A Robust Contactless Fingerprint Enhancement Algorithm

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Abstract. Compared to contact fingerprint images, contactless fingerprint images have three particular characteristics: (1) contactless fingerprint images have less noise than contact fingerprint images; (2) there are less discontinuities of ridges in contactless fingerprint images; and (3) the ridge-valley pattern of contactless fingerprint is much more unclear than that of contact fingerprint images. These properties increase a great difficulty to the contactless fingerprint enhancement. In this paper, we propose a robust contactless fingerprint enhancement algorithm based on simple sinusoidal-shaped filter kernel to fully take advantage of the properties of contactless fingerprint. First, an effective preprocessing is proposed to preliminarily strengthen the ridge-valley contrast of contactless fingerprint images. Then, simple sinusoidal-shaped filter kernel is proposed to enhance the contactless fingerprint images. Finally, we propose a score-filtering procedure to effectively recover the ridge-valley pattern. Comprehensive experiments were performed to evaluate the proposed method from aspects of image quality, minutiae extraction and fingerprint verification. Experimental results demonstrate the high performance of the proposed algorithm in contactless fingerprint enhancement.

Keywords: Contactless fingerprint enhancement
Sinusoidal-shaped filter · Ridge orientation · Ridge frequency
Fingerprint

1 Introduction

With the development and popularity of sensing technologies, contactless biometrics technologies (e.g., identification and verification) have become a hot research area and have attracted great attentions in commercial applications [8,10,11,13,22]. The National Institute of Standards and Technology (NIST) has announced the plan to develop *Next Generation Fingerprint Technologies*. In this project, the contactless fingerprint technology is one of the most important parts, which demonstrates the highly promising prospects of contactless fingerprint technologies in the future. Compared with the contact fingerprint

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collection, contactless fingerprint caption system can avoid many risks such as image contamination, time-consuming issue, nonlinear distortion and hygienic concern. However, contactless fingerprint images tend to suffer from low ridge-valley contrast. Figure 1 gives an example of the two types of fingerprint images. As shown in the figure, the ridge-valley contrast of the contactless fingerprint is quite unclear compared to that of contact fingerprint. This would badly affect the performance of minutiae extraction progress [5] and other subsequent progresses [16,20]. Therefore, it is essential to develop a reliable and effective technique for contactless fingerprint enhancement.

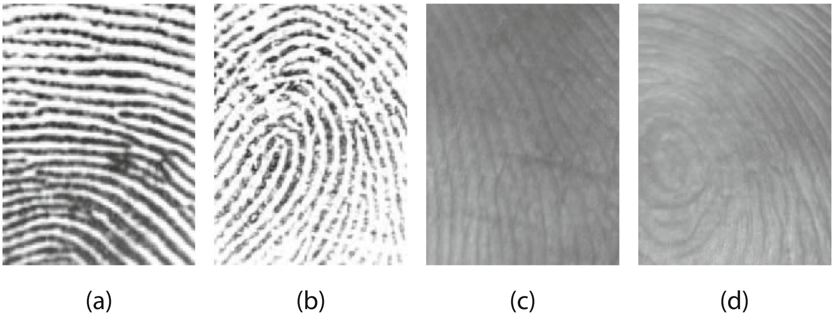

Fig. 1. Examples of two types of fingerprint images: (a) and (b) are partial images of contact fingerprints from FVC2004 DB1 [9], (c) and (d) are partial images of contactless fingerprints from public dataset [22].

Over the past few decades, many methods have been proposed to enhance the ridge-valley contrast of fingerprint images and have made a remarkable progress. According to the filtering domain, the enhancement methods can be basically categorized into two classes: (1) spatial domain filtering [7,12,19,21,23] and (2) Fourier domain filtering [4,15,18].

