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Automated Pupil and Iris Segmentation in Human Eye Images Using Classical Image Processing

Anil Kishore Mugalapalli, Dr T Bhaskara Reddy
Research Scholar, Dept. of CS & T, S.K. University, Anantapuram, India, m.anilkishore@gmail.com
Professor, Dept. of CS & T, S.K. University, Anantapuram, India, bhaskarreddy.sku@gmail.com

Abstract
A simple image processing pipeline for pupil and iris localization was developed, based on classical image processing steps such as grayscale conversion, contrast enhancement, Gaussian filtering, Otsu's thresholding, morphological operations, and circular Hough transform for pupil and iris boundary detection. The performance of the proposed method was evaluated using Accuracy, Intersection over Union (IoU), and Dice coefficient. Experimental results showed that the proposed method was able to detect the pupil accurately under different lighting conditions and was able to run in real time on a standard CPU making it suitable for resource and embedded systems.
Keywords: *human eye, image processing, pupil detection, iris segmentation, Otsu thresholding, Hough transform*

1. Introduction

The human eye contains a multitude of information that is utilized in numerous applications. Iris texture is unique to individuals and can be used for biometric authentication [1]. The pupil's size and position can be utilized for gaze tracking, driver drowsiness monitoring, and for screening of neurological and ophthalmic disorders.
In many existing studies, detecting the pupil and iris is an important first step in eye image analysis. An eye image also contains other parts, such as the sclera, eyelids, and eyelashes, along with unwanted reflections. These factors make accurate detection difficult. Although deep learning models provide high accuracy, they generally require large amounts of labeled data and powerful computing resources. In contrast, classical image processing[8] techniques are simpler and require fewer computational resources. These techniques include grayscale conversion, thresholding, edge detection, and morphological operations. The selection of suitable research methods and reliable scientific publications is also important for maintaining research quality and credibility. Different journal indexing databases contribute to the visibility, accessibility, and dissemination of scientific research findings [7]. methods are still interesting because they are fast, explainable and can be easily implemented on embedded hardware.
The main contributions of this paper are:
1. A simple, step-by-step segmentation pipeline for pupil and iris localization using classical techniques.
2. A mathematical description of each stage of the pipeline.
3. A quantitative evaluation of the results using standard overlap metrics with discussion of successful and unsuccessful cases.
In Section 2 we review related work. In Section 3 we present the proposed methodology. Results are presented in Section 4. Section 5 provides an analysis of the results. Section 6 concludes the paper.

2. Related Work

The integro-differential operator introduced by Daugman in order to find the circular iris and pupil boundaries was used in the first widely deployed iris recognition system [1]. This operator was later replaced by the circular Hough transform [2], which searches for circles by voting in a parameter space. The edge detection is typically done by the Canny detector [3] and the automatic

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thresholding by Otsu's method [4]. Contrast-limited adaptive histogram equalization (CLAHE) is used in order to enhance local contrast in low-quality images [5]. Recent approaches for iris segmentation use convolutional neural networks for an end-to-end segmentation.

3. Proposed Methodology

The overall pipeline is shown in Figure 1.

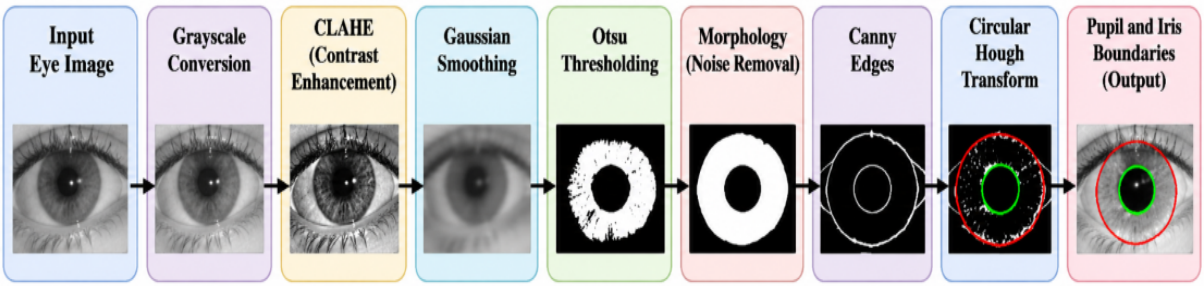


Fig. 1. Block diagram of the proposed pipeline.

3.1 Image Acquisition

The images used in this work are either collected from publicly available eye image databases or acquired with a near-infrared camera in our lab. The images are then resized to 320 × 240 pixels.

3.2 Grayscale Conversion

The RGB image is converted to a single intensity channel:

$$I(x, y) = 0.299\, R(x, y) + 0.587\, G(x, y) + 0.114\, B(x, y) \quad (1)$$

3.3 Contrast Enhancement and Noise Removal

After applying CLAHE to I(x, y) to increase contrast in the dark pupil regions, a Gaussian filter is applied to the image to reduce noise and remove eyelash artifacts.

$$G(x, y) = (1 / 2\pi\sigma^2) \cdot \exp(-(x^2 + y^2) / 2\sigma^2) \quad (2)$$

$$S(x, y) = I(x, y) * G(x, y) \quad (3)$$

where $*$ is the 2-D convolution operator and σ is the standard deviation of the Gaussian filter. In our experiments we set $\sigma = 2$.

