Fast Separable Gabor Filter for Fingerprint Enhancement

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Abstract. Since two-dimensional Gabor filter can be separated into one-dimensional Gaussian low pass filter and one-dimensional Gaussian band pass filter to the perpendicular, a new set of separable Gabor filters are implemented for fingerprint enhancement. This separable Gabor filtering consumes approximately 2.6 time faster than the conventional Gabor filtering with comparable enhancement results. This alternative fingerprint enhancement scheme is very promising for practical fast implementation in the near future.

1 Introduction

Goal of fingerprint enhancement is to make ridges clear and genuine as much as possible. The successful enhancement process is used in conjunction with feature extraction process resulting in genuine minutiae and other important features. These original features are very important for fingerprint matching performance. However, fingerprint enhancement process could introduce some artifacts and noise, which leads to fault and missing minutiae, degrading verification performance.

The most popular fingerprint enhancement technique employs contextual filters [1] which their characteristics adapted depending on local context. These filters are designed to make ridges clearly differentiated from each another. Moreover, they also connect broken ridges, fill pores and remove noise and dust. Basically, these filters provide a low-pass along the ridge direction in order to link small ridge gabs and reduce some pores and noise. On the other hand, these filters perform band-pass in the direction orthogonal to the ridges in order to separate ridges from each another. One of the most used contextual filter for fingerprint enhancement is Gabor filter, which proposed by Hong, Wan, and Jain [2].

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In this paper, Hong, Wan, and Jain's work [2] was extended by introduced the less computational complexity for Gabor filtering process. In section 2, the separable Gabor filter and realization is presented. Then experimental results and performance comparison between separable Gabor filter and conventional Gabor filter are shown in section 3.

2 Separable Gabor Filter and Practical Implementation

Gabor filters have both frequency-selective and orientation-selective properties. They also have optimal joint resolution in both spatial and frequency domains [1]. Equation (1) shows the 2-Dimensional (2-D) Gabor filter form [1] as follows,

$$G(x, y, \theta, f_0) = \exp\left\{-\frac{1}{2}\left(\frac{x_\theta{}^2}{\sigma_x^2} + \frac{y_\theta{}^2}{\sigma_y^2}\right)\right\}\cos(2\pi f_0 x_\theta),$$
$$\begin{bmatrix} x_\theta \\ y_\theta \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}, \tag{1}$$

where θ is the orientation of the filter, f_0 is the ridge frequency, $[x_\theta, y_\theta]$ are the coordinates of $[x,y]$ after a clockwise rotation of the Cartesian axes by an angle of $(90°-\theta)$, and σ_x and σ_y. are the standard deviations of the Gaussian envelope along the x- and y-axes, respectively.

Consider 2-D Gabor filter in equation (1), if θ is equal to 90°, equation (1) is simplified as follows;

$$G(x, y, f_0) = \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)\right\}\cos(2\pi f_0 x) \tag{2}$$

The Gabor filter at orientation $\theta = 90°$ of equation (2) can be separated into two independent functions as:

$$G(x, y, f_0) = G_{BP}(x, f_0)G_{LP}(y) = \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}\right)\right\}\cos(2\pi f_0 x)\exp\left\{-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}\right)\right\} \tag{3}$$

where $G_{BP}(x, f_0) = \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}\right)\right\}\cos(2\pi f_0 x)$, and $G_{LP}(y) = \exp\left\{-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}\right)\right\}$.

G_{BP} in Equation (3) is only a band pass Gaussian function of x axis, and G_{LP} in equation (3) is only a low pass Gaussian function of y axis. Because f_0 can be determined by ridge frequency, f_0 can be obtained as a constant. Therefore equations (3) are only functions with one variable (x or y variable) or 1-Dimensional (1-D) Gabor filters. Clearly, this Gabor filter at $\theta = 90°$ can be implemented as a separable transform [3]. By first apply 1-D band pass Gabor filter (G_{BP}) convolution along each row of a fingerprint block and then follow by 1-D low pass Gabor filter (G_{LP}) convolution along each column of this fingerprint block image.

