High-accuracy measurement of rotational eye movement by tracking of blood vessel images*

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Abstract— **This study focuses on a technique for measuring the angle of rotational eye movement by tracking the conjunctival blood vessel ends of sclera, instead of grayscale iris patterns used in the existing techniques. It is because the blood vessel images of sclera have high grayscale contrasts. This technique especially recognizes the contour of the iris to detect the target conjunctival blood vessel end and use the degree of similarity by means of template matching to select automatically the blood vessel end to be tracked. The search region is limited by template matching to achieve low processing cost and high accuracy and resolution even when the background light varies.**

I. INTRODUCTION

When the head is inclined right or left, eye balls rotate in the opposite direction accompanying inclination of the eyesight even with the head or body inclined. Similarly, rotating images are watched, rotational eye movement occurs. Moreover, the rotational eye movement serves as suitable physiological indicators for discomfort feeling: it is because in many cases, car sickness, space sickness, visually-induced motion sickness (VIMS), 3D image- (stereoimage-) induced sickness and their accompanying dizziness and sickness feeling are associated with rotational eye movement [1][2].

However, the existing techniques for measuring rotational eye movement track the rotational components of the iris pattern (grayscale iris pattern) on the image captured by a camera. With these techniques, in the first place, the pupil diameter, as well as the form and position of the iris pattern varies depending on the ambient environment of lighting, making it difficult to measure correctly eye movement. In the second place, these techniques are sensitive to any mismatch in relative positions between the camera and the eye ball because the contrast of the grayscale iris pattern is not so high and the iris pattern is generally similar. For this reason, the measurement devices using any of these existing techniques require unavoidably a google device, which should be firmly fixed to the head by winding any of bands, such as belt [3][4]. On the other hand, if the rotational eye movement measuring system could be mounted on an ultraportable frame, the device would be light and small as a whole with less restraint, allowing it to be used for various applications. For example, in the medical setting, rotary nystagmus and dizziness can be easily measured without putting an excessive psychological load on children. Furthermore, long-time monitoring may be performed in daily life. The system, which has been mounted on a convenient see-through HMD typified by a Google Glass[5], may be used for physical health monitoring during car driving and image watching.

This study focuses on a technique for measuring the angle of rotational eye movement by tracking the conjunctival blood vessel ends of sclera, instead of grayscale iris patterns used in the existing techniques. It is because the blood vessel images of sclera have high grayscale contrasts. The conjunctival blood vessel ends, on which attention is focused, can be used to measure rotational eye movement at a constant accuracy because they are not deformed due to subject to pupillary reaction. It should be noted that all the conjunctival blood vessel ends cannot be necessarily used and only the vessel ends attached to the cornea in terms of the eye ball structure must be selected. To measure rotational eye movement correctly, it is required to recognize only the conjunctival blood vessel end to be tracked among a plurality of conjunctival blood vessel ends for obtaining accurate coordinates.

To address the above problem, this technique recognizes the contour of the iris to detect the target conjunctival blood vessel end and use the degree of similarity by means of template matching to select automatically the blood vessel end to be tracked. Such a technique for measuring rotational eye movement is proposed that to make real-time measurement, the search region is limited by template matching to achieve low processing cost and high accuracy and resolution even when the pupil diameter varies. Specifically, on the eye ball images, the y coordinate for the center of the pupil are compared with the y coordinate of the blood vessel end to select the nearest blood vessel end for tracking.

II. SYSTEM CONFIGURATION

A. Camera

As shown in Fig. 1, with no need for fixation to the head by a belt, etc., the prototype of a rotational eye movement measurement device with a wireless ultra-miniature camera attached to a light and convenient frame was made. The color camera was used with 90 degrees in angle of view and resolution equivalent to VGA. The imaging part and the wireless transmitter are driven by three AAA batteries. To the frame, a near-infrared and blue LEDs were attached. Near-infrared LED was irradiated onto the iris and the pupil to enhance iris-pupil contrast on the images. Blue LED was irradiated onto the sclera on the outside of the iris to enhance sclera-blood vessel contrast. The intensity of the near-infrared LED was set to the level, at which the images

