New Fingerprint Image Enhancement Using Directional Filter Bank

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ABSTRACT

This paper describes a new method of directional filter-based analysis for fingerprint enhancement. Fingerprint images can be represented by a directional field of regular structure of ridge patterns. The dominant directional component of ridge plays a very important role in the pre-processing steps of fingerprint image analysis such as ridge's linking and noise removal for minutiae extraction. A directional filter bank analyzes an input image into directional subband images and synthesizes them to the perfectly reconstructed image. In this paper, a new fingerprint enhancement algorithm based on a directional filter bank is proposed. The algorithm decomposes a fingerprint image into directional subband images in the analysis stage, processes the subband images in the processing stage, and reconstructs them as the enhanced image in the synthesis stage. The experiment results show that the proposed method reduces the influence of noise on the ridges and valleys, enhances the ridge's moving shape, and preserves the spatial characteristics at minutiae and singular points.

Keywords

DFB, directional filter bank, fingerprint image, directional image, enhancement

1. INTRODUCTION

The performance of automatic fingerprint matching algorithms depends on local ridge characteristics because ridge direction and minutiae such as ridge endings and ridge bifurcations are used for matching. In an ideal fingerprint image, the ridges can be easily detected and minutiae can be correctly extracted from a thinned image. However, the quality of many fingerprints is often poor due to the injured part on the skin and the surroundings in which it was taken. The ridge structures in these poor-quality fingerprint images are not well defined and minutiae cannot be correctly detected. To make matters worse, spurious ridge structures can change the character of the input fingerprints. Therefore, a distinct ridge structure is necessary to guarantee robust minutiae detection regardless of image quality. As such, the goal of fingerprint enhancement processing is to improve the clarity of ridge structures to facilitate the correct extraction of ridges. A number of techniques to enhance fingerprint images have been proposed, which take advantage of ridge characteristics such as directionality [She94, Bam90, San99, Hon98].

Sherlock presented a fingerprint enhancement method based on directional Fourier domain filtering [She94]. An enhanced image is reconstructed by combining the pixel values from the prefiltered images corresponding to the direction of the pixel at the position in the original image. Lin Hong [Hon98] defined an enhancement algorithm using the computationally efficient Gabor filtering technique. This algorithm can adaptively enhance the ridge structures using both one local ridge direction and local frequency information as inputs for filtering. Bamberger [Bam90] proposed a directional filter bank (DFB) for image analysis and applied it to fingerprint enhancement. The algorithm used a DFB

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which decomposes a fingerprint image into many directional subband images and reconstructed the enhanced output image by synthesizing the filtered outputs, which are blocks with the greatest energy among the subband images. Park [San99] presented an enhancement system using a new DFB, which makes visualizable subbands to enable pixel processing. Once an input image is decomposed based on its directionality, the pixels in the local block of the subband image that has the greatest energy and those in the two blocks of the adjacent subband images are taken and synthesized to enhance the local linear feature.

The directionality of a fingerprint is frequently used in fingerprint applications, such as enhancement, detection of singular points, ridge structure detection, and fingerprint pattern classification [She94]. The DFB splits the original image into directional passed subband images, not by a frequency domain procedure using frequency transformation. The subband images are composed of directional components of the image.

In this paper, we propose a method of fingerprint image enhancement using the DFB. It is achieved by handling the directional subband images effectively using the directionality of the fingerprint image. In the proposed algorithm, the ridge direction is represented in the directional image by an energy estimate of the directional subband components. The enhanced image is reconstructed by synthesizing the subband images followed by subband processing, in which a few essential subband components are strengthened while others are weakened. This enhancement algorithm preserves spatial characteristics such as shape and position of singular points and minutiae in the enhanced image because a few directional components corresponding to some dominant directions are contributed for synthesis. Thus, it reduces the influence of noise on the ridges and valleys, resulting in directional filtering against noise being spread to every direction in the frequency domain.

