Two Stage Fingerprint Image Enhancement Algorithm by Anisotropic Diffusion

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Abstract. A new fingerprint enhancement algorithm is presented. The technique consists of two anisotropic diffusion schemes. One is the coherence-enhancing diffusion. Another is the modified edge-enhancing diffusion. At first, the degraded fingerprint image is processed by the coherence-enhancing diffusion to obtain the initial processed image. And then, the modified edge-enhancing diffusion operates on the initial processed image to obtain the final enhancement image. The tests show the proposed new method gets the better performance obviously compared to the original coherence-enhancing diffusion-based method.

Introduction

Among all the biometrics, fingerprint-based identification is one of the most popular and reliable biometric techniques. The performance of the automatic fingerprint identification system relies heavily on the quality of input fingerprint images. These bad quality fingerprint images lower the accuracy of automatic fingerprint identification system. Therefore, an enhancement process is often used prior to the fingerprint identification. A large number of algorithms have been proposed. The wavelet based algorithms and the partial differential equations (PDE) based algorithms are populous. In [1] and [2], the wavelet based methods were proposed. By the wavelet transform, the method in [1] improves the clarity and continuity of ridge structures based on the multiresolution analysis of global texture and local orientation. The algorithm in [2] consists of two stages. The first stage is decomposing the input fingerprint image into four subbands by applying two-dimensional discrete wavelet transform. At the second stage, the compensated image is produced by adaptively obtaining the compensation coefficient for each subband based on the referred Gaussian template. In [3-7], the PDE-based methods were used to enhance fingerprint images. Concretely speaking, the coherence-enhancing diffusion filtering was presented in [3, 4]. Based on coherence-enhancing diffusion filtering, the improved methods were developed by coupling the orientation domain in [5, 6]. In [7], by developing multi-scale decimation-free directional filter bank, the improved coherence enhancement diffusion is used to process the fingerprint image. In [8], Zhang produced an image enhancement scheme based on anisotropic tensor diffusion. This method is used as the post-processing scheme in the process of image denoising. The desired result is obtained. This paper will focus on the improvement of tensor diffusion methods because the literature [6] has shown that the tensor diffusion methods can enhance the fingerprint image while computing the oriented domain.

This paper is organized as follows. The proposed method is presented in Section 2. In Section 3, the experiment results are given to verify the performance of the proposed method. In Section 4, the conclusion is concluded.

The Proposed Method

The proposed enhancement algorithm is based on anisotropic diffusion methods. Therefore, the tensor diffusion proposed by Weickert et al. in [3] is reviewed firstly. And then, the coherence
enhancement anisotropic diffusion in [3] and the contrast enhancement using modified edge enhancement anisotropic diffusion proposed by Zhang in [8] are described, respectively. Finally, to clearly present the proposed method further, the structure of proposed algorithm is demonstrated in detail.

**The Anisotropic Tensor Diffusion**

Anisotropic tensor diffusion proposed by Weickert et al. [3] is represented by

\[
\partial_t u = \nabla (DUu)
\]

In Eq. (1), \( D \) is the \( 2 \times 2 \) diffusion matrix given by

\[
D = \begin{pmatrix}
    d_{11} & d_{12} \\
    d_{21} & d_{22}
\end{pmatrix}
\]

The diffusion matrix \( D \) is adapted to the local structure of image. It is computed from the structural tensor matrix \( S_\rho \), defined as:

\[
S_\rho = \begin{pmatrix}
    s_{11} & s_{12} \\
    s_{21} & s_{22}
\end{pmatrix} = G(\rho)^* \begin{pmatrix}
    u_{x,\sigma}^2 & u_{x,\sigma}u_{y,\sigma} \\
    u_{x,\sigma}u_{y,\sigma} & u_{y,\sigma}^2
\end{pmatrix}
\]

