using the derivative of the Gaussian function as the wavelet function. Based on their analysis, a simple and computationally efficient algorithm is proposed here.

'Corner' is a relative term. Corners are largely dependent on the shape of the object under consideration. If there are sharp corners at the boundary, smooth curvature changes will not be recognised as corners. On the other hand, if the shape consists only of smooth curvature changes then these curvature changes will be recognised as corner points. To provide such robustness, this algorithm starts with the normalisation of the wavelet transform modulus maxima. This normalisation is obtained at each level with the global maxima of that level; it also enables the algorithm to still be suitable when another wavelet is to be used for analysis. This normalisation is carried out in step 1 of the algorithm.

(i) *Step 1:* The orientation profile is decomposed using a wavelet transform at scales 2^1 , 2^2 , 2^3 and 2^4 . The wavelet transform modulus maximum (WTMM) is computed at each of these levels. These WTMMs at each level are normalised with respect to the maximum peak at that level.

(ii) *Step 2:* The events (valid corners) are observed at the highest scale (2^4). Peaks higher than some threshold τ_1 are recognised as valid events. These events are successively tracked at lower scales (2^3 , 2^2 , 2^1) to find their exact locations.

(iii) *Step 3:* Those events which are increasing at decreasing scales and are greater than some threshold τ_2 ($< \tau_1$) at scale 2^4 are also taken as valid events. These events are also successively tracked at lower scales (2^3 , 2^2 , 2^1) to find their exact locations.

(iv) *Step 4:* Find large (greater than some threshold τ_3) events in the vicinity of previously detected events in the preceding steps from the lowest scale (i.e. 2^1).

Results and discussion: The result of corner detection using the proposed scheme is shown in Figs. 1 and 2, where $\tau_1 = 0.4$, $\tau_2 = 0.1$ and $\tau_3 = 0.65$. These values of threshold are found after testing the algorithm with a large number of images. We used similar images to those of other groups such as Asada and Brady [8] (Fig. 1a), Lee *et al.* [4] (Fig. 1b) and Rattarangsi and Chin [9] (Fig. 2a). Here we observe that the performance of the proposed technique is better than, or at least the same as, that presented in the literature.

Fig. 3 Corner detection results under noise

- (a) $\sigma_N = 2.82$
(b) $\sigma_N = 3.59$
(c) $\sigma_N = 3.85$

As far as computational efficiency is concerned, the technique reported by Asada and Brady [8] is time consuming because it requires the computation of decompositions using both first and second derivatives of the Gaussian function. These derivatives are not orthogonal and no fast computing algorithm for discrete dyadic wavelet transforms exists. The technique presented in [4] is computationally complex because it requires taking the derivative of the ratio of wavelet transform modulus maxima and then splitting the orientation profile to detect corners. The proposed technique does not require these complex steps. Hence, the proposed technique is computationally efficient and simple to implement. We also performed corner detection tests under additive white Gaussian noise. Noise was added at the co-ordinates of the tracked boundary. We performed corner detection tests with different standard deviations (σ_N) of Gaussian noise. These results are shown in Fig. 3.

Conclusions: Here a wavelet based scheme is presented for the detection of corners in 2D planar curves. We observed that the proposed method gives competitive results with respect to the other available techniques. The proposed technique has the advantage that it is computationally inexpensive when compared with the other techniques. It also performs well under noise. Moreover, the proposed algorithm is robust with respect to object geometry and the type of wavelet used for the decomposition.

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Fingerprint feature extraction using Gabor filters

Chih-Jen Lee and Sheng-De Wang

A Gabor filter-based method for directly extracting fingerprint features from grey-level images without pre-processing is introduced. The proposed method is more efficient and suitable than conventional methods for a small-scale fingerprint recognition system. Experimental results show that the recognition rate of the k -nearest neighbour classifier using the proposed Gabor filter-based features is 97.2%.

