J. Korean Soc. Ind. Appl. Math. Vol.25, No.4, 327–336, 2021 https://doi.org/10.12941/jksiam.2021.25.327

A STUDY ON PUPIL DETECTION AND TRACKING METHODS BASED ON IMAGE DATA ANALYSIS

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ABSTRACT. In this paper, we will introduce the image processing methods for the remote pupillary light reflex measurement using the video taken by a general smartphone camera without a special device such as an infrared camera. We propose an algorithm for estimate the size of the pupil that changes with light using image data analysis without a learning process. In addition, we will introduce the results of visualizing the change in the pupil size by removing noise from the recorded data of the pupil size measured for each frame of the video. We expect that this study will contribute to the construction of an objective indicator for remote pupillary light reflex measurement in the situation where non-face-to-face communication has become common due to COVID-19 and the demand for remote diagnosis is increasing.

1. INTRODUCTION

The pupillary light reflex test is a test for checking a pupillary light reflex in which the size of the pupil becomes smaller and larger due to the stimulation of light entering the eye. The pupil size of a normal person is a circle with a diameter of about 6 mm, but when exposed to light, the pupil becomes smaller with a diameter of about 2 mm. Abnormal pupillary light reflex do not respond to light and show a phenomenon of not becoming smaller or shaking. Through the pupillary light reflex test, it is possible to check whether or not there is an abnormality in the optic nerve and the third cranial nerve, and it is used as a basic test in various medical departments such as ophthalmology, neurosurgery, and internal medicine. Nowadays, the pupillary light reflex test is diagnosed by the subjectivity of the examiner, so that an analytical error may occur depending on the skill level and the difference in experience. And while other ophthalmologic tests such as refraction test, intraocular pressure and fundus test can make it easy to communicate by making the test results into image data, there are no objective and standardized test results for the pupillary light reflex test. Therefore, in order to expand the telemedicine system in the field of ophthalmology, it is necessary to study a remote pupillary light reflex measurement and an objective test result derivation method. In this paper,

Received November 22 2021; Accepted December 15 2021; Published online December 25 2021.
2000 *Mathematics Subject Classification.* 93B05.
Key words and phrases. Pupillary Light Reflex Test, Real-Time Image Processing, Object Detection.

we present a method to detect the pupil region by dividing the iris and pupil region in real time without learning, and to measure the size of the pupil that changes with light. Then, we will visualize the measured pupil size and introduce the research for objective remote pupillary light reflex test. We collected video data using a device developed by DN Corp., and tested the method we studied on this video data.

2. RELATED WORK

Methods for measuring pupil size have been studied in recent years using various approaches. Starburst algorithm[1] is a representative method. This is an algorithm that assumes that the pupil is elliptical and uses the feature points of the image to find the ellipse near the pupil and the location of the screen that the pupil looks at. The feature point is a point on an image that can be easily identified even if the shape, size, or position of the object changes. There are corner points as typical feature points, and there are Harris Corner[2] and Sift-DoG[3] as methods for finding corner points. Applying this, D. Temel et al.[4] studied a method for measuring changes in pupil size of eyes exposed to light, and using this to determine RAPD (Relative Afferent Pupillary Defect). These algorithms were developed and tested using high-quality image data taken by infrared rays, wearing a headset that blocks the surroundings. Since we took the videos with a general smartphone in a situation where the surroundings were not blocked and controlled, the eyes are not fixed, video is too noisy and the boundary between the iris and the cornea is ambiguous. Therefore, it is difficult to apply these methods directly.

There are other studies that measure the pupil area with general video taken with a smartphone. N. Kim and four others[5] introduced a pupil tracking results required for pupillary light reflex measurement using a video data taken with smartphone and the OpenCV library. The eyes were illuminated using a smartphone flash, and videos taken with a smartphone fixed to the device were analyzed to measure pupillary light reflex and changes. This algorithm was implemented by converting an image into an HSV color model and detecting the pupil region as a result obtained by the AND operation of the Hue image and the Saturation image. The experimental results under various conditions and environments such as several smartphone models, light color, with or without lighting, flash direction, etc. were shown. This paper has shown that the pupil region can be detected quickly by analyzing the video taken without special equipment. However, since the pupil tracking accuracy is too low and the method of measuring the size of the pupil has not been dealt with, there is a limit to the use for the pupillary light reflex measurement. In this paper, we propose a method to measure the size of the pupil in real time with a video taken by a smartphone without expensive equipment, and a method of generating a change graph that can objectively determine the pupillary light reflex.

