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An Effective and Robust Fingerprint Enhancement by Adaptive Filtering in Frequency Domain

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Abstract: Extensive research of automatic fingerprint identification system (AFIS), although started in the early 1960s, has not yet give the answer to reliable fingerprint recognition problem. A critical step for AFIS accuracy is reliable extraction of features (mostly minutiae) from the input fingerprint image. However, the effectiveness of a feature extraction relies heavily on the quality of the input fingerprint images. This leads to the incorporation of a fingerprint enhancement module in fingerprint recognition system to make the system robust with respect to the quality of input fingerprint images. In this paper we propose an adaptive filtering in frequency domain in order to enhance fingerprint image. Two different directional filters are proposed and results are compared.

Keywords: Fingerprint, enhancement, image filtering, orientation estimation, Gabor filter.

1 Introduction

RELIABLE PERSON identification is an important problem in diverse businesses such as law enforcement, physical access control, information system security, finance, health care etc. Often, it is necessary to do it remotely and automatically. Biometrics, which refers to identifying an individual based on his or her physiological or behavioral characteristics, are becoming dominant over traditional means of authentication based on what you know (knowledge-based e.g. password or PIN) or what you have (token-based e.g. ID card). Among several human characteristics that can be used in biometric systems (face, retina, iris, voice,

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hand geometry etc.), fingerprints are, due to their characteristics, one of the most researched, used and mature method of authentication. [1]. They have been extensively used by forensic experts in criminal investigations for decades [1]. The main reason for popularity of fingerprint-based approaches is that each fingerprint of a person is unique and remains invariant with age [2].

There were different realizations of automatic fingerprint identification systems (AFIS) in the last 50 years. We can either digitalize fingerprint image taken by ink, or use inkless scanners to provide input image for AFIS. A number of operations are then applied in order to extract features later used in matching process, so it is obvious that the accuracy of fingerprint identification methods relies heavily on the reliability of those extracted features.

The goal of feature extraction in pattern recognition system (in general) is to extract information from the input data that is useful for determining its category. In the case of fingerprints a natural choice are features based directly on the fingerprint ridges and ridge-valley structure. However, the effectiveness of a feature extraction depends greatly on the quality of the images. Consequently, fingerprint image enhancement has become a necessary and common step after image acquisition and before feature extraction in most AFIS. Following, binarization, feature extraction and matching algorithms are executed on the enhanced image. The fingerprint enhancement can be employed on, both the gray-scale, and binary images, in spatial or frequency domain. In this paper we propose method based on filtering of original input gray-scale fingerprint image in frequency domain.

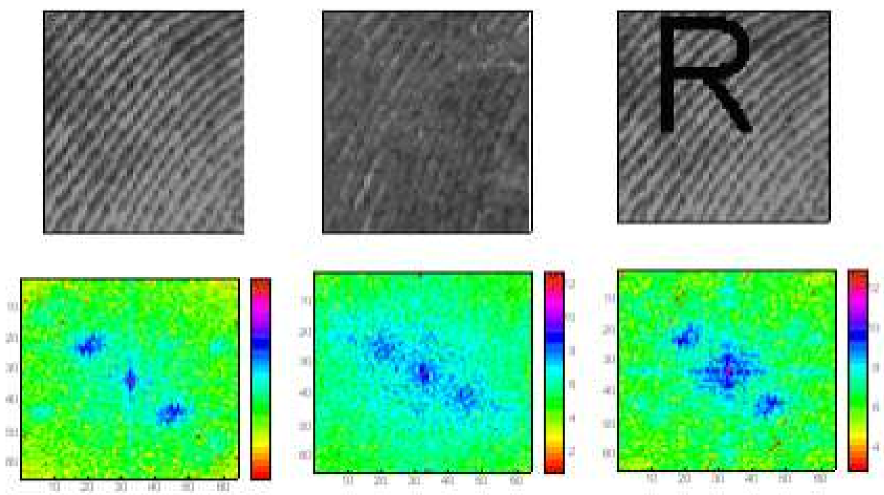
The rest of this paper is organized as follows. In Section II fingerprint structure and its characteristics in frequency domain are briefly described. In Section III enhancement process and filters used for adaptive filtering in frequency domain are presented. Parameters of proposed filters as well as results of enhancement obtained from available database sets are shown in Section IV, and a conclusion is given in Section V.

