Eye-gaze Detection by Image Analysis under Natural Light

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Abstract. We have developed an eye-gaze input system for people with severe physical disabilities, such as amyotrophic lateral sclerosis (ALS). The system utilizes a personal computer and a home video camera to detect eye-gaze under natural light. Our practical eye-gaze input system is capable of classifying the horizontal eye-gaze of users with a high degree of accuracy. However, it can only detect three directions of vertical eye-gaze. If the detection resolution in the vertical direction is increased, more indicators will be displayed on the screen. To increase the resolution of vertical eye-gaze detection, we apply a limbus tracking method, which is also the conventional method used for horizontal eye-gaze detection. In this paper, we present a new eye-gaze detection method by image analysis using the limbus tracking method. We also report the experimental results of our new method.

Keywords: Eye-gaze detection, Image analysis, Natural light, Limbus tracking method, Welfare device.

1 Introduction

Recently, eye-gaze input systems were reported as novel human–machine interfaces [1], [2], [3], [4], [5]. Users can use these systems to input characters or commands to personal computers. These systems require only the eye movement of the user as an input. In other words, the operation of these systems involves the detection of the eye-gaze of the users. As in the case of our study, these systems have been used to develop communication aid systems for people with severe physical handicaps such as amyotrophic lateral sclerosis (ALS).

We have developed an eye-gaze input system [4], [5]. The system utilizes a personal computer and a home video camera to detect eye-gaze under natural light. Eye-gaze input systems usually employ a non-contact-type eye-gaze detection method. Natural light (as well as artificial light sources such as fluorescent lamps) can be used as a light source for eye-gaze detection. The eye-gaze input systems that operate under natural light often have low accuracy. Therefore, they are capable of classifying only a few indicators [2]. To resolve this problem, a system using multi-cameras is proposed [3].

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We have developed a new eye-gaze input system, which employs multi-indicators (27 indicators in 3 rows, and 9 columns) [4]. This system comprises a personal computer and a home video camera. In other words, the system is not only inexpensive but also user friendly; therefore, it is suitable for personal use such as in welfare device applications. In addition, we developed an application system for our eye-gaze input system that supports personal computers (Microsoft Windows XP or Vista), English and Japanese text input, web browsing, etc. [5].

The practical eye-gaze input system described above is capable of classifying the horizontal eye-gaze of users with a high degree of accuracy [4]. However, it can detect only three directions of vertical eye-gaze. If the detection resolution in the vertical direction is increased, more indicators will be displayed on the screen. This factor is an advantage when designing a more user-friendly interface. The conventional method developed by us for vertical eye-gaze detection is based on a similar method that uses light intensity distributions (the results of a one-dimensional projection) of an eye image. Therefore, if the resolution of the vertical eye-gaze detection increases, many eye images will be required as reference data.

To improve this point, we apply a limbus tracking method for vertical eye-gaze detection, which is also the conventional method used for horizontal eye-gaze detection. In other words, we developed a detection method for obtaining the coordinate data of the user's gazing point. This method arranges its detection area on the open-eye area of the eye image. The eye-gaze of the user is estimated by the integral values of the light intensity on the detection area.

2 Eye-gaze Detection by Image Analysis

The aim of the eye-gaze system is to detect the eye-gaze of the user. Several eye-gaze detection methods have been studied. To detect eye-gaze, these methods analyze eye images captured by a video camera [1], [2], [3], [4], [5]. This method of tracking the iris by image analysis is the most popular detection method that is used under natural light [2], [3]. However, it is difficult to distinguish the iris from the sclera by image analysis, because of the smooth transition of the luminance on between the iris and the sclera. In some users, the iris is hidden by their eyelids, which makes it difficult to estimate the location of the iris by elliptical approximation.

We propose a new eye-gaze detection method that involves image analysis using the limbus tracking method [4], [5]. This method does not estimate the edge of the iris. Here, we describe the eye-gaze input detection method in detail. The location and the size of detection area is fixed, as described below.

