Wavelet Based Fingerprint Image Enhancement

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Abstract—**Fingerprint image enhancement is aimed to improve the quality of local features for automatic fingerprint identification. It will allow accurate feature extraction and identification. In this paper we have considered the use of wavelets for fingerprint enhancement mainly due to their spatial localization property as well as capability to use of oriented wavelets such as Gabor wavelets for orientation flow estimation. The proposed algorithm consists of two-stage processing: smoothing and Gabor wavelet filtering. Our smoothing part of enhancement algorithm reduces the noise by a new technique based on Gaussian filtering. Since Gaussian filters meets uncertainty principle at its limits, it is considered here as the best choice for smoothing and noise reduction. Gabor wavelet is applied to improve the quality of smoothed image. Gabor filters are commonly used for enhancement in which the frequency and orientation estimation is required for the enhancement. However, the proposed algorithm is independent of estimation part. Simulation results are included illustrating the capability of the proposed algorithm.**

Index Terms— fingerprint image enhancement, Gabor wavelet, Gaussian filter, variance.

I. INTRODUCTION

Fingerprints are basically oriented texture fields of quasi-periodic and smooth pattern of ridges and valleys having dominant frequency that reside in mid frequency range (1/2~1/4pi). Ridge orientation, ridge spatial frequency and more significantly structure of minutiae and their distribution in the fingerprint image, are the main intrinsic features of a given fingerprint. A preprocessing of fingerprint image for enhancement applications is aimed to improve the quality of local features for automatic fingerprint identification, it involves enhancement of low resolution ridge, minutiae enhancement, ridge thinning and orientation flow estimation [1]. Accordingly, for constructing an effective fingerprint identification system, a robust enhancement algorithm is necessary. From viewing in the frequency domain, ridges and valleys in a local neighborhood form a sinusoidal-shaped wave, which has a well-defined frequency and orientation. Thus some techniques take advantage of this information to enhance gray-level fingerprint image [2]. Hsieh [2] propose a wavelet-based method for enhancement of fingerprint image, which uses both the global texture and local orientation characteristic. It uses standard wavelet that is able to utilize dyadic scale and specific frequencies. Hong [3] present fingerprint enhancement algorithm based on the estimated local ridge orientation and frequency As the spatial orientations as well as intensity of the ridges in a fingerprint image differ at different locations, an enhancement method to be acceptable is required to have capability focusing on local features. In this paper we have considered the use of wavelets for fingerprint enhancement mainly due to their spatial localization property as well as capability of using oriented wavelets such as Gabor wavelets for orientation flow estimation.

The paper organized as follows: In Section II, a brief review of wavelets is given. In Section III the outline of the proposed enhancement algorithm for fingerprint images is discussed. Section IV denotes Postprocessing. Experimental result and evaluation is presented in Section V. Finally, paper is concluded in Section VI.

II. REVIEW OF WAVELETS

Wavelets are basis functions that are capable of signal representation in time-frequency domain locally. Wavelet bases are constructed from translation and scale of a mother wavelet [4].

$$\psi_{(a,b)}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \qquad (1)$$

a and b are the scaling and translation parameters, respectively.

Wavelet transform of a function $f(t) \in L^2$ is defined as follow:

$$Wf(a,b) = \left\langle f, \psi_{(a,b)} \right\rangle = \int_{-\infty}^{+\infty} f(x)\frac{1}{\sqrt{a}}\psi^*\left(\frac{t-b}{a}\right)dt \qquad (2)$$

The reconstruction relation can be expressed as:

$$f = \frac{1}{c_\psi}\int_0^\infty\int_{-\infty}^{+\infty} Wf(a,b)\psi_{(a,b)}(t)\,db\,\frac{da}{a^2}$$
$$c_\psi = \int_0^\infty \frac{\left|\hat{\psi}(\omega)\right|^2}{\omega}d\omega < +\infty \qquad (3)$$

Where $\hat{\psi}(\omega)$ is Fourier transform of $\psi(t)$. Gabor wavelet can be used to generate non orthogonal frames that can assume the following form:

$$\psi(x) = \frac{1}{\sqrt{2\pi\sigma x}} e^{\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x}\right)+2\pi j\, w_x\right]} \qquad (4)$$

Gabor function meets Heisenberg uncertainty principle at it limits and thus achieves best localization in time and frequency simultaneously.