2. Directional filter bank (DFB)

Directional filtering can be implemented with fan-type band-pass filters and the filter is embodied by filter banks. In this paper directional subband images are created in the spatial domain using a decimation matrix and a separable 1-d filter. It does not use a frequency domain procedure which is composed of frequency transformation, fan-type separation in the frequency domain, and as many times inverse-frequency transformation as the number of directional subbands. Thus, processing time for directional subband image generation is reduced.

A digital filter bank is a collection of digital filters with a common input or output. The DFB [Bam90, Bam92] is composed of an analysis bank (analysis filter bank) and a synthesis bank. The analysis bank of the DFB splits the original image into eight directionally passed subband images while the synthesis bank combines the subband images into one image. As such, a DFB guarantees separable one-dimensional filtering and perfect reconstruction of the original input image, yet it has the disadvantage of frequency scrambling, when a low frequency area is misplaced in the subband images resulting in distortions in the decomposed directional subband images [Bam90, Bam92]. However, the DFB used in the current study eliminates frequency scrambling through re-sampling and back-sampling matrices [San99]. The procedures of the DFB used in this paper are shown in Figure 1. The frequency partition map for the eight bands directional filter bank and positions of the decomposed subband images in the analysis bank are shown in Figure 2.

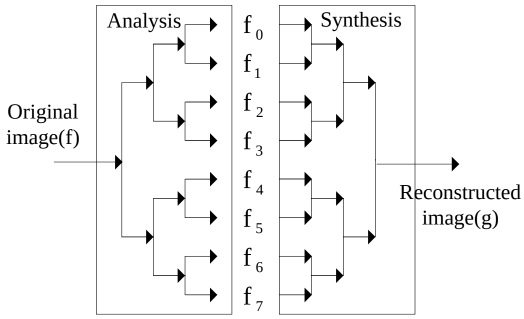


Fig. 1. Analysis and synthesis process in DFB.

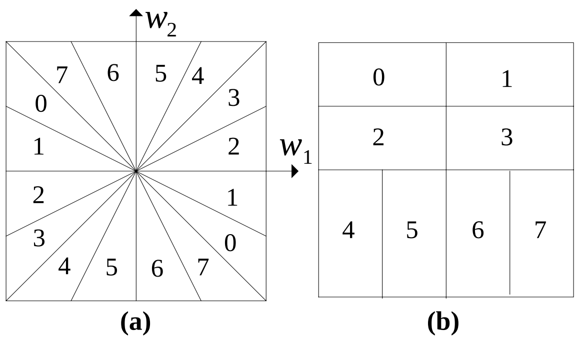
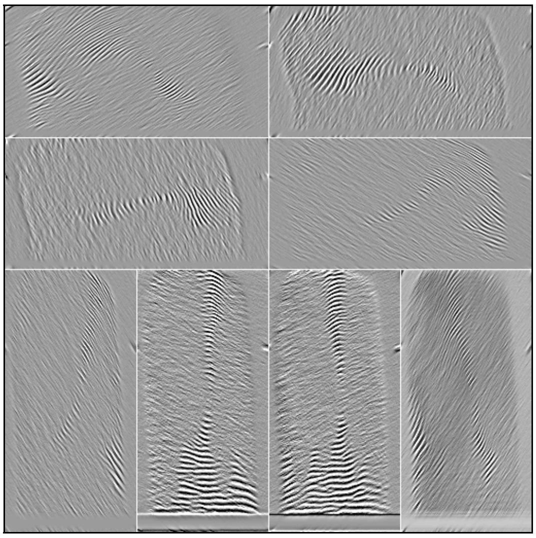


Fig. 2. Frequency partition map for eight-band directional filter bank: (a) Frequency map; (b) positions of each subband images in the decomposed image.

In the analysis section of the DFB, the original image is split into 2 directional subband images and then two more times into 2^3 directional subband images. At this point, the output is used as the input for the next stage. In the synthesis bank, the directional subband images are combined into a reconstructed image in the reverse order of the analysis stage. An original fingerprint image and its decomposed subband images are shown in Figure 3. In this paper the decomposed image is stretched in each subband and contrast adjusted image for visual appearance because the value of the components in the decomposed image is small (Figure 3, 6, 7).