Among the spatial domain filtering methods, contextual filters are the most widely used for fingerprint image enhancement. Nickerson and O'Gorman [12] firstly introduced contextual filters for fingerprint enhancement. The shape of those filters is controlled by the ridge frequency and the ridge orientation. However, in order to reduce computational complexity, the local ridge frequency is assumed constant in this method, leading to imprecise filtering result in some regions. Hong et al. [7] proposed an effective enhancement method based on Gabor filter, whose shape is controlled by four parameters. The advantage of this method is that the frequency and the orientation of the filter are adaptively determined by the local ridge frequency and the local ridge orientation. However, the filtering result is poor in regions where the fingerprint ridge and valley pattern are not similar with a pure sinusoidal pattern. In order to address this problem, Yang et al. [19] proposed to use positive and negative ridge frequencies based on the local ridge width and local valley width, respectively. Compared to squared Gabor filter kernel in [7,19], Zhu et al. [23] proposed using circular filter kernel, which is helpful to avoid artifacts in the filtering progress. The above-mentioned methods are mainly focused on contact fingerprint enhancement. A novel method which focuses on contactless fingerprint enhancement is proposed by Yin et al. [21]. In this method, intrinsic image decomposition [14] and guided image filtering [6] are firstly introduced for contactless fingerprint enhancement. However, this method tends to fail in the regions near singularity points.

Besides spatial domain filtering methods, Fourier domain filtering is another widely used technique for fingerprint enhancement. In these methods, filters are explicitly defined in the Fourier domain. Sherlock et al. [15] proposed using Fast Fourier Transform to enhance fingerprint images. In this method, the Fourier transform of the fingerprint image is multiplied by n precomputed filters. The pixel value of enhancement fingerprint is determined by the result of the filter whose orientation is closest to the local ridge orientation. The drawback of this method is that the ridge frequency is constant. Watson et al. [18] proposed an enhancement method in the Fourier domain, where the local ridge frequency and the local ridge orientation are no need to compute explicitly. However, this method is time-consuming because a large amount of overlap is introduced between the neighboring blocks. Chikkerur et al. [4] proposed an efficient enhancement method based on short-time Fourier transform (STFT). The enhancement result of the method is relatively similar to that of the method in [7]. The advantage of this method is that it costs less time than the method in [7] while the disadvantage is that this method tends to fail in the regions near singularity points.

Most of above-mentioned methods are proposed to enhance contact fingerprint images. These methods do not take the properties of contactless fingerprint images into account. Compared to contact fingerprint images, contactless fingerprint images have three particular properties: (1) contactless fingerprint images have less noise than contact fingerprint images, as shown in Fig. 1; (2) there are less discontinuities of ridges in contactless fingerprint images, which is helpful for the filtering process to enhance fingerprint images; and (3) the ridge-valley contrast of contactless fingerprint is much more unclear than that of contact fingerprint images, which increases a great difficulty to the contactless fingerprint enhancement. Based on the above analysis of contact fingerprint enhancement methods and in order to fully take advantage of the contactless fingerprint properties, in this paper, we propose a robust contactless fingerprint enhancement algorithm based on simple sinusoidal-shaped filter kernel. The main contributions of this paper are summarized as follows. First, an effective preprocessing is proposed to strengthen the ridge-valley contrast of contactless fingerprint images. Second, simple sinusoidal-shaped filter kernel is proposed to enhance contactless fingerprint images. Third, we propose score-filtering procedure to effectively recover the ridge-valley pattern. Experimental results demonstrate the validity of the proposed method in contactless fingerprint enhancement.

The rest of this paper is structured as follows: Sect. 2 describes the proposed approach. Experimental validation and results are presented in Sect. 3. Finally, Sect. 4 concludes the paper.

2 The Proposed Method

In this section, we present the details of the proposed contactless fingerprint enhancement algorithm, which contains the following main steps: contactless fingerprint image preprocessing (Sect. 2.1), dominant ridge orientation estimation (Sect. 2.2), local ridge frequency estimation (Sect. 2.3), filtering (Sect. 2.4) and score-filtering procedure (Sect. 2.5).

2.1 Image Preprocessing

Compared with contact fingerprint images whose ridge-valley pattern is relatively clear, contactless fingerprint images tend to have a low ridge-valley contrast in small local regions. This negatively affects the filtering result. Image preprocessing is aimed at stretching ridge-valley contrast initially and hence facilitates effective filtering in the subsequent process.