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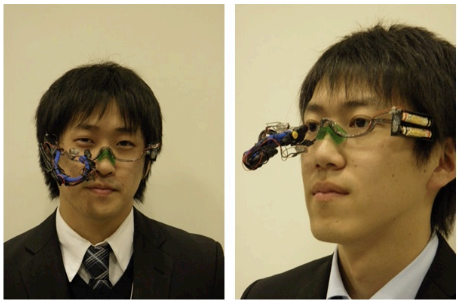


Fig. 1. Rotational eye movement measurement device.

of the pupil may be clearly captured, whereas the intensity of blue LED was set to the level, at which the subjects do not be dazzled or feel visually discomfort. The weight of the device is 85 g excluding the weight of batteries, 45 g.

B. Setting a polar coordinate system using the contour of pupil

To get the direction and angle of rotational eye movement, an elliptic coordinate system along the contour of pupil is obtained. The pupil area is characterized in that it has lower pixel values other than those of other areas; accordingly, the area with lower pixel values is obtained by image binary processing to extract the pupil area. The contour of the obtained pupil area is elliptically approximated by the least square method to set a coordinate system with 0 degree of elliptic long axis (Fig. 2). Assuming that the coordinates of the elliptic center be the origin (x_0,y_0) of the coordinate system for camera images, this coordinate system may be represented by the parameters: coordinate h along the long axis; coordinate w along the short axis; counterclockwise angle relative to the long axis; and elliptic inclination ϕ relative to the camera coordinate systemDThe equation for converting any elliptic parameters (w,h,θ) to any coordinates (x,y) of the camera coordinates is expressed in (1).

$$\begin{cases} x = x_0 + w \cdot cos(\phi)cos(\theta) + h \cdot sin(\phi)sin(\theta) \\ y = y_0 + w \cdot sin(\phi)cos(\theta) + h \cdot cos(\phi)sin(\theta) \\ w = \frac{a}{b}h \end{cases} \quad (1)$$

C. Detecting the target conjunctival blood vessel end

Prior to actual measurement, the target conjunctival blood vessel end to be tracked is automatically selected. The blood vessel end used for measurement exists in the contour of the iris. For this reason, the iris area is obtained and then the end of the conjunctival blood vessel extending from the contour of the iris is detected. To enhance the contrast between the sclera and the iris, he infrared LED is turned off and the pixel values are sampled along the arrow shown in Fig. 3 extending from the center point of the pupil ellipse obtained one frame before the infrared LED goes off. Using the intermediate value between the maximum and minimum values among the obtained pixel values as the threshold, the pixels values are referenced from the pupil side. The coordinates larger than the threshold are recorded on the sampling line as the

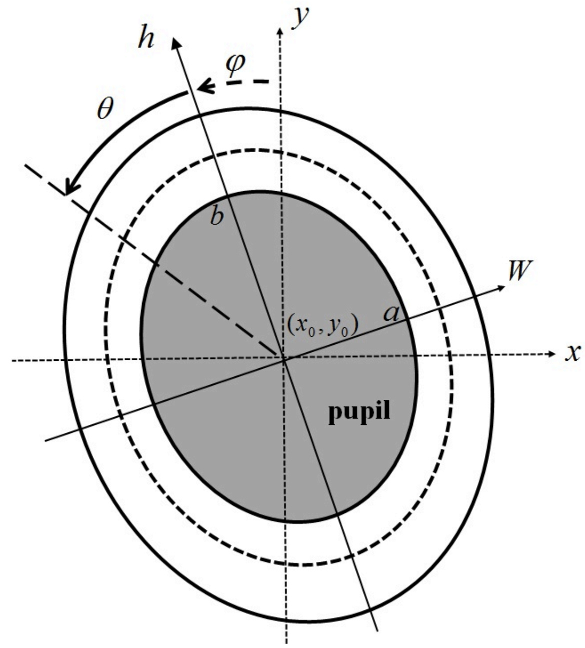


Fig. 2. Basic coordinate system using parameters for pupil-elliptic approximation.

sclera-iris boundary coordinates. The boundary coordinates are used to obtain an elliptic locus for determining the range, in which the target conjunctival blood vessel end is detected, using equation (1).