(a)



(b)

Fig. 3. Result of analysis stage in DFB: (a) Original image; (b) decomposed subband image.

3. Fingerprint image enhancement based on DFB

The main processes involved in a fingerprint image processing based on the DFB are shown in Figure 4. Once an input fingerprint image is decomposed based on its directionality, the subband signal components are the maximally decimated outputs of the analysis section of the DFB. The *i*th subband signal components are represented by f_i. All the remaining processes are composed by estimating the local directional energies, generating the directional image, and subsequently processing the subband components based on the directional energy estimate to enhance the given fingerprint images. The enhanced fingerprint image is then reconstructed through the synthesis section of DFB using the processed subband components ($\bar{f}_i$).

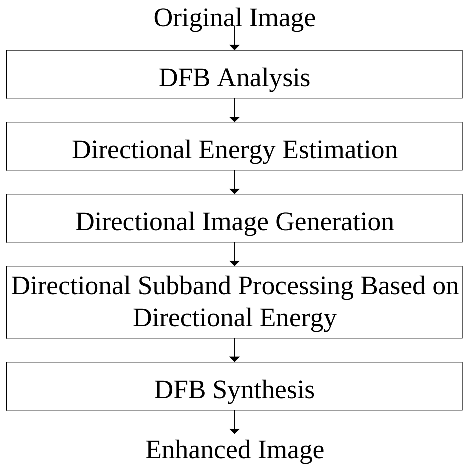


Fig. 4. Processing steps for enhancement.

3.1. Notations

A gray-level fingerprint image, *f*, is defined as an $M \times N$ matrix, in which $f(i, j)$ represents the intensity of a pixel at (i,j).

A directional subband image, f_k, is defined as an $M_k \times N_k$ image in which $f_k(i, j)$ represents the value of component at (i,j) in the *k*th directional subband. As a result of directional decomposition in DFB, the size of *k*th subband image, $M_k \times N_k$, is equal to $M/4 \times N/2$ if *k* is 0~3 and otherwise to $M/2 \times N/4$.

A directional image, *d*, is defined as an $M/m \times N/n$ matrix in which $d(I,J)$ represents the local ridge direction at block (I,J). Local ridge direction is usually specified for a block rather than every pixel in *f*; an image is divided into $M/m \times N/n$ nonoverlapping blocks and a single local ridge direction is defined for each block. The size of a block is defined as $m \times n$ in the original image, while that of a block in the *k*th directional subband image is defined as $m_k \times n_k$ and is equal to $m/4 \times n/2$ if *k* is 0~3 and $m/2 \times n/4$ otherwise.

A value of pixel (i,j) at block (I,J) is defined as $f(I, J; i, j)$ in the original image and that in the *k*th directional subband image is defined as $f_k(I, J; i, j)$. After the subband processing stage, the pixel (i,j) at block (I,J) in the *k*th directional subband image is defined as $\bar{f}_k(I,J;i,j)$ which is called the processed component.

A reconstructed image, *g*, is defined as an $M \times N$ matrix, which is generated by synthesizing the processed components through the synthesis stage of DFB .

3.2. Directional image generation

Based on viewing a fingerprint image as an oriented texture, a number of methods have been proposed to estimate the directional image of the flow-like patterns of a 500 dpi spatial resolution image [Meh93, Rao90, Hon98]. In general, a block direction computed from many pixel directions is used for a directional image, which is also referred to as an orientation field.

In this paper, a directional image is obtained based on a directional energy estimate from a local window of a block after the directional decomposition of the original fingerprint image is made. The input image is decomposed into directional subband images using the DFB; then the energy for each subband image is used to estimate the direction of each block in the original image. The directional energy of block (*I*,*J*) including the pixel (*i*,*j*) from the *k*th subband image is defined in Eq. (1).

$$E_k(I,J) = \sum_{i=0}^{m_k} \sum_{j=0}^{n_k} \left| f_k(I,J;i,j) \right| \quad (1)$$

The direction of each block for a directional image is generated based on the direction corresponding to the subband with maximum energy among all bands at each block. In conventional methods, the direction of a block in a fingerprint is calculated by using gradient-based methods, in which a gradient operator or eight one-dimensional masks in eight directions are used [She94, Meh93, Hon98]. As a gradient operator uses a derivative operation, the results are sensitive to noise. However, our algorithm is more robust to noise because of determined in principle by taking the direction corresponding to the largest information content among completely directional-decomposed components.