2 Fingerprint Structure

A fingerprint represents the image of the surface of the skin of the fingertip. A typical structure of a fingerprint consists of ridges (black lines) separated by valleys.

The ridge pattern in a fingerprint can be described as an oriented texture pattern with fixed dominant spatial frequency and orientation in a local neighborhood. The frequency is depending on inter-ridge spacing, and orientation on flow pattern exhibited by the ridges.

When looking at Fourier spectrum, two distinct symmetric peaks along with the DC component are clearly visible indicating the existence of the (almost) parallel ridges as shown in Fig 1(a). We can obtain two characteristics from this spectrum: local ridge orientation as direction normal to line connecting two peaks, and local ridge frequency is determined by the distance between those peaks. When image is noisy or smudged, peaks are not clearly separated as shown in Figure 1(b). If there exist additional content in the image such as letter then the Fourier spectrum has additional components too as shown in Figure 1(c).



(a) (b) c)

Fig. 1. Fourier spectrum of region (a) of good quality, (b) smudged, (c) containing letter.

Region of a fingerprint where the ridge pattern makes it visually prominent are called singularities. There are two types of fingerprint singularities: core and delta, and they are very useful for determining fingerprintXs class. A closer analysis of the fingerprint reveals some anomalies of the ridges, such as ridge endings, bifurcations, crossovers, short ridges, etc. These local features of fingerprints, called minutiae, can be used for manual or automatic fingerprint identification [3]. A good quality fingerprint contains between 60 and 140 minutiae, but different fingerprints have different number of minutiae. Those characteristics of fingerprint images are shown in Figure 2.

Enhancement may be viewed as a process of improving the clarity of the ridge structure in the fingerprint image [4–6]. Result is expected to be more suitable than the original, for visual examination and automatic feature extraction. A variety of algorithms for image enhancement can be used in case of fingerprint images. One group of algorithms, such as contrast manipulation and histogram equalization, are dealing with each pixel independly. Other algorithms are considering local

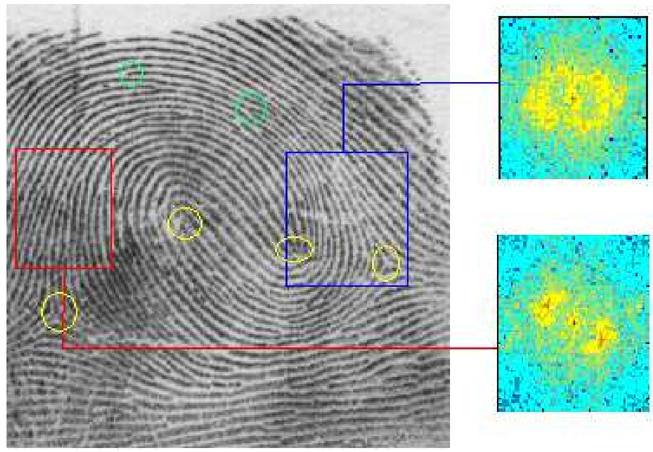


Fig. 2. A fingerprint image with marked singularities, minutiae and the frequency spectrums corresponding to the local regions.

neighbourhood of each pixel during its processing. Typicall algorithms from this class are linear filtering in spatial or frequency domain, nonlinear filtering, adaptive filtering etc. Although noise content is reduced, enhancement process itself can also introduce false ridges, resulting in false or missing minutiae.

Since in local area, ridges and vallyes have well-defined frequency and orientation, it seems natural to use contextual (directional) filters whose parameters depend on the local ridge frequency and orientation, in which case the filtering process is called adaptive. Due to the regularity and continuity properties of the fingerprint image, occluded and corrupted regions can be recovered using the contextual information from the surrounding neighborhood. There were some research in directional filtering in spatial domain [2, 7]. In frequency domain Fourier transforms [4, 8, 9], and Gabor filters [5, 10] are analyzed.

