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The study of remote saccade sensing system based on retroreflective feature of the retina

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Abstract

We present a new method for detecting rapid eye movements called a saccade without constraining the head, based on the fast, robust pupil detection technique [1][2]. The technique uses two infrared light sources synchronized with the camera's frame rate. The two light sources generate an image with a bright pupil and an image with a dark pupil. By taking a subtraction between the two images, we can carve out the positions of the pupils. From the series of the captured images, the change of gaze direction is measured as the displacement of the pupils' positions within the image. Measuring the displacement with a line scanning camera, which can take one line image with high frequency (more than 1kHz), the saccade can be detected. In this study we investigated the feasibility of this method by clarifying the retroreflective feature of the pupil and composed prototype system to detect saccadic eye movements.

Key words ：Saccade, Remote Measuring, Pupil Detection, Gaze Direction, Blue eyes

1. Introduction

1.1 Requirements for applications using gaze

With the improvement of measurement techniques for eye movements, many applications using eye gaze are developed. Especially, gaze as information input interfaces have been investigated [3]. Moreover, the eye gaze also plays an important role in tele-communication [4] [5] and in measuring psychological state such as attention and arousal of consciousness [6] [7]. To realize such applications, measurement techniques on eye movements require not only the spatial and time accuracy, but to free persons measured from equipments on the head, constraint of the head and calibration before the measurements.

1.2 Current remote measurement systems

Current measurement techniques on eye movements are realized by attaching a camera or an infrared sensor near the eyeball, which sense difference of reflectance between the sclera and the cornea or the infrared reflective image on the cornea (Purkinje image). The video based methods are also used, in which images around the eyeball are captured and the pupil center is carved out by image processing. Elements used in these techniques are shown in figure 1. Although these techniques enable the measurement with the high spatial and time accuracy, bothers such as equipments on the head, constraint of the head and calibration before the measurements, are forced. Therefore, it is difficult to perform measurement outside of experimental environments.

Most previous remote measurement techniques capture the eye with a video camera and compute the eye position by comparing displacements of the corneal light reflex (Purkinje image) with the pupil center. Due to the low frame rate of the camera this technique can't measure rapid eye movements like a saccade, which has the maximum velocity of more than 700 ms/s and the duration less than 50 ms. Moreover this technique doesn't allow head movements due to low spatial resolution. In consequence, this technique is not suitable for the following applications. The remote measurement for nystagmus patients should be performed with high spatial and time resolution [8]. The information display using the Saccade-based display [9], which can display images by presenting one line image during a saccade, requires real time information of the eye position with high time accuracy.

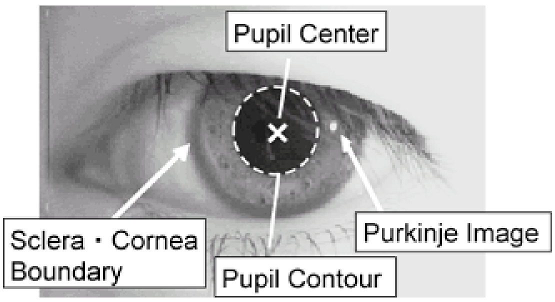

Fig. 1 Elements used in measurements

Consequently, we present a new method for detecting rapid eye movements called a saccade without constraining the head, based on the fast, robust pupil detection technique [1] [2]. In this paper, we investigated the feasibility of this method by clarifying the retroreflective feature of the retina and composed prototype system to detect saccadic eye movements.

2. Proposed method

In this paragraph, we will describe the principle and characteristics of the proposed method.

