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2012

Li, S., & Kot, A. C. (2012). An Improved Scheme for Full Fingerprint Reconstruction. IEEE Transactions on Information Forensics and Security, 7(6), 1906-1912.

<https://hdl.handle.net/10356/84790>

<https://doi.org/10.1109/TIFS.2012.2212012>

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An Improved Scheme for Full Fingerprint Reconstruction

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Abstract—Different fingerprint recognition systems store minutiae-based fingerprint templates differently. Some store them inside a small token, some can be found in a server database. As the minutiae template is very compact, many take it for granted that the template does not contain sufficient information for reconstructing the original fingerprint. This paper proposes a scheme to reconstruct a full fingerprint image from the minutiae points based on the amplitude and frequency modulated (AM-FM) fingerprint model. The scheme starts with generating a binary ridge pattern which has a similar ridge flow to that of the original fingerprint. The continuous phase is intuitively reconstructed by removing the spirals in the phase image estimated from the ridge pattern. To reduce the artifacts due to the discontinuity in the continuous phase, a refinement process is introduced for the reconstructed phase image, which is the combination of the continuous phase and the spiral phase (corresponding to the minutiae). Finally, the refined phase image is used to produce a thinned version of the fingerprint, from which a real-look alike grayscale fingerprint image is reconstructed. The experimental results show that our proposed scheme performs better than the-state-of-the-art technique.

Index Terms—fingerprint, reconstruction, minutiae, AM-FM model

I. INTRODUCTION

Nowadays, fingerprints are widely used in biometric recognition systems. In general, a fingerprint is stored somewhere as a template for subsequent verification. The template could be a grayscale fingerprint image [2], a thinned fingerprint image [3] or minutiae [4] according to the fingerprint matching algorithm being adopted in the system. A minutiae template usually contains a set of minutiae points recording the position and direction of the ridge ending or bifurcation in a fingerprint. The positions and directions of these minutiae points are the most stable features of a fingerprint, which have been observed to be distinctive among individuals. Due to its compactness, the minutiae is commonly used to be stored in a template in a fingerprint recognition system.

For many years, researchers assume that the minutiae does not contain enough information for reconstructing the original fingerprint. However, some recent published works [5]–[8] have shown that it is possible to reconstruct a fingerprint from the minutiae. A fingerprint image reconstructed from the minutiae (hereinafter termed as a reconstructed fingerprint for simplicity) can be used to manufacture a fake finger or directly injected into a communication channel to deceive the fingerprint recognition system, which will cause serious security problems.

C. Hill [5] and Ross *et al.* [6] pioneer the work of reconstructing a fingerprint from the minutiae. In [5], the author assumes that the minutiae template stores the coordinates of the singular points, based on which an orientation field is computed. Then, a sequence of spines passing through the minutiae points are heuristically drawn, which form a partial skeleton of the fingerprint. In [6], a set of three minutiae points (minutiae triplet) is used to estimate the orientation field defined by the triplet, while the ridges are drawn by using streamlines. The work in [6] shows promising results that it is possible to reconstruct a fingerprint from the minutiae.

Cappelli *et al.* [7] first propose an approach that is able to reconstruct a full fingerprint image from a standard minutiae template. They estimate the orientation field by adopting an orientation field model described in [9]. According to the orientation field and a predefined ridge frequency, the ridges of the fingerprint are iteratively

grown from an initial image which records the minutiae local pattern. This approach produces many obvious spurious minutiae in the reconstructed fingerprint, which can be easily detected.

The fingerprint reconstruction (from minutiae) approach proposed by Feng *et al.* [8] takes advantage of the amplitude and frequency modulated (AM-FM) fingerprint model [10], in which the phase image is used to determine the ridges and minutiae. The phase image contains two parts: the continuous phase and the spiral phase (which corresponds to the minutiae). In [8], the authors propose to incorporate a piecewise planar model for the continuous phase reconstruction. This model predicts the continuous phase block by block based on the gradient of the continuous phase. The fingerprint is reconstructed by combining the continuous phase and the spiral phase, which has a good matching against the original fingerprint. However, the reconstructed fingerprint does not match well when compared with different impressions of the original fingerprint. Furthermore, the piecewise planar model introduces blocking effects in the continuous phase and the reconstructed fingerprint. For fingerprint with singularity, additional artifacts may appear in the reconstructed fingerprint due to the discontinuity in the continuous phase.