As the directional energy of a block in a subband image expresses its directional intensity, the direction of the subband with the maximum directional energy can be viewed as the direction of the block. The direction of a block is defined by Eq. (2), and the directional image can be composed of these block directions over all blocks.

$$d(I,J) = m, \text{ if } \underset{m}{\text{Maximize}}[E_m(I,J)] \quad (2)$$

If necessary, in order that the injured ridge should not affect the ridge directions, a directional averaging process [Hon98] can be performed and its block direction defined by $\bar{d}(I,J)$.

The resulting directional image overlapping with the original image is shown in Figure 5. In a region with only a small variance in the ridge gradient, the block of a subband image with maximum energy corresponds to the prominent direction, whereas in a region with singular points it corresponds to the most frequent direction.

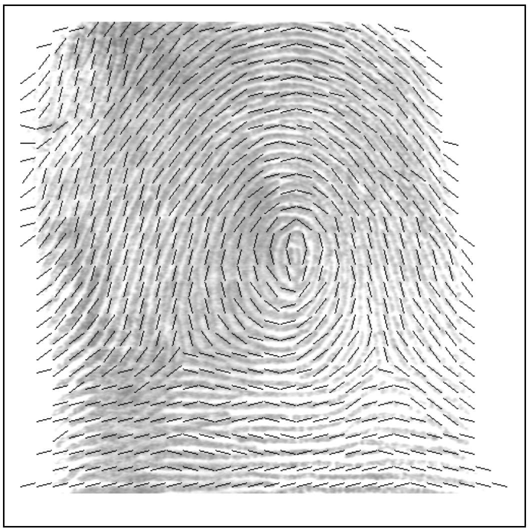


Fig. 5. Directional image.

3.3. Fingerprint image enhancement

In [Bam90], the enhanced image results in a directional filtered image that corresponds to the maximum energy direction($d(I,J)$). That is, enhancement is achieved by taking the components of the block in the subband image having maximum energy and synthesizing the components, as shown in Eq. (3).

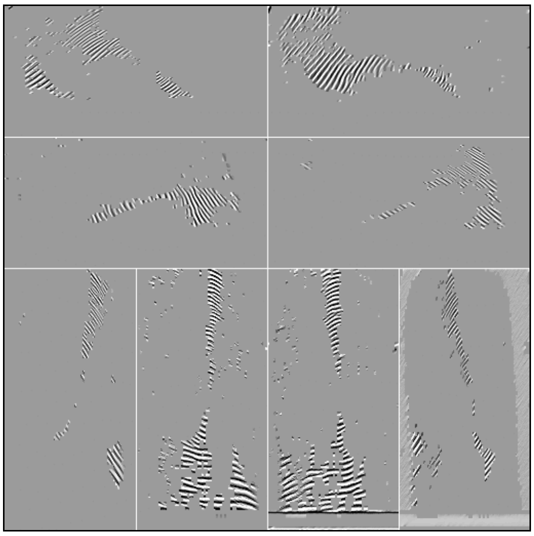
$$\bar{f}_l(I,J;i,j) = w_l \, f_l(I,J;i,j)$$
$$w_l = \begin{cases} 1, & \text{if } l = d(I,J) \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Where $\bar{f}_k(I,J;i,j)$ means the value of at (*i*,*j*) at block (*I*,*J*) in the *k*th subband image, which is retained as the input to the DFB synthesis stage.