In Eq. (3), \( u_{x,\sigma} \) and \( u_{y,\sigma} \) represent the partial derivatives along the \( x \) and \( y \) directions, respectively. At this time, the image has been pre-smoothed with the first Gaussian filter of the local noise scale \( \sigma \). The second Gaussian filter \( G(\rho) \) of standard deviation \( \rho \) is used to define the integration scale. The matrix \( S_\rho \) is positive symmetric semidefinite. It has two normalized orthonormal eigenvectors \( \nu_1 = (\cos \theta, \sin \theta)^T \) and \( \nu_2 = (-\sin \theta, \cos \theta)^T \). The parameter \( \theta \) represents the orientation field of the given image. The eigenvector \( \nu_1 \) with eigenvalue \( \mu_1 \) is parallel to the gradient. The \( \nu_2 \) is eigenvector of eigenvalue \( \mu_2 \). The \( \mu_1 \) and \( \mu_2 \) are computed as follows:

\[
\mu_1 = \frac{1}{2} (s_{11} + s_{22} + \sqrt{(s_{11} - s_{22})^2 + 4s_{12}^2})
\]
\[
\mu_2 = \frac{1}{2} (s_{11} + s_{22} - \sqrt{(s_{11} - s_{22})^2 + 4s_{12}^2})
\]

By \( \mu_1 \) and \( \mu_2 \), some useful image feature information can be obtained. Constant areas are characterized by \( \mu_1 = \mu_2 = 0 \), straight edges by \( \mu_1 >> \mu_2 = 0 \), corners by \( \mu_1 \geq \mu_2 >> 0 \), and flat regions by \( \mu_1 = \mu_2 \approx 0 \). On the average, the expression \((\mu_1 - \mu_2)^2\) is large for anisotropic structures and tends to zeros for isotropic structures.

The diffusion matrix \( D \) can be constructed from the corresponding eigenvalues and eigenvectors as:

\[
d_{11} = \lambda_1 \cos^2 \theta + \lambda_2 \sin^2 \theta \\
d_{21} = d_{12} = (\lambda_1 - \lambda_2) \sin \theta \cos \theta \\
d_{22} = \lambda_1 \sin^2 \theta + \lambda_2 \cos^2 \theta
\]

where \( \lambda_1 \) and \( \lambda_2 \) depends on \( \mu_1 \) and \( \mu_2 \). The different selection of \( \lambda_1 \) and \( \lambda_2 \) will lead to different anisotropic diffusion scheme.
The Coherence Enhancement Anisotropic Diffusion

The orientation of the eigenvector corresponding to $\mu_2$ is called the coherence orientation. This orientation is the feature direction of fingerprint image. To enhance the feature of fingerprint image, $\lambda_1$ and $\lambda_2$ is taken as:

$$
\lambda_1 = c_1
$$

$$
\lambda_2 = \begin{cases}
  c_1, & \text{if } \mu_1 = \mu_2 \\
  c_1 + (1 - c_1) \exp \left( -\frac{c_2}{(\mu_1 - \mu_2)^2} \right), & \text{else}
\end{cases}
$$

(6)

where $0 < c_1 < 1$ and $c_2 > 0$. In the subsequent experiments, the value of $c_1$ and $c_2$ is taken as 0.001 and 1, respectively. The anisotropic diffusion with Eq. (6) is called the coherence enhancement anisotropic diffusion (CED). In the proposed method, the initial enhanced image processed by CED is represented by $U$.

In [3], authors showed that the CED can be used to enhance the coherence of flow-like textures existing in fingerprint image. But, there is a shortage for CED. That is, in the process of fingerprint image, the contrast of image can be contracted, and which will degrade the visual effect of fingerprint image (cf. Figs. 1a and b).

![Figure 1](image)

(a) (b) (c)

Figure 1. Comparison of enhancement results. (a) Original fingerprint image with interrupted ridges and additional false details. (b) Enhancement result using original CED approach. (c) Enhancement result using the proposed approach.

