MVA2002 IAPR Workshop on Machine Vision Applications, Dec. 11-13, 2002, Nara-ken New Public Hall, Nara, Japan

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Precise Pupil Contour Detection based on Minimizing the Energy of Pattern and Edge

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Abstract

We propose a new method to precisely detect pupil contours in faces. The method is based on minimizing the energy of pattern and edge. The basic idea of this method is that the energy, which consists of the pattern and the edge energy, has to be minimized. An efficient search method is also introduced to overcome the underlying problem of efficiency of energy minimization methods. "Guide patterns" are introduced for this purpose. Moreover, to detect pupils more precisely we use an ellipse model as pupil shape in this paper. Experimental results are also described.

1 Introduction

To detect feature points (eyes, nostrils, etc.) in face image is necessary for face recognition, gaze detection, and so on. Eyes are considered to be the most important feature among those facial feature points. To detect pupils precisely in a face image is a very difficult problem. One reason of the difficulty is that contours of pupils consist of weak edges and the other is that edges are lacking along the contour.

Many pupil detection methods have been reported. Some are based on edge and shape information, for example, using deformable templates [1]. A method using view-based pattern matching is also reported [2]. However, there are problems respecting the robustness and accuracy in those methods.

We propose a new method to precisely detect pupil contours in faces. The method is based on minimizing the energy of pattern and edge. Edge detection and pattern matching have complementary characteristics. Table 1 shows features of those methods. Pattern matching has a problem on the accuracy and edge detection has a problem on the robustness.

In [3] a method to extract facial feature points based on a combination of pattern matching and shape extraction has been proposed. It is a very robust system compared with the other methods mentioned above. But in [3] pattern matching and edge detection have been used only separately, i.e., the edge detection was used only as the pre-processing for the pattern matching.

The method proposed in this paper is more generalized one. It integrates pattern matching and edge detection to a unique framework of energy minimization and therefore it has become a more robust and flexible method.

An efficient search method using "guide patterns" is also introduced to overcome the optimization problem lying in energy minimization methods.

If pupils are detected accurately, they can be used for face recognition for example. In view-based face recognition, the performance highly depends on the accuracy in the detection of face location and size. Accurate location is thus necessary for view-based face recognition. In gaze detection the problem is more serious. In view-based gaze detection, in addition to accurate locations of the pupils, shape information is also needed. The proposed method has a possibility to be used for gaze detection since it can handle an ellipse model as pupil shape.

Table 1 Features of edge and pattern.

Features	Edge	Pattern
Scale	Local	Global
Accuracy of locating	Good	Poor
Robustness for noise	Poor	Good

2 Basic concept

Basically we use the energy minimization method. Regarding the energy minimization method in image recognition, various methods have been proposed. For example, an active contour model [4] is one of the most

