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Residual orientation modeling for fingerprint enhancement and singular point detection

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ABSTRACT

This paper presents a novel method for fingerprint orientation modeling, which executes in two phases. Firstly, the orientation field is reconstructed using a lower order Legendre polynomial to capture the global orientation pattern in the fingerprint structure. Then the preliminary model around the region with presence of fingerprint singularities is dynamically refined using a higher order Legendre polynomial. The singular region is automatically detected through the analysis on the orientation residual field between the original orientation field and the orientation model. The method does not require any prior knowledge on the fingerprint structure. To validate the performance, the method has been applied to fingerprint image enhancement, fingerprint singularity detection and fingerprint recognition using the FVC 2004 data sets. Compared with the recently published Legendre polynomial model, the proposed method attains higher accuracy in fingerprint singularity detection, lower error rates in fingerprint matching.

1. Introduction

As an important feature in fingerprint images, ridge orientation pattern plays a critical role in fingerprint image enhancement [1–3], singularity characterization [4–13], fingerprint classification [14–24], fingerprint indexing [24–28], fingerprint recognition [29–32], etc. There have been a large number of research efforts towards the reliable estimation of fingerprint orientation pattern from acquired fingerprint images, which can roughly be classified into two categories: local estimation and global modeling.

For local estimation methods, the orientation at a pixel is derived based on the information in a neighborhood of the pixel. The most frequently used local method is gradient estimation, which firstly calculates the gradient using the gradient operator (such as the Sobel operator) in digital image processing. Then the orientation is simply the direction perpendicular to the gradient. Despite of its numerical efficiency, the gradient operator is known to be sensitive to noise. To address this issue, a low-pass filter can be applied to the estimated orientation field for noise removal. Alternatively, one can resort to more sophisticated methods, for example, filter-bank [33,34], statistical techniques [35], structure tensor [36–38], local voting [39], integration operator [40] and ridge projection [41].

In practice, the quality of acquired fingerprint can easily be degraded for reasons like wet finger, dry finger and finger with presence of crease, wound or scar. Under these circumstances, the structure of fingerprint in a local region can be very weak and the local signal to noise ratio can be low, leading to difficulty for reliably estimating the ridge orientation by local estimation methods. In general, the fingerprint orientation field is sufficiently smooth except for a few points with singularities, thus it is possible to infer local structure using more global information. Pioneered in this direction is the zero-pole model by Sherlock and Monro [42], where singular points, cores and deltas, are modeled as zeros and poles in the complex plane, and the orientation is estimated by the summation of the influence of singular points. This model has received a number of interests and there have been several improvements. Vizcaya and Gerhardt [43] improved this zero-pole model to deal with more degree of freedom around the singular points. Gu et al. [44–46] propose a combination model for orientation field representation, in which the global orientation is firstly constructed by a polynomial model and subsequently corrected by a point-charge model in regions near singular points. A similar idea has been presented in [47]. Very recently, a unified model is presented in [48] where the zero-pole model and its various generalizations can be regarded as special cases.

In spite of impressive results presented in the above works, these global modeling methods have a common limitation, i.e., they all require the prior knowledge on singular points in the acquired fingerprints. However, fingerprint singular point

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detection by itself is a nontrivial issue in the characterization of fingerprints, which depends very much on the quality of the fingerprint image. For good quality fingerprints, Poincare index method would suffice in the localization of singular points. But for poor quality fingerprints, there would be a large number of spurious singular points if a simple singular point detection method, such as the Poincare index method, is in use. For most of aforementioned global modeling methods, singular points are often detected manually, which evidently limits their application to realistic system. In [49], an SVM classifier is employed to remove the spurious points detected by the Poincare index method, thus avoiding the manual detection for each fingerprint image. However, a set of training data with manually labeled singular points is necessary before the method can be used. In view of this problem, Wang et al. [50] present a fingerprint orientation model which fits the orientation field using a set of trigonometric polynomials. The method does not require the prior knowledge on singular points and has also been demonstrated to be advantageous over the combination model in fingerprint image enhancement and fingerprint matching. The method has recently been extended in [51], where Legendre polynomial is utilized and a step of singularity preservation using the Levenberg–Marquardt algorithm to minimize the modeling cost functional is introduced after the initial modeling. This method is advantageous in preserving singular points, but at cost of computation load. In addition, the step of minimizing the modeling cost helps to preserve true singularities, but at times some false singularity could be kept as well.