3. PROPOSED METHOD

In this section, we introduce a remote pupillary light reflex measurement method based on image data analysis that separates the pupil and iris region from the image and measures changes in pupil size with respect to light. The test subject fixed his face on a pupillary light reflex measurement device (Figure 8), and the video was taken with a general smartphone. The

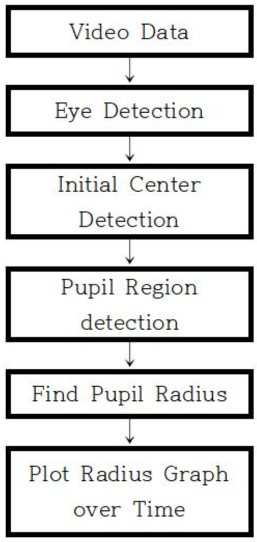


FIGURE 1. Algorithm flow

taken video data was divided into frames and analyzed for each frame. Assuming that the shape of the pupil is a circle and after recognizing a part of the image with light, we studied how to measure the size of the pupil by approaching the pupil while narrowing the RoI(region of interest). Since videos were taken in a general environment, we could not obtain significant results by the conventionally known pupil detection methods. So we have strategically constructed the algorithm in various ways. The whole algorithm flow is in Fig.1.

3.1. **Detect the target eye.** Firstly, for efficient operation, we found the eyes in the image and fixed the area around the eyes to the area of interest. And since the pupillary light reflex measurement is to measure the change in the size of the pupil when illuminating the light, we found the frames with the light.

(Region of eye detection) Firstly, we applied the Haar Cascades algorithm[6], which is a well-known method for finding eyes, to the frame image. Haar Cascades is a feature based step-by-step classifier based object detection algorithm proposed by Paul Viola and Michael Jone in 2001. This algorithm detects feature points in the window while moving the window on the image and determines if there is a face. Haar feature is composed of adjacent rectangles as shown in Fig. 2 (a), and the value obtained by subtracting the total number of pixels in the white area from the total number of pixels in the black area. If it is larger than the threshold, that point is a feature point. Figure 2 (b) is an example of features related to eye detection. A feature with black and white squares in the horizontal direction indicates the characteristic that the eyes are darker than the nose and cheeks, and the other feature with black, white, and black squares in the vertical direction indicates the characteristic that the eyes on both sides are darker than

(a) Haar features[11]   (b) Two features related to eye detection[2]

FIGURE 2. Haar Features

the nose in the center. If there are enough feature points in the window, it is determined that there is a face in the window area. However, this method has a large amount of computation and a slow detection speed. The Haar Cascades algorithm has effectively reduced the amount of computation using a step-by-step checking method. For example, the eye-related features in a window are compared first, and if there are no related feature points, it is determined that the window has no face and the window is moved. We used Haar Cascades to detect the eye area, which is a small rectangular area containing the eye in the frame image. In this process, we found two problems. At first, the Haar Cascades algorithm has detected an area containing a circular object that is not an eye. To solve this problem, we assumed that the test subject's eyes were symmetrical. Therefore, after dividing the image in half with respect to the horizontal axis, we determined that the regions with the widest width in each side include the eye. And the second problem was that it can not detect eyes correctly when the light is strong, whereas it detects eyes well when there is no light. The video were taken with the test subject's face fixed, so the location of eyes were fixed in each videos. Therefore, the region of the eye was fixed which were obtained from the first frame without light.

(Selection of target eye) We used HSV color model to check if there is light in the frame image and to find the position of the illuminated eye. HSV color model is driven by human recognition of color. In this model, color is represented by three components: Hue, Saturation, and Value. Color represents the relative angle of arrangement when red, which has the longest wavelength, is $0°$ on the color wheel in which visible light is arranged in a ring shape, and has a value within the range $0° \sim 360°$. Saturation represents the degree of saturation when the darkest color for a specific color is 100%, and 0% means achromatic color. Value indicates the brightness when white, red, etc. are 100%, and black is 0%. The formula for converting the RGB to HSV in OpenCV library, which is best known for image processing, is as follows.