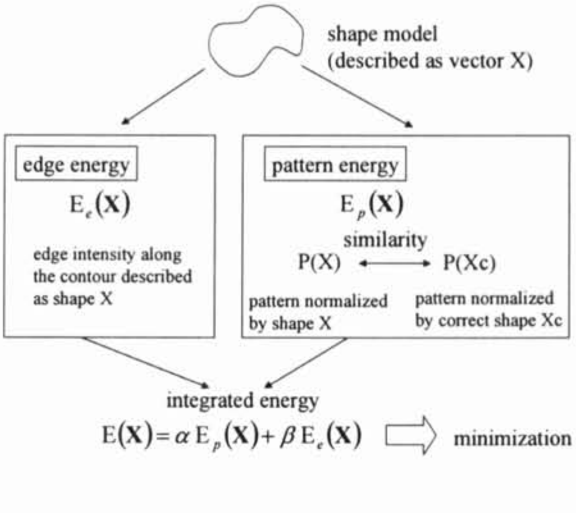

Figure 1 Conceptual diagram of the proposed method

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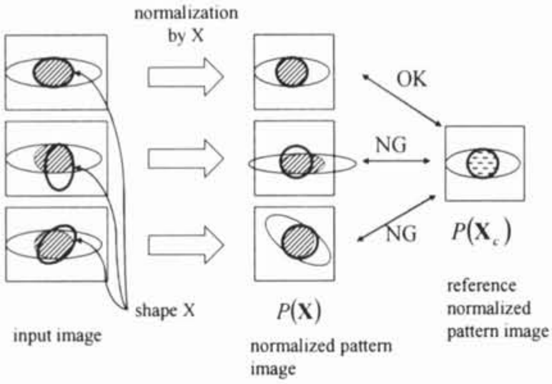
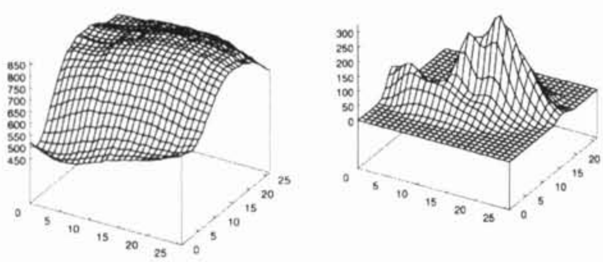


Figure 2 Examples of the images normalized by shape model



(a) pattern energy (b) edge energy

Figure 3 Examples of the pattern and the edge energy maps.

famous. Employment of pattern energy, however, has not been discussed sufficiently. Figure 1 shows a conceptual diagram of the proposed method. The integrated energy is defined in equation 1.

$$\mathrm{E}(\mathbf{X}) = \alpha\,\mathrm{E}_p(\mathbf{X}) + \beta\,\mathrm{E}_e(\mathbf{X}) \tag{1}$$

The integrated energy consists of the pattern energy $\mathrm{E}_p(\mathbf{X})$ and the edge energy $\mathrm{E}_e(\mathbf{X})$. α and β are weighting coefficients. $\mathbf{X} = (x_0, x_1, \ldots, x_{n-1})$ is a feature vector which describes the object shape and location. For example, if the object shape is described by the coordinates of its contour, the set of coordinates can be used for $\mathbf{X}$. In case of a parametric shape object, dimension of the feature vector can be reduced by using their parameters.

The pattern energy $\mathrm{E}_p(\mathbf{X})$ is the similarity between a pattern $P(\mathbf{X})$ normalized by shape $\mathbf{X}$ and a reference pattern $P(\mathbf{X}_c)$ normalized by a correct shape $\mathbf{X}_c$ (Figure 2). The edge energy $\mathrm{E}_e(\mathbf{X})$ is based on the edge intensity along the contour of shape $\mathbf{X}$. The energy originated in edge has the problem that the energy is not correct when the initial position is far from the correct position. The pattern energy does not dramatically change as the edge energy does. Examples of the pattern and the edge energy maps are shown in Figure 3. The edge energy has an acute peak, which is important to determine the shape precisely.

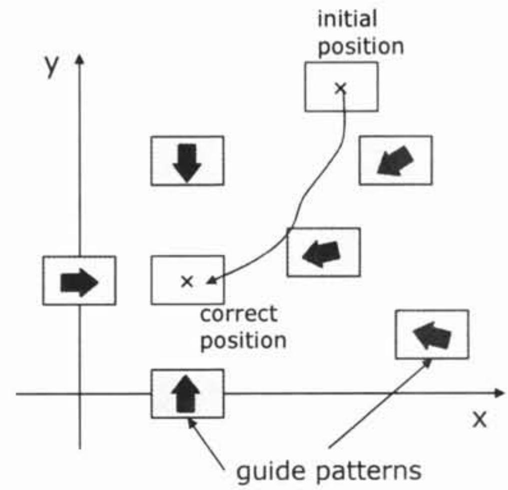


Figure 4 Guide patterns along the path to the true position in 2-D.

