30th Annual International IEEE EMBS Conference
Vancouver, British Columbia, Canada, August 20-24, 2008

Characterization of iris pattern stretches and application to the measurement of roll axis eye movements

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Abstract— **Eye movements are utilized in many scientific studies as a probe that reflects the neural representation of 3 dimensional extrapersonal space. This study proposes a method to accurately measure the roll component of eye movements under the conditions in which the pupil diameter changes. Generally, the iris pattern matching between a reference and a test iris image is performed to estimate roll angle of the test image. However, iris patterns are subject to change when the pupil size changes, thus resulting in less accurate roll angle estimation if the pupil sizes in the test and reference images are different. We characterized non-uniform iris pattern contraction/expansion caused by pupil dilation/constriction, and developed an algorithm to convert an iris pattern with an arbitrary pupil size into that with the same pupil size as the reference iris pattern. It was demonstrated that the proposed method improved the accuracy of the measurement of roll eye movement by up to 76.9%.**

I. Introduction

Eye movements are utilized in many scientific studies, from basic neuroscience research to human engineering experiments, as they reflect the neural representation of 3 dimensional extrapersonal space[1] and objects of interest in visual scenes[2]. Eye movements are generated by 3 pairs of extra-ocular muscles (lateral and medial recti, superior and inferior recti, and superior and inferior obliques) that produce yaw, pitch, and roll components of the eye movements. There have been 3 popular methods to measure eye movements: electro-oculography (EOG), the scleral search coil technique (SSC), and video-oculography (VOG). Among these, roll eye movements can be measured by SSC and VOG. While the former method requires suturing an eye coil (or coils) onto the sclera, or wearing a contact lens with an embedded eye coil. The latter method does not require any invasive treatment, and is thus more practical for use with human subjects. In VOG, roll eye movements are measured as the angle of iris pattern rotation around the center of the pupil which is usually estimated by pattern matching between a reference and a test iris image. Although the iris pattern is known to be unique for an individual subject, it is not constant for that subject because the iris pattern is subject to change due to changes in pupil size[3]. Apparent iris patterns also change due to changes in gaze direction relative to the camera axis.

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This variable nature of the iris pattern in an individual subject is a potential source of errors in pattern matching for the measurement of roll eye movement. Previously we developed a method that compensates for the effects of changes in gaze direction on iris patterns[4]. Currently we have developed a method that compensates for the effects of changes in pupil size on iris patterns to enable the measurement of roll eye movement that is robust for changes in pupil size. We have conducted experiments on human subjects and characterized the spatially non-uniform expansion/contraction of iris patterns due to changes in the pupil size. This characteristic is utilized to convert a test iris pattern with an arbitrary pupil size into one with the same pupil size as the reference iris image. We demonstrate that the proposed method improves the accuracy of the measurement of roll eye movements by up to 76.9% compared to the conventional method.

II. Methods

A. Acquisition of iris patterns with various pupil sizes

To acquire iris images with various pupil diameters, the following experiments were conducted on healthy human subjects. The subjects sat comfortably on a seat in a dark room. They wore goggles (NEWOPTO ET-60-L) equipped with 2 CCD cameras (1 for each eye), each of which took infrared images of the eyes at a rate of 29.97 fps (NTSC). These goggles were also equipped with 2 white LEDs to deliver light stimuli to each eye. A flash stimulus (duration 200 msec) was applied to an eye to change the pupil diameter. The video images recorded during the pupillary flash responses were saved on a hard drive for offline processing using MATLAB (MathWorks).

B. Characterization of iris pattern stretches

The pupil diameter was extracted from each frame of the video images, and 24 frames were chosen so that pupil diameters in these frames were distributed as evenly as possible between the minimum and the maximum pupil diameters. In the iris pattern with the minimum pupil diameter, a total of 26 feature points were specified manually, along the radial axes 45 degrees apart, except along the 90 degree axis, the upper part of which is occasionally occluded by the eyelid or eyelashes (Figure 1). A maximum of 4 points were chosen for each direction. Each feature point was identified and tracked for each of the 24 iris images, and the dependency of the position (distance from the pupil center) of each feature point on the pupil diameter was characterized.

C. Measurement of roll eye movements

To measure the roll eye movement in each frame, the pupil edge was first detected as an ellipse. The iris pattern was then extracted outward from this pupil edge, and the roll angle around the axis of the detected pupil center was defined as the angle that gives the minimum hamming distance between the reference and test iris patterns. The details of this process are described in previous work [5], but here, additionally, the original iris patterns with various pupil sizes were converted to those with the pupil diameter equal to that of the reference iris pattern by using the identified characteristics of iris pattern stretches.