The two dimensional Gabor wavelet function can be written as follows [5]:

$$\psi(x,y) = \frac{1}{2\pi\sigma x\sigma y} e^{\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x{}^2}+\frac{v^2}{by^2}\right)+2\pi j w_x\right]} \qquad (5)$$

With Fourier transform that is also in an exponential form

$$\hat{\psi}(u,v)=e^{\left[-\frac{1}{2}\left\{\frac{(u-w)^2}{\sigma_u^2}+\frac{v^2}{\sigma_v^2}\right\}\right]} \qquad (6)$$

Where σ_u is $\frac{1}{2\pi\sigma x}$ and σ_v is $\frac{1}{2\pi\sigma y}$.

Gabor function can represent a Frame [4] if it meets necessary requirements for a frame. In this paper we introduce a bank of filters defined in specific range of frequency that is useful for our work, but they do not necessarily generate a Frame.

We introduce the following

$$\begin{aligned}\psi_{mn}(x,y)&=a^{-m}\psi(x',y'),\ a>1,\ m,n\in N\\ x'&=a^{-m}(x\cos\theta+y\sin\theta)\\ y'&=a^{-m}(-x\sin\theta+y\cos\theta)\\ \theta&=\frac{n\pi}{k}\end{aligned} \qquad (7)$$

Where k is the total number of chosen orientations.

Since Gabor wavelets are not orthogonal, Gabor transform introduces redundancies that are to be reduced in order to generate a computationally efficient frame structure. We use the following strategy to decrease this redundancy [6].

Suppose that U_l and U_h are the lower and upper center frequency of the region of interest and k is total number of orientation and s is total scale in multi resolution decomposition. The design strategy is that frequency bands with half-peak magnitude support of the filter response in frequency spectrum touch each other. This strategy is showed in Fig. 1. The parameters is calculated as follow

$$a=\left(\frac{U_h}{U_l}\right)^{\frac{1}{s-1}}, \quad \sigma_u=\frac{(a-1)U_h}{(a+1)\sqrt{2\ln 2}} \qquad (8)$$

$$\sigma_v=\tan\left(\frac{\pi}{2t}\right)\left[U_h-2\ln\left(\frac{\sigma_u^2}{U_h}\right)\right]\left[2\ln 2-\frac{|2\ln 2|^2\sigma_u^2}{U_h^2}\right]^{-\frac{1}{2}} \qquad (9)$$

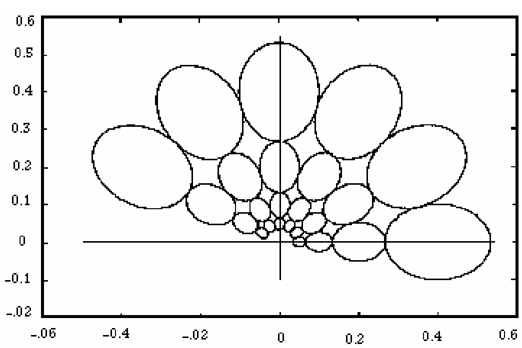


Figure 1. The contour indicates the half-peak magnitude of the filter responses in the Gabor filter dictionary. The filter parameters used are U_h=0.4, U_l=0.05, K= 6, and S=4

III. ENHANCEMENT ALGORITHM

We introduce the enhancement algorithm that is based on two following steps:

Step 1:

- Apply Gaussian filter to the image in equally spaced directions with number of directions K that is specified by user.
- Divide the filtered image to blocks $k\times k$,where k is chosen such that frequency of the ridges are retained.
- Choose the filtered block that is in the orientation of the ridge. Then reconstruct the final image by adjoining these blocks.