The parameters: xy coordinates for sclera-iris boundary coordinates; pupil ellipse center $x0$, $y0$; length along the long axis a; length along short axis b; and inclination ϕ of pupil ellipse are substituted into the equation and then the equation is solved to obtain the elliptic coordinates (w,h,θ) for sclera-iris boundary coordinates.

θ of the obtained elliptic coordinates is varied to convert to the camera coordinates (x,y), which gives an elliptic locus passing through the sclera-iris boundary coordinates. The target conjunctival blood vessel end is detected in the range within 10[pixels] in width from this elliptic locus.

The pixel values for the conjunctival blood vessel are lower than those of the sclera as the background. Accordingly, when the pixel values for the original image smoothed in the range within 19[pixels] are subtracted from those for the unsmoothed original image, another image can be achieved. This new image is characterized in that the pixel values in the blood vessel area are increased, while those in the sclera area as the background are decreased, all the these values being almost constant.

This image is smoothed within 3 pixels to filter out salt-and-pepper noise. The obtained image is binarized using the threshold to extract the blood vessel area (Fig. 4b). Hilditchfs thinning algorism is applied to the blood vessel area and for each of the obtained thin lines (Fig. 4c), the proximate point to the pupil center is obtained. Using this point as the target conjunctival blood vessel end, the 20   20 pixels range around the target conjunctival blood vessel end is recorded

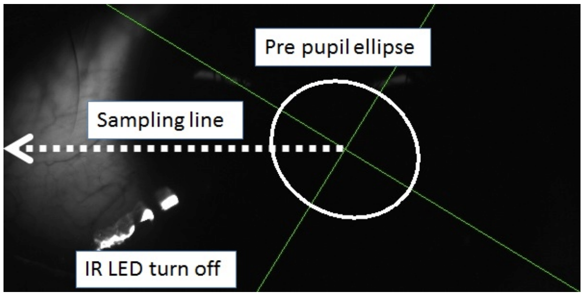
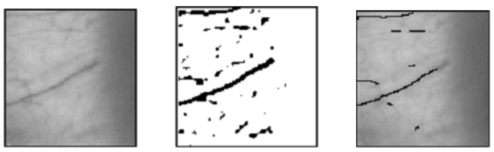


Fig. 3. Sampling line or obtaining the sclera-iris boundary.



(a) (b) (c)

Fig. 4. Image processing of Conjunctiva blood vessel end. (a) Original image, (b) Binarized image, (c) Thinning and noise removal image.

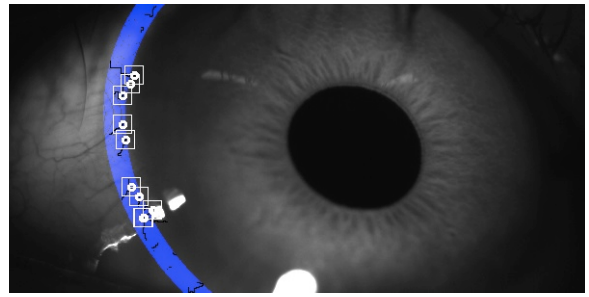


Fig. 5. Range, in which the conjunctival blood vessel end and the template are obtained.

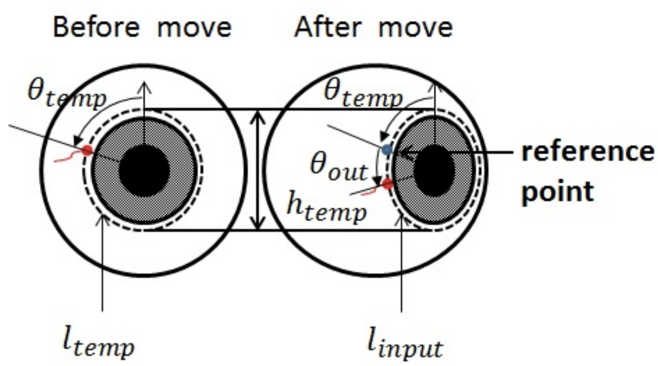


Fig. 6. Schematic illustrating the variations of the elliptic locus passing through the conjunctival blood vessel end and the position of the conjunctival blood vessel end associated with eye movement.

as a template image (Fig. 5).

