Fingerprint Image Processing for Automatic Verification

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Abstract
The performance of an automatic fingerprint verification approach relies heavily on the quality of the fingerprint image. Enhancement of the fingerprint image is then a crucial step in automatic fingerprint verification. This paper discusses the fingerprint image processing methods for automatic verification and proposes an adaptive oriented low pass filter to enhance the fingerprint image quality. For automatic fingerprint verification the fingerprint image processing is not aimed at improving the visual appearance of the fingerprint image but aimed at facilitating the subsequent processing. Therefore, the fingerprint image processing method is closely related to the method employed for the subsequent minutiae detection. The proposed approach takes efforts to increase the chances for success of the subsequent processes and at the same time avoid producing undesired side effects such as losing of the original ridge structure information or introducing additional spurious ridge structure information. Some sample results are given to illustrate the performance of the proposed approach.

1. Introduction
A gray level fingerprint image can be considered as an oriented texture pattern that contains narrow ridges separated by narrow valleys. The uniqueness of a fingerprint for automatic verification is exclusively determined by the local ridge characteristics and their relationships. The two most prominent local ridge characteristics, called minutiae, are ridge ending and bifurcation. A critical step in fingerprint verification is automatically and reliably detecting these minutiae from fingerprint images. The performance of a minutiae detection algorithm relies heavily on the quality of fingerprint images. Unfortunately, the fingerprint images obtained in practice are of poor quality due to the variations in impression conditions, ridge configuration, skin condition and acquisition devices. The ridge structures in such low quality fingerprint images are not always well defined. Consequently, they cannot be accurately detected. Therefore, the problem of automatically processing fingerprint images to facilitate minutiae detection is an area that has received significant research interest.

In the fingerprint image processing, various approaches have been suggested, such as using band pass filter [1], directional Fourier transform filter [2] and fuzzy approach [3] to enhance or smooth the raw gray level fingerprint image. O’Gorman and Nickerson in [4] and Mehre in [5] performed image enhancement by using contextual/directional filters, or called matched filters. A. K. Jain, L. Hong, R. Bolle in [6] and [7] detected the ridge with two masks, which in principle perform some kinds of band pass filtering. L. Hong, Y. Wan and A. K. Jain in [8] introduced a fingerprint image enhancement method that employed a Gabor filter.

Although different names and proposed by different authors, all approaches above actually perform low pass filtering along the ridge orientation and band-pass filtering along the orientation orthogonal to the ridge orientation. So these filters could be called oriented band pass filter. The oriented band pass filter undoubtedly increases the clarity of ridge structure or the contrast between the ridges and valleys and therefore gives a good visual appearance of the image. Moreover it is also able to separate some linked ridges in cases where the ridge frequency is similar to the value estimated before the design of the band pass filter. However, a fingerprint enhancement algorithm based on the oriented band pass filter may result in spurious ridge structures. Although this can be avoided by using the correct ridge frequency information, the exact estimation of the ridge frequency is a difficult task, especially in the noisy regions and in the regions in which the minutiae or singular points exist. The performance of the band pass filter strongly relies on the accurate estimation of the ridge frequency. In our experiments, the ridge frequency estimation error may cause ridge location errors, introduce false ridge structure and consequently result in a large number of spurious minutiae.

An important purpose of employing band pass filters is separating the cluttered or linked parallel ridges that will produce spurious minutiae. Such spurious minutiae have location, associated ridge and direction relationships. Consequently, they are recognizable from the true minutiae and can be effectively removed in the post processing stage [9]. Another intention of using band pass filters is to increase the clarity of ridge structure or the contrast between the ridges and valleys. Minutiae extraction is usually performed based on the detection of one-pixel-wide ridges (skeleton image) of the fingerprint. For ridge
detected methods based on thresholding and thinning, the clarity of ridge structure or the contrast between the ridges and valleys is very important. As a consequence, most fingerprint image processing methods involve normalizing and sharpening the image contrast by using oriented band pass filters. Our ridge detection algorithm [9] determines the skeleton ridge by searching the maximum and minimum points of the local ridge section set while tracing the gray level ridge. The low contrast between the ridges and valleys and the contrast inconsistency throughout the fingerprint image will not cause significant inconsistency in the correct detection of the skeleton ridge. Therefore, sharpening of the image is not necessary for our skeleton ridge detection although it will give a much better visual appearance of the image. In contrast, the image smoothing is very important for reducing the noise, linking the ridge breaks and having the maximal gray values of the image locating at the ridge center.