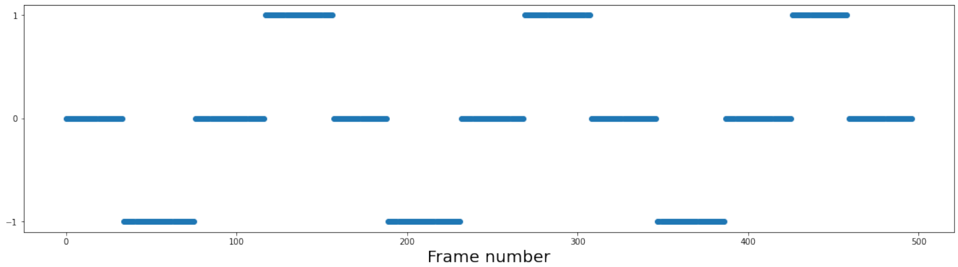


FIGURE 3. Light detection result using HSV color model

$$V = \max(R, G, B)$$

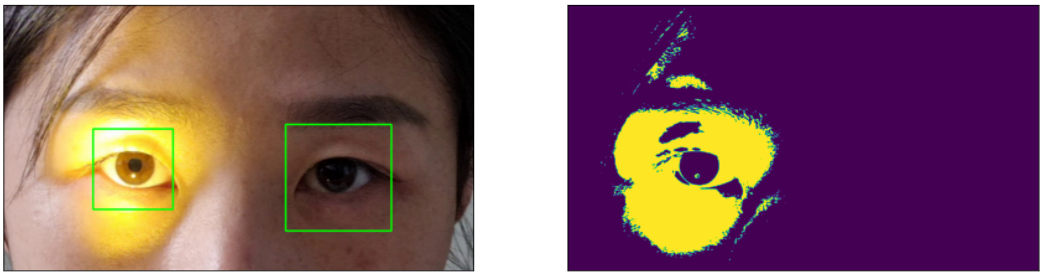
$$S = \begin{cases} \frac{V - \min(R,G,B)}{V}, & \text{if } V \neq 0 \\ 0, & \text{if } V = 0 \end{cases}$$

$$H = \begin{cases} 0, & \text{if } V = \min(R, G, B) \\ (360 + \frac{60(G-B)}{V - \min(R,G,B)}) \bmod 360, & \text{if } V = R \\ 120 + \frac{60(B-R)}{V - \min(R,G,B)}, & \text{if } V = G \\ 240 + \frac{60(R-G)}{V - \min(R,G,B)}, & \text{if } V = B \end{cases}$$

RGB colors are easy to represent different colors, but they are sensitive to changes in light, and it is difficult to detect objects in images exposed to the external environment[7]. Therefore, we found the illuminance range of the light used in the experiment using HSV color model, and found the frames with light and the eyes illuminated by the light. Figure 3 is the result of detecting the light for each frame in the video. -1 and 1 indicate that the light was on the left eye and right eye, respectively. If there was no light, it is indicated by 0. In this paper, light was detected for each frame, and the pupil size was measured only for the frame with light.

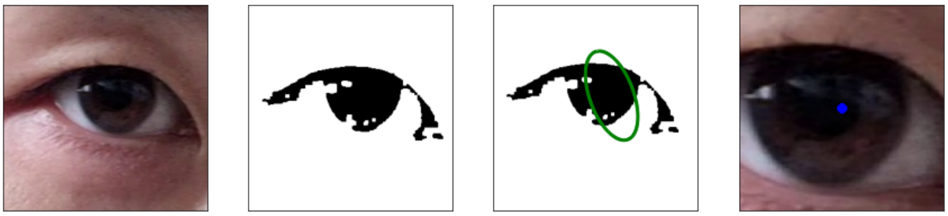
In this paper, the eye for the pupillary light reflex measurement is called **the target eye**, and the region of target eye is called **the wide RoI**.

3.2. **Find the center of the pupil.** Since the surrounding environment is not controlled in the videos taken with a smartphone, objects and light can be reflected on the cornea. Therefore, it was difficult to directly apply the Hough circle detection and Contour detection algorithms that detect circular objects in a wide RoI to detect the pupil boundary. Both Hough circle detection and Contour detection are algorithms for detecting the boundaries of objects in an image. Hough circle detection is an algorithm for finding boundaries close to the circle equations in a binarized image using circle equations, and Contour detection is the similar algorithm to find the boundaries of an object using the same pixel value. The color of the pupil varies from person to person and is affected by the shooting environment, so it can not be fixed to a specific



(a) Results of Haar cascades eye detection (b) Detect light using HSV color transform

FIGURE 4. Target eye detection



(a) Wide RoI (b) Results of binarization and image filtering (c) Results of MCD (d) RoI

FIGURE 5. MCD center with image binarization filtering

color value. So we tried to detect the pupil in a way that would find different pupil colors for each individual. The color of the pupil varies from person to person, but we found that the area of the pupil was the darkest in the wide RoI. As a result, the dark part was extracted from the image to find the pupil region, and the center of this region was found to find the HSV color of individual pupil.