An overview of the horizontal eye-gaze detection method developed by us is shown in Fig. 1 (a). The difference in the reflectance between the iris and the sclera is used to detect the horizontal eye-gaze. In other words, the horizontal eye-gaze is estimated by using the difference between the integral values of the light intensity on areas A and B, as shown in Fig. 1 (a). We define this differential value as the horizontal eye-gaze value.

An overview of the proposed vertical eye-gaze detection method is shown in Fig. 1 (b). Vertical eye-gaze is also based on the limbus tracking method. We estimate the vertical eye-gaze by using the integral value of the light intensity on area C, as shown in Fig. 1 (b). We define this integral value as the vertical eye-gaze value. If the eye-gaze input system is calibrated using the relations between these eye-gaze values and the angle of sight, we can estimate the horizontal and vertical eye-gaze of the user. The details of the calibration method are described in chapter 4.

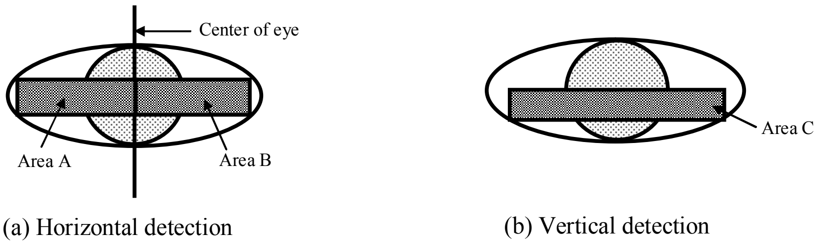

Fig. 1. Overview of eye-gaze detection

3 Automatic Arrangement of Detection Area

We are developing an eye-gaze input system, as described above. By using this system, users can select icons on the computer screen or control the mouse cursor by eye-gaze. In general, if the user's eye-gaze moves, the shape of the eyelids (upper or lower) change. We have observed that the error of detection increases with a change in the shapes of the eyelids because the shape of the detection area also changes. To resolve this problem, we developed a new method for estimating the detection area. This method extracts the exposed eye area from an eye image by analyzing the part of the image where the exposed eye area is not hidden by the eyelids. The detection area can be used to detect both the horizontal and the vertical eye-gaze.

3.1 Extraction of Exposed Eye Area

We can estimate the exposed eye area by merging the open-eye areas. The merging method uses a bitwise AND operation. The open-eye areas are extracted from eye images when the user directs his or her gaze at indicators 1 to 9, shown in Fig. 2. These open-eye areas are extracted by binarization using the color information of the skin [4]. To reduce the calculation cost without losing accuracy, we conducted pre-experiments that use some groups of indicators. Here, we used the open-eye areas extracted by the four eye images when the user directs his or her gaze at indicator 2 (up), 4 (left), 6 (right), and 8 (down). We use the exposed eye area estimated from these open-eye areas for extracting the detection area for the horizontal and vertical eye-gaze. An overview of the exposed eye area extraction is shown in Fig. 3.

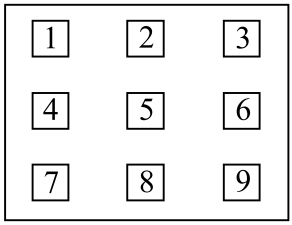

Fig. 2. Gaze indicators

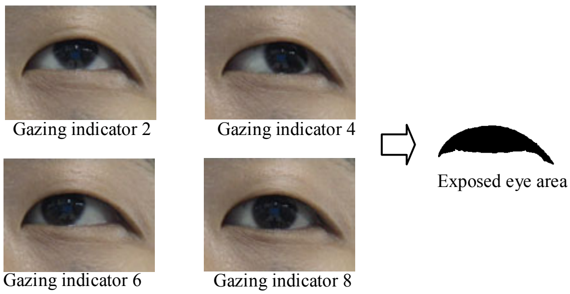

Fig. 3. Extraction of exposed eye area

3.2 Estimation of Detection Area

To utilize the image analysis based on the limbus tracking method, we have to focus the detection area on the pixels whose light intensity changes. Therefore, we estimate the detection area of the vertical and horizontal eye-gaze by using the eye images when a user looks at indicator 2 (up) and 8 (down), or indicator 4 (left) and 6 (right), respectively. First, we create an image that consists of the difference in the images captured when a user looks at indicator 2 and 8. We estimate the detection area of the vertical eye-gaze from the created image. In practical terms, the detection area for the vertical eye-gaze is arranged on the pixels with positive differences values. This process is executed inside the exposed eye area, as shown in Fig. 3.