3 Fingerprint Enhancement

In order to improve the clarity of the ridge structure in the fingerprint image, enhancement filter have to increase the contrast between foreground ridges and background, and also to reduce noise in smudgy regions. To achieve this, the query image is first normalized to have desired mean and variance. The image is then divided into non-overlapping blocks and dominant ridge orientation (direction) is determined for each block to be used in the subsequent processes. The dominant ridge directions are then smoothed and subsequently the block-direction image is formed. The next step is to estimate the average ridge distance (or frequency). In order to reduce the computational cost, average ridge distance is computed once for the whole input image instead of determinig it for each block of the image. The image is then enhanced using the directional filtering method. In summary, to enhance the fingerprint image we:

(1) normalize the input fingerprint image,
(2) compute the local ridge orientations and frequencies,
(3) smooth the obtained directions and compute average frequency,
(4) implement directional filtering to enhance the image.

The details of each stage are given next.

3.1 Local normalization

Before filtering the fingerprint image, we normalize the image in each block separately to a constant mean and variance The main purpose of normalization is to have input images with similar characteristics, to remove the effects of sensor noise and also to reduce the variation in gray-level values along the ridges and vallyes (without changing the ridge and valley structures). Let $I(x,y)$ denote the gray value at pixel (x,y), M_i and V_i, the estimated mean and variance of block B_i, respectively, and $N_i(x,y)$, the normalized gray-level value at pixel (x,y). For all the pixels in block , the normalized image is defined as (1):

$$N_i(x,y) = \begin{cases} M_0 + \sqrt{\dfrac{V_0(I(x,y)-M_i)^2}{V_i}}, & \text{if} \quad I(x,y) > M_i \\ M_0 - \sqrt{\dfrac{V_0(I(x,y)-M_i)^2}{V_i}}, & \text{otherwise} \end{cases} \tag{1}$$

where and are the desired mean and variance values, respectively. Normalization is a pixel-wise operation which does not change the clarity of the ridge and valley structures. If normalization is performed on the entire image, then it cannot compensate for the intensity variations in different parts of the image due to the elastic nature of the finger. Separate normalization of each individual block alleviates this problem.

3.2 Determination of ridge orientation and frequency

Let us first define the *orientation field O* for a fingerprint image. The orientation field O is defined as a $P \times Q$ image (called orientation or directional image), where

$O(i,j)$represents the local ridge orientation at pixel (i,j). It is used in fingerprint systems in different modules: enhancement, classification, ridge detection. Local ridge orientation is usually specified for a block rather than at every pixel. There are a number of techniques that can be used to calculate orientation fields [5, 11]. We use the least mean square orientation estimation based on gradient [11]:

- First, the input fingerprint image is divided into nonoverlaping blocks of size $W \times W$;
- For each pixel (i,j) of the block the x and y component of the gradient, G_x and G_y respectivly, are calculated. Gradient operator may vary from the simple Sobel operator to the more complex Marr-Hildreth operator;
- The average squared gradient $[\overline{G}_{s,x}\overline{G}_{s,y}]^T$ in the block can be calculated as:

$$\begin{bmatrix} \overline{G}_{s,x} \\ \overline{G}_{s,y} \end{bmatrix} = \begin{bmatrix} \sum_W G_x^2 - G_y^2 \\ \sum_W 2\, G_x\, G_y \end{bmatrix} \tag{2}$$

  The average gradient Φ direction and dominant local orientation for the block are given by:

$$\begin{aligned} \Phi &= \frac{1}{2}\tan^{-1}\frac{\sum_W 2\, G_x\, G_y}{\sum_W G_x^2 - G_y^2} \\ O(i,j) &= \Phi + \frac{\pi}{2} \end{aligned} \tag{3}$$

  Correction for 90° is necessary since the angle of gradient is perpendicular to the ridge orientation.
  In our experiment we used Sobel gradient operator to obtain G_x and G_y, and the dimension of blocks we used for orientation estimation is $W = 8 \times 8$.
- Aditional smoothing (low pass filtering) must be applied on the orientation values in order to eliminate wrongly estimated ridge orientation values at the distorted and noisy regions. It is done by converting orientation image into a continuous vector field defined as follows:

$$\begin{aligned} \Psi_x(i,j) &= \cos[2\, O(i,j)] \\ \Psi_y(i,j) &= \sin[2\, O(i,j)] \end{aligned} \tag{4}$$

  Consequently, the filtering is implemented by:

$$\begin{aligned} \Psi)'_x(i,j) &= \sum_W W(u,v)\Psi_x(i-uv, j-uv) \\ \Psi)'_y(i,j) &= \sum_W W(u,v)\Psi_y(i-uv, j-uv) \\ O'(i,j) &= \frac{1}{2}\tan^{-1}\frac{\Psi)'_y(i,j)}{\Psi)'_x(i,j)} \end{aligned} \tag{5}$$

where W is a two-dimensional low-pass filter with unit integral, specifies the size of the filter (e.g 5×5), and represent the smoothed orientation field.