(Setting of the RoI using MCD) We converted the wide RoI obtained above into grayscale and binarized it based on the lower 10% values of wide RoI. We applied image filters such as erosion and dilation to the binarized image to remove noise, and the result is as shown in Fig. 5 (b). The position of the denoised binarized image was coordinated, and it was appeared in the form of a union of the circular cornea and the outer cornea of the circle. So we tried to find the center of the dense circle to find the center of the cornea. Considering the characteristics of the binarized image, we used MCD(Minimum covariance determinant)[8], which is an algorithm for detecting abnomal data in a population that follows a multivariate normal distribution. MCD is an algorithm that finds a subset of a specific size (usually 75% of all data) that minimizes the determinant of the covariance matrix. We can obtain the mean vector and covariance matrix of the dense data by removing the influence of noise, anomaly data, and data deviating from the dense data, and we put the mean vector as the **initial center**. The data was randomly sampled in the experiment to reduce the time required to calculate the MCD algorithm. As you can be

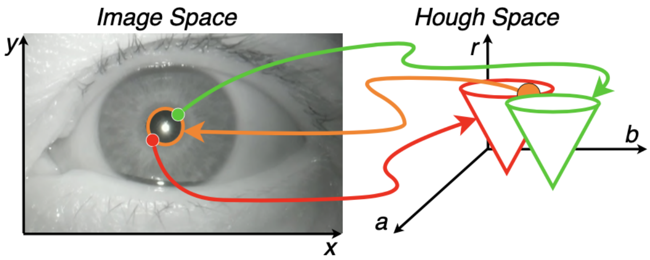
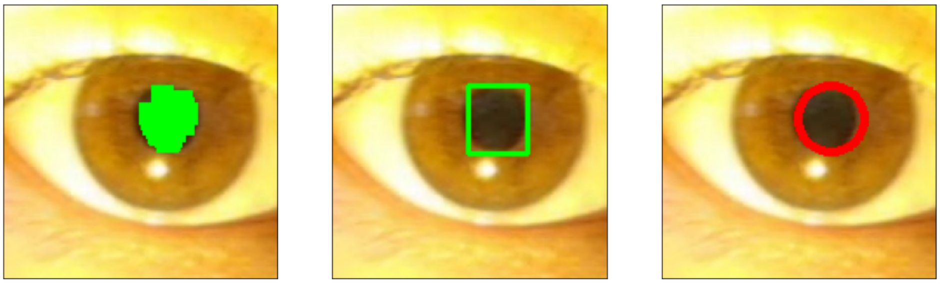


FIGURE 6. Circle Hough transform from image space to Hough space [4]

seen in Fig. 5 (b), the initial center was close to the pupil, but it tended to be slightly biased out of the pupil due to shadows in the front and tail of the eye.

(Pupil center detection using Circle Hough Transform) As a result of the experiment, it was verified that the initial center was off the pupil, but most of it was located in the cornea, as shown in Fig. 5 (c). Therefore, we set a smaller RoI relative to the initial center to exclude areas other than the pupil. This RoI was set to a square relative to the initial center, taking into account the width and height of the image frame (e.g. Figure 5 (c)). We applied the Circle Hough Transform, which is a circle detection algorithm, to the RoI where there are no unnecessary parts. The Circle Hough Transform converts a binarized image with borders detected image using Hough transform[9]. It is a well-known technique for detecting circles. The Hough transform is a transform that represents points on the image space in the Hough space. Let (x, y) be one point on the Image space. The circles passing through this (x, y) are represented as a cone in Hough space like Fig. 6. If two points on the Image space are on the same circle, like the orange circle in Fig. 6, the orange circle on the Hough space is the intersection of the two cones. Based on this principle, if the number of cones passing through a point on the Hough space is large, it is considered that there is a circle in the Image space. With the Circle Hough Transform, we obtained the center and radius of the detected circle.