In general, the first step of applying conventional 2-D Gabor filter for fingerprint enhancement is to partition a fingerprint image into square sub-blocks, size $M\times M$, where $M = 16$ in our experiment. Each block was searched and calculated Gabor filter parameters such as its orientation (θ) and its ridge frequency (f_0). The orientation and ridge frequency of any fingerprint block were found by implementing Hong's method [2] for our approach. Once orientation and ridge frequency were found, the Gabor filter was set and designed to perform 2-D convolution operation. The window $N\times N$ of conventional 2-D Gabor filter was convolved along rows and columns of fingerprint image; i.e. multiplied all pixels in the overlapped windows and summed to obtain a window center pixel in the enhanced image. Clearly, this process needs high computational complexity in general.

Instead of applying 2-D convolution, a separable 1-D band pass Gabor filter, size N, can be applied to convolve along the ridge direction θ for all pixels in the block. Then, a 1-D low pass Gabor filter, size N, is convolved along the perpendicular to the ridge direction θ for all pixels in the block. Unfortunately, 1-D pixel sequence along the ridge direction θ is not well-defined due to square sampling grid pattern. For example, if a straight line in any chosen direction is drawn on an image, it is difficult to pick consecutive pixels in order to form a straight line in that particular direction. Hence, separable approach needs resampling process in order to get a precise sequence of pixels. This makes the separable approach is more complicate.

Fortunately, in practical conventional Gabor enhancement, ridge direction is quantized into 8 directions; i.e. 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° [1],[2]. For practical separable Gabor Enhancement, direction of filter is shaped by sampling grid and tessellated pixels, resulting in approximate eight directions i.e. 0°, 26.6°, 45°, 63.4°, 90°, 116.6°, 135°, 153.4°. Obviously, for these eight particular directions, locations of pixels in a sequence are well-defined and tessellated as shown in Fig.1, hence it is possible to implement a separable 2-D Gabor transform without additional computational complexity. However, since a fingerprint image is sampled within square grid as shown in Fig.1, a space between sample to the next sample in any direction may be varied. For example, assume that distance between sample to sample, "*a*", for 1-D filter with orientation 0° and 90° is equal to 1 unit. Then, a distance between two samples in direction of 45° and 135° is equal to $\sqrt{2}$ unit and a distance between two samples in direction of 26.6°, 63.4°, 116.6°, and 153.4° is equal to $\sqrt{1.25}$ unit. Hence equation (3) should be generalized by adding a distance parameter "*a*" as the following equation,

$$G_{BP}[n] = \exp\left\{-\frac{1}{2}\left(\frac{(an)^2}{\sigma_x^2}\right)\right\}\cos(2\pi f_0 an) \quad \text{and} \quad G_{LP}[n] = \exp\left\{-\frac{1}{2}\left(\frac{(an)^2}{\sigma_y^2}\right)\right\} \tag{4}$$

where n represents discrete pixel in 1-D direction, and a represents a distance between pixel to pixel in particular direction; i.e. $a = 1$ for 0° and 90°, $a = \sqrt{2}$ for 45° and 135°, and $a = \sqrt{1.25}$ for 26.6°, 63.4°, 116.6°, and 153.4° orientations.

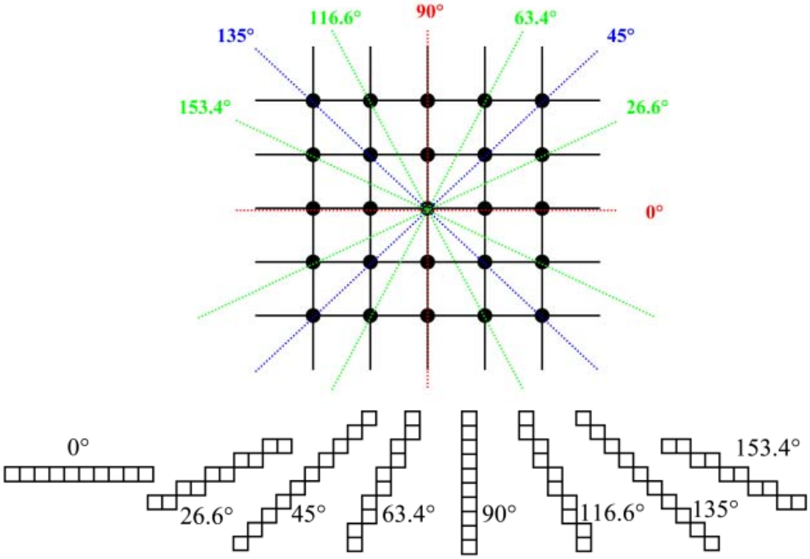

Fig. 1. The square grid samples of an image with eight selected orientations, and the example of practical eight-direction 1-dimensional filter