With the widespread applications of minutiae-based fingerprint recognition systems, it is very important to investigate to which extreme a reconstructed fingerprint can be similar to the original fingerprint. So as to prompt the research of countermeasures against the attacks due to the reconstructed fingerprints. The techniques for reconstructing a fingerprint from minutiae would be useful when the original fingerprint is not available or of low quality. For example, Cappelli *et al.* [7] point out that such fingerprint reconstruction techniques could be used for dealing with the template interoperability problem [11] among different minutiae encoders and matchers. While Feng *et al.* [8] indicate that these techniques may be applied for the latent fingerprint restoration.

In this paper, a novel scheme is proposed to further explore to what extreme a reconstructed fingerprint can be similar to the original fingerprint. The reconstruction process is based on the AM-FM fingerprint model. Instead of using a piecewise planar model [8] to reconstruct a continuous phase with blocking effects. We propose to estimate the continuous phase from a ridge pattern which has a similar ridge flow to that of the original fingerprint. Such process is quite intuitive and will produce a continuous phase without any blocking effect. Furthermore, we can ensure that no spiral exists in the reconstructed continuous phase except at some line segments which can be easily identified. After combining the continuous phase and the spiral phase computed from the minutiae, a phase image refinement process is introduced to reduce the artifacts located at those line segments. Finally, a real-look alike fingerprint image is reconstructed according to the thinned version estimated from the refined phase image. Unlike the previous works, our reconstructed fingerprint does not contain obvious artifacts such as blocking effects or many spurious minutiae points. The experimental results show that our proposed scheme performs very well when compared with the-state-of-the-art technique [8].

The organization of the paper is as follows. Section II gives a brief review on the AM-FM fingerprint model and the phase decomposition process. Section III introduces our proposed scheme for fingerprint reconstruction from minutiae points. Section IV presents the experimental results and discussions, followed by the conclusions in the last section.

II. PRELIMINARIES

In this section, we give a brief description of the AM-FM fingerprint model [10], [12] and the phase decomposition process [13].

Fig. 1. The phase image of a grayscale fingerprint image. (a) A grayscale fingerprint image I (FVC 2002 DB1, 6_7), (b) phase image ψ , (c) fingerprint $\cos(\psi)$

The AM-FM fingerprint model is proposed by Lakin and Fletcher [10], where the fingerprint structure is represented as a hologram, i.e., a phase modulated fringe pattern. For a fingerprint image I , its intensity in each pixel is represented as

$$I(x, y) = a(x, y) + b(x, y) \cdot \cos[\psi(x, y)] + n(x, y) \quad (1)$$

where $a(x, y)$ is the offset, $b(x, y)$ is the amplitude, $\psi(x, y)$ is the phase, and $n(x, y)$ refers to the noise.

Among the parameters in an AM-FM fingerprint model, the phase image ψ determines ridges and minutiae of the fingerprint, which can be demodulated by

$$\psi(x, y) = \text{Arg}\{-e^{-i\beta(x, y)} \cdot \Re[I(x, y) - a(x, y)] + I(x, y) - a(x, y)\} \quad (2)$$

where $\text{Arg}(z)$ returns the principal value of the argument of z , $\beta(x, y)$ is the local gradient (uniquely defined from 0 to 2π) which is perpendicular to local fingerprint orientation and $\Re$ is a demodulation operator such that

$$\Re[I(x, y) - a(x, y)] \cong F^{-1}\{e^{i\varphi(u, v)} F\{I(x, y) - a(x, y)\}\} \quad (3)$$

where $F(\cdot)$ and $F^{-1}(\cdot)$ are the Fourier transform and inverse Fourier transform, respectively, $e^{i\varphi(u, v)}$ is a spiral phase Fourier multiplier [12]:

$$e^{i\varphi(u, v)} = \frac{u + iv}{\sqrt{u^2 + v^2}} \quad (4)$$

Fig. 1 shows a grayscale fingerprint image in (a) and its phase image in (b). It can be seen that the phase image has the same ridge flow and minutiae as the original fingerprint. Given a phase image ψ , we can obtain a fingerprint $\cos(\psi)$ as shown in (c).