3.3. **Measuring the radius of the pupil.** We can obtain the center and radius of the circle in RoI by using the Circle Hough Transform, but this circle tends to be smaller than the pupil. This problem occurs because only the inside of the pupil is filtered in the case of a person with a large pupil in the binarization step. Therefore, it was difficult to detect the pupil directly by using the Circle Hough Transformation, but we found that the color of the detected circle is the pupil color by taking advantage of the fact that most detected circle is located in the pupil. The test subject's pupil color was defined within the ± 6 standard deviation range from the average values of Hue, Saturation, and Value of the pixels in the detected circle. We detected the pixels within the range of pupil color and applied binarization and image filters to find the pupil region. As a result, we found the pupil region as shown in the Fig. 7 (a). After that, we found the contour of the pupil region and the circumscribed rectangle of it. We determined



(a) Find pupil region using individual HSV color (b) Contour detection (c) Final result of pupil detection

FIGURE 7. HSV contour detection

the minimum value of the horizontal and vertical lengths of circumscribed rectangle as the diameter of the pupil.

4. EXPERIMENTAL EVALUATION

In this section, we will introduce the results of visualization of the pupillary light reflex measurement by the radius graph measured at each frame in the video using the proposed pupil radius measurement algorithm. As shown in Fig. 8, the test subject fixed her face on the device for the pupillary light reflex measurement and the light was alternately illuminating the left and right eyes of the test subject. The videos were taken with a smartphone. The smartphone model used in the experiment was the Galaxy s20, and the penlight model was the CK-908. The test subjects who participated in the experiment have a normal pupillary light reflex.

To remove noise in the graph, we smoothed the graph using the median of the radius measured in the previous five frames. As a result, we obtained the graphs in the Fig. 9. As you can see in Fig. 9, the radius of the pupil decreases when the light is illuminated and increases again when it is adapted to the light.

FIGURE 8. The device for the pupillary light reflex measurement

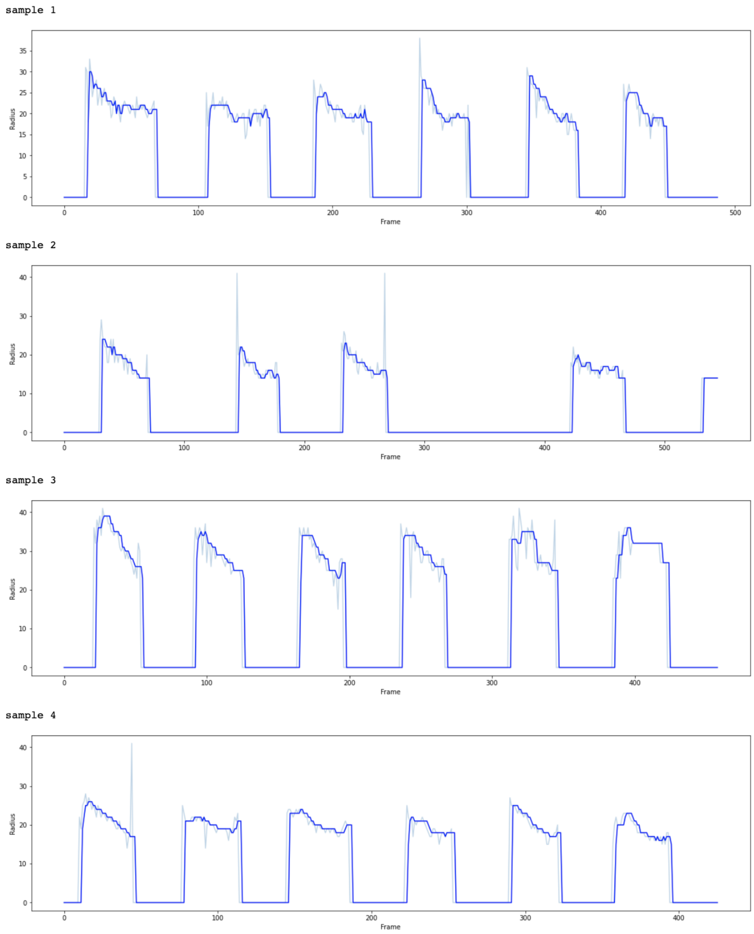


FIGURE 9. Graphs for the pupillary light reflex measurement This graphs show the radius of the eyes exposed to light for each frame in the videos of 4 test subjects with normal pupillary light reflex. Frames without light are indicated by 0.

ACKNOWLEDGMENTS

The work of H. Choi and M. Gim was supported by National Institute for Mathematical Sciences(NIMS) grant funded by the Korea government(MSIT) No.B21810000. The work of S. Yoon was supported by the technology transfer and commercialization Program through INNOPOLIS Foundation funded by the Ministry of Science and ICTm 2020-JB-RD-0199.

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