The example of the practical separable Gabor filter implementation with 0° orientation is shown in Fig.2. For this example, 8×8 block size is used (M=8) and 1-D Gabor filter length is 13 (N=13). To perform a separable filtering, the convolution process is divided into two phases. At the first phase, a 1-D Gabor band pass filter is convolved along the columns of a extended block, size (M+N-1)×(M+N-1), resulting in all gray pixels in Fig.2 (a). Note that the convolution result or gray pixels must be larger than 8×8 block size in order to obtain the correct results in the second phase. The second phase performs convolution with 1-D Gabor low pass filter along the rows of 8×8 block. The gray pixels in Fig.2 (b) are the final separable filtering result.

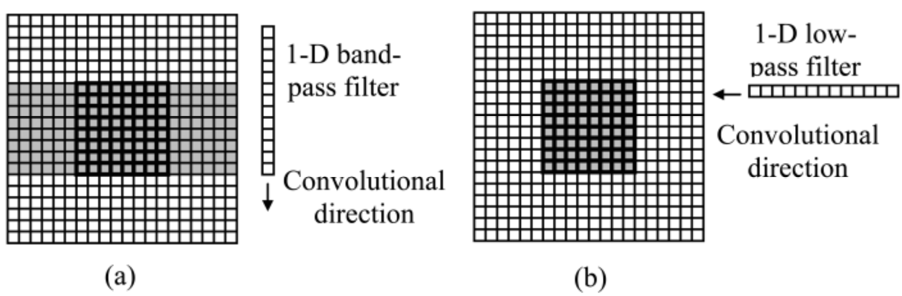

Fig. 2. Separable Gabor filter implementation performing on 0° direction with (a) column operation with band pass filter, and (b) row operation with low pass filter

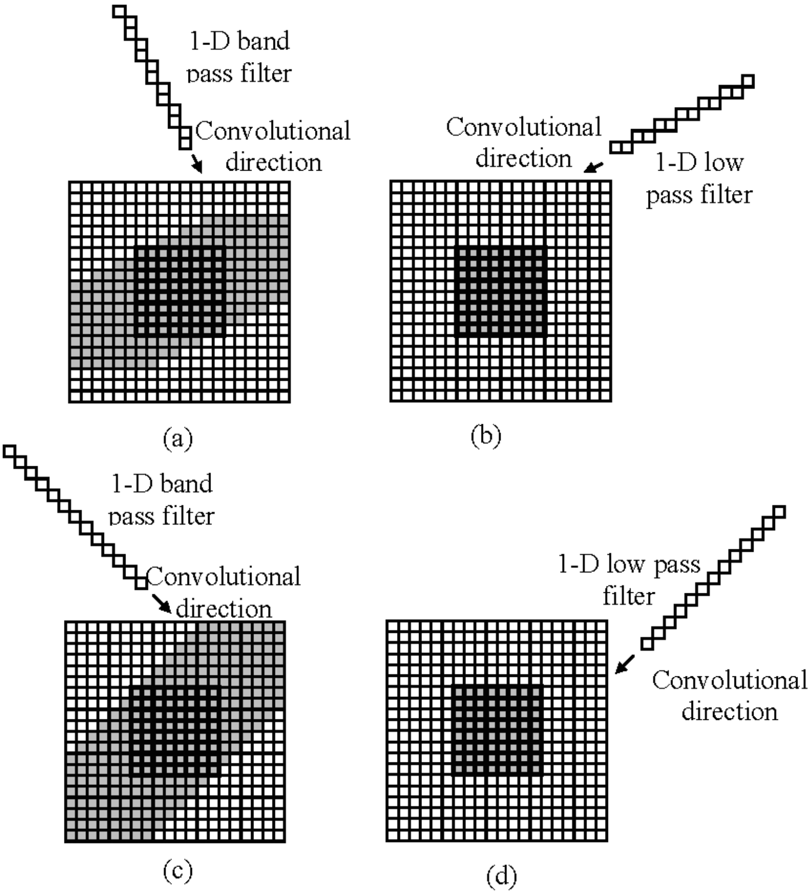

Fig. 3. Separable Gabor filter implementation performing on 26.6° and 45° direction with (a) & (c) column operation with band pass filter, and (b) & (d) row operation with low pass filter

The other examples of the practical separable Gabor filter implementation with 26.6° and 45° orientations are shown in Fig.3. Note that the gray pixels in Fig.3 represent the effective area that must be kept for the next 1-D convolution in perpendicular direction.