In addition, the phase image in an AM-FM fingerprint model (hereinafter termed as the phase image) can be decomposed into two parts according to the Helmholtz Decomposition Theorem [13]:

$$\psi(x, y) = \psi_c(x, y) + \psi_s(x, y) \quad (5)$$

where ψ_c is the continuous phase and ψ_s is the spiral phase. The continuous phase mainly depends on the gradient and frequency of the fingerprint ridge. The spiral phase can be calculated from a set of spirals with polarity:

$$\psi_s(x, y) = \sum_{k=1}^n p_k \arctan\left(\frac{y - y_k}{x - x_k}\right) \quad (6)$$

where n is the total number of the spirals, (x_k, y_k) indicates the location of each spiral and $p_k \in \{-1, 1\}$ is the corresponding polarity. Generally speaking, a spiral in the phase image is a point where there is an abrupt change in the fingerprint ridge frequency. It has been observed that the minutiae points can be represented by the spirals of either positive or negative polarity [10]. By adding or removing a spiral, a minutiae point emerges or disappears in the phase image.

Fig. 2. The proposed fingerprint reconstruction scheme.

Fig. 3. Estimating the orientation field from minutiae points. (a) A set of minutiae points (FVC 2002 DB1, 3_3), (b) the fingerprint area (shown in gray), (c) the estimated orientation field O .

III. THE PROPOSED METHOD

Given a set of minutiae points $M = \{m_1, m_2, \dots, m_n\}$ of a fingerprint, where each minutiae point is represented as a triplet $m_i = (x_i, y_i, \theta_i)$, with (x_i, y_i) be the position and θ_i ($0 \leq \theta_i < 2\pi$) be the direction. In order to reconstruct the fingerprint image from M , we carry through six different stages below as illustrated in Fig. 2.

A. Orientation field estimation

The orientation field defines the overall ridge flow of the fingerprint. In recent years, various orientation models are proposed for global fingerprint representation [9], [14]. Most of these orientation models can be utilized to estimate the orientation field from minutiae points. For example, the model from [9] is adopted in [7] for the orientation estimation. While the authors of [14] have shown that the orientation can be reconstructed from the minutiae points using Smooth Extensions. There are also some algorithms designed specifically for reconstructing the orientation from minutiae points [6], [8].

Here, we adopt the orientation reconstruction algorithm proposed in [8]. This algorithm assigns an orientation value for each 8×8 block located at the fingerprint area according to some neighboring minutiae points of the block. The fingerprint area is determined by dilating the convex hull of the minutiae points using a disk shaped structure. Fig. 3 shows a set of minutiae points with the corresponding fingerprint area and the estimated orientation field O .

Fig. 4. The binary ridge pattern generation process for the minutiae shown in Fig. 3(a).

B. Binary ridge pattern generation

Cappelli *et al.* [15] show that starting from an initial image with some seed points, a synthetic fingerprint image can be generated according to the orientation field and a predefined ridge frequency. We use this approach here to generate a binary ridge pattern which shows the main ridge flow in the original fingerprint. In order to generate a ridge pattern with a few minutiae points, an initial image is created by placing one single seed point at the center of the fingerprint area. For each pixel located at (x, y) in the initial image, we iteratively apply a Gabor filter:

$$G(x', y'; f_l, O_l, \sigma) = e^{-((x'^2 + y'^2)/2\sigma^2)} \cdot \cos[2\pi \cdot f_l \cdot (x' \cdot \cos(O_l) + y' \cdot \sin(O_l))] \quad (7)$$

where $f_l = f(x, y)$ is the local ridge frequency, $O_l = O(x, y)$ is the estimated local orientation and σ is the bandwidth of the filter. The value of σ is chosen such that the filter does not contain more than three effective peaks, which is determined by the solution of the following equation [16]:

$$e^{-\left[\left(\frac{3}{2f(x,y)}\right)^2 / 2\sigma^2\right]} = 10^{-3} \quad (8)$$

As it is difficult to estimate the fingerprint ridge frequency from the minutiae points, we assume a constant frequency $f = 0.12$ (corresponding to an average ridge wavelength of 8.3 pixels in a 500 dpi image) for the whole image, which is the same as the frequency adopted in [8]. The iterative process will be terminated until the fingerprint is filled with uniform ridge pattern, as shown in Fig. 4. Finally, the uniform ridge is binarized to produce a binary ridge pattern.