2.1 Principle of the method

The proposed method is based on the fast, robust pupil detection technique [1][2]. The technique uses two infrared light sources synchronized with the camera's frame rate. The two light sources (one is on the optic axis of the camera, the other is off the axis) generate an image with a bright pupil and an image with a dark pupil. By taking a subtraction between the images we can carve out the positions of the pupils as shown in figure 1a. From the series of the captured images, rotation of the eyeball is measured as the displacement of the pupil's position. Measuring the displacement with a line scanning camera, which can take one line image with high frequency (more than 1kHz), rapid eye movements can be detected (figure 1b). The line scanning camera is used due to its high temporal resolution. If an area camera is available, which can capture the same large area as the line scanning camera, we can use it instead of the line scanning camera.

The composition of our method is shown in figure 1c. A half mirror is installed to set the on-axis infrared LED on the optic axis of the camera. A lenticular lens is attached in front of the camera in order to extend retinal retroreflective light perpendicularly, since elements of the line scanning camera are arranged only horizontally. Infrared LEDs of on-axis and off-axis shine alternately, and then, horizontal pupil positions can be acquired by subtracting each captured images.

Considering the spatial resolution of this method, when the eyeball, whose diameter is 26 mm, rotates by 1 deg horizontally, the pupil center moves 0.23 mm horizontally. When the displacement is captured by the line scanning camera from 1m's distance, which has 3000 elements horizontally and 30 deg field angle. One element of the camera (one pixel) occupies 0.18 mm, which corresponds to about 1 deg of the rotation. Therefore saccades, whose amplitudes are about 10deg, can be measurable by this method.

2.2 Characteristics of the method

Previous remote measurement techniques needed a high resolution image around the eye. Specifically, it was reported that the eye movement can be measured with 0.5 deg accuracy when the pupil image is described in 160 x 120 pixel [10]. When the vicinity of the pupil is captured, resolution more than standard NTSC (640 x 480 pixel) is needed. Additionally, when the whole head image is captured to allow head movements and to measure with 0.5 deg accuracy, more than 2000-3000 pixel in resolution are needed, as shown in figure 3. However, normal area camera cannot acquire an image with both high spatial resolution and high frequency at the same time. Therefore, if a normal camera is used, the allowance of the head movement leads to the low frame rate. Previous techniques contain a tradeoff between the measurement frame rates and the head movement, which is determined by the spatial resolution. On the other hand, our method realizes high temporal accuracy and allowance of the head movements, at the sacrifice of vertical resolution.