3 Guide patterns

There is always a search problem in energy minimization. If the initial point is far from the correct one, the energy minimization does not work correctly. To overcome this problem, we introduce a "guide pattern", which plays a role in navigating to the correct point. Figure 4 shows examples of the guide patterns along the path from the initial point to the correct point in 2-dimensional space. The guide pattern $P(\mathbf{X}_c + \mathbf{dX})$ is a set of pattern images that are normalized by slightly shifted shape ($\mathbf{X} = \mathbf{X}_c + \mathbf{dX}$).

Figure 5 shows examples of pupil image patterns described as circles. The guide pattern can suggest the most likely direction in energy minimization procedure, because the shift parameters are known in advance. The direction is the opposite of the shift parameter used in normalization. If $Sim(\mathbf{X}_c + \mathbf{dX}, \mathbf{X})$, which is the similarity between a pattern at $\mathbf{X}$ and a pattern at $\mathbf{X}_c + \mathbf{dX}$, is greater than $Sim(\mathbf{X}_c, \mathbf{X})$, we can guess that $\mathbf{X}$ is near $\mathbf{X}_c + \mathbf{dX}$. Therefore to get close to the correct point $\mathbf{X}_c$, we move it to $-\mathbf{dX}$ direction.

This idea is similar to the parametric eigenspace method for navigating a robot to the target position. Maeda et al. [5] adopted the strategy of estimating the current position of the robot by learning the images along the path to the target.

4 Pupil contour detection with ellipse models

4.1 Overview

In this section we describe the pupil contour detection method based on the energy minimization. The contour of a pupil is approximated by an ellipse model.

For the generalized feature vector, $\mathbf{X}$, we use five ellipse parameters that are the location of the center point, (x, y), major and minor axes, a and b, and the rotation angle, θ.

To calculate the similarity for pattern energy $\mathrm{E}_p(\mathbf{X})$, subspace method [6] is used. Subspace method, which can absorb pattern deformation, is more robust than simple

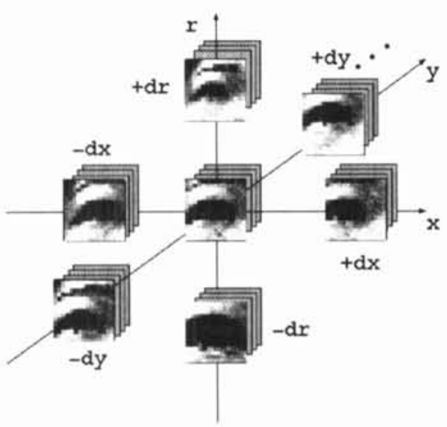


Figure 5 Example of the images normalized with shifted parameters

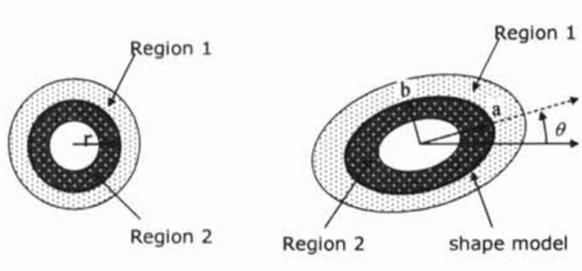
correlation. Therefore it can be used for pupils that change their appearances depending on the individuals of persons or lighting conditions. "Guide pattern subspaces" are used instead of simple guide patterns. The correct pattern subspace is made from images normalized by correct ellipse parameters. The guide pattern subspaces are generated from images normalized by slightly shifted parameters that describe an ellipse shape. The feature vector used for the subspace method is created by raster scan of a normalized image.