In order to avoid the minutia location error and spurious minutiae, which may be caused by band pass filtering due to estimation error of the ridge frequency, band pass filter is not employed in our work. Instead, we use adaptive oriented low pass filter to reduce the noise of fingerprint image, link the small breaks in a ridge and accentuate the gray values of the ridge center.

2. Processing the fingerprint image

A gray level fingerprint image \( g(i, j), i, j \in I \), consists of oriented narrow ridges separated by narrow valleys. Ridge orientation and ridge frequency are two intrinsic characteristics of the fingerprint image, which define invariant coordinates for ridges and valleys in a local neighborhood. To perform an effective filtering, the filter parameter should be adaptive to these two intrinsic features of the fingerprint image. D. Maio and D. Maltoni in [10] smoothed the fingerprint image with a low pass filter mask typically of size 3 along the ridge orientation and 7 along the orientation orthogonal to the ridge orientation. However, a filter with a short length along the ridge orientation can not effectively link the ridge break. A filter with a too long length along the orientation orthogonal to the ridge orientation may link two parallel ridges that are not well separated. Therefore the length of the filter along the ridge orientation should be distinctly greater than along the orientation orthogonal to the ridge orientation.

A low pass filter can reduce the noise, smooth the small hole and even link the small break in a ridge if the length of the filter mask along the ridge orientation is long enough or its cutoff frequency is low enough. A one-dimensional low pass filter with very low cutoff frequency along the ridge orientation can be employed because the desired one-dimensional signal along the ridge orientation is a constant in a local window. We choose a Hamming window [11] of length \( N \) (typically \( N=11 \))

\[
h_{l}(n)=\begin{cases} 0.54 - 0.46 \cos \left( \frac{2\pi n}{N-1} \right), & 0 \leq n \leq N-1 \\ 0, & \text{otherwise.} \end{cases}
\]  

as our low pass filter along the ridge orientation.

In the orientation orthogonal to the ridge orientation, the low pass filter should on one hand reduce the noise and smooth the small hole while on other hand not link two not well separated parallel ridges. Therefore, the cut off frequency of the filter along the orientation orthogonal to the ridge orientation should be adaptive to the ridge frequency because the desired one-dimensional signal along the orientation orthogonal to the ridge orientation is a sinusoidal-shape wave. This sinusoidal-shape wave, which has the same frequency as that of the ridges and valleys in the local window, should be allowed to pass through the filter. Therefore, the ridge frequency should be estimated before filtering the image along the orientation orthogonal to the ridge orientation because the fingerprint ridge frequency has a large variance (from 1/3 to 1/25 (1/pixels) [8]).

D. Maio and D. Maltoni proposed an approach [12] to estimate the ridge frequency, which is based on the assumption that the one-dimensional signal along the orientation orthogonal to the ridge orientation is a sinusoidal-shape wave. However, the one-dimensional signal along the orientation orthogonal to the ridge orientation is often not a well-defined sinusoidal-shape wave. Therefore, the estimation errors may be resulted. L. Hong, Y. Wan and A. Jain [8] estimated the ridge frequency by counting the average number of pixels between two consecutive peaks of the one-dimensional signal along the orientation orthogonal to the ridge orientation. However, This signal may be heavy noised for a fingerprint image of poor quality. Fig. 1 illustrates an example of such a signal. We see from Fig. 1 that it is very difficult to obtain an accurate ridge frequency estimation in the space domain. However, in the frequency domain, the maximal peak of its power spectrum (Fig. 2) clearly indicates the ridge frequency.