Step 2:

- Divide the image to the blocks $k\times k$.
- Apply Gabor wavelet decomposition in direction orthogonal to direction that was chosen in first part and at different scales, and then reconstruct the final image based on adjoining chosen filtered blocks.

A. Gaussian filter applying

In the first part we want to smooth the image. We choose Gaussian function because for a given band in time domain, its frequency support is lowest among other functions, this leads to maximal high frequency noise filtering.

Proposition: Each local part of finger can be considered as subimages in specific orientation and frequency. If the subimage is filtered with Gaussian filter in different direction, the subimage that is filtered in ridge orientation, will have maximum variance.

Proof: We suppose that fingerprint image is a two dimensional function that is uniform in one direction and periodic with specific frequency in a direction perpendicular to the first.

$$f(x,y)=\sin(2\pi v_0 y) \qquad (10)$$

Where v_0 is frequency and x specifies orientation.

We want to prove that the variance is maximized for an image filtered in a direction in line with ridge orientation.

Now, consider two-dimensional Gaussian filter (11) as:

$$g(x,y)=\frac{1}{2\pi\sigma_x\sigma_y}\exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)\right] \qquad (11)$$

The filter in α direction can be written as:

$$g(x,y,\alpha)=\frac{1}{2\pi\sigma_x\sigma_y}\exp\left[-\frac{1}{2}\left(\frac{(x\cos\alpha+y\sin\alpha)^2}{\sigma_x^2}+\frac{(-x\sin\alpha+y\cos\alpha)^2}{\sigma_y^2}\right)\right] \qquad (12)$$

With a Fourier transform as

$$G(u,v,\alpha)=\exp\left[-\frac{1}{2}\left(\frac{(u\cos\alpha+v\sin\alpha)^2}{\sigma_u^2}+\frac{(-u\sin\alpha+v\cos\alpha)^2}{\sigma_v^2}\right)\right] \qquad (13)$$

$$\sigma_u=\frac{1}{2\pi\sigma_x}, \quad \sigma_v=\frac{1}{2\pi\sigma_y}$$

Filtering $f(x,y)$ with $g(x,y)$ can be written as follows,

$$F=\begin{cases}G(u,v_0,\alpha)=\exp\left[-\frac{1}{2}\left(\frac{(u\cos\alpha+v_0\sin\alpha)^2}{\sigma_u^2}+\frac{(-u\sin\alpha+v_0\cos\alpha)^2}{\sigma_v^2}\right)\right]\\ 0 \qquad v\neq v_0\end{cases} \qquad (14)$$

For the inverse Fourier tra*ns*form of F , F^{-1}, variance will be:

$$var(F^{-1}) = \int (F^{-1})^2 \, dxdy = F * F$$

$$= \int exp\rho^{-1/2}\left(\frac{(u\cos\alpha + \upsilon\sin\alpha)^2}{\sigma^2 u} + \frac{(-u\sin\alpha + \upsilon\cos\alpha)^2}{\sigma^2 \upsilon}\right) \quad (15)$$

$$* exp\rho^{-1/2}\left(\frac{(-u\cos\alpha + \upsilon\sin\alpha)^2}{\sigma^2 u} + \frac{(u\sin\alpha + \upsilon\cos\alpha)^2}{\sigma^2 \upsilon}\right) du d\upsilon$$

When Gaussian filter has small variance in one direction, we may assume $\sigma_\upsilon \to 0$, then

$$\alpha = 0 \to var(F^{-1}) = 0$$
$$\alpha = \frac{\pi}{2} \to var(F^{-1}) = \infty \quad (16)$$
$$0 < \alpha < \frac{\pi}{2} \to var(F^{-1}) \neq \infty$$

We see that if $\alpha = \frac{\pi}{2}$ the value of integral is larger than other directions and in ideal manner the result of integral is infinite.