C. Continuous phase reconstruction

The continuous phase reconstruction is crucial for the whole fingerprint reconstruction process. Feng *et al.* [8] have proposed a piecewise planar model for the continuous phase reconstruction. This model reconstructs the continuous phase block by block based on the gradient of the continuous phase, which cannot be well estimated in the blocks containing minutiae points. Furthermore, the model will produce blocking effects in the continuous phase. In this section, we propose a novel continuous phase reconstruction algorithm which does not introduce blocking effects. This algorithm ensures that no spiral exists in the reconstructed continuous phase except at some line segments which can be easily identified.

We apply an existing fingerprint enhancement method [17] on the binary ridge pattern, such that the pixel value between the ridge and valley is smooth. For simplicity, the enhanced version of the ridge pattern is termed as the enhanced ridge pattern. Next, we compute the phase image ψ of the enhanced ridge pattern. As discussed in Section II, the phase image ψ can be computed if the AC component (i.e., $I(x, y) - a(x, y)$ in Eq. (2)) of the fingerprint and the gradient image β are known. We estimate the AC component by removing the mean pixel value from the enhanced ridge pattern. As for the gradient image β estimation, we need to unwrap the estimated orientation

O before estimating the gradient image β to solve the ambiguities problem. Larkin *et al.* [10] suggest to incorporate some branch cuts to perform the orientation unwrapping. However, we found that such orientation unwrapping is not appropriate for the continuous phase reconstruction because the ridges around the branch cut may be severely displaced in the rest of the fingerprint reconstruction process. We therefore propose a new orientation unwrapping algorithm for the continuous phase reconstruction, which causes fewer ridge displacements in the fingerprint reconstruction. The main steps of the proposed orientation unwrapping algorithm are summarized below:

- 1) Compute a horizontally unwrapped orientation O_{hu} from the estimated orientation O . The unwrapping is processed row by row from left to right. For each pixel located at (x, y) , we have

$$O_{hu}(x, y) = O(x, y) + k\pi \quad (9)$$

where

$$k = \arg \min_{k' \text{ is an integer}} |O(x, y) + k'\pi - O_{hu}(x - 1, y)| \quad (10)$$

and the horizontally unwrapped orientation of the first pixel in each row is initialized as the estimated orientation.

- 2) Compute the unwrapped orientation O_u from the horizontally unwrapped orientation O_{hu} . The unwrapping is processed from top to bottom. For each row located at $y = j$, we have

$$O_u(x, j) = O_{hu}(x, j) + k\pi \quad (11)$$

where

$$k = \arg \min_{k' \text{ is an integer}} \sum_x |O_{hu}(x, j) + k'\pi - O_u(x, j - 1)| \quad (12)$$

and the unwrapped orientation of the first row is initialized as the horizontally unwrapped orientation.

With the unwrapped orientation O_u , the gradient image β can be estimated from $O_u + \pi/2$. The phase image ψ of the enhanced ridge pattern can then be calculated according to Eq. (2).

Fig. 5 illustrates the orientation unwrapping process for the enhanced ridge patterns with zero, one and two singular points. Note that the singularity of the enhanced ridge pattern determines the singularity of the fingerprint to be reconstructed. For fingerprint without singularity, no discontinuity appears in the unwrapped orientations as shown in Fig. 5(a). For fingerprint with singularity, however, the orientation rotates through π or $-\pi$ around the singular points, which will create discontinuities in the unwrapped orientations as shown in Fig. 5(b) and (c). These discontinuities appear in some line segments, where the unwrapped orientations will be advanced by π . The discontinuity in O_u will create discontinuity in ψ at the same location as shown in Fig. 6(a). In order to identify these discontinuities, we define a line segment from pixel (x_1, y) to pixel (x_2, y) (assume $x_2 > x_1$) in a phase image as a Discontinuity Segment $D_s(x_1, x_2, y)$ if the following two conditions are satisfied: (i) $|O_u(x, y) - O_u(x - 1, y)| \geq \pi/2$ when $x \in [x_1, x_2]$, and (ii) $|O_u(x, y) - O_u(x - 1, y)| < \pi/2$ when $x \notin [x_1, x_2]$.