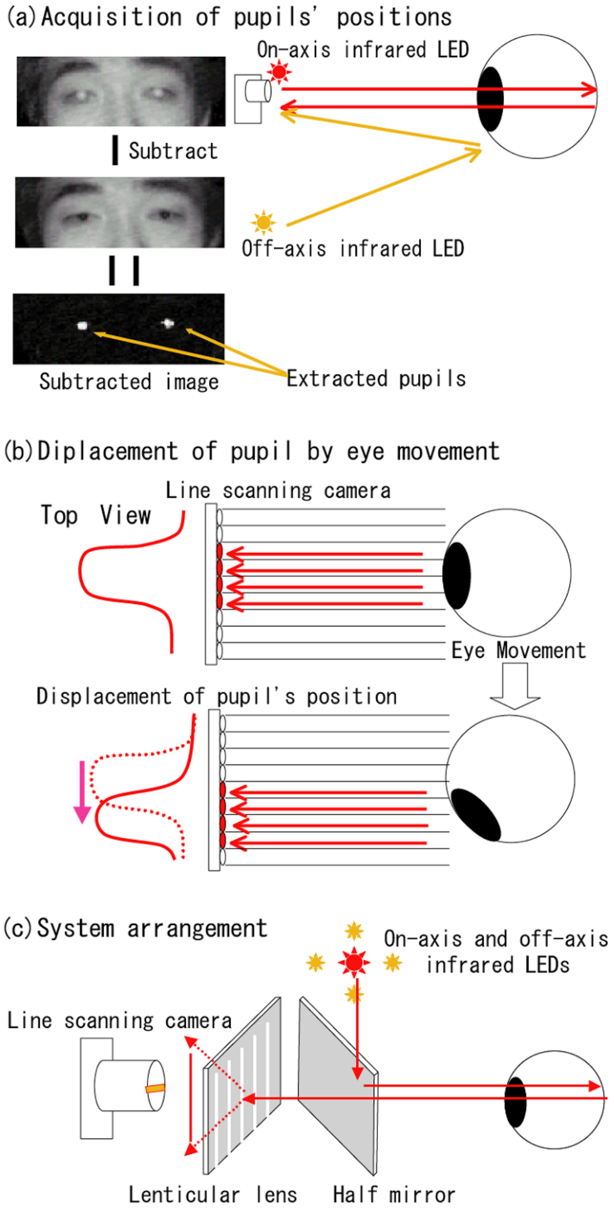

Fig. 2 Principle of proposed method

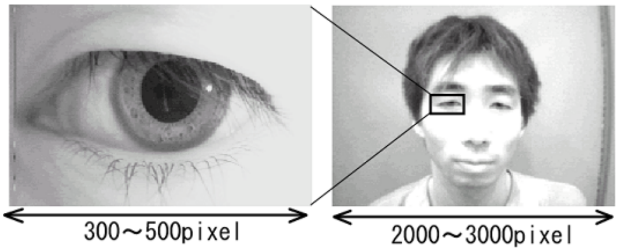

Fig. 3 Resolution required for measuring eye movement

2.3 Requirements to realize proposed method

In order to realize our method, it is necessary to investigate the relation between gap of the light source to the optic axis and the amount of retinal reflection, and the relation between gaze angle to the axis and the amount of retinal reflection. However, few researches have been performed about retororeflective features of the retina, which is used as the basic principle in our method. Therefore, we investigated the feasibility of our method by clarifying the retroreflective feature of the retina.

3. Retroreflective feature of the retina

3.1 Apparatus and procedure

Experimental arrangement is shown in figure 4. Since this experiment was intended to investigate the retroreflective feature of the retina, the head was fixed with the chin rest. The subject fixated the eye gaze to one of the fixation points and the amount of retinal reflection from infrared LED was measured with a USB area camera. The camera's frame rate is 30Hz, the resolution is 320 x 240 pixel, and the angle of view is 92.6 deg. The distance between the eyeball of the subject and the camera is 25 cm. In the captured image, the eyeball occupied approximately 50 pixels horizontally. IR pass filter was installed in front of the camera to eliminate noise. The infrared LED (Light Emitting Diode) was placed on one place of the 11 points, placed from –5 to + 5 deg, varying 1 deg each. The LED is displaced to the optical axis of the camera via half mirror. The LED's peak wave length is 880 nm, emitting angle is 120 deg, and emissive power is 60mw/sr. The fixation points are set from –40 to +50 deg by 10 deg. Therefore there are 110 combinations for LED's positions and fixation points. In the experiment, the eyeball was captured for three second (90 frames) and then, the subject kept the eye gaze to a point. While the subject fixated a point, the position of the LED is changed by 11 steps and the eye image was captured in each step. Additionally, in the condition of fixation 0 deg, the measurement was done in 2 lighting condition, in a dark room (0 lx) and indoor (100 lx). In other conditions, measurements were done only inside the dark room. The subjects were two naïve male with normal visual accuracy. A typical result is shown in the following figures.