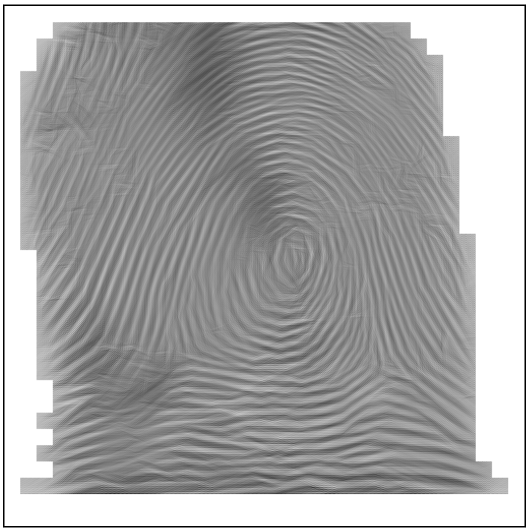
However, for poor quality images, this method is sensitive to noise and injured ridges; therefore, the ridge direction($\bar{d}$) needs to be used in a local neighborhood in the enhancement instead of the maximum energy direction(d). As a result, the input components for the synthesis stage are as follows :

$$\bar{f}_l(I,J;i,j) = w_l f_l(I,J;i,j)$$
$$w_l = \begin{cases} 1, & \text{if } l = \bar{d}(I,J) \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

The processed subband image and reconstructed image are shown in Figure 6. Note that the effects of noise are reduced, and the moving direction of the ridge is accentuated along the ridge direction.



(a)



(b)

Fig. 6. Enhanced image using only maximum energy band: (a) Subband images; (b) synthesized image.

A fingerprint image processed by this method preserves the ridges corresponding to the dominant direction, and removes all ridge components in any other direction. Moreover, the reconstructed image produces noticeable image degradation near block boundaries, particularly where there are changes in the direction angle around ridge curves. Other crucial problems occur with singular points of ending, bifurcation, cores, and delta points, which have more than one direction. As a result, the minutiae can be expected to change; for example, endings become bifurcations, or vice versa, and the coordinates of the minutiae are moved.

A minutiae point region has more than one direction. In addition, a high ridge curvature occurs when the local ridge direction changes rapidly near cores and deltas. In such regions, since a wider range of directions is present, more than one directional subband should be included to preserve the feature characteristics. Based on the empirical results, at least three directional subband components need to be appropriately compounded to preserve the ridge shape and local characteristics, such as singular points in a fingerprint image.

Fingerprint enhancement is then simplified on how the subband image blocks are selected using their directional information contents and how they are combined. An enhanced image is constructed for each block by selecting the subband components from the filtered subband images, processing these components using the directional information, and then synthesizing these processed components which are made by the product of the subband components and the relative importance of them among the entire subbands. Relative importance is defined as weighting value by using their directional energy content. An enhanced fingerprint image is reconstructed through the synthesis stage using the processed subband components, i.e., the components of weighted filtered images.

The simple approach is to use the ratio of each subband energy to maximum energy as the weighting value.

$$\bar{f}_l(I,J;i,j) = w_l f_l(I,J;i,j)$$
$$w_l = \begin{cases} 1, & \text{if } l = \bar{d}(I,J) \\ \dfrac{E_l(I,J)}{\text{Maximize}[E_m(I,J)]}, & \text{otherwise} \end{cases} \tag{5}$$

From the above equation, we can see the subband block corresponding to ridge direction is preserved while others are attenuated by the lower weighting value below one. As a result, the directional filtering is naturally carried out by their energy contents. Therefore, the spatial information in minutiae points and singular points with two or three high energy is preserved even though they have a little attenuation and the effect of other directional noise is reduced.