As the pixel intensity varies considerably in different regions of contactless fingerprint images, it is unsuitable to perform global image enhancement technique on entire image. In this paper, we propose a region-based technique to preprocess contactless fingerprint images. First, contrast-limited adaptive histogram equalization [24], which is an effective region-based method to improve regions' contrast, is used to stretch the ridge-valley contrast of contactless fingerprint images. Then, each small region is normalized according to Eq. (1)

$$p_i' = (p_i - \mu)/S, \tag{1}$$

where μ and S are the pixel mean value and standard deviation in a small region, respectively. p_i and p_i' are the pixel value and transformed pixel value, respectively. In order to eliminate artificial boundaries, the normalized neighboring regions are then combined using bilinear interpolation.

2.2 Dominant Ridge Orientation Estimation

Since contactless fingerprint image has better ridge continuity quality than contact fingerprint image, in this paper, we use the gradient-based method [2,7,17] to estimate the dominant ridge orientation. First, we calculate the x-gradient (G_x) and the y-gradient (G_y) based on the preprocessed image. In order to avoid orientation average problem, doubling the angle of gradient vector and squaring the length of gradient vector are performed as Eq. (2)

$$\begin{bmatrix} G_{sx} \\ G_{sy} \end{bmatrix} = \begin{bmatrix} \sqrt{G_x^2 + G_y^2}^{\,2} \cos 2\theta \\ \sqrt{G_x^2 + G_y^2}^{\,2} \sin 2\theta \end{bmatrix} = \begin{bmatrix} G_x^2 - G_y^2 \\ 2G_xG_y \end{bmatrix}, \tag{2}$$

where $[G_{sx}, G_{sy}]^T$ denotes the squared gradient vector. Since the dominant ridge orientation varies steadily in a small local regions, G_{sx} and G_{sy} is therefore smoothed by a Gaussian filter of radius r_0 pixels with standard deviation σ_0.

Then, the average squared gradient $[\overline{G}_{sx}, \overline{G}_{sy}]^T$ in a local window W is calculated as Eq. (3)

$$\begin{bmatrix} \overline{G}_{sx} \\ \overline{G}_{sy} \end{bmatrix} = \begin{bmatrix} \sum_W G_{sx} \\ \sum_W G_{sy} \end{bmatrix} = \begin{bmatrix} \sum_W (G_x^2 - G_y^2) \\ \sum_W 2G_x G_y \end{bmatrix}. \tag{3}$$

Finally, the dominant ridge orientation θ at pixel i is given by Eq. (4)

$$\theta_i = \frac{\pi}{2} + \frac{atan2(\overline{G}_{sy}, \overline{G}_{sx})}{2}. \tag{4}$$

2.3 Local Ridge Frequency Estimation

Since contactless fingerprint images have less noise than contact fingerprint images, it is easily to compute the average number of pixels between two consecutive peaks in a sinusoidal-shaped ridge-valley pattern. In this paper, x-signature method [7] is used to estimate the local ridge frequency. Let W denotes the rectangle region oriented by θ_i degree, where θ_i is the dominant ridge orientation at the center of the region, the average length l_i can be computed as Eq. 5

$$l_i = \sum (p_{j+1} - p_j)/(N-1), \tag{5}$$

where p_j is the position of the j_{th} peak, N is the number of consecutive peaks in the rectangle region. The local ridge frequency f_i in a local region is presented by

$$f_i = 1/l_i. \tag{6}$$

2.4 Filtering

Compared to contact fingerprint images, contactless fingerprint images have two different properties: (1) good sinusoidal-shaped pattern quality, which is less contaminated by image noise and (2) better ridge continuity quality than contact fingerprint images. Therefore, in order to take fully advantage of the two properties, in this paper, we propose using a simple sinusoidal-shaped filter kernel to effectively improve the ridge-valley contrast. The sinusoidal-shaped filter kernel is formulated as