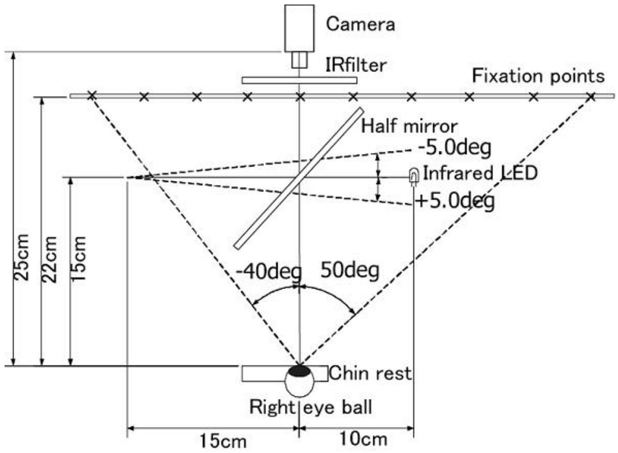

Fig. 4 Experimental arrangement

3.2 Image processing

Image processing for the analysis of the obtained images are as follows. First, 50 frames are extracted from the movie file obtained in one trial, and the average image among the 50 images is calculated. The image is translated into 256 level grayscale, and then, the histogram of the brightness is equalized to adjust the contrast. Second, a pupil contour was extracted as a pupil extract filter from the image, where the infrared LED is on the camera's optical axis. When the subject keeps the gaze on one point, since the head is fixated, the area and location of the pupil doesn't change. Therefore, the filter was multiplied to the other images obtained in the condition of other LED's position. This process was performed to all data, and then, the sum of brightness in the pupil area, the area of the pupil and the brightness per unit pixel are computed.

4. Results of the experiment

4.1 Gap between LED's position and optical axis

Figure 5a shows the amount of retinal reflection when the subject fixates the eye at 0 deg. The horizontal axis represents the gap angle [deg] between the LED's position and the optic axis of the camera. The vertical axis represents the sum of brightness in the pupil area. The square and triangle symbols represent the results from the conditions in the dark room and the indoor, respectively. In both conditions, when the gap is 0 deg, the sum of brightness takes the maximum. The value of brightness decreases as the gap angle increase until around 3 deg. This means that the retroreflective light from the retina is unobservable when the LED position is separated by more than 3 deg from the camera axis. Therefore, the two LEDs used for collecting the images for bright and dark pupils should be separated by at least 3 deg. The fact that the same tendency was observed in the indoor condition, means that this method can be used indoors. The maximum value of the indoor condition is smaller than in the dark room condition. This can be caused by the shrinkage of the pupil. As to the size of the pupil, the principle of this method is based on the displacement of the pupil. Hence, the size is not concerned with the accuracy of the measurement. However, the size of the pupil can have an influence on the spatial measuring range.

4.2 Differences according to the fixation position

Figure 5b shows the results with regard to the fixation positions from –20 to +30 deg. Though the data was obtained from –40 to 50 deg, same tendencies were observed. Therefore, the data from –20 to +30 deg are shown. The horizontal and vertical axes are same as in figure 5a. Same tendency is observed in all data that retinal reflection is no longer observed when the gap reaches 3 deg. This means that our method can detect eye positions even when large eye movements like a saccade, whose amplitude is more than 10 deg, are performed. When the maximum values in each condition are compared, the value in 0 deg fixation condition takes the maximum. As the fixation point becomes further from 0 deg, the maximum value decreases. Figure 5c shows that as the eyeball rotate, the brightness per pixel doesn't change, regardless of the decrease of the pupil area. Therefore, it is likely that the amount of the retinal reflection decreases due to the decrease of the captured pupil area.

4.3 Pupil's displacement by eye movements

When the subject changes the gaze direction, the pupil position within the image is displaced. Figure 5d shows the displacement of the pupil position according to the rotation of the eyeball. This figure was made by subtracting the image of LED 0 deg condition and the image of LED 3deg condition, and then, by extracting the line that passes through the pupil's center in each fixation point. The horizontal axis represents the position measured from the right tail of the eye [pixel] or [mm]. The vertical axis represents the brightness of each pixel (256 level). The measured value of pupil displacement coincided with the expected value when assuming that the eyeball is a sphere with 13 mm radius. When the eyeball rotates by 30 deg, the displacement of the pupil center is 6.5 mm.