In fingerprint image the ridges reside within certain bands so it will not be necessary to choose a very small variance in one orientation; it would suffice to choose the variance of a band of filter which is equal to the width of ridges.

The Gaussian function in two different orientations is showed in Fig. 2.

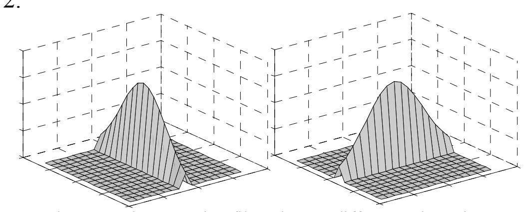
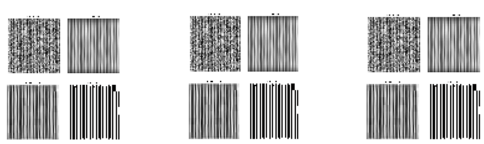


Figure 2. The Gaussian filters in two different orientations

In the smoothing step of the proposed algorithm, the image is divided into non-overlapping blocks. The number of filtered images corresponds to the number of orientations. The variances of different direction are computed and direction having maximum variance is chosen. The smoothed image is constructed by adjoining all of the chosen blocks. Fig. 3 (a) and (b) shows the original periodic image and with additive noise, with SNR= 15db respectively and Fig. 3 (c) represents smoothed noisy image with SNR= 15db. The smoothed image illustrates the capability of proposed algorithm for noise reduction.



(a) (b) (c)

Figure 3. (a): original periodic image (b) noisy periodic image with SNR=15db (c) smoothed image with SNR=25db

B. Gabor wavelet applied to image

As mentioned in previous section, in the first step image is smoothed, where noise and distortion is decreased. In next step of algorithm, complex Gabor wavelet is applied to image. Gabor filter is commonly used for image enhancement. This filter is formed from a Gaussian function multiplied with sinusoid function in certain direction.

Regularly before applying Gabor function, frequency and direction of local block of image are calculated using various methods. However noise and distortion content of image, reduces the accuracy of frequency and direction estimation. We note that proposed method is free from frequency and direction computation. Our algorithm aims to decrease these shortcomings.

As mentioned before complex Gabor wavelet is written as bellow:

$$\psi_{mn}(x,y) = a^{-m}\frac{1}{2\pi\sigma x\sigma y}exp\left[-\frac{1}{2}\left(\frac{x^2}{\delta_x^2} + \frac{y^2}{\delta_y^2}\right) + 2\pi jwx\right] \quad (17)$$
$$x' = a^{-m}(x\cos\theta + y\sin\theta) \,,\, y' = a^{-m}(-x\sin\theta + y\cos\theta)$$

A Gabor Filter is even symmetric if real part of this filter is chosen.

$$g_{mn}(x,y) = a^{-m}\frac{1}{2\pi\sigma_x}\exp$$
$$\left[-\frac{1}{2}\left(\frac{x'^2}{\sigma_x^2} + \frac{y'^2}{\sigma_y^2}\right)\right] \times \cos(2\pi w a^{-m} x) \quad (18)$$
$$x' = a^{-m}(x\cos\theta + y\sin\theta) \,,\quad y' = a^{-m}(-x\sin\theta + y\cos\theta)$$

$w \times a^{-m}$ is frequency of sinusoid function and θ is it's direction.

Image is divided to non-overlapped blocks. According to (7), filtered block in different scales and the direction that is orthogonal to direction in previous step is calculated. The variances of these filtered blocks are computed and the block having maximum variance is chosen. The final image is constructed by adjoining all of the chosen blocks.

