

Gaussian Mixture Model), which can be seen explicitly in Figure.1 (b).

In the case of the non-ideal eye images, shown as Figure.2(a), the histogram of eye image is first smoothed with a mean filter, and then fitted with three weighted Gaussian distributions.

$$H_{GMM}(x) = \sum_{k=1}^3 \alpha_k G_k(x | \mu_k, \sigma_k)$$

Variable x represents the gray level values from the image gray level histogram; and $G_k(x | \mu_k, \sigma_k)$ denotes the Gaussian function; (μ_k, σ_k) is the parameters of the k_{th} Gaussian; α_k is the weight for each Gaussian; $\alpha_k > 0$ and $\sum_{k=1}^3 \alpha_k = 1$.

The parameters of every Gaussian component are iteratively estimated using Expectation Maximization method (EM) [9] with the following iterative equations:

$$\omega_{nk} = \frac{\alpha_k^{old} f_k(x_n | \mu_k, \sigma_k)}{\sum_{k=1}^3 \alpha_k^{old} f_k(x_n | \mu_k, \sigma_k)}$$

$$\alpha_k^{new} = \frac{1}{N} \sum_{n=1}^N \omega_{nk}, \quad \mu_k^{new} = \frac{\sum_{n=1}^N \omega_{nk} x_n}{\sum_{n=1}^N \omega_{nk}}$$

$$\sigma_k^{new} = \frac{\sum_{n=1}^N \omega_{nk} (x_n - \mu_k^{new})(x_n - \mu_k^{new})^T}{\sum_{n=1}^N \omega_{nk}}$$

Then the threshold is set as the closest gray level corresponding to the minimum probability between the maxima of the first two Gaussian distributions, which will result in minimum error segmentation.

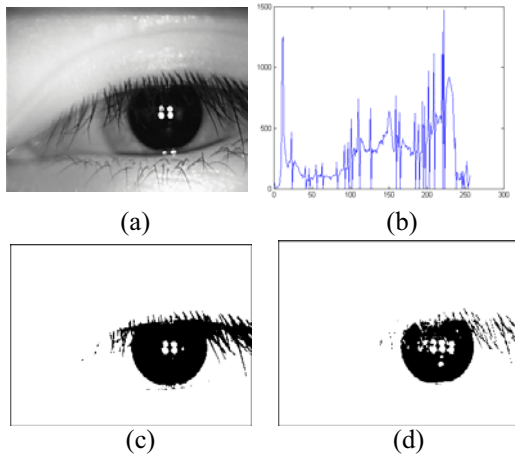


Figure 2. Rough Segmentation of Pupil Region (a) Original image; (b) Gray level distribution; (c) result

of mode method; (d) result of rough segmentation

2.2 Modification of Rough Segmentation

Because global thresholding method is sensitive to the interferential factors such as uneven illumination, blur, occlusion etc, totally correct and complete segmentation of pupil usually cannot be achieved in the first processing step. As can be seen in Figure.2 (d), though the pupil region is detected, the result still involves some eyelashes and illumination artifacts. Morphological method (shown in Figure.3) is applied to modify the rough segmentation result before the estimation of pupil parameters.

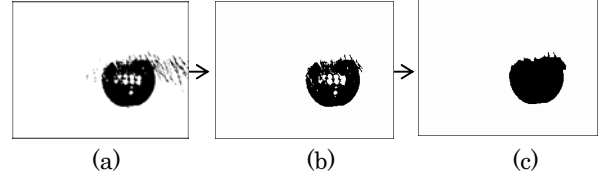


Figure 3. Modification of rough segmentation (a) Rough pupil region; (b) Find the biggest connective area and apply open operation to erase eyelashes; (c) Perform close operation to fill illumination artifacts;

2.3 Fitting the Pupil Region to a Circle

The pupil can be approximated by a circle according to its physiological shape property. Though the rough pupil region is segmented after the first two processing steps, it is usually not complete or still leaves some eyelashes adhere to the pupil region. Therefore, if projection is used to determine the parameters of the pupil circle, localization error will occur.

In this paper we determine the circle parameters (center parameter (x, y) , and radius R by minimizing the least square error [10]. The square error J is:

$$J = \sum \omega_i \left[(x_i - x_0)^2 + (y_i - y_0)^2 - R^2 \right]^2$$

where the summation is over all edge points (x_i, y_i) by differentiating J with respect to x_0 , y_0 and R . Then x_0 , y_0 and R are iteratively given by:

$$x_0 = \frac{B_y C_x - B_x C_y}{A_x B_y - A_y B_x}, \quad y_0 = \frac{A_y C_x - A_x C_y}{A_y B_x - A_x B_y}$$

$$R^2 = \frac{1}{W} \sum \omega_i \left[(x_i - x_0)^2 + (y_i - y_0)^2 \right]$$

where:

$$W = \sum \omega_i, \quad \bar{x} = \frac{1}{W} \sum \omega_i x_i, \quad \bar{y} = \frac{1}{W} \sum \omega_i y_i$$

$$A_x = \sum \omega_i (x_i - \bar{x}) x_i, \quad B_x = \sum \omega_i (x_i - \bar{x}) y_i,$$

$$C_x = \frac{1}{2} \sum \omega_i (x_i - \bar{x}) (x_i^2 + y_i^2)$$

$$A_y = \sum \omega_i (y_i - \bar{y}) x_i, \quad B_y = \sum \omega_i (y_i - \bar{y}) y_i$$

$$C_y = \frac{1}{2} \sum \omega_i (y_i - \bar{y}) (x_i^2 + y_i^2)$$

The initial values of the weights ω_i are all set to 1; other variables are initially set to 0. The procedure of fitting and weighing is executed ten times. The localization result is shown in Figure.4.