3 Experimental Results and Performance Comparison

The experimental results reported in this paper have been conducted on public fingerprint database, DB2A of FVC2000 [4]. The DB2A comprises 800 fingerprint images from 100 fingers, 8 impressions per each finger, with 500 dpi resolution. Three major experiments are conducted in order to compare performance between conventional 2-D Gabor filter and separable Gabor filter such as effect on computational complexity, effect on minutiae, and effect on matching results.

Table 1. The 1st Experiment: average execution time on a Pentium 4 (1.8A GHz) comparison

Average time (second) per a fingerprint image (364×256)	
2-D Conventional Gabor filter	Separable Gabor filter
0.574047 second	0.219285 second

The 1st experiment is the advantage of separable Gabor filter over conventional method. The experiments were tested on a Pentium 4 (1.8A GHz) personal computer with 256MB at 333MHz. Table 1 shows the corresponding execution times comparison between two methods. The 2-D conventional Gabor filter was implemented on the fly using a set of priori created and stored filters [1]. Moreover, symmetric of 2-D Gabor filter was also exploited in this process. Clearly, separable transform gave less computational complexity approximately 2.6 times. Both programs were not optimized to a commercial application level and these times are shown just to give an indication of the method's speed. Gabor parameters searching algorithm such as ridge frequency f_0 and ridge orientation θ are also included and both programs shared the same routines.

The 2nd experiment related to the minutiae extraction process. The dropped minutiae, spurious minutiae, and exchanged minutiae could be obtained from enhancement outputs of two schemes. The minutiae extraction employed in this experiment using basic thinning technique with crossing ridge number [5]. Assume that conventional 2-D Gabor enhancement gave the correct minutiae. The minutiae extraction from separable enhancement gave small different results with comparison shown in Table 2.

Finally, the impact of both enhancement to the verification performance was tested in the 3rd experiment. Fingerprint verification algorithm by Xudong Jiang and Wei-Yun Yau [6] was simulated and used in conjunction with both enhancement schemes. The equal error rate (EER) performance evaluation results [4] are shown in Table 3. The conventional Gabor filtering gains over the separable Gabor filtering about 0.593976% EER. Note that verification performance using separable Gabor filtering were only marginally inferior to conventional 2-D Gabor filtering.

In conclusion, the separable Gabor filter with 8 selected orientations for fingerprint enhancement was proposed. The advantage of the separable Gabor filter over the conventional Gabor filter is less computational complexity, approximately 38.2% of conventional enhancement execution time. The disadvantage is that separable Gabor filter creates more noise and error comparing with conventional Gabor filter. However, both schemes always create spurious minutiae, dropped minutiae, and exchanged minutiae resulting in slightly different in verification performance. In conclusion, the separable Gabor filter could be a good candidate for low computational complexity in low power digital signal processor applications in the near future.

Table 2. 2nd Experiment: extracted minutiae comparison, assuming that extracted minutiae from conventional 2-D Gabor is perfect, using 800 fingerprint images of DB2A, FVC2000

Dropped minutiae (%)	Spurious minutiae (%)	Exchanged minutiae (%)
22.942208	16.296314	6.272873

Table 3. 3rd Experiment: verification performance of two enhancement approaches

Threshold (%)	Separable Gabor Filtering Enhancement		Conventional 2-D Gabor Filtering Enhancement	
	FAR (%)	FRR (%)	FAR (%)	FRR (%)
9	47.517677	10.678572	50.807137	8.821428
10	36.579231	13.964287	39.296715	11.714286
11	26.840910	17.714287	29.068180	15.035714
12	18.821339	21.428572	20.490530	18.571428
13	12.608902	24.535713	13.806187	21.892857
14	8.144255	29.857143	8.879735	25.321430
15	4.989267	33.428570	5.429924	29.000000
16	2.898043	37.250000	3.143308	33.714287
	EER $\approx$ 20.124955 %		EER $\approx$ 19.530979 %	

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