Because the local part of image is like a sinusoid function in specific direction when the orientation of filter is perpendicular to orientation of ridges, the values of pixel is amplified in that direction so it has maximum variance on that direction

IV. POSTPROCESSING

One of the important parts in fingerprint identification systems is minutiae extraction. In common minutiae extraction algorithms, minutiae are extracted from skeleton images .The method that we use is binarized image with local thresholding. Then we use morphological operator for thinning the binary image, till we achieve skeleton image.

The enhancement part may introduce some artifact to the image, so a postprocessing algorithm should apply to detect this flaw and correct them. There are different methods for detecting false minutiae that much of them are of statistical nature. We use the method [7] and the result show that the method has good capabilities.

V. EXPERIMENTAL RESULT AND EVALUATION

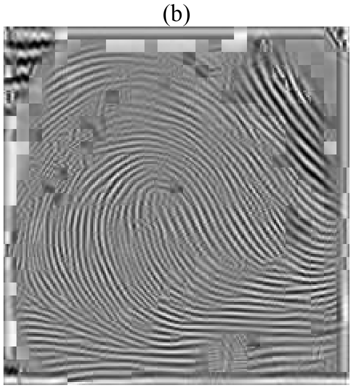
A criterion for increasing the quality is to consider the enhancement in quality of a noisy image after applying enhancement algorithm. Because the aim of algorithm is improvement in the performance for identification, so for the estimation of the efficiency of the enhancement algorithm, performance of identification part is evaluated. For computing algorithm performance, we use following formula [2]:

$$PE = \frac{N_M - N_L - N_S}{Total_H} \quad (19)$$

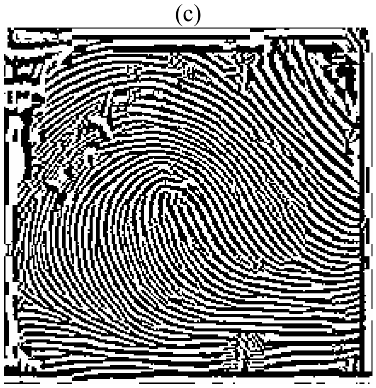
N_M is the number of minutiae that are the same in algorithm and with human expert and N_L , N_S are the number of lost and superabundant minutiae, respectively, and $Total_H$ represents the number of minutiae extracted by human expert. It is obvious that the maximum value of $PE = 1$, which is obtained when $N_L = N_S = 0$ and $N_M = Total_H$.

(a)

(b)



(c)



(d)

Figure 4. (a) fingerprint image, (b) smoothed image (c) enhanced image, (d) binary image

Our fingerprint enhancement algorithm was tested on 50 typical fingerprint images (image size=256 × 256). Sample fingerprint image and its smoothed, enhanced and binary image are shown in Fig. 4.

Table I shows the PE value before and after applying enhancement algorithm that show the performance of the enhancement algorithm.

Table I. Performance evaluation of proposed algorithm

Image	Performance Evaluation(PE)	
	Without enhancement	With Enhancement
1	0.51	0.84
2	0.33	0.76
3	0.41	0.79
4	0.34	0.72
5	0.45	0.88
mean	0.40	0.79
std	0.07	0.06

Table II shows comparison of the result of our algorithm with three other algorithms.

Table II. comparison of our algorithm with other work

Performance	Method			
	Sherlock[2]	Wahab[2]	Hsieh[2]	Proposed
PE	0.49	0.40	0.64	0.79

6. Conclusion and Summary

This paper proposes a novel enhancement algorithm based on Gabor wavelet and Gaussian smoothing function. It attains the high performance results. Algorithm is composed of two steps, first is applying Gaussian function that smoothes the image and extracts directions in subimage blocks with maximal variance, then Gabor wavelet is applied on the enhance image based on local frequency. In contrast of other commonly used algorithms, this algorithm is independent of local frequency and direction estimation. The experimental results show higher performance in fingerprint enhancement as compared with several reported algorithms.

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