In order to estimate local ridge frequency we:

- project the gray values of all the pixels located in each block along a direction orthogonal to the local orientation computed above. This projection forms a 1D wave with the local extrema corresponding to the ridges and valleys of the fingerprint;
- Let $K(i, j)$ be the average number of pixels between two consecutive peaks in the 1D wave generated above. The frequency $f(i, j)$ is computed as $f(i, j) = 1/K(i, j)$.

For typical fingerprint image scanned at 500 dpi, there is a little variation in the spatial frequencies (inter-ridge distances) among different fingerprints. This implies that there is an optimal scale (or range of spatial frequencies) for analyzing the fingerprint texture.

3.3 Directional filtering

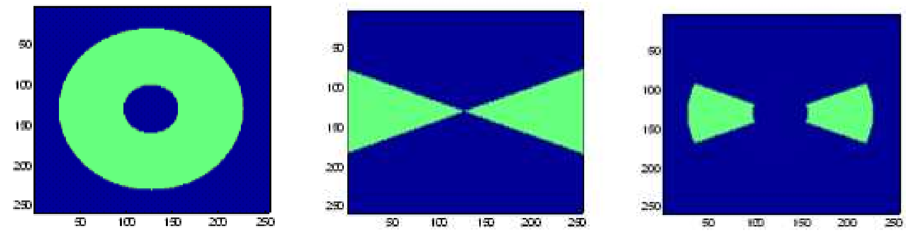
Due to development of fast algorithms and power of modern computer systems, the filtering is often done in frequency domain. Filter we want to use must satisfy the following criteria:

- Must be frequency and orientation selective since those parameters changes;
- It has to pass spectral components corresponding to ridges, while attenuating noise components;
- DC and low frequencies are to be eliminated since they have no impact to the ridge frequency and orientation whatsoever;
- Band pass has to be properly selected since its upper boundary attenuate high frequency noise such as scars, and lower boundary attenuate low frequency noise such as smudges by ink. We must pay attention that narrow band pass do enhance the contrast, but can also cause unwanted ridge joining.

When describing filter in frequency domain it is through combination of two separate components: radial depends only on local ridge spacing ($\rho = 1/f$) and the angular depends only on local ridge orientation (ϕ)

$$H(\rho, \phi) = H_r(\rho) H_a(\phi). \tag{6}$$

An ideal model of band pass directional filter in Fourier domain is shown in Figure 3.



(a) (b) c)

Fig. 3. Filter in Fourier domain (a) band pass (radial) component, (b) directional (angular) component, (c) combination of previous two.

Positional dependence of those filters requires defining and applying appropriate filter for each pixel which is computationally very expensive. Instead we apply a finite number of predefined filters (regarding to finite number of discrete orientations, and fixed frequency). It must be taken care of satisfying some requests, namely that number of filters must be small enough, and that degradation of filtered image is sufficient small. It can be obtained in following way:

1. elimination filter dependence of local ridge frequency; either an average ridge frequency is used, or a constant is set empirically for entire database set. By doing so the context of the filter is determined only by the orientation;
2. by discretization of orientation values to fix number (8 or 16) we can obtain a small number of directional filter components.

The Fourier transform P_i, $i = 1,\ldots,n$ of the filters is pre-computed and stored. Filtering an input fingerprint image f is performed as follows (see Figure 4):

- The FFT F of input fingerprint image f is computed,
- Each directional filter P_i is point-by-point multiplied by F, obtaining n filtered image transforms PF_i, $i = 1,\ldots,n$.
- Inverse FFT is computed for each PF_i resulting in n filtered images pf_i, $i = 1,\ldots,n$ (spatial domain) [12].

The enhanced image is obtain in following manner: all pixels in one block of enhanced image take the value of pixels on the same position from the filtered image which emphasizes determined orientation for corresponding block.