For the edge energy $E_e(\mathbf{X})$, separability [3] is used. It represents the degree of difference between regions. Separability η is defined by equation 2.

$$\eta = \frac{\sigma_b^{\ 2}}{\sigma_T^{\ 2}}$$
$$\sigma_b^{\ 2} = n_1\left(\overline{P_1} - \overline{P_m}\right)^2 + n_2\left(\overline{P_2} - \overline{P_m}\right)^2 \qquad (2)$$
$$\sigma_T^{\ 2} = \sum_{i=1}^{N}\left(P_i - \overline{P_m}\right)^2$$

where P_i is an image intensity at pixel *i*, $\overline{P_1}, \overline{P_2}, \overline{P_m}$ are the means of the image intensity in region 1, 2 ,1+2, and n_1, n_2, N are the numbers of pixels in each region. We use ellipse separability filter to calculate the edge intensity. Figure 6(b) shows an example of the ellipse separability filter. The shape of the filter represents an ellipse shape model.

The framework of the proposed method is shown in Figure 7. The details of each step are as following.



(a) circle shape (b) ellipse shape

Figure 6 Separability filter

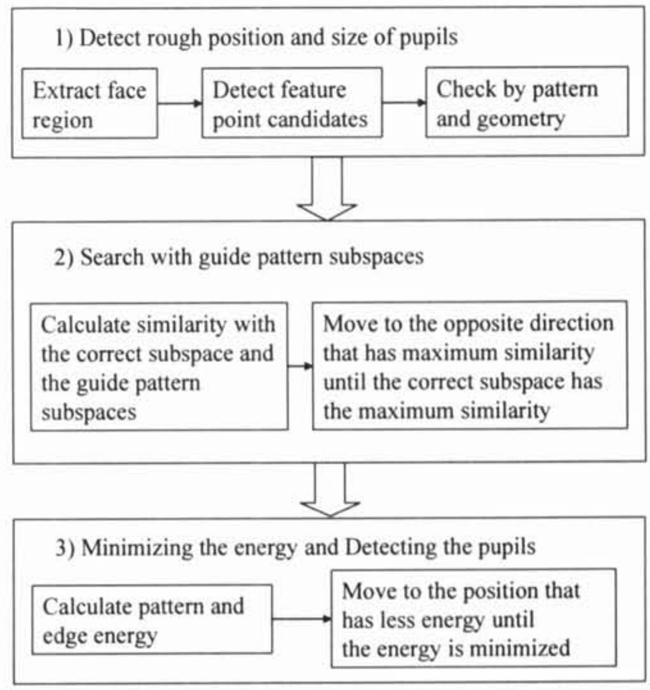


Figure 7 Framework of the proposed pupil contour detection method

4.2 Detection of rough location and size

The parts detection method based on a combination of pattern and shape [3] is used to detect the initial position and the size of the pupils as a circle. The rough location and the size of the pupil can be detected by that.

First the face region is detected in an input image. We use face detection method based on pattern matching using the subspace method [6].

And then candidates of feature points are detected by separability filters with circular shape (Figure 6(a)). For each pixel in the detected face region, the separability is calculated while changing the position and radius of the filter. The candidate feature points are selected among the local maximum peaks of separability value.

Finally the candidate points are verified by pattern matching.

4.3 Search with guide pattern subspaces

In order to avoid detecting wrong contours and to reduce processing time, we use "guide pattern search". The guide pattern search is carried out according to following procedure.

First the similarity is calculated with the correct pattern subspace and the guide pattern subspaces which are created in advance. The correct pattern subspace is made from the images normalized by correct parameters. The guide pattern subspaces, on the other hand, are made from the images normalized by the parameters at the known distance from the correct one. We use two guide pattern subspaces for each ellipse parameter (Figure 5).

The position is moved to the opposite direction of the shift parameter that has the maximum similarity with an input pattern. The search is continued until the similarity with the correct pattern subspace becomes greater than that with any guide pattern subspace.