![Fig. 1. A one-dimensional signal of fingerprint along the orientation orthogonal to the ridge orientation.](image-url)
Therefore, we use the spectrum analysis technique to estimate the ridge frequency. Given a pixel \((i^*, j^*)\), \((i', j')\) \(\in I\), a section set \(\Omega^k\) orthogonal to the local ridge orientation \(\phi(i^*, j^*)\) can be defined as follows:

\[
\Omega^k = \{ (i, j) | i = i^k + rd(\tan(\phi^k_i)), j \in \Omega_j \}
\]  
(2)

\[
\Omega_j = [j^k - rd(\sigma \cdot \cos(\phi^k_j)), j^k + rd(\sigma \cdot \cos(\phi^k_j))]
\]  
(3)

\[
\phi^k_{ij} = \begin{cases} 
\phi(i^k, j^k) - \pi/2, & \text{if } \phi(i^k, j^k) > 0 \\
\phi(i^k, j^k) + \pi/2, & \text{otherwise}
\end{cases}
\]  
(4)

where \(rd(\cdot)\) rounds its argument to the nearest integer and \(\sigma\) is a predetermined constant (typically \(\sigma=16\)). With equation (4), we keep \(-\pi/2 < \phi^k_i \leq \pi/2\).

The ridge frequency is then estimated based on the calculation of the DFT of the one-dimensional section set \(\Omega^k\) that is already filtered with \(h_l(n)\) along the ridge orientation. That is: each pixel of the section set \(\Omega^k\) is filtered along the ridge orientation by using the one-dimensional filter of a long fixed length \(N\) given by equation (1). The filtering along the ridge orientation before the ridge frequency estimation increases the reliability of the ridge frequency estimation. This is possible because the filter parameter along the ridge orientation is independent of the ridge frequency. After the ridge frequency estimation, the filter parameter along the orientation normal to the ridge orientation is adjusted adaptive to the estimated local ridge frequency \(rf^k\) or the local ridge distance \(rd^k=1/\sqrt{rf^k}\).

We choose a Blackman window [11] of length \(M^k+2\)

\[
h_b^k(m) = \begin{cases} 
0.42 - 0.5 \cos \left( \frac{2\pi m}{M^k + 1} \right) + 0.08 \cos \left( \frac{4\pi m}{M^k + 1} \right), & \text{if } 0 \leq m \leq M^k + 1 \\
0, & \text{otherwise}
\end{cases}
\]  
(5)

as our low pass filter of length \(M^k\) along the orientation orthogonal to the ridge orientation.

For a Blackman window of length \(M^k+2\), the length of the filter is actually \(M^k\) because \(h_b^k(0)=h_b^k(M^k+1)=0\). The filter length \(M^k\) is chosen to be equal to \(round(2\beta rf^k)\). So the cutoff frequency of the filter is adaptive to the ridge frequency by adjusting the filter size. Although the filter parameter is also dependent on the ridge frequency, the filtering output is much less sensitive to the accuracy of the local ridge frequency estimation as compared to that of the oriented band pass filter.

The section set \(\Omega^k\) is then further filtered along the orientation normal to the ridge orientation. The decomposition of the filtering into two steps, one before the ridge frequency estimation and another after that, not only increases the reliability of the ridge frequency estimation, but also reduces the computation time.

The equivalent two-dimensional oriented filter mask of size \(M^k \times N\), which is oriented horizontally to match the horizontally oriented ridges, should be:

\[
h^k(m,n,0) = h_l(n - \frac{N + 1}{2}) \cdot h_b^k \left( m - \frac{M^k + 1}{2} \right)
\]  
(6)

A 5\times11 horizontally oriented filter, \(h^k(m, n, 0)\), is shown in space domain in Fig. 3 and in frequency domain in Fig. 4.