Next, we estimate the centerline of the detection area using the horizontal eye-gaze detection method, shown in Fig. 1 (a). In practical terms, this centerline is located where the horizontal eye-gaze value is at a maximum. We estimate the horizontal eye-gaze from the eye images when a user looks at indicators 4 and 6. This process is executed inside the detection area of the vertical eye-gaze. Fig. 4 shows a sample of the detection area estimated by our proposed method.

We estimate the vertical eye-gaze by using the integral value of the light intensity on the total detection area. We estimate the horizontal eye-gaze from the difference between the integral values of the light intensity on the two detection areas split by the centerline.

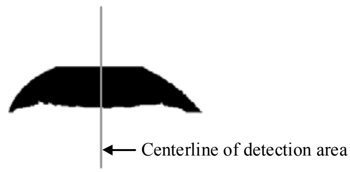

Fig. 4. Detection area estimated by our proposed method

4 Calibration

4.1 Calibration for Eye-gaze Detection

The characteristics of eye-gaze detection of our proposed method are different for different users. Therefore, the eye-gaze input system needs to be calibrated for eye-gaze detection. For typical calibration, the user looks at the indicators arranged at regular intervals on the computer screen. The system is calibrated by using these results. The characteristics of the vertical and horizontal eye-gaze are shown in Fig. 5 as a scatter plot. In Fig. 5, the abscissa axis and longitudinal axis indicate the horizontal and vertical eye-gaze value respectively. In addition, the indicator numbers (Ind. 1 to 9) are displayed near the plot points. These correspond to the indicator numbers shown in Fig. 2.

From Fig. 5, it is evident that if the eye-gaze of the user moves only in a horizontal direction, the vertical eye-gaze values do change as well. For example, indicators 1 to 3 are arranged on the same horizontal line, but the estimated vertical eye-gaze values have different values. Similarly, it is also evident that if the user's eye-gaze moves in a vertical direction only, the horizontal eye-gaze values change as well.

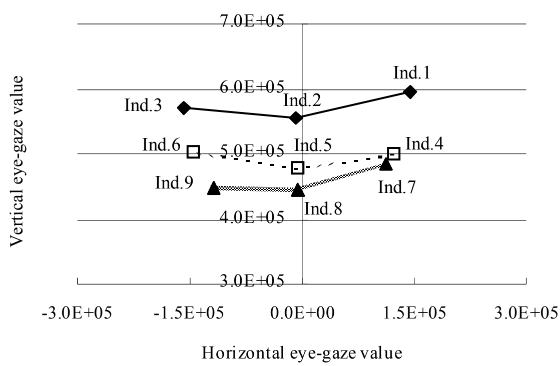

Fig. 5. Characteristics of vertical and horizontal eye-gaze (Subject A)

4.2 Calibration Method by Interpolation between Indicators

There is a dependency relationship between the characteristics of the horizontal and the vertical eye-gaze, as described in section 4.1. Considering this point, we calibrate our eye-gaze input system by using the four indicator groups. The indicators are separated into four groups, for example, “indicator 1, 2, 4, 5 (upper left group)”, “indicator 2, 3, 5, 6 (upper right group)”, “indicator 4, 5, 7, 8 (lower left group)”, and “indicator 5, 6, 8, 9 (lower-right group)”. The eye-gaze input system is calibrated by using each indicator group. An overview of the calibration method using indicators 1, 2, 4, 5 is shown in Fig. 6.