Introduction: Most methods for fingerprint identification use minutiae as the fingerprint features. The main steps for minutiae extraction are smoothing, local ridge orientation estimation, ridge extraction, thinning, and minutia detection [1]. For a small-scale fingerprint recognition system, however, it would not be efficient

to process all the steps and the recognition result will be heavily dependent on the accuracy of each step. Gabor filter-based features have been successfully and widely applied to texture segmentation [2], face recognition [3], handwriting recognition [4] and fingerprint enhancement [5]. This is because the characteristics of the Gabor filter, especially the frequency and orientation representations, are similar to those of the human visual system [6]. In this Letter, we use Gabor filter-based features, directly extracted from grey-level fingerprint images, as the input vectors to a k -nearest neighbour (k -NN) classifier to test our fingerprint database, and study the performance of the proposed method.

Gabor filters and fingerprint feature extraction: The general form of a 2D Gabor filter is defined by

$$h(x, y, \theta_k, f, \sigma_x, \sigma_y) = \exp \left[-\frac{1}{2} \left(\frac{x_{\theta_k}^2}{\sigma_x^2} + \frac{y_{\theta_k}^2}{\sigma_y^2} \right) \right] \times \exp(i2\pi f x_{\theta_k}) \quad (1)$$

where $x_{\theta_k} = x \cos \theta_k + y \sin \theta_k$ and $y_{\theta_k} = -x \sin \theta_k + y \cos \theta_k$, f is the frequency of the sinusoidal plane wave, θ_k is the orientation of the Gabor filter, and σ_x and σ_y are the standard deviations of the Gaussian envelope along the x and y axes, respectively. To analyse the Gabor filter in terms of the even-symmetric and the odd-symmetric, we express eqn. 1 in the complex form $h = h_{\text{even}} + i h_{\text{odd}}$, where

$$h_{\text{even}}(x, y, \theta_k, f, \sigma_x, \sigma_y) = \exp \left[-\frac{1}{2} \left(\frac{x_{\theta_k}^2}{\sigma_x^2} + \frac{y_{\theta_k}^2}{\sigma_y^2} \right) \right] \times \cos(2\pi f x_{\theta_k}) \quad (2)$$

$$h_{\text{odd}}(x, y, \theta_k, f, \sigma_x, \sigma_y) = \exp \left[-\frac{1}{2} \left(\frac{x_{\theta_k}^2}{\sigma_x^2} + \frac{y_{\theta_k}^2}{\sigma_y^2} \right) \right] \times \sin(2\pi f x_{\theta_k}) \quad (3)$$

Since most local ridge structures of fingerprints come with a well-defined local frequency and orientation, we set f as the reciprocal of the average inter-ridge distance and m as the number of orientations for calculating $\theta_k = \pi(k-1)/m$, $k = 1, \dots, m$. Also, the cosine/sine form and the sinusoidal-shape of Gabor filters is suitable for modelling ridge/valley structures and smoothing out noise, respectively.

After deciding the parameters of the Gabor filters, the magnitude Gabor feature, the even one, and the odd one at sampling point (X, Y) can be defined as follows:

$$g_{\text{mag}}(X, Y, \theta_k, f, \sigma_x, \sigma_y) = \left| \sum_{x=-w/2}^{w/2-1} \sum_{y=-w/2}^{w/2-1} I(X+x, Y+y) h(x, y, \theta_k, f, \sigma_x, \sigma_y) \right| \quad (4)$$

$$g_{\text{even}}(X, Y, \theta_k, f, \sigma_x, \sigma_y) = \left| \sum_{x=-w/2}^{w/2-1} \sum_{y=-w/2}^{w/2-1} I(X+x, Y+y) h_{\text{even}}(x, y, \theta_k, f, \sigma_x, \sigma_y) \right| \quad (5)$$

$$g_{\text{odd}}(X, Y, \theta_k, f, \sigma_x, \sigma_y) = \left| \sum_{x=-w/2}^{w/2-1} \sum_{y=-w/2}^{w/2-1} I(X+x, Y+y) h_{\text{odd}}(x, y, \theta_k, f, \sigma_x, \sigma_y) \right| \quad (6)$$

where $I(\cdot, \cdot)$ denotes a $w \times w$ 256 grey-level image. We find that the magnitude Gabor features at the sample point and those of its neighbouring points within three pixels are similar, while the others are not. This is because the magnitude Gabor filter consists of both the cosine and sine form, so the magnitude Gabor feature has the shift-invariant property.