$$k(x, y; \theta, f) = \cos(2\pi f \cdot (x \cos\theta + y \cos\theta)), \tag{7}$$

where θ and f are the orientation and the frequency, respectively. x, y are the coordinates. Given a filter of size $(2r_1 + 1) \times (2r_2 + 1)$, the filtering process can be expressed as

$$I'(x, y) = \sum_{s=-r_1}^{r_1} \sum_{t=-r_2}^{r_2} k(s, t; \theta_{xy}, f_{xy}) I(x + s, y + t), \tag{8}$$

where θ_{xy} is the dominant ridge orientation and f_{xy} is the local ridge frequency.

2.5 Score-Filtering Procedure

In order to effectively improve the ridge-valley contrast of contactless fingerprint images, we propose a score-filtering procedure which has two advantages: (1) eliminating artificial boundaries accused by block filtering and (2) avoiding disconnectedness in the regions near singularity points and minutiae.

First, the preprocessed image is divided into overlap blocks with size $(2r + 1) \times (2r + 1)$ with r pixels overlapping in x or y direction. Then, for each small block $\boldsymbol{b}_i$ centered at pixel (x_i, y_i), the filtering result of the central pixel is calculated as Sect. (2.4) while the filtering result of each pixel is determined by the filtering result of the central pixel, which is formulated as

$$I'(\boldsymbol{b}_i) = I'(x_i, y_i). \tag{9}$$

Since each pixel is covered by N blocks, the final-filtering result of each pixel is calculated by

$$\overline{I}(x, y) = \frac{\sum I'(x_i, y_i)}{N}, \tag{10}$$

where (x_i, y_i) is the center of each covering block.

3 Experimental Results

In this section, we evaluate the performance of the proposed algorithm in terms of fingerprint image quality (in Sect. 3.1), minutiae extraction (in Sect. 3.2) and fingerprint verification (in Sect. 3.3). The experiment is evaluated on contactless fingerprint benchmark database [22], which contains 1500 objects. In the experiment, we compare the proposed algorithm with the best two enhancement methods, traditional Gabor-based method (TGM) [7] and short-time Fourier transform method (STFT) [4]. Parameter values used in the proposed algorithm are reported in Table 1 while parameter values for the other two algorithms are directly employed from the papers.

Table 1. Parameter values used in the proposed algorithm

Symbol(s)	Value(s)	Description
r_0	25	Parameter in Sect. 2.2
σ_0	8	Parameter in Sect. 2.2
r_1, r_2	$1/f_{xy}$	Parameters in Sect. 2.4
r	5	Parameter in Sect. 2.5

3.1 Evaluation on Fingerprint Image Quality

In this section, we evaluate the performance of the proposed algorithm in terms of fingerprint image quality. This experiment is evaluated on contactless fingerprint images from publicly fingerprint database [22]. We compare the performance of the proposed algorithm with the best two enhancement methods, TGM [7] and STFT [4]. Figure 2 shows the comparison of enhancement results evaluated on contactless fingerprint image sample F3620. As shown in the figure, the proposed algorithm precisely strengthens the ridge-valley contrast in the entire image, while TGM and STFT fail in some regions, for example in the red rectangle and yellow rectangle regions in Fig. 2(b) and (c). Moreover, the proposed algorithm achieves better enhancement performance in the region near singularity point than the other two methods, as shown in the blue rectangle regions in the figure. In the blue rectangle region, the proposed algorithm accurately keeps ridge continuity while the other two methods result in bad ridge discontinuity.