![Fig. 3. A horizontally oriented low pass filter (\(\varphi=0\)).](image3.png)

![Fig. 4. Frequency response of the filter in Fig. 1.](image4.png)
angle $\phi$ back to the location $(m, n)$ on the horizontally oriented filter mask as follows:

$$
\begin{bmatrix}
  n \\
  m
\end{bmatrix} =
\begin{bmatrix}
  \cos(\phi) & \sin(\phi) \\
  -\sin(\phi) & \cos(\phi)
\end{bmatrix}
\begin{bmatrix}
  n' \\
  m'
\end{bmatrix}
$$

(7)

Hence, each pixel $g(i, j)$ is equivalently convolved with such an oriented filter $h'(m, n, \phi)$ as follows:

$$
g'(i, j) = \sum_{n=-(N/2)}^{(N/2)-1} \sum_{m=-(M/2)}^{(M/2)-1} h'(m, n, \phi) g(i-m-n)
$$

(8)

This filter effectively smoothes the fingerprint image. The small gaps caused by noise are smoothed and the small breaks of the ridge caused by scar are linked. Therefore, the filtering accentuates the local maximal gray-level values of the ridge and minimizes the location error of the local maximum of the section.

The proposed filtering method reduces the noise, links the ridge breaks and ensures that the maximal gray values of the image is located at the ridge center. Furthermore, this method does not result in any spurious ridge structure. Although the proposed method can not separate the linked parallel ridges, the spurious minutiae introduced by such defect can be identified and removed in the post processing stage [9]. In addition, the proposed algorithm decomposes the filtering into two one-dimensional filtering and integrates the three procedures together: section set building, ridge frequency estimation and filtering. This will avoid repeating some of the common computation, which significantly reduces the computation time.

### 3. Sample results

The proposed fingerprint image processing approach is aimed at facilitating the subsequent ridge detection and minutiae extraction and avoiding undesired side effects in the subsequent processing. Therefore, we give the results of the ridge detection and minutiae extraction instead of the enhanced gray level images to illustrate the performance of proposed approach.

Fig. 5 shows a sample fingerprint image captured using a solid-state fingerprint sensor. Fig. 6 illustrates the skeleton image and minutiae detected from the fingerprint image as shown in Fig. 5 using an oriented band pass filter. Fig. 7 is the combination of Fig. 5 and Fig. 6. Some spurious ridge structures and the corresponding spurious minutiae can be seen in Fig. 7. The skeleton image and minutiae detected from the same fingerprint image using the proposed oriented low pass filter is depicted in Fig. 8. Fig. 9 is the combination of Fig. 5 and Fig. 8. From Fig. 9 it can be seen that the problem of the spurious ridge structure is successfully avoided and that the location error of skeleton ridge is much smaller than that of Fig. 7. Fig. 9 illustrates that the proposed approach results in a reliable ridge detection and minutiae extraction.
4. Conclusions

This paper proposed a fingerprint image processing method for automatic fingerprint verification. The proposed approach includes ridge frequency estimation and adaptive oriented low pass filter design. The two-dimensional filtering is decomposed into two one-dimensional filtering, one before the ridge frequency estimation and another after that. The proposed fingerprint image processing method takes efforts to facilitate the subsequent processing and avoid undesired side effects for the subsequent processing. Therefore, the proposed method is related to the subsequent ridge detection and minutiae extraction methods. In the concrete, the proposed approach reduces the noise, links the ridge breaks and ensures the maximal gray values of the image being located at the ridge center. Furthermore, this method does not result in any spurious ridge structure. Although the proposed method cannot separate the linked parallel ridges, the spurious minutiae introduced by such defect can be easily removed in the post processing stage. In addition, the proposed algorithm integrates the three procedures together: section set building, ridge frequency estimation and filtering. This will avoid repeating some of the common computation, which significantly reduces the computation time. The experimental results showed that our proposed approach provides a reliable fingerprint image processing for the automatic fingerprint verification.

References