D. Evaluation of the proposed method

To evaluate the accuracy of the roll eye movement measurement using the proposed iris pattern compensation, the following experiments were performed. The subject wore the same goggles used in the experiment *A* in the same dark room. He was asked to tilt his head (roll head motion) to induce roll-axis vestibuloocular reflex (VOR) while staring at a visual target to keep his gaze direction straight ahead. This maneuver was repeated 3 times under different background light levels to record roll-axis VOR when the average pupil size was large, intermediate, and small. The iris image in the first frame of each of the roll-axis VOR records was chosen as the reference iris image for each average pupil size, and the rest were used as test images. The true magnitude of roll angles for these iris images was determined by manually tracking one of the distinctive feature points in each iris image. Namely, the feature point and the center of the pupil were detected in each iris image, and the angle between the line connecting them and x axis was measured. The angles of the 3 reference images are assumed to be 0, and roll angles of the test images were calculated as the difference from the measured angle for the reference image.

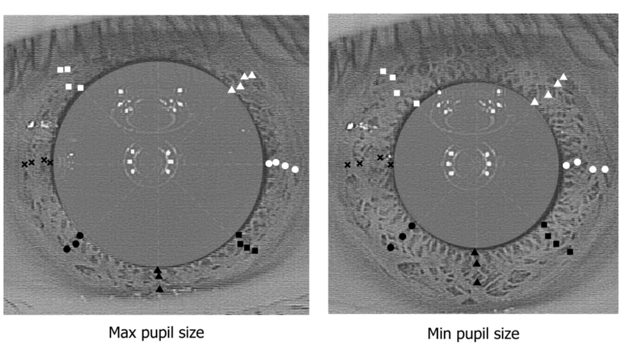

Fig.1 Change in iris pattern due to pupil constriction. Markers are feature points specified along 7 radial axes (0, 45, 135, 180, 225, 270, 315 deg).

III. RESULT

A. Characteristics of iris pattern stretches

Figure 2 illustrates relationship between the pupil diameter and the position (distance from the pupil center) of the 26 feature points in the right eye of a subject. Each line is the regression line for each feature point tracked for 24 different pupil diameters. Different symbols indicate different radial axes. For all the feature points, the dependencies of their positions (distance *d* from the pupil center) on the pupil diameter *PD* can be well approximated by a linear function as described in equation (1) ($R^2 > 0.82$).

$$d = a \cdot PD + b_0 \tag{1}$$

Where a is the slope of the regression line, and b_0 is the position of a feature point when the pupil diameter would be 0. The slopes (a) for the feature points at shorter distance from the pupil center (smaller b_0) have greater values because the feature points closer to the pupil center move more when the pupil size changes. Figure 3 illustrates the dependency of the slope (a) on the position of a feature point from the pupil center (b_0). Each open circle indicates data from each of the 26 feature points. These open circles at different b_0 can be well approximated by the linear function as in equation (2) ($R^2 > 0.99$).

$$a = \alpha \cdot b_0 + \beta \tag{2}$$

where the slope α and offset β are –0.0073 and 1.0127, respectively for this subject. Substituting a in equation (1) with the right hand side of equation (2), we obtain

$$\begin{aligned} d &= (\alpha \cdot b_0 + \beta)PD + b_0 \\ &= (\alpha \cdot PD + 1)b_0 + \beta \cdot PD \end{aligned} \tag{3}$$

Thus b_0 of an arbitrary point at the distance d from the pupil center in an iris pattern with the pupil diameter *PD* can be calculated by equation (4).

$$b_0 = \frac{d - \beta \cdot PD}{\alpha \cdot PD + 1} \tag{4}$$

Given b_0, the slope a for this point in the iris image can be calculated by equation (2). Therefore the corresponding distance $d(PD_{ref})$ from the pupil center in the iris image with the pupil diameter PD_{ref} can be calculated by equation (1). By repeating this procedure for all pixels in an iris pattern, the iris pattern with the pupil diameter *PD* can be converted to that with the pupil diameter PD_{ref}.