D. Limiting the search range

To save the excessive processing cost required when template matching is applied to the entire range of an image, the target template matching range is limited.

The travel of a conjunctival blood vessel end can be expressed by adding a component generated associated with a variation in the visual line and a component generated along with rotational eye movement. With no rotational eye movement, the coordinates for the conjunctival blood vessel end can be obtained as described below.

Assuming such an elliptic locus, which meets the conditions: 1) passing through the coordinates for the blood vessel end when a template image is acquired; 2) being similar to the pupil ellipse, 3) having the same center point as that of the pupil ellipse; and 4) having the same inclination as that of the pupil ellipse, the elliptic $locus_{temp}$ when the template is acquired and the elliptic locus 1_{input} during rotational eye movement are drawn as shown in Fig. 6. Using the relationship indicated in the Figure, the coordinates for the blood vessel end, when the eye ball moves only in the vertical and horizontal directions, are obtained.

When the template is acquired, the length h_{temp} along the long axis of the elliptic locus passing through the conjunctival blood vessel end, and the coordinates for the angle θ_{temp} of the blood vessel end relative to the elliptic locus are obtained. To obtain these two parameters, the coordinates (x_{temp},y_{temp}) for the conjunctival blood vessel end obtained when the template is acquired is substituted into (x,y) of equation (1). The value obtained by ellipse approximation of the contour of pupil, the elliptic center (x_{0temp},y_{0temp}), the length a_{temp} along the short axis of the ellipse, the length b_{temp} along the long axis of the ellipse, and the inclination ϕ_{temp} of the ellipse are substituted into (x_0,y_0,a,b,ϕ) of equation (1). Then, equation (1) is solved to obtain the values for w,h,θ and the values for h and θ are recorded as h_{temp} and θ_{temp}, respectively.

The elliptic locus passing through the conjunctival blood vessel end during rotational eye movement can be obtained using elliptic parameters h_{temp} and θ_{temp}.

The pupil elliptic parameters obtained during visual line movement: the coordinates ($x0_{input}$,$y0_{input}$) for the center of the pupil ellipse; the inclination ϕ_{input} of the pupil ellipse; the length a_{input} along the short axis of the pupil ellipse; and the length b_{input} along the long axis of the pupil ellipse are substituted into (x_0,y_0,ϕ,a,b) of equation (1).b_{input}.

Moreover, h_{temp} is substituted into h in equation (1) with any variation in length along the long axis of the elliptic locus passing through the conjunctival blood vessel end during rotational eye movement because the distance between the eye and the camera is considerably short. θ_{temp} is substituted into θ in equation (1).

Substitutions are performed as described above to obtain the values for x and y. These a and y values is defined as a reference point (x_{input},y_{input}), which serves as the coordinates for the conjunctival blood vessel end with no rotational eye movement.

The travel component of the blood vessel end associated with rotational eye movement is θ_{out} shown in Fig. 6. The value for θ_{out} is unknown at this point because it is the

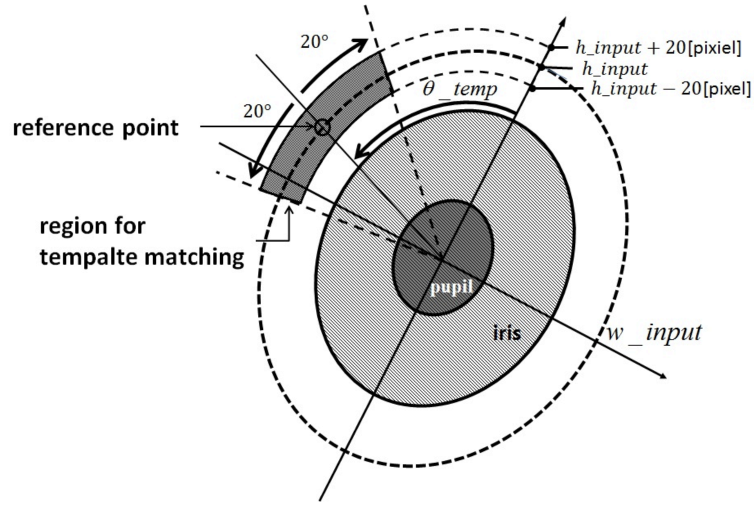


Fig. 7. Range, in which template matching is performed considering the maximum range of rotational eye movement and elliptic errors along the long axis.