The Modified Edge Enhancement Anisotropic Diffusion

In [8], a modified edge enhancement anisotropic diffusion (MEEAN) was proposed. That is because that the contrast ratio of the initial denoised image is reduced compared with the original observed noisy image. MEEAN is used to enhance the edge with large gradient while removing or weakening the artifacts with little gradient so that the visual of denoised image becomes better. In the proposed method, MEEAN will be used to enhance the fingerprint textures with large gradient so that contrast ratio of original fingerprint image can be restored or enhanced as much as possible.

In MEEAN, $\lambda_1$ and $\lambda_2$ is determined as follows:

$$
\lambda_1 = g(\lvert \nabla U \rvert) = \begin{cases}
  1, & \text{if } \lvert \nabla U \rvert = 0 \\
  1 - \theta \exp \left( -1/(\lvert \nabla U \rvert/K)^2 \right), & \text{if } \lvert \nabla U \rvert \neq 0
\end{cases}
$$

(7)

$$
\lambda_2 = 0
$$

where $\theta > 1$ is the introduced tuning parameter and $K$ is a gradient thresholding. Eq. (7) shows that one allows a flux component parallel to the gradient which is responsible for the minified edges and enhanced edges. The $\lambda_2$ is taken to 0 because the coherence orientation has been processed in the
CED stage. The important role of the parameter $\theta$ in distinguishing important information with large gradient from unimportant information with little gradient. The edges are enhanced when $\theta \exp\left(-\frac{1}{|\nabla U|/K}\right) > 1$ while that are minified when $\theta \exp\left(-\frac{1}{|\nabla U|/K}\right) \leq 1$. In the subsequent experiments, the value of $K$ and $\theta$ is chosen as 4.8 and 1.35, respectively.

**The Proposed Two Stage Diffusion Method**

The proposed method consists of two diffusion stages. In each diffusion stage, the employed discritized scheme is as follows:

$$u(x, y; t+1) = u(x, y; t) + \Delta t \times \nabla(D\nabla u(x, y; t))$$

The specific steps of the proposed algorithm are as follows: (1) Input original degraded fingerprint image $u$; (2) Perform the CED with Eq. (6) on original fingerprint image $u$, and obtain the initial enhancement image $U$; (3) Implement the MEEAN with Eq. (7) on the initial enhancement image $U$; (4) Output the final enhanced image $E$.

In the subsequent experiments, in the CED step, the iteration number is 20. In the MEEAN step, the iteration number is 30. And then, in each stage, the other parameters are taken so that the best results are achieved.

**The Experiment Results**

To evaluate the proposed method, two fingerprint images with different features are used in test. Fig. 1 presents the processed results using CED and proposed method on fingerprint with interrupted ridges and additional false details. Fig. 2 presents the processed results using CED and proposed method on fingerprint with low contrast and additional false details. It can be seen that the proposed method exhibits better fingerprint image processed effects. Compared to CED method, the proposed method removes or weakens the additional false details and reconnected the interrupted ridges in a sense while the contrasts of original fingerprint image are enhanced. The disadvantage of CED method is improved that the contrast ratio is reduced in the process of fingerprint image.

![Figure 2](image-url)

Figure 2. Comparison of enhancement results. (a) Original fingerprint image with low contrast and additional false details. (b) Enhancement result using original CED approach. (c) Enhancement result using the proposed approach.

**Conclusions**

In this paper, a new fingerprint image enhancement method is presented by combining the coherence enhancement diffusion scheme proposed by Weickert et al. and the edge enhancement diffusion scheme proposed by Zhang. Using the proposed new method, the better enhancement effects are achieved in the test. In this method, to deal with the problem of reducing contrast of the coherence enhancement diffusion, the edge enhancement diffusion scheme proposed by Zhang is used to post-process the initial enhancement image. The proposed method is an important supplementary for
the denoising approach based on wavelet domain diffusion and image domain diffusion proposed by Zhang.

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