Besides, the phase image ψ has some spirals due to the minutiae points in the enhanced ridge pattern (see Fig. 6(a)). These spirals can be identified from the residues of ψ , which are calculated by summing the phase difference clockwise around each set of four adjacent pixels [18]. For each pixel located at (x, y) , the set of four adjacent pixels are defined as pixel (x, y) , pixel $(x + 1, y)$, pixel $(x + 1, y + 1)$ and pixel $(x, y + 1)$ as shown in Fig. 7. For simplicity, the corresponding phase values of the four adjacent pixels

Fig. 5. Illustration of orientation unwrapping process for the enhanced ridge patterns (a) without singularity (FVC 2002 DB1, 70_5), (b) with one singular point (FVC 2002 DB1, 3_3), and (c) with two singular points (FVC 2002 DB1, 9_8). From left to right: the enhanced ridge pattern; the estimated orientation O ; the horizontally unwrapped orientation O_{hu} ; and the unwrapped orientation O_u . O , O_{hu} and O_u are shown as grayscale images.

Fig. 6. Illustration of continuous phase reconstruction. (a) The phase image of the enhanced ridge pattern from Fig. 5(b), circles and squares indicate the positive and negative spirals detected from the pixels which are not located at the Discontinuity Segment, (b) the reconstructed continuous phase (FVC 2002 DB1, 3_3).

are termed as ϕ_0 , ϕ_1 , ϕ_2 and ϕ_3 (see Fig. 7). The residual $\varepsilon(x, y)$ for the pixel (x, y) is then computed to obtain

$$\varepsilon(x, y) = \sum_{i=0}^3 \Gamma(\phi_{(i+1) \bmod 4}, \phi_i) \quad (13)$$

where **mod** is the modulo operator and $\Gamma(\phi_a, \phi_b)$ is the function calculating the phase difference between ϕ_a and ϕ_b :

$$\Gamma(\phi_a, \phi_b) = (\phi_a - \phi_b + \pi) \bmod 2\pi - \pi \quad (14)$$

It has been proved that $\varepsilon(x, y)$ will either be zero, 2π or -2π [19]. In our case, pixels with residuals equal to 2π or -2π indicate positive spirals or negative spirals, respectively. At this stage, we do not consider the pixels along the Discontinuity Segment for the spirals detection because the nonzero residuals (2π or -2π) of these pixels could be created due to the discontinuity in O_u .

Finally, the continuous phase ψ_c is reconstructed by

$$\psi_c(x, y) = \psi(x, y) - \psi_s(x, y) \quad (15)$$

where $\psi_s(x, y)$ is the spiral phase calculated from all the detected spirals in ψ using Eq. (6). As shown in Fig. 6(b), the reconstructed

$$\begin{array}{cc} \phi_0 \bigcirc & \phi_1 \bigcirc \\ (x, y) & (x+1, y) \\ \phi_3 \bigcirc & \phi_2 \bigcirc \\ (x, y+1) & (x+1, y+1) \end{array}$$

Fig. 7. The set of four adjacent pixels defined for pixel (x, y) , where ϕ_0 to ϕ_3 are the corresponding phase values.

Fig. 8. Reconstructed phase images for the minutiae of (a) FVC 2002 DB1, 70_5, (b) FVC 2002 DB1, 3_3, and (c) FVC 2002 DB1, 9_8.

continuous phase does not contain any spiral except at the Discontinuity Segment, where the discontinuity appears due to the discontinuity in O_u .

D. Continuous phase and spiral phase combination

With the continuous phase ψ_c reconstructed, the phase image of the fingerprint ψ_f can also be reconstructed by combining ψ_c and the spiral phase computed from $\mathbf{M}$. Note that the polarity p_i of each minutiae point m_i depends on the difference between $O_u(x_i, y_i)$ (after modulo 2π) and θ_i where

$$p_i = \begin{cases} 1 & \text{if } |O_u(x_i, y_i) - \theta_i| < \pi/2 \text{ or} \\ & |O_u(x_i, y_i) - \theta_i| > 3\pi/2 \\ -1 & \text{if } \pi/2 \leq |O_u(x_i, y_i) - \theta_i| \leq 3\pi/2 \end{cases} \quad (16)$$

Fig. 8 shows some examples of the reconstructed phase images. It can be seen that all the minutiae points in $\mathbf{M}$ can be found in the reconstructed phase image (see the black circles). Besides, no spurious minutiae point (i.e., the one not included in $\mathbf{M}$) exists in the reconstructed phase image for fingerprint without singularity (see Fig. 8(a)). For fingerprint with singularity, however, the ridges along the Discontinuity Segment may be displaced (see Fig. 8(b) and (c)) due to discontinuity in ψ_c . Such artifacts may create some spurious minutiae points.