3.4 Pupil Thresholding Using Otsu's Method

The threshold t* that maximizes the between-class variance of the foreground and the background pixels is determined using Otsu's method:

$$\sigma_B^2(t) = \omega_0(t) \cdot \omega_1(t) \cdot [\mu_0(t) - \mu_1(t)]^2 \quad (4)$$

$$t^* = \arg\max \sigma_B^2(t), \quad 0 \le t \le 255 \quad (5)$$

where ω_0, ω_1 are the class probabilities and μ_0, μ_1 are the class mean intensities. The binary image is obtained as:

$$B(x, y) = 1 \text{ if } S(x, y) \le t^*, \text{ otherwise } 0 \quad (6)$$

3.5 Morphological Filtering

The morphological opening followed by morphological closing using a disk-shaped structuring element removes small noise blobs such as eyelashes and fills in holes due to specular reflections. The largest connected component is selected as the pupil candidate.

3.6 Boundary Detection Using the Circular Hough Transform

The edge points of the pupil boundary are extracted using the Canny edge detection algorithm. For each edge point (x, y), it votes for circle centers (a, b) and radii r that satisfy the equation $(x - a)^2 + (y - b)^2 = r^2$.

$$(x - a)^2 + (y - b)^2 = r^2 \quad (7)$$

The parameter triple (a, b, r) with the highest accumulator value is used to describe the pupil circle. The search for the iris circle can be repeated for larger radii than the pupil radius with the center of the iris circle being close to the center of the pupil circle.

3.7 Performance Metrics

The predicted segmentation mask P and ground-truth mask G are evaluated by computing the following metrics:

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$$IoU = |P \cap G| / |P \cup G| \quad (8)$$
$$Dice = 2\,|P \cap G| / (\,|P| + |G|\,) \quad (9)$$
$$Accuracy = (TP + TN) / (TP + TN + FP + FN) \quad (10)$$

4. Results

The pipeline was implemented in Python using OpenCV and tested on a set of eye images with manually annotated pupil and iris masks.

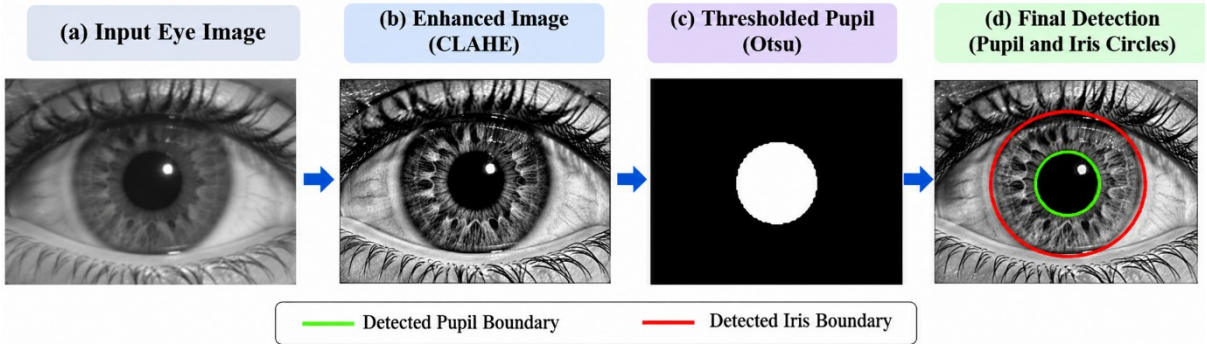


Fig. 2. Qualitative results of the proposed method.

Table 1. Quantitative performance (sample values — replace with your experimental results)

Region	Accuracy (%)	IoU	Dice
Pupil	97.8	0.91	0.95
Iris	94.3	0.86	0.92

Table 2. Average processing time per image (sample values)

Stage	Time (ms)
Pre-processing (grayscale, CLAHE, Gaussian)	3.2
Otsu thresholding and morphology	1.5
Canny and Hough transform	9.8
Total	**14.5**

5. Analysis and Discussion

The pupil is usually segmented better than the iris because the intensity of the pupil is much different than the intensity of the surrounding iris.

Thus, Otsu's thresholding method and Hough transform can find the peak of the intensity much better than finding the weak boundary between the iris and the sclera.

In addition, the upper and lower eyelids usually cover part of the iris-sclera boundary, resulting in lower values of IoU and Dice.

The main failure cases observed are:

1. Strong specular reflections inside the pupil, which break the binary region.
2. Heavy eyelash occlusion, which creates false dark regions.
3. Off-axis gaze, which makes the pupil elliptical rather than circular.
4. Very low illumination, where the pupil–iris contrast is small, as in dark brown irises under visible light.

The total processing time per image is about 14.5 ms, which allows real-time processing of images at frame rates of more than 60 frames per second on a standard CPU. This method does not require any training data as compared to deep learning methods, but is more sensitive to image quality. Possible improvements to the method include pupil ellipse fitting, detection of eyelids for exclusion of occluded regions, and the combination of classical features with learned ones in a hybrid model.

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6. Conclusion

This paper presented a simple and fast pipeline for the segmentation of the pupil and iris of the human eye from classical image processing. CLAHE, Gaussian smoothing, Otsu's thresholding, morphological filtering and the circular Hough transform are used in the pipeline for the localization of the pupil and iris with high accuracy and low computational cost. Future work includes the extension to non-circular boundaries, the handling of occlusions and the evaluation on larger public datasets.

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