In our experiment two different realizations of directional filters are proposed and tested, and their short descriptions are given below.

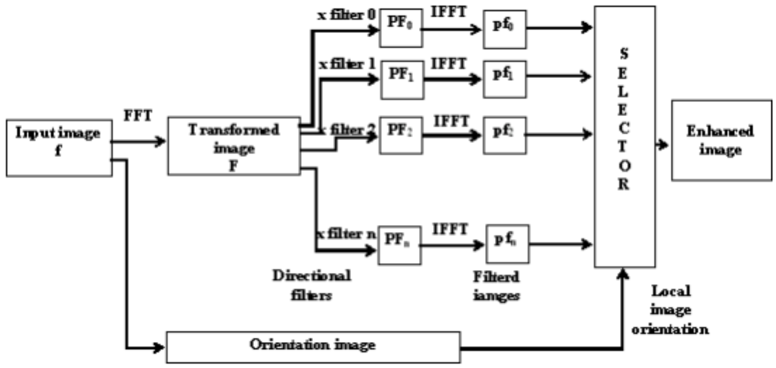


Fig. 4. Algorithm for fingerprint enhancement.

3.4 Butterworth filter

Our first proposal for filter whose transfer function is given as in (6) is the band pass Butterworth filter for radial component (7) of order n (usually $n = 2$), having center frequency ρ and bandwidth ρ_{BW}

$$H_r(\rho) = \sqrt{\frac{(\rho\rho_{BW})^{2n}}{(\rho\rho_{BW})^{2n} + (\rho^2 - \rho_0^2)^{2n}}} \tag{7}$$

and directional component is defined as (8)

$$H_a(\phi, \phi_o) = \begin{cases} \cos^2 \dfrac{\pi(\phi - \phi_0)}{2\phi_{BW}} & |\phi - \phi_0| < \phi_{BW} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

Where ϕ_{BW} is the angular bandwidth, and ϕ_0 is the orientation of the filter.

3.5 Gabor filter

Our second proposal is Gabor filter, since they are recognized as a very useful tool in computer vision and image processing applications such as texture analysis, image compresion etc. Gabor filters are very useful both in frequency and spatial domain, due to their frequency-selective and orientation-selective properties. Impulse response of these filters, which can be viewed as a Gaussian modulated sinusoid bandpass filter, are very similar to impulse response of receptive fields in the brainXs visual cortex [13]. By simple adjustment of mutualy independent parameters, Gabor filters can be configured for different shapes, orientations, different width of band pass and different central frequences. Properly tuned, Gabor filter can filter an image, maintaining only regions of a given frequency and orientation, and this has profound implications for research in fingerprint image analyse and enhancement using this filter [5, 10].

An even Symmetric Gabor filter general form [5] in the spatial domain is given by (9):

$$h(x,y,\phi,f) = e^{-0.5[(\frac{x}{\delta_x})^2+(\frac{y}{\delta_y})^2]}\cos[2\pi f(x\cos\phi + y\sin\phi)] \quad (9)$$

where ϕ is the orientation of the Gabor filter, f is the frequency of the sinuusoidal plane wave along the x-axis, δ_x and δ_y are the standard deviations of the Gaussian envelope along the x and y axes, respectively. If δ_x and δ_y are too large, the filter is more robust to noise, but is more likely to create spurious ridges and valleys. If they are too small, the filter is not effective in removing the noise. An example of Gabor filter and its response in spatial and frequency domain are shown in Figure 5.