In the case that we adopt the branch cut to perform the orientation unwrapping [10] (see Fig. 9(a)). We will reconstruct a phase image ψ_f shown in Fig. 9(b). It can be seen that the ridges around the branch cut in ψ_f are severely displaced as what we have pointed out in Section III-C.

E. Reconstructed phase image refinement

We present here a technique to reduce the artifacts along the Discontinuity Segment in the reconstructed phase image ψ_f , so as to reduce the number of spurious minutiae points in the reconstructed fingerprint. If there is only one Discontinuity Segment, say $D_s(x_1, x_2, y=a)$ in ψ_f . We modify the unwrapped orientation O_u by adding or subtracting π for all the rows located at $y < a$, such that the discontinuity only appears in pixel (x, a) where $x \notin [x_1, x_2]$. For simplicity, the unwrapped orientation after the modification is termed as O_u' (see Fig. 10(a)). With $O_u' + \pi/2$ as the gradient image and $\cos(\psi_f)$ as the AC component of the fingerprint, another form of reconstructed phase image ψ_f' can be estimated (see Fig. 10(b)). For ψ_f' , we detect the spirals from the

Fig. 9. The result of the reconstructed phase image ψ_f in the case that we adopt the branch cut for the orientation unwrapping [10]. (a) O_u with the branch cut shown in white (FVC 2002 DB1, 3_3), (b) the corresponding ψ_f .

Fig. 10. Reconstructed phase image refinement (a) O_u' , (b) ψ_f' (circles and squares indicate the positive and negative spirals detected along the Discontinuity Segment), (c) ψ_{fr} , (d) $\cos(\psi_{fr})$ for ψ_f given in Fig. 8(b) with the corresponding unwrapped orientation from Fig. 5(b).

pixels (which shall not be overlapped with any minutiae point in $\mathbf{M}$) located at $D_s(x_1, x_2, y=a)$. From these spirals, we calculate a spiral phase using Eq. (6), which will then be subtracted from ψ_f' to produce a refined phase image ψ_{fr} (see Fig. 10(c)). It can be seen from Fig. 11 that the ridge displacement along $D_s(x_1, x_2, y=a)$ disappears in ψ_{fr} . On the other hand, all the current detected spirals are located at $y = a$ with $x_1 \leq x \leq x_2$, the corresponding spiral phase will be zero in (x, a) when $x \notin [x_1, x_2]$ according to Eq. (6). That is to say

$$\psi_{fr}(x, a) = \psi_f'(x, a), \quad x \notin [x_1, x_2] \quad (17)$$

As the discontinuity in O_u' only appears in (x, a) where $x \notin [x_1, x_2]$, the ridges along the locations of these discontinuities in ψ_f' will not be displaced during the refinement process, as shown in Fig. 10(d).

For ψ_f with more than one Discontinuity Segment, we draw a branch cut of one pixel width for each Discontinuity Segment by tracing the ridge of ψ_f . The branch cut starts from a singular point (i.e., an end point of a Discontinuity Segment located inside the fingerprint area), and terminates when meeting another singular point or a boundary point of the fingerprint area [10]. The unwrapped orientation O_u within the area enclosed by the branch cut and the Discontinuity Segment is modified by adding or subtracting π , such that the discontinuity in O_u' appears only in the branch cut (see Fig. 12(a)). Similar to the previous case, another form of reconstructed phase image ψ_f' is estimated from $O_u' + \pi/2$ and $\cos(\psi_f)$ (see Fig. 12(b)). The spirals located at the Discontinuity Segments are detected and removed to produce a refined phase image ψ_{fr} (see Fig. 12(c)).

F. Noising and Rendering

In order to produce a real-look alike fingerprint image, some noising and rendering processes are necessary for the refined phase image. We first obtain a thinned version from the fingerprint image $\cos(\psi_{fr})$. The thinned version is dilated to make the ridges thick, from which a phase image ψ_{fp} is estimated. An ideal grayscale

Fig. 11. The enlarged area around the Discontinuity Segment in ψ_f (top) and ψ_{fr} (bottom). ψ_f and ψ_{fr} are shown in Fig. 8(b) and Fig. 10(c), respectively.