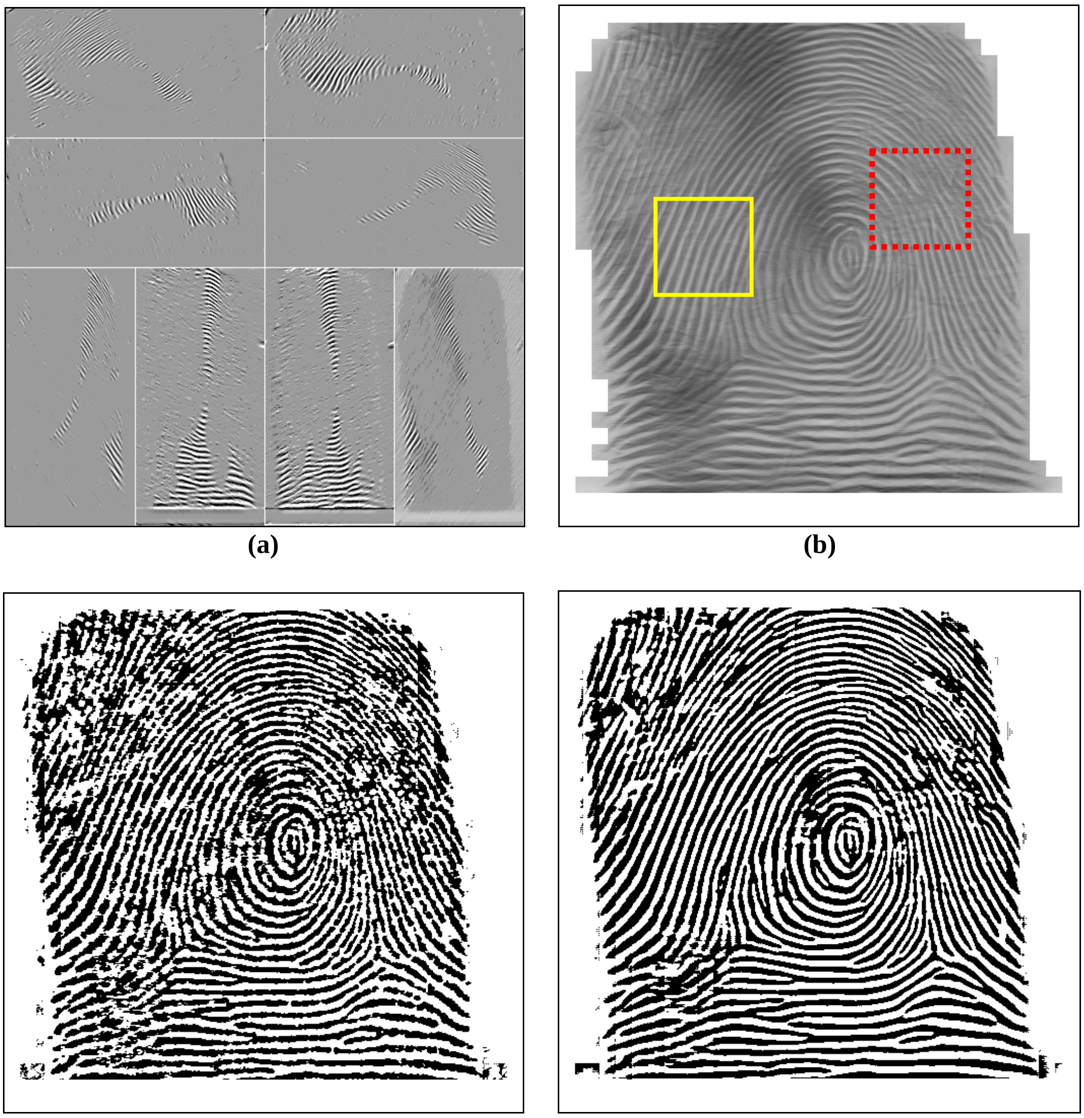


Fig. 7. Enhanced image by weighted subband components: (a) Processed subband images; (b) synthesized image; (c) binarized image of original image; (d) binarized image of synthesized image.

However, since the contrast of the enhanced image resulting from above equation is lower than those of the original one due to smaller weighting value below one, to maintain the same contrast before and after processing, the weighting value is need to be normalized and the resulting subband component is given by

$$\bar{f}_l(I,J;i,j) = \overline{w}_l\, f_l(I,J;i,j)$$

$$\overline{w}_l = \frac{w_l}{\sum_l w_l E_l(I,J)} \qquad (6)$$

The processed subband images, enhanced image, binarized image of the original image, and binarized image of the enhanced image are shown in Figure 7.