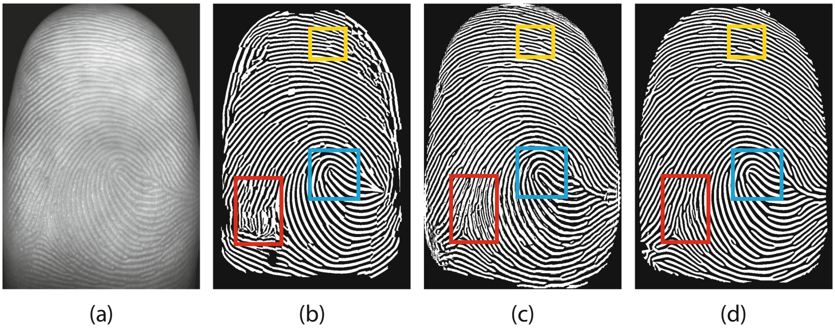
(a) (b) (c) (d)

Fig. 2. Comparison of contactless fingerprint image enhancement results on sample F3620: (a) Original contactless fingerprint, (b) TGM method [7], (c) STFT method [4], and (d) The proposed algorithm. (Color figure online)

3.2 Evaluation on Minutiae Extraction

In this section, we evaluate the performance of the proposed algorithm in terms of minutiae extraction. This experiment is evaluated on 100 contactless fingerprint images randomly selected from the database [22]. The commercial fingerprint software Verifinger SDK [1] is used for the minutiae extraction. In order to accurately compare minutiae extraction results, the minutiae are manually labelled in advance as the ground-truth. In this experiment, three measures are used to evaluate the accuracy of minutiae extraction:

- AGM: the average number of genuine minutiae, which are extracted on the enhanced fingerprint images but are not extracted on the original images.

Table 2. The comparison of average numbers of minutiae

	AGM	AFGM	AFM
TGM method [7]	5.1	2.8	18.3
STFT method [4]	5.8	1.9	10.1
Proposed method	6.7	0.5	3.6

- AMGM: the average number of genuine minutiae, which are not extracted on the enhanced fingerprint images but are extracted on the original images.
- AFM: the average number of detected minutiae, which are not genuine minutiae.

Table 2 shows the average number of three types of minutiae. As shown in Table 2, the proposed algorithm achieves better performance on the three measures than the other two methods. Compared to the other two methods, the proposed enhancement algorithm recover more genuine minutiae (AGM 6.7) and generates less false minutiae (AFM 3.6). This demonstrates that the proposed algorithm achieves remarkable performance.

3.3 Evaluation on Fingerprint Verification

In this section, we evaluate the performance of the proposed contactless fingerprint enhancement algorithm in terms of verification accuracy. MCC method [3] is used to perform the fingerprint verification. Three measures are used to evaluate the verification accuracy:

- False Matching Rate (FMR): the rate of different fingerprints which are decided to come from the same finger by a matching method.
- False Non-Matching Rate (FNMR): rate of corresponding fingerprints which are decided to come from the different fingers by a matching method.
- FMR100: the lowest FNMR at the threshold where FMR $\leqslant 1\%$.
- FMR1000: the lowest FNMR at the threshold where FMR $\leqslant 0.1\%$.
- Equal-Error Rate (EER): the error rate at the threshold where FMR and FNMR are equal.

Table 3. The comparison of verification accuracy

	EER %	FMR100 %	FMR1000 %
Without enhancement	9.73	12.58	14.08
With enhancement	5.8	7.22	9.32

Table 3 shows the experimental results of the three measures without enhancement and with enhancement using the proposed algorithm. As shown in the table, by using the proposed algorithm, the fingerprint verification achieves significant improvement in terms of EER, FMR100 and FMR1000.

4 Conclusion

In conclusion, this paper developed a robust contactless fingerprint enhancement algorithm, which takes full advantage of the special properties (less noise, low contrast and a good quality of ridge continuity). First, an effective preprocessing is proposed to preliminarily strengthen the ridge-valley contrast of contactless fingerprint images. Then, a simple sinusoidal-shaped filter kernel is proposed to enhance contactless fingerprint images. Finally, we proposed score-filtering procedure to effectively recover the ridge-valley pattern by eliminating artificial boundaries accused by block filtering and avoiding disconnectedness in the regions near singularity points and minutiae. The performance of the proposed algorithm is evaluated in terms of image quality, minutiae extraction and fingerprint verification. Experimental results show that the proposed algorithm considerably improves the performance of minutiae extraction and the performance of fingerprint verification.

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