Fig. 12. The reconstructed phase image refinement for ψ_f given in Fig. 8(c). (a) O_u' with the branch cut shown (the corresponding O_u is from Fig. 5(c)), (b) ψ_f' with the spirals (circles and squares indicate the positive and negative spirals) detected along the Discontinuity Segments, (c) ψ_{fr} .

fingerprint image is then calculated by

$$F_i(x, y) = 255 \cdot \frac{1 + \cos(\psi_{fp}(x, y))}{2} \quad (18)$$

Fig. 13(a) and (b) shows the thinned version and the ideal grayscale fingerprint image for the refined phase image in Fig. 12(c). The noising and rendering steps proposed in [15] are applied on F_i to create a real-look alike reconstructed fingerprint, as shown in Fig. 13(c).

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The proposed fingerprint reconstruction technique is evaluated using FVC2002 DB1_A and FVC2002 DB2_A databases, each of which contains 800 grayscale fingerprint images from 100 fingers with 8 impressions per finger. We use the VeriFinger 6.3 [20] for the minutiae extraction and matching. For each database, we extract 800 minutiae templates, which contain only the positions and directions of the minutiae points. Fingerprint images are reconstructed from all 800 minutiae templates (of each database) using our proposed technique and the state-of-the-art method proposed in [8]. The method in [8] does not incorporate any noising and rendering steps to make the reconstructed fingerprints look real. Therefore, in order to do a fair comparison, we create our reconstructed fingerprint without the noising and rendering (i.e., the fingerprint $\cos(\psi_{fr})$) for the performance evaluation. There are two sets of reconstructed fingerprints (800 images per set) for each database, where Set-I contains the reconstructed fingerprints using our technique (without the noising and rendering) and Set-II includes the reconstructed fingerprints using the method proposed in [8].

A. The performance evaluation

To practically evaluate how well a fingerprint is reconstructed, we match each reconstructed fingerprint against the different impressions of the original fingerprint. In the following discussions, a match refers to the match between a reconstructed fingerprint and a different impression of the original fingerprint. Therefore, we have $800 \times 7 = 5600$ matches for a set of reconstructed fingerprints. For each database, we also use a set of 800 original fingerprint images (treated as perfectly

Fig. 13. Illustration of noising and rendering. (a) A thinned version obtained from the refined phase image shown in Fig. 12(c), (b) the ideal grayscale fingerprint image F_i , (c) the real-look alike reconstructed fingerprint.

Fig. 14. The performance evaluation on FVC2002 DB1_A (a) and FVC2002 DB2_A (b) for different sets of reconstructed fingerprints.

reconstructed fingerprints) to perform these matches, the results of which could be served as a reference. Note that every match is performed by calculating a matching score between two minutiae templates extracted from two input fingerprint images.

For different sets of reconstructed fingerprints, the Successful Match Rates at different decision thresholds are shown in Fig. 14. The decision thresholds correspond to the False Acceptance Rate (FAR) of the minutiae matching algorithm, which are priori computed over each database based on the FVC2002 protocol. We can see from Fig. 14 that our technique performs better than the one proposed in [8]. On FVC2002 DB1_A, the Successful Match Rates are 86.48% and 70.25% (at FAR=0.01%) when using Set-I and Set-II, respectively. On FVC2002 DB2_A at the same FAR, the Successful Match Rate is 86.96% by using Set-I, which is reduced to 68.96% by using Set-II.

A visual comparison between the images in Set-I and Set-II is shown in Fig. 15. It can be seen that the fingerprint image from Set-II (which are reconstructed from the method in [8]) has some blocking effects. Additional artifacts appear near the branch cut area, which make the fingerprint more unnatural. On the contrary, by using our technique, the image in Set-I does not have the blocking effects and the artifacts are fewer. It also contains fewer spurious minutiae points than the image from Set-II.

Fig. 16 and Fig. 17 show some other examples of the reconstructed fingerprints. Fig. 16(a) shows an image (in Set-I) that is able to match a different impression of the same finger (see Fig. 16(c)) at FAR=0.01%. While the corresponding image in Set-II (see Fig. 16(b)) fails to provide a successful match against the fingerprint in Fig. 16(c) at the same FAR. Fig. 17(a) and (b) give two different impressions of the same finger that succeed in the fingerprint matching at FAR=0.01%. Fig. 17(c) shows the image (in Set-I) reconstructed for the fingerprint in Fig. 17(a), which is not able to match the fingerprint in Fig. 17(b) at the same FAR.