4.4 Summary of the experimental result

The consequences of the experiment are as follows. The LEDs for the bright and dark pupil should be separated by more than 3 deg to extract the pupil position efficiently, and the pupil position is detectable even during large eye movements like a saccade. Additionally, the displacement of the pupil in the captured image coincides with the expected value by the physical model of the eyeball. Since the retoreflective feature is a stable phenomenon regardless of the fixation position, the variation of the retinal reflection is caused by the change in the captured pupil area.

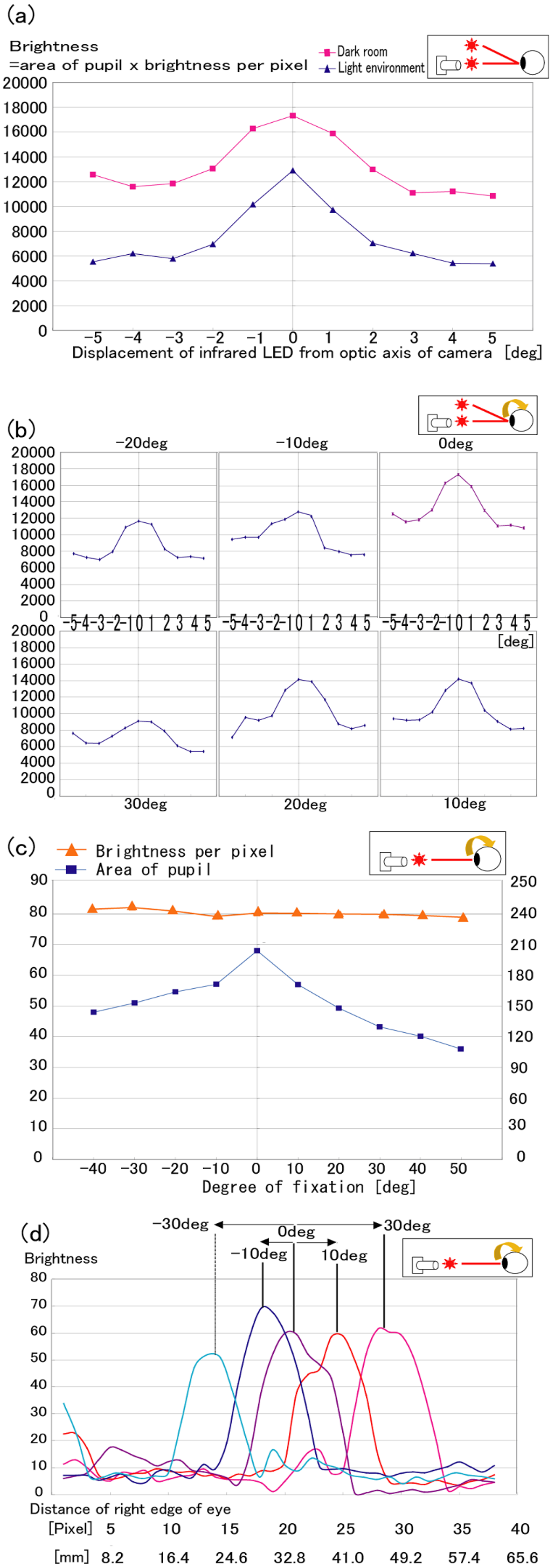

Fig. 5 Experimental result

5. Other factors to be discussed

5.1 Influence of the lenticular lens

Our method realizes high time accuracy by using a line scanning camera. However, since the line scanning camera has only one vertical element, it is necessary to install a lenticular lens in front of the camera in order to spread the image vertically. In this section, we will discuss the influence of the lens. Figure 6 shows the subtracted images captured without and with the lenticular lens. The positions of the pupils are detectable, when the lens is not used, even if the subtracted image contains other less bright areas. However, when the lens is used, the other bright areas are spread out and the brightness is added. Consequently, it prevents the detection of the pupils. When the lenticular lens is used, the areas excluding the pupil should be captured in the same luminance. The human face, however, doesn't reflect the lights as the mirror, therefore, in order to match the brightness, elaborate model of the human face should be used or adjust the luminance of the LEDs by sensing the brightness. Another practical way is to use a partial scan camera, which can take a line image of arbitrary vertical level.