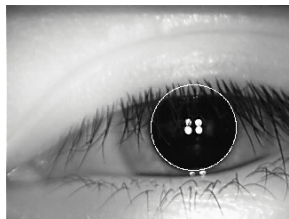


Figure 4. The pupil localization result

3 Experiments

We test our procedure first on the CASIA eye images dataset [11]. The images in the previous version of this dataset are somewhat ‘ideal’ because they have been modified to remove the illumination artifacts; and few images have the occlusion or blur problem. Some samples are shown in Figure.5 (a). The correct localization rate on this set is 100%. The images in the second version of CASIA are captured with remote device, so the images extend a larger area and easy to be influenced by external illuminations, some samples are shown in Figure.5 (b). The correct localization rate on this set is 95.2%.

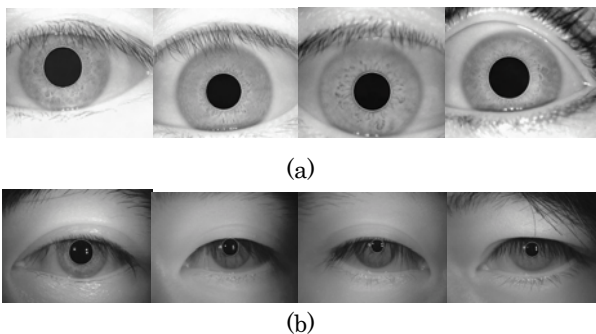


Figure 5. CASIA eye images
(a) Previous version; (b) Second version

In order to further test the performance of our proposed method, we also do experiments on the eye images which we practically collected using the capture device for iris recognition. To test the robustness of the proposed method, we haven't put much restriction when capturing, so this dataset has more variety and not so ‘ideal’ as other datasets.

First the traditional pupil localization method is re-implemented, i.e. use mode method to select threshold and projection to determine the circle parameters. Then our proposed pupil localization procedure is employed. Moreover, we test the performance when the first step in our method is changed to simple threshold, and also when the second step (modification of rough segmentation) is dropped from the proposed procedure. The localization results are shown in Table.1. The propose method get a higher correct rate than the traditional method.

Some localization results of non-ideal eye images are shown in Figure.6 to indicate the robustness of the proposed method. Some failed samples are also shown in Figure.7.

Table 1. Experiences on SJTU-IDB

	Image number	Localization method	Correct rate
Image set 1 ^{*1}	5320	Integro-Differential	72.9%
		Thresholding only	62.7%
		Our proposed method	87.2%
Image set 2 ^{*2}	4531	Integro-Differential	87.0%
		Thresholding only	70.2%
		Our proposed method	98.9%
		Modification 1 ^{*3}	83.3%
		Modification 2 ^{*4}	84.9%

^{*1} Image set 1: all images in SJTU-IDB

^{*2} Image set 2: images after some low-quality samples are excluded from SJTU-IDB

^{*3} Modification 1: the first step change to simple threshold, other steps are same as our proposed method.

^{*4} Modification 2: drop the second step (Modification of rough segmentation) from our proposed method, other steps are same.

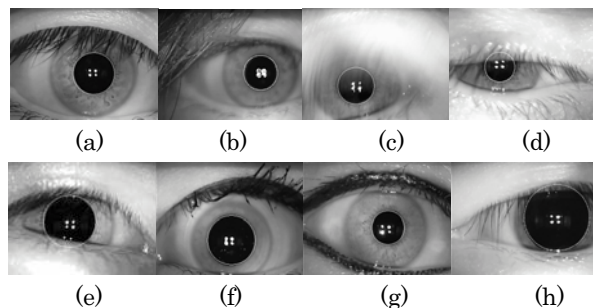


Figure.6. Localization Results of Non-ideal Images
(a) average eye image; (b) defocus image; (c) motion blur; (d)(e) occlusion; (f)(g) makeup eye images; (h) big pupil (by mydriatic when surgery)

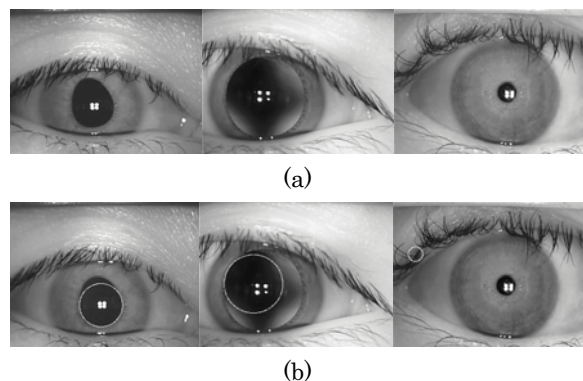


Figure.7. Some Failed Samples
(a) Original samples; (b) their localization results

In this paper, we only take into consideration of the single frame of eye image. If video sequences of eye movements are employed, accurate localization of pupil will be more challenging. This is part of our future work.

4 Conclusion

In this paper, a detailed method of pupil localization in non-ideal eye image is proposed. This method is implemented in three main steps: first segment the rough pupil region based on GMM and EM; then modify the rough segmentation using morphological method to minimize the influence of eyelids, eyelashes and illumination artifacts; last estimate the parameters of pupil based on minimizing the least square error. The proposed method is first tested on CASIA iris image dataset, and then on our self-captured iris dataset that with more variety. Experiments show that the proposed method can perform well for non-ideal eye images of various qualities.

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