value for the angle of rotation eye movement to be finally found with respect to this technique. However, it has been known that the maximum amplitude value for rotational eye movement is approx. ± 20 degrees relative to the elliptic locus. For this reason, search in the range including the amplitude ± 20 degrees relative to the reference point on the elliptic locus allows the coordinates for the conjunctival blood vessel end during rotational eye movement to be found. On the other hand, error may actually occur because the reference point is calculated with the assumption that the value for the value for the long axis of the ellipse is almost the same as h_{temp}. To this end, the target conjunctival blood vessel end is searched in the range with 40[pixels] in width relative to the elliptic locus l_{input} and in the range within ± 20 degrees from the reference point (Fig. 7).

E. Template matching

The input image is matched with the template image of the conjunctival blood vessel end in the searching range obtained. In the pre-template matching process, the template and input images are processed so that their maximum value is 255 and the minimum value is 0 and the contrast of the blood vessel end is enhanced. Then, template matching is performed using the contrast-enhanced images. The technique for calculating the similarity by means of template matching uses Zero-mean Normalized Cross-Correlation (ZNCC). Assuming that the similarity be R_{zncc} using ZNCC, it may be expressed by:

$$R_{zncc} = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I(i,j)-\bar{I})(T(i,j)-\bar{T})}{\sqrt{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I(i,j)-\bar{I})^2}\sqrt{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(T(i,j)-\bar{T})^2}} \quad (2)$$

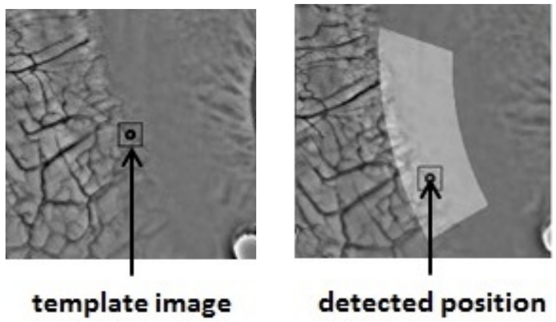
$$\bar{I} = \frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I(i,j)) \quad (3)$$

$$\bar{T} = \frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(T(i,j)) \quad (4)$$

Where, $T(i,j)$ is the pixel value for the template image at the coordinates (i,j), $I(i,j)$ is the pixel value for the input image at the coordinates (i,j), M and N are the height and width of the template image, which are assumed to be $M = 20$ and $N = 20$, respectively. x and y, which are variables for sliding the template relative to the input image, vary in the range obtained in 2.4. After template matching, the position with the highest similarity is recorded as the position of the blood vessel end and converted to the angle θ_{out} using equation (1). The angle θ_{temp} of the blood vessel end with the largest similarity obtained when the template is acquired (Fig. 8a) is subtracted from the angle θ_{out} after the template is slid (Fig. 8b) and the obtained value is defined to be the angle of rotational eye movement (Fig. 9).

F. Video stabilizing

The video stabilizing function as shown below was attached to an eye movement measuring device to ensure that the device can measure eye movement at a high accuracy even when the glass frame equipped with the measuring device is displaced from the userfs face due to userfs head movement or the framefs own weight. First, a camera attached to the glass frame, which the user wears, acquires eye ball images: they are assumed to be reference images. On an eye ball image, the first one of these reference images, rectangles defined between the outer and inner corners of the userfs eye are extracted to obtain two feature points, and the third feature point is determined in accordance with the criteria described later. Then, on the subsequent eye ball images, the positions of the both corners of the userfs eye



(a) (b)

Fig. 8. The image used for the template and the position of the blood vessel end obtained by template matching.