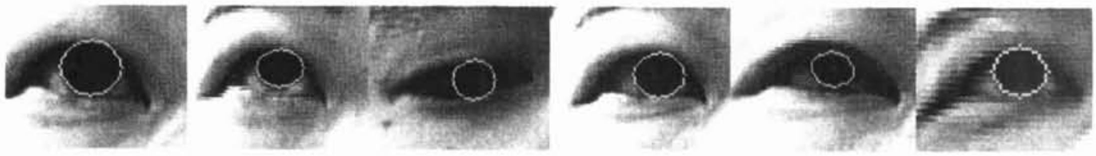


Figure 8 Examples of detected pupil contours

4.4 Minimizing the energy and detecting the pupils

Pupil contours are detected by minimizing the total energy which consists of pattern energy and edge energy. The pattern energy $E_p(\mathbf{X})$ and the edge energy $E_e(\mathbf{X})$ are described in equation 3. $Sep(\mathbf{X})$ is the separability value at $\mathbf{X}$, which was described as η in equation 2. $Sim(\mathbf{X}_c, \mathbf{X})$ is the similarity between an input pattern and the correct pattern subspace.

$$\begin{aligned} E_e(\mathbf{X}) &= -Sep(\mathbf{X}) \\ E_p(\mathbf{X}) &= -Sim(\mathbf{X}_c, \mathbf{X}) \end{aligned} \tag{3}$$

The position is moved step by step to the location that has less energy from the initial point detected by guide pattern search. This process will be continued until the current position has the minimum energy in the neighboring area.

5 Experimental Result

We show the experimental result obtained by the above mentioned method. Figure 8 shows examples of correctly detected pupil contours. The proposed method was applied to real face images. Pupil contours were almost correctly detected when the distance from the initial point to the correct position is within half the radius of the pupil. The estimation of contour accuracy was performed by difference of area inside the detected contour from that of correct contour (Figure 9). The difference of area includes both inner and outer region of the correct contour. The error of detected contours is much smaller than that of previous method.

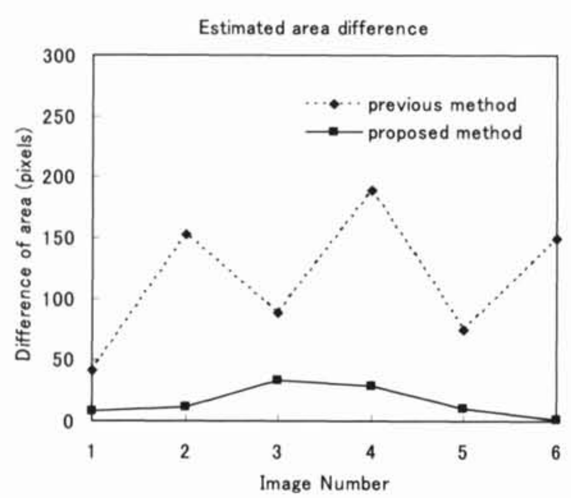


Figure 9 Estimated area differences from correct contour. (Image numbers are corresponding to the images in Figure 8.)

Evaluation by the center points was also performed for two test objects. We have used 1600 sample images of eight persons to generate both the correct pattern subspace and the guide pattern subspaces. The data of test persons are not contained in above sample images. 225 dimensions for the image size of 15 x 15 pixels are used in the experiment. The error in finding the center points of pupils has been used for evaluation. Table 2 shows the estimated errors of center points. The result is compared with the previous method proposed in [3]. The proposed method shows an improved performance than the previous method.

Table 2 Estimated errors of center points of pupils (pixels).

	previous method		proposed method	
	left	right	left	right
person1	2.29	1.75	1.55	1.63
person2	1.48	2.48	0.78	1.40
mean	1.88	2.12	1.16	1.52

6 Conclusion

We have proposed a precise pupil detection method based on minimizing the energy of pattern and edge. An ellipse model is introduced to detect more precisely. We have also proposed the guide pattern subspace that helps to make it smooth and stable to minimize the energy. The method has been verified through experimental results.

Future works will be directed to applying this algorithm to a large number of samples and also extending it to treat other objects such as lip contours.

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