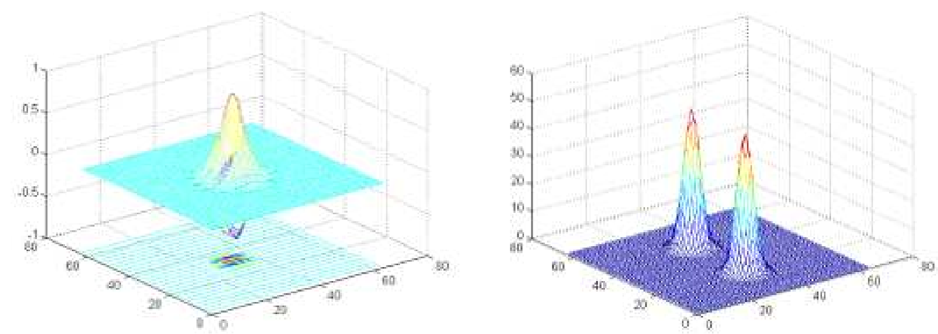


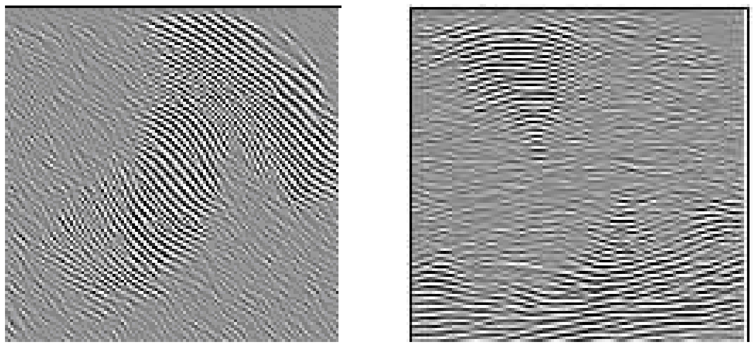
Fig. 5. The Gabor filter and its response in spatial and frequency domain.

4 Experimental Results

We have tested the performance of the proposed enhancement algorithm on two different databases of fingerprint images we have. First one consists of 100 fingerprint images taken by ink and then digitized with optical scanner using spatial resolution of 300 dpi and amplitude resolution of 8 bit per pixel. Dimension of each image is 256×256 pixels. Second one is taken from [14]. It contained 104 grayscale fingerprint images of size 256×256 pixels, including eight images per finger from 13 individuals. The spatial resolution used in scanning process was 500 dpi, and amplitude resolution was 256 gray levels (8 bits per pixel).

Parameters for normalization are set to 100 for both M_0 and V_0. The ridge orientations were discretized to 8 values (step 22.5°).

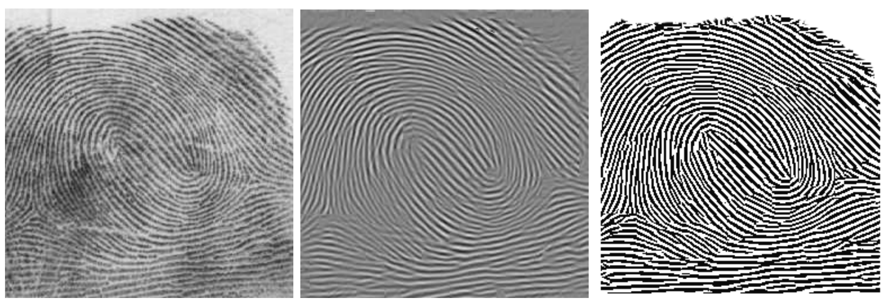
For first proposed filter we use the following parameter set: $n = 2$, $\rho_0 = 60$, $\rho_{BM} = 30$, $\phi_0 = i\pi/8$, $i = 1, \ldots, 7$, $\phi_{BW} = \pi/16$. Set of 8 filtered images are obtained where in each of them direction normal to orientation of applied filter is enhanced as shown in Figure 6 for two different orientations.



(a) (b)

Fig. 6. Filtered images for directions (a) 22.5° (b) 90°.

The enhancement of the ridge-valley structure is clearly noticed, as shown in Figure 7.

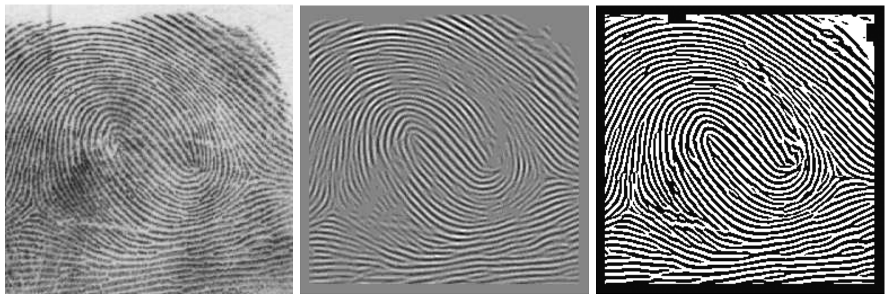


(a) (b) (c)

Fig. 7. (a) Original fingerprint image, (b) Enhanced image, (c) Binarized image.