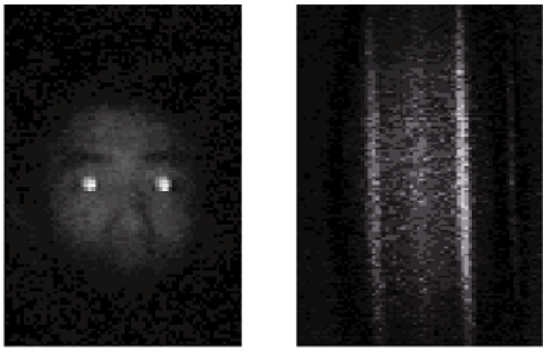

Fig. 6 Influence of lenticular lens

5.2 Segregation of head movements

One of the characteristics of our method is the allowance of head movements. The head movements, however, also cause the displacement of the pupil position. Hence, when a saccade is measured with one camera, it is needed to discriminate whether the pupil movement comes from the head movement or the saccade. Obviously, if two cameras or a marker on the head are used, we can easily discriminate the two factors.

When the translational movements to front and back are performed, the pupils of both eyes move in the opposite direction. When the subject moves to the camera, the distance between the two pupils extends. When the subject moves away from the camera, the distance between the two pupils shrinks. By contrast, both eyes move in the same direction on the occurrence of the saccade. Therefore, we can segregate the saccade and the translational movement to front and back by observing the directions of the pupils' movement.

As to the segregation of the traslational movement to right and left, it can be thought that the segregation can be done, by focusing the velocity of the movement. The maximum velocity of the saccade reaches about more than 700 deg/s, which is equivalent to 16 cm/s horizontal movement of the pupil. Assuming that the hip of the subject is fixed on the chair while the measurement is performed, it is difficult to move the head faster than 10 cm/s. Moreover, since the duration of the saccade is very short (less than 50 ms), it is effective to consider the duration.

As to the segregation of the rotation of the head, since the features of vestibulo-ocular reflex accompanied with the head rotation is similar to the feature of the saccade, the segregation with one camera is difficult.

6. Future works

The measurable parameters of this method can be extended, by using another camera(s) or a maker on the head. The possibilities of this method are shown in table 1. If a marker made from retroreflective material is attached on the head, the light from the head can also be captured, and the displacement caused by the saccade and that of the head movement can be easily segregated. When two cameras are used, the positions of the pupils on the same vertical level are determined based on the principle of the triangular surveying. Additionally, if two pupils and the maker on the head are captured by two cameras, the positions of pupils and the directions of the gazes can be measured. Moreover, one more camera for measuring the vertical position enable the measurement of three dimensional positions of the pupils.

Our method uses the retroreflective light from the retina. If another part of the body has retroreflective feature, movements of these parts can also be measured at the same time. Therefore, by attaching a marker made from retroreflective material to another part of the body, eye gazes and bodily movements can be measured simultaneously.

Table 1. Possibilities of this method

	Saccade Detection	Horizontal Eye Positon Saccade Detection	Horizontal Eye Positon Gaze Direction	3D Eye Position Gaze Direction
One camera	○	×	×	×
One camera with a marker	○	×	×	×
Two cameras	○	○	×	×
Two cameras with a marker	○	○	○	×
Three cameras with a marker	○	○	○	○

7. Conclusion

In this paper, we presented a new method for detecting rapid eye movements called a saccade without constraining the head, based on the fast, robust pupil detection technique. Specifically, we investigated the feasibility of this method by clarifying the retroreflective feature of the retina, which is basis of our method. The ability of this method can be extended, by adding camera(s) or a marker on the head. In the future, we will seek the improvement of the current system and developments of the applications.

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