *normal* keyboard and the *interactive* keyboard were 92% and 96%, respectively. The correct typing rate for the *interactive* keyboard is more accurate as compared with the *normal* keyboard. The character with a lot of failures was  $\Box$  and  $\vartheta$ . Figure 10 shows fixation maps of two font-sizes key.

Ten black points show the detected eyegaze. There was no significant difference between results of the two font sizes. In general, people can clearly see the scene in two degrees. Therefore, it can be considered that there is no effect of the detection accuracy due to the font size. The deviation of points in the fixation maps may depend on the camera resolution and the position of a gazing target. The detailed analysis will be required for designing useful and efficient applications.

# 5. Conclusions

In this paper, a simple eyegaze detection algorithm and its application to the eyegaze keyboard were described. It is non-contact with the subject and does not need to use any specific equipment excluding the monocular video camera. Moreover, this method needs neither the reference light nor the infrared rays, and it does not require any optical condition. In the proposed system, we assumed that all users have the same eyeball size based on physiological eyeball models, but we calibrated the physiologic movement of the eyeball center depending on the gazing direction by approximating it as a change in the eyeball radius.

In the verification experiment, the average of the eyegaze detection errors was within 1.1–1.7 deg. for the horizontal and vertical directions. We developed two types of eyegaze keyboard systems as an example of its application. The average correct typing rates for *normal* keyboard and *interactive* keyboard were 92% and 96%, respectively.

The system proposed in this paper detects eyegaze independently in each frame. Though the proposed algorithm uses a low-resolution camera, it takes much time for eyegaze detection. For the actual applications, the processing time between frames still needs to be reduced. Moreover, taking account of the gap of an eyegaze and an optical axis, the camera positions, etc. is future work. Especially, the decision of the best number of calibration points and the optimum position are important problems. Additionally, we experimented under the head fixation condition in this paper to verify the effectiveness of the model. When the severely handicapped users such as quadriplegics use this device, the head fixation is more effective condition. We have to detect the orientation of the face when healthy person use this device. The search area of the iris extraction is expanded to the entire image for developing it into one with the head free condition. An improved Hough transform method may be useful to solve this problem. Here, the observation and analysis of the user's gazing action including the error correction is an interesting subject. As the viewpoint of the actual application, reducing the mental stress becomes an important problem in the future works.

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