First, we note the characteristics of the horizontal eye-gaze. The characteristics from indicators 1 and 2 and indicators 4 and 5 are defined as Line l and Line m, respectively. From Fig. 6, it is evident that the gradient of Line l is greater than Line m. If the user’s eye-gaze moves down, the horizontal eye-gaze value increases. The calibration method for horizontal eye-gaze detection calculates the change in the parameters of these calibration functions to calculate their gradients. We assume that the changes in the parameters are proportional to the horizontal eye-gaze movement. We estimate the calibration function for the vertical eye-gaze detection using a similar method. If we calculate the calibration functions by using the horizontal and vertical eye-gaze values, ($V_{h1,2,4,5}$, $V_{v1,2,4,5}$), while the user looks at the indicators (Ind. 1, 2, 4, 5), we can estimate where the user is looking.

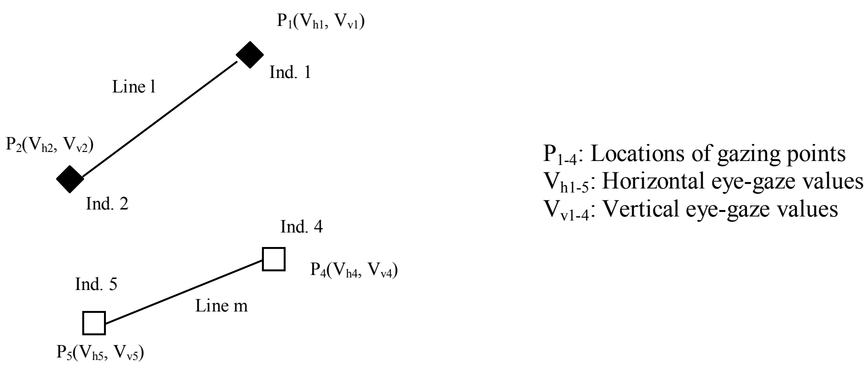

Fig. 6. Calibration method by interpolation between indicators

5 Evaluation Experiments for the Proposed Method

Evaluation experiments were conducted with five subjects. In the evaluation experiments, we detected the horizontal and vertical eye-gaze of each subjects, and then estimated the gaze-detection errors. The evaluation system was calibrated by using the method described in section 4.

5.1 Overview of the Experiment System

The evaluation experiment system comprises a personal computer, a home video camera, and an IEEE1394 interface for capturing the images from the video camera. The experiments were conducted under general room lighting (fluorescent light). The hardware configuration of the experimental setup is shown in Fig. 7. The video camera records images of the user’s eye from a distant location (the distance between the user and camera is approximately 70 cm) and then this image is enlarged. The user's head movements induce a large error in the detections. We compensated for the head movement by tracing the location of an inner corner within the eye [4], [5].

Subjects must calibrate the system before using it, as described above. While the calibration is being performed, subjects look at each of the nine indicators shown in Fig. 8 (a). If the calibration terminates successfully, the subject then looks at the indicators shown in Fig. 8 (b). We estimate the gaze-detection errors as described earlier. The indicators are square and 1.5(deg.) in size. The maximum breadths of displayed indicators are 18(deg.) (vertical) and 24(deg.) (horizontal). These sizes are shown as angle of sight.