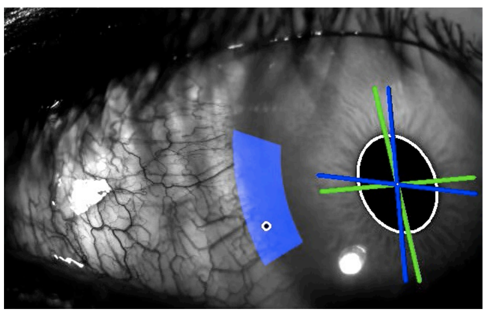


Fig. 9. Measuring rotational eye movement using the conjunctival blood vessel end.

and the third feature point are determined based on template images created from the first image, and an Affine matrix is calculated. Based on two sets of three feature points on the reference images and the second and its subsequent images, the second and its subsequent images are moved back to those on the reference images by Affine transformation.

The third point here is set so that the triangles defined by the three points on both the reference images and the transformed images (the second and its subsequent images) have similar figures to each other to a maximum extent, enabling the distance between two points, namely the outer and inner corners of the userfs eye to be increased or decreased. The triangles are defined as isosceles triangles and the third points are determined on the side close to the inner corner of the userfs eye.

Feature extraction and template matching are limited to the region, in which the outer and inner corners of the userfs eye may be found, achieving high-speed processing with less false detection. A Harris edge detector is used for feature extraction. With respect to template matching, low degree of coincidence is assumed to be an error.

Fig. 10 shows snap shots of the eye ball images captured with the spectacle type measuring device, some of which were displaced from the userf s face. As known from the figure, rotational eye movement can be measured with no problem even when the glass frame is slightly displaced from the userfs face as usual.

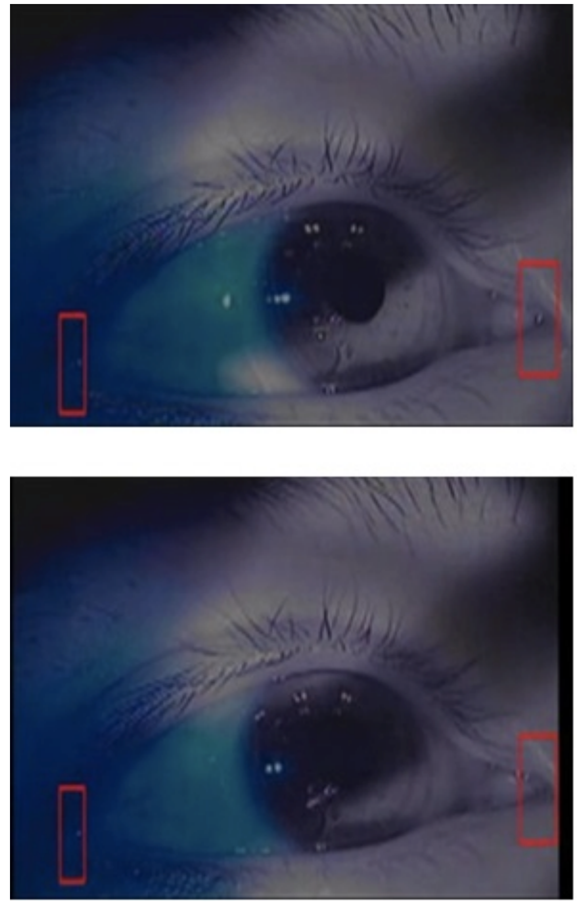
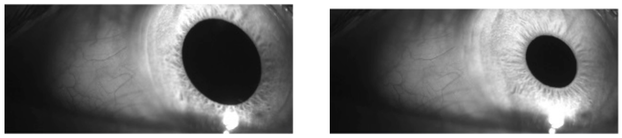


Fig. 10. Snapshots of video stabilizing function.

III. EVALUATION

To validate this technique, three subjects were participated in the study to measure 1) any variation in pupil diameter; and 2) the mean error and standard deviation for the angles of rotational eye movement when rotational eye movements simultaneously occur. In order to cause the pupil to vary, the subjects stayed in a dark room for five minutes for dark adaptation to widen the pupil (Fig. 11a). Acquisition of a moving image was started from the point when the pupil widened, and a white LED was irradiated on the pupils of the subjects for constriction (Fig. 11b). To induce two rotational eye movements simultaneously, the subjects inclined the head laterally during acquiring the moving image to trigger rotational eye movements by vestibulo-ocular reflex.