Parameters f, δ_x and δ_y, for optimal Gabor filter depends on inter-ridge distance in fingerprint image. We set filter frequency to average ridge frequency $f = 1/K$ where K is the average inter-ridge distance. If we want to save some computational time, we can set parameter K to its approximated value. For our databases ridge distance is approximately 5 pixels, so f is set to $f = 1/5$. If f is too large spurious ridges are created in the filtered image, whereas if f is too small nearby ridges are merged into one. We set parameters to be $f = 1/5$, and $\delta_x = \delta_y = 4.0$. Trade-off in selection of δ_x and δ_y is done based on empirical data [9], so that the filter is robust to noise, but still can capture ridge information at fine level. We have used eight different values for $\phi = i\pi/8$ with respect to the *x*-axis.

Original image and enhanced images obtained by filtering with Gabor filter are shown in Figure 8.



(a) (b) (c)

Fig. 8. (a) Original image, (b) Enhanced image obtained by Gabor filtering (c) Binarized image.

Fingerprint image shown on both Figure 7 and Figure8 is taken from our first database set. Example of fingerprint image taken from our second database set is shown in Figure 9.

(a) (b) (c)

Fig. 9. (a) Original image, (b) Enhanced image obtained by Gabor filtering (c) Binarized image.

Similar results were obtained for entire database sets. We can notice that ridge structure is obviously enhanced as expected. Also some ridge breaks caused by scars are eliminated, but not all of them. Obtained enhanced and then binarized image is then processed in following AFIS steps: segmentation, thinning, minutiae extraction, minutiae validation (filtering), and generating minutiae template. In process of user enrolment that template is stored in database, and if verification or identification is applied then that template is compared with those previously stored in database (one or all respectively).

In order to quantify effect of enhancement, rather than to rely on subjective opinion (visual examination), we compared number of extracted minutiae from original image and from enhanced one. As basic fingerprint minutiae extraction method we used the one presented in [15] Results for two fingerprints already shown in Figure 8 and Figure 9 are given in Table1. E represents number of minutiae determined by the expert; A is the number of automatically extracted minutiae; P is the number of matched minutiae; M is number of missing minutiae and F is the number of false minutiae.

Table 1. Comparison of number of minutiae before and after enhancement for presented images

Fig. 8(a)	A	P	M	F	E
Original fingerprint image	187	70	30	117	100
I proposed filter (directional Butterworth)	140	77	23	63	
II proposed filter (Gabor)	131	80	20	51	
Fig. 9(a)	A	P	M	F	E
Original fingerprint image	56	23	3	33	26
I proposed filter (directional Butterworth)	40	24	2	16	
II proposed filter (Gabor)	33	24	2	9	

We can see that there is a significant decrease of number of automatically extracted minutiae after enhancement is applied (for both proposed filters). Reduction of false minutiae is over 50%, and for the whole set of tested images it varies from 30% to 75% depending from the quality of original fingerprint image. Majority of false minutiae are due to boundary effect (bed segmentation), smudgy parts and existence of broken ridges (so called creases or scars). Directional filtering applied in enhancement process can reconnect some ridge breaks (as shown in Figure 9(c)), but some broad creases remains. Although for both presented images Gabor filter give slightly better result, we can say that both proposed filters are adequate solutions for fingerprint enhancement process.

5 Conclusion

Fingerprint enhancement is a common and critical step in AFIS. Enhancement process should increase the contrast between ridge and valley and remove noise in image. The directional filtering technique, a general image-processing operation, is widely used for fingerprint image enhancement. Due to the described characteristics of fingerprint image in frequency domain it seems natural to use directional band pass filter to enhance fingerprint image. In this paper, we propose two filter realizations for adaptive filtering in frequency domain, where both of them enhance fingerprint ridge-valley structure and attenuate existing noise. It is shown that enhanced image is more suitable for following steps in AFIS. As a result of enhancement process more reliable feature extraction is obtained, less spurious minutiae are extracted, which improves the overall AFIS accuracy. Our future work will be focused on effort to filter false minutiae to maximal extent possible.

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