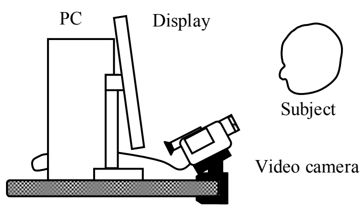

Fig. 7. Hardware configuration of experiment system

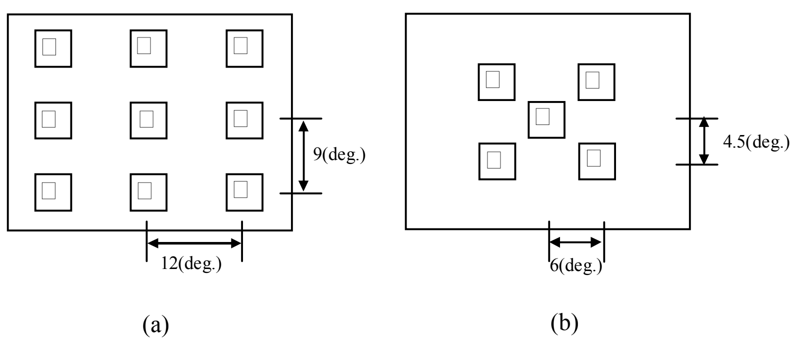

Fig. 8. Indicators for evaluation experiments

5.2 The Detection Errors of Gaze Points

Tables 1 and 2 show the gaze-detection errors of the five subjects and the results of the horizontal and vertical eye-gaze detection. It is evident that the horizontal detection errors are smaller than the vertical detection errors. We confirmed the trend for all the subjects. In practical terms, the results of subjects A, B, D, and E indicate that the errors of vertical detection are over 2(deg.). These errors are larger than the errors of horizontal detection. We confirmed that the dynamic range of the vertical eye-gaze value is narrower than the horizontal value. In the results, the negative effect of the noise on the eye image is increased. The change in illumination on the experimental conditions cause this noise.

Table 1. Detection errors of gazing points(deg.) (horizontal)

	Subject A	Subject B	Subject C	Subject D	Subject E
Ind. 1	0.29	0.11	0.72	0.33	0.53
Ind. 2	0.82	0.53	0.52	0.62	0.88
Ind. 3	0.09	0.67	0.81	1.33	0.35
Ind. 4	0.19	0.76	1.23	0.37	0.32
Ind. 5	0.50	0.01	0.33	0.82	0.78
Average	0.38	0.42	0.72	0.69	0.57
Standard variation	0.29	0.34	0.34	0.41	0.25

Table 2. Detection errors of gazing points(deg.) (vertical)

	Subject A	Subject B	Subject C	Subject D	Subject E
Ind. 1	2.53	0.20	0.62	1.53	2.06
Ind. 2	0.38	2.79	0.60	0.63	1.06
Ind. 3	1.76	1.48	0.25	1.37	0.61
Ind. 4	0.03	0.49	0.65	0.04	2.02
Ind. 5	0.07	0.16	1.31	2.93	1.78
Average	0.95	1.02	0.69	1.30	1.51
Standard variation	1.13	1.12	0.39	1.09	0.64

We can summarize the obtained results as follows: From Tables 1 and 2, it is evident that the average errors of vertical and horizontal eye-gaze detection are 1.09(deg.) and 0.56(deg.), respectively. These results indicate that our proposed method can detect vertical and horizontal eye-gaze to a high degree of accuracy, and performs as well as the detection method that uses infrared light [6]. Our conventional method is capable of classifying the horizontal eye-gaze of users with a high degree of accuracy. However, it can detect only three directions in the vertical eye-gaze. Therefore, the conventional eye-gaze input system is capable of classifying 27 indicators (in 3 rows and 9 columns). If our proposed method is used in an eye-gaze input system, the system can classify approximately 45 indicators because it can detect five indicators in the vertical eye-gaze.

6 Conclusions

We present a new eye-gaze input system using image analysis based on the limbus tracking method. This system uses a personal computer and a home video camera to detect eye-gaze under natural light. The eye-gaze detection method for our proposed system is simple. In other words, this method does not need special devices, such as infrared light. Therefore, the size of this system is small and it is highly versatile.

Our conventional eye-gaze detection method can detect the horizontal eye-gaze with a high degree of accuracy. However, it can only detect three directions in the vertical eye-gaze. Our proposed method can detect both the horizontal and the vertical eye-gaze with a high degree of accuracy. Therefore, by using our proposed method, we can estimate where the user is looking in a two-dimensional plane.

The evaluation experiments for our proposed method were conducted with five subjects. The results for the five subjects show that the average detection errors of vertical and horizontal gaze points are approximately 0.56(deg.) and 1.09(deg.), respectively. These results indicate that the eye-gaze input system using the method developed by us is capable of classifying approximately 45 indicators. In other words, the system can classify nearly double the number of indicators.

In future studies, we will develop a new detection method for vertical eye-gaze, and enhance its detection accuracy. Furthermore, we will develop a more user-friendly eye-gaze input system by using the newly developed method for eye-gaze detection.

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