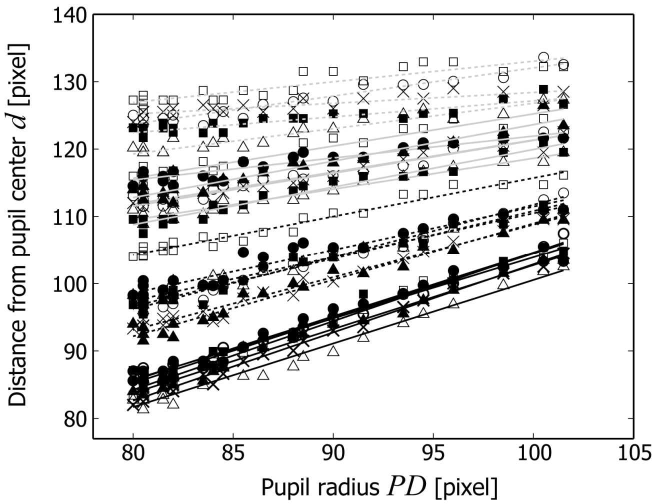

Fig.2 Relationship between pupil radius and each feature point in the iris pattern.

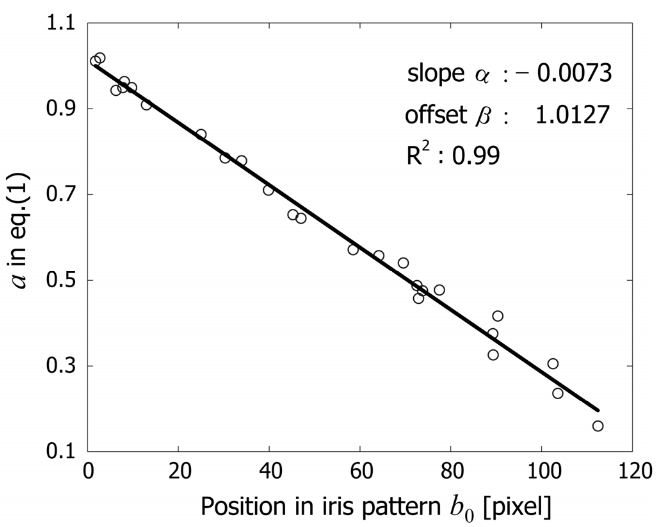

Fig.3 Relationship between a and b_0 in equation (1).

B. Differences in the characteristics of iris pattern stretches in individual subjects

We performed the feature point tracking for iris images with different pupil sizes in 3 subjects (age OT: 22, JN: 26 and HY: 40). Iris images of the right eye of all subjects were used to evaluate inter-subject differences, while those of the right and left eye of one of the 3 subjects (HY) were used to evaluate within-subject differences. Estimated parameters α and β in equation (2) for each subject are shown in Table 1 together with R^2 values from the regression performed to estimate these parameters. Surprisingly, the differences in the estimated parameters over different subjects were minimal, as were the differences in those for right and left eyes in the same subject (p>0.634; two tailed student t test). Therefore, a common set of parameters independent of the subjects may be used for the iris pattern compensation without estimating these parameters for each individual subject.

TABLE 1 α and β in eq. (2) for each subject.

Subject	HY(R)	HY(L)	OT(R)	NJ(R)
Slope α	-0.0073	-0.0074	-0.0076	-0.0076
Offset β	1.0127	1.0112	1.0174	1.0233
R^2	0.991	0.991	0.983	0.957

R: right eye, L: left eye

C. Evaluation of the proposed method

Iris images recorded during roll-axis VOR under 3 different average pupil sizes (approx. 3, 5, 7mm) were used to evaluate the accuracy of the roll eye movement measurement with the method proposed in the current study. We call these iris images test iris images of small, medium and large pupil, each of which consists of 30 images (roll angle ± approx. 15 degrees). Among the 30 images, the first image recorded when the head was straight up was chosen as the reference iris image for each pupil size condition, whose roll angle is assumed to be 0 deg (Figure 4). Roll angles of the test iris images of small, medium, and large pupil were estimated in relation to the reference iris images of small, medium, and large pupil for a total of 9 conditions.