4. Experimental Results

The fingerprint images used in the current experiment were selected from the NIST4 fingerprint image database and acquired using a fingerprint input device. The fingerprint images are 512 by 512 pixels and 192 by 192 pixel-sized 256-gray images. Images from the input device were selected to have poor quality. The experiment was performed using a personal computer with a Pentium-3 (800MHz) CPU and visual C++ compiler. Foreground segmentation was performed using the directional energy estimate from the analysis section of the DFB. However, a more detailed discussion on this topic is beyond the scope of this paper. The time consumed for each step is shown at Table 1. The time is the average value of experiments with many fingerprint images.

Procedure	512 × 512	192 × 192
Analysis	0.883	0.104
Directional image generation	0.015	0.004
Enhancement	0.015	0.003
Synthesis	1.172	0.141
Total	2.085	0.252

Table. 1. Time consumed for each process (sec)

To confirm the image enhancement results qualitatively, a simple binarization algorithm with a threshold value as an average value in the block was applied to the resulting image. Therefore the binarized image may have a blocking artifact. Figure 8 shows an original image, an enhanced image, a binarized image of the original image, and a binarized image of the enhanced image. As shown in Figure 7(d) and Figure 8(d), the binarized result of the enhanced image is good due to ridge clarity accentuated in spite of the simple binarization algorithm. If a binarization algorithm suitable for fingerprint images is applied instead, the results will be better.

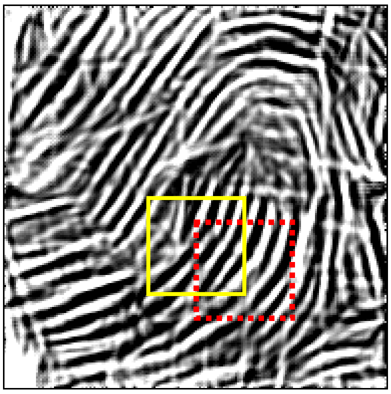
Moreover, because the components of subband images with a higher directional energy are used and those with lower energy are excluded for the synthesis, the influence of noise on the ridges and valleys is reduced. As shown in the region bounded with '—' in Figure 7(b) and Figure 8(b), the ridge direction of a block is accentuated in the ridge direction, and effect of noise and flaw on ridge is attenuated, so the clarity between ridge and valley is accentuated.

This is because only a few relatively important bands with higher directional energy are used for ridge reconstruction. In addition, the broken ridge is recovered as shown in the region bounded with '**…**' in Figure 7(b) and Figure 8(b), because the ridge direction of a block is accentuated by a higher weighted value.

5. Conclusions

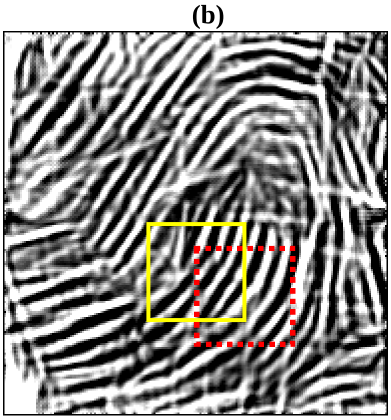
A new fingerprint enhancement algorithm based on a DFB has been proposed. The method uses DFB procedures, ridge-direction estimation, and the weighted subband components for directional filtering in which the ridge direction is based on the energy estimate of directional subband components

(a)



(b)

(b)



(c)

(d)

Fig. 8. Enhanced result of a bad quality image by weighted subband images: (a) Original image; (b) enhanced image; (c) binarized image of original image; (d) binarized image of synthesized image.

from the analysis section of the DFB. There was one important component corresponding to the ridge direction.

The influence of noise on the ridges and valleys was reduced because the components of a few subband images with higher directional energy were used for the synthesis. The subband components corresponding to a prominent direction in a block were accentuated, while the others were weakened by a lower weighted value from the experimental results. As such, the status of travel of the ridges and intensity contrast of ridges and valleys were accentuated. In addition, for singular points and minutiae including several similar higher directional energies, the spatial characteristics (such as shape and position) of these points were preserved because similar higher weighted values were applied to these directions.

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