On the acquired 200 moving images, the true values for the angle of rotational eye movement are visually obtained and the mean error and standard deviation from the measured values output by the system are calculated. The specifications of the PC used for this study are Intel(R) corei5, 3.30[GHz], and 8G of memory. The image resolution is 640 480[pixel] and the number of the detected blood vessel end is one. In this operating environment, the resolution in measuring rotational eye movements depend on the distance between the position of the pupil center and the position of the conjunctival blood vessel end, being approx. 0.25 degrees.



(a) (b)

Fig. 11. Variations in pupil diameter. (a) at being widened, (b) at being constricted.

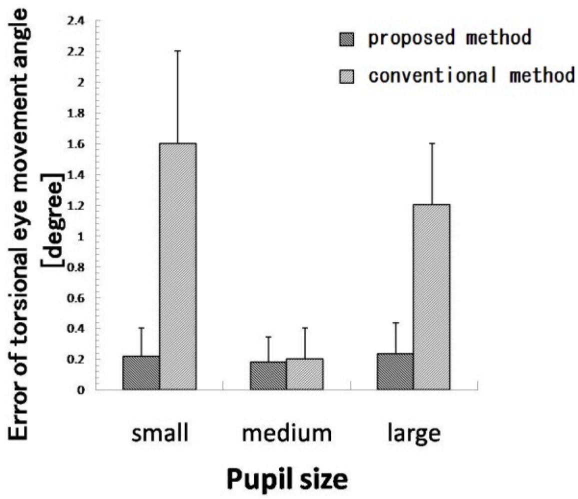


Fig. 12. Comparison of errors for the angle of rotational eye movement with those of the existing technique.

The error between the true values and the values output by the system was measured for each of three levels of lengths of pupil along the long axis and the result is shown in Table I. As known from the above descriptions, even when the pupil diameter varies, rotational eye movement may be achieved with the mean error less than or equal to 0.24 degrees, which is close to the resolution. It is obvious that compares with the existing technique [6] (Fig. 12), the accuracy of this technique is not affected by any variation in pupil diameter. With the image reading speed set to 16.6[ms] (60[fps]), the time required to calculate the angle of rotational eye movement was 23.7[ms] and the whole processing speed was 42.1[fps], which was achieved by parallelizing the process for reading images and the process for calculating the angle of rotational eye movement. The result shows that with this technique, although the processing speed is slightly lower than that of the previous study conducted by the authors, namely the technique for narrowing the rough region, in which the target blood vessel end is searched using the iris [7], the estimation accuracy is the same level as that of the previous technique in spite of only one blood vessel end being used.

IV. CONCLUSION

This study has proposed the technique for measuring rotational eye movement using the conjunctival blood vessel end.

TABLE I
ROTATIONAL ANGLE ERROR AND STANDARD DEVIATION IN PROPOSED METHOD.(A)SUBJECT A.(B)SUBJECT B.(C)SUBJECT C

pupil size(pixel)	Error angle(degree)	Standard deviation(degree)
small	0.153	0.071
mid	0.192	0.199
large	0.232	0.154

This technique detected the conjunctival blood vessel end in the contour of iris to use for tracking. Template matching was used for tracking with the search range limited to avoid any delay in processing time occurring when search is performed on the whole image. The coordinates for the conjunctival blood vessel end obtained by template matching was converted to the angle of rotational eye movement to measure rotational eye movement. The rotational eye movement was measured with the pupil varied. The result demonstrated that rotational eye movement could be measured with the mean error lower than or equal to 0.24 degrees at the processing speed of 42.1 measurements/second, under the condition of the limiting resolution for the angle of rotational eye movement being approx. 0.25 degrees. The result shows that with this technique, although the processing speed is slightly lower than that of the previous study conducted by the authors, namely the technique for narrowing the rough region, in which the target blood vessel end is searched using the iris, the estimation accuracy is the same level as that of the previous technique in spite of only one blood vessel end being used.

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