In this paper, we will propose a method for fingerprint orientation reconstruction. The method basically consists of two phases: a preliminary modeling phase by a polynomial regression model, followed by a refined phase for fingerprint regions around singularities. What is different from the combination model is that the proposed method does not require the prior knowledge of fingerprint singularities. And more importantly, instead of having a fixed model for region with singularity, the model for region with singularity in the proposed method is updated through an iterative process, where the singular region is gradually determined from the analysis of the residual field between the original orientation field and the global orientation model. The process is fully automatic and robust against various perturbations. Compared with existing polynomial regression model (in particular, the recently published Legendre polynomial model [51]), the proposed method addresses the issue of singularity preservation and differentiates the true singularity from the singularity due to various artifacts in order to reduce the false alarm rate and to preserve true singularities.

The rest of the paper is organized as follows. Section 2 gives a brief account on polynomial modeling for fingerprint orientation reconstruction, which serves as a preliminary modeling in the proposed method. After that, details on orientation residual analysis are given in Section 3, including singularity region detection as well as the refined model. In Section 4, experiment for validating the proposed method and comparison with the state-of-the-art are presented. Finally the paper is concluded in Section 5 with a discussion.

2. Preliminary orientation modeling

A recent trend in fingerprint orientation modeling is to fit the orientation field using a set of basis functions, such as polynomial basis, and Fourier basis. Usually the calculation is carried out in the cosine and the sine domain other than in the original orientation field directly. In addition, the orientation angle is doubled before the sine/cosine operation to avoid the problem of orientation cancellation [33]. For completeness, a brief account is given in the following. Firstly, let us denote the original orientation field as $\boldsymbol{\theta}$ and the transformed orientation field as

$$\mathbf{f}_c = \cos 2\boldsymbol{\theta}, \tag{1a}$$

$$\mathbf{f}_s = \sin 2\boldsymbol{\theta}. \tag{1b}$$

Then the transformed orientation field is approximated by a linear combination of basis functions as

$$\mathbf{f}_c \approx \mathbf{a}^T \boldsymbol{\varphi} \tag{2a}$$

$$\mathbf{f}_s \approx \mathbf{b}^T \boldsymbol{\varphi}, \tag{2b}$$

where $\mathbf{a}$ and $\mathbf{b}$ are the parameters, the superscript T stands for the transpose operation and $\boldsymbol{\varphi}$ represents the set of basis functions. The parameters can be estimated through the least square or the weighted least square method by minimizing the following cost functions

$$\min_{\mathbf{a}} \left|\left| \boldsymbol{\omega}(\mathbf{f}_c - \mathbf{a}^T \boldsymbol{\varphi}) \right|\right|^2, \tag{3a}$$

$$\min_{\mathbf{b}} \left|\left| \boldsymbol{\omega}(\mathbf{f}_s - \mathbf{b}^T \boldsymbol{\varphi}) \right|\right|^2, \tag{3b}$$

where $\boldsymbol{\omega}$ is the weight to be determined from the data. Finally, the orientation field can be reconstructed by

$$\hat{\boldsymbol{\theta}} = \frac{1}{2}\arctan\frac{\hat{\mathbf{f}}_c}{\hat{\mathbf{f}}_s} = \frac{1}{2}\arctan\frac{\hat{\mathbf{a}}^T \boldsymbol{\varphi}}{\hat{\mathbf{b}}^T \boldsymbol{\varphi}}, \tag{4}$$

where $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$ are the parameters estimated from Eqs. (3a) and (3b).

As mentioned in Section 1, a major problem in fingerprint orientation modeling is how to remove the noise and preserve the singularity in the meantime. Higher order polynomial model is usually advantageous in singularity preservation, but tends to over-fit the data and some noisy structure would be kept as well. In contrast, lower order polynomial model performs better in noise removal, but at the cost of larger error in singularity preservation. In this study, a lower order Legendre polynomial is utilized for preliminary modeling of the entire orientation field. As aforementioned, the orientation field is ordinarily smooth except for a few positions where singularities occur. In spite of the poor performance in singularity preservation, the lower order polynomial model is mostly sufficient in modeling the orientation field that is away from singular points. After the preliminary modeling, regions containing singular points are detected and the corresponding orientation field is refined. This process is carried out in the orientation residual field in an iterative fashion to adapt the orientation estimation toward the presence of singular point. Fig. 1 depicts the flow chart of the proposed orientation modeling method and the detail is given in the following section.

3. Analysis of residual orientation field for orientation refining

For notational convenience, let us denote the transformed orientation field as

$$\mathbf{z} = \mathbf{f}_c + i\mathbf{f}_s. \tag{5}$$

Thus, the analysis of the orientation field can be carried out in the complex domain. In this section, we will focus on the analysis of the residual orientation field $\mathbf{z}_{residual}$, which is the discrepancy between the original orientation field and the reconstructed one

$$\mathbf{z}_{residual} = \mathbf{z} - \hat{\mathbf{z}}; \quad \left|\mathbf{z}_{residual}\right| \in [0,2], \tag{6}$$