B. Discussions

Our reconstructed fingerprint may still have a very small number of spurious minutiae points around the singular point area (see the

Fig. 15. A visual comparison between the images in Set-I and Set-II (FVC 2002 DB1, 3_7), the gray circles and white squares denote the positions of the original minutiae points and the spurious minutiae points, respectively. Left: the reconstructed fingerprint from Set-I. Right: the reconstructed fingerprint from Set-II.

Fig. 16. A comparison between the images in Set-I (a) and Set-II (b) (FVC 2002 DB1, 1_2) in matching a different impression of the same finger (c) (FVC 2002 DB1, 1_4).

left image in Fig. 15). On the other hand, our scheme does not use the type of minutiae points for the fingerprint reconstruction, which may be different in an original fingerprint and the reconstructed fingerprint. A pair of minutiae points that are close in distance may not be detected in the reconstructed fingerprint due to the change in minutiae type, as shown in Fig. 18. The spurious and not detected minutiae points will affect the Successful Match Rate for our reconstructed fingerprints, especially for those reconstructed from a small number of minutiae points.

Let's denote the number of minutiae points in an original minutiae template as N . We classify the 800 reconstructed fingerprints in Set-I of each database into the following three categories of images reconstructed from the minutiae templates with (i) $N \leq 15$, (ii) $15 < N \leq 30$ and (iii) $N > 30$. Table I lists the Successful Match Rates for different categories at FAR=0.01%, where "No." refers to the number of images fall in different categories. It can be seen that our scheme does not perform well for category (i), where the Successful Match Rate is around 52%. Therefore, when the minutiae template contains no more than 15 minutiae points, the possibility to produce an unsuccessful match is high using our reconstructed fingerprint.

Besides, the accuracy of the orientation field estimation also affects the performance of our scheme. For each of the two aforementioned databases, we further reconstruct a set of 800 fingerprint images based on the 800 minutiae templates and the original orientation fields using our proposed technique. By using these images, the Successful Match Rates are 94.29% on FVC2002 DB1_A and 92.97% on FVC2002 DB2_A, which are only 4.32% and 4.89% lower than using the original fingerprints, respectively.

Fig. 17. Illustration of a failure between an image in Set-I and a different impression of the same finger. (a) FVC 2002 DB1, 4_2, (b) FVC 2002 DB1, 4_7, (c) the image in Set-I reconstructed for (a).

Fig. 18. Part of an original fingerprint (left) and the corresponding reconstructed fingerprint (right) in Set-I, the two minutiae points in the original fingerprint are not detected in the reconstructed fingerprint.

V. CONCLUSIONS

A novel scheme is proposed to reconstruct a full fingerprint image from minutiae points based on the AM-FM fingerprint model. Specifically, we propose a new and effective continuous phase reconstruction algorithm. In this algorithm, the continuous phase is intuitively reconstructed by removing the spirals in the phase image of a ridge pattern which has a similar ridge flow to that of the original fingerprint. A new orientation unwrapping algorithm is proposed during the continuous phase reconstruction. Compared with using the existing branch cut based orientation unwrapping technique, our orientation unwrapping algorithm causes fewer ridge displacements in the reconstructed fingerprint. Next, we introduce a refinement process for the reconstructed phase image which is the combination of the continuous phase and the spiral phase corresponding to the minutiae points, so as to reduce the artifacts created due to the discontinuity in the continuous phase. Finally, a real-look alike grayscale fingerprint image is reconstructed based on the thinned version of the refined phase image. Experimental results show that the reconstructed fingerprint using the proposed technique contains fewer artifacts and fewer spurious minutiae points when compared with the-state-of-the-art technique.

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TABLE I
SUCCESSFUL MATCH RATES FOR DIFFERENT CATEGORIES AT
FAR=0.01%

Category	Successful Match Rate (%)			
	FVC2002 DB1_A		FVC2002 DB2_A	
	No.	Rate	No.	Rate
(i)	24	55.36	5	51.43
(ii)	268	83.48	138	79.40
(iii)	508	89.54	657	88.82

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