Figure 5 summarizes the results of each of the 9 conditions. Results from the conventional method in which the compensation for iris pattern stretches were done assuming uniform stretches (constant a for any b_0) are also shown for comparison. In all the 9 conditions, the measurement errors by the proposed method are smaller than those of the conventional method. When the pupil sizes are similar in the reference and test images, the measurement errors are not much different in the proposed and conventional methods. This is because minimal compensation is required for the test images to match their pupil diameters to that of the reference image. Also the errors are minimal in the cases of the reference image with small pupil vs test image with small pupil (reference small vs test small), and the reference image with medium pupil vs test image with medium pupil (reference medium vs test medium). When the pupil sizes are large both in the reference and the test images, the measurement errors are relatively large for both the proposed and conventional methods. This is because the area of the iris (number of pixels) to be used for the pattern matching between the reference and test images is small when the pupil size is large, and the pattern matching algorithm becomes less robust for noise in iris images. The least accurate roll angle estimation was found in the case of the small reference vs large test condition. This result was predictable because many features in an iris pattern are compressed into a sub-pixel when the pupil is large, and thus it is theoretically impossible to convert the iris image with large pupil into that with small pupil perfectly. In contrast, the conversion from an iris image with small pupil into that with large pupil is possible. Thus we found much smaller error in the case of the large reference vs small test condition. Percentages of improvement in the proposed method in comparison with the conventional method are summarized in Table 2.

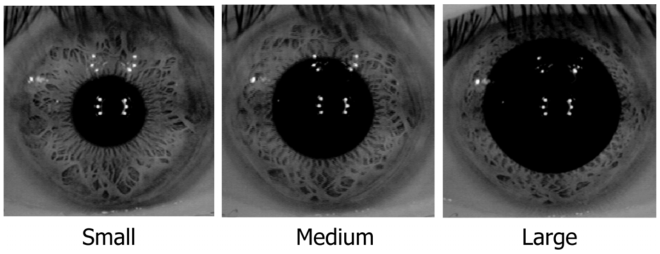

Fig.4 The reference iris patterns with small, medium and large pupil of the same subject.

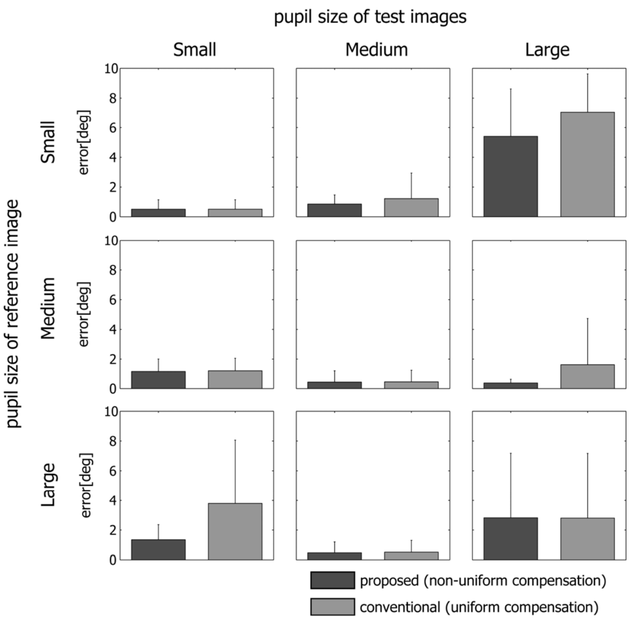

Fig.5 Rotational angle error of proposed and conventional method.

TABLE 2 Improvement of the measurement of roll eye movements (proposed vs conventional method)[%].

		Pupil size of test images		
		Small	Medium	Large
Pupil size of reference image	Small	–	30.0	23.2
	Medium	4.0	–	76.9
	Large	64.7	9.2	–

IV. CONCLUSION

Human iris patterns are subject to change when the pupil diameter changes. This change in iris pattern potentially causes estimation errors in the measurement of roll eye movements. In the current study, we found that the expansion and contraction of human iris patterns that occurs as the pupils dilate and contract is spatially non-uniform. This non-uniformity can be characterized by simple linear functions whose parameters are minimally variable between subjects and between the left and right eyes in the same subject. We implemented an iris pattern compensation algorithm that employs the described non-uniformity of pattern stretching prior to the pattern matching procedure in the measurement of roll eye movements. The algorithm improved the accuracy of the measurements significantly, especially when the pupil diameter was different between the reference and test iris images. We conclude that the proposed algorithm is useful for obtaining accurate measurements of roll eye movement, and should be particularly valuable under conditions where the pupil diameter is likely to change. Furthermore, the proposed algorithm should be advantageous for other applications of iris pattern matching, such as iris recognition in biometrics.

ACKNOWLEDGMENT

We thank Shinichi Kinoshita for his help in data collection, Shane Heiney and Josh Bassett for their valuable comments on the earlier version of this manuscript. This work was partly supported by a grant from the High-Tech Research Center Establishment Project from Ministry of Education, Culture, Sports, Science and Technology.

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