In the proposed method the procedure for obtaining the Gabor features of fingerprint images is as follows:

(i) find the core point of each fingerprint image

(ii) crop the fingerprint image into 96×120 pixels using its core point as the centre

(iii) divide the cropped image into a set of 8×8 non-overlapping blocks and sample the set by the Gabor filters; then $12 \times 15m$ Gabor features can be obtained for each image.

Fig. 1 Some examples of fingerprint database

Experimental results: In our database, we collected 192 inked fingerprint images from 16 persons (12 images per finger) and captured their digital format with a scanner at 200dpi and 256 grey-level resolution. Although the fingerprint databases of NIST and FBI are sampled at 500dpi, the fingerprint images can be recognised at 200dpi by the human eye. The recognition of low quality images is efficient and practicable for a small-scale fingerprint recognition system. Fig. 1 shows some of the fingerprint images in our database with different ink pressures and different positions and orientations.

Fig. 2 Magnitude Gabor features of two fingerprints belonging to same person with $m = 4$ ($\theta = 0, 45, 90$, and 135°)

Fig. 3 Magnitude Gabor features of two fingerprints belonging to different persons

First, we point out their core points manually to avoid errors caused by the core point detection algorithm. We then set $f = 1/2\sqrt{2}$, the reciprocal of the average inter-ridge distance, which is approximately equal to $2\sqrt{2}$ pixels, and $\sigma_x = \sigma_y = 2.0$ is determined empirically. Fig. 2 shows the magnitude Gabor features of two fingerprints belonging to the same person with $m = 4$ ($\theta = 0, 45, 90$, and 135°). Fig. 3 shows the magnitude Gabor features of two fingerprints belonging to different persons. From Figs. 2 and 3, we

find that the same persons magnitude Gabor features are similar and those of different persons are not. This reveals that the magnitude Gabor features can be used as the fingerprint features. In the following, we use these features as the input vectors to the classifiers and compare their accuracy.

Table 1: Results of recognition rate

Classifier	1-NN		2-NN		3-NN	
	4	8	4	8	4	8
<i>m</i>	%	%	%	%	%	%
Magnitude	88.6	90.9	93.8	94.4	96.5	97.2
Even	52.8	55.1	54.4	55.6	56.3	54.9
Odd	47.7	51.7	48.1	52.5	47.2	51.4

In *k*-NN experiments, we selected *k* images per individual as the training database (16*k* images) and the remaining $16 \times (12-k)$ images as the test database. The results of recognition rates with no rejection option for *m* = 4 and *m* = 8 are shown in Table 1. From Table 1, we find that the accuracy for *m* = 8 is only slightly better than that for *m* = 4. This means that magnitude Gabor features with four orientations are sufficient and would lead to an efficient small-scale fingerprint recognition system. Besides, only the magnitude Gabor features can be successfully applied to fingerprint recognition. Either using the even Gabor features or the odd features alone would make the recognition rate too low for successful fingerprint recognition.

Conclusion: We have developed a one-step method using Gabor filters for directly extracting fingerprint features from grey-level images for a small-scale fingerprint recognition system. From experimental results, we can see that the use of magnitude Gabor features with eight orientations as fingerprint features lead to good shift-invariant properties and an accuracy of 97.2% with 3-NN classifiers. The result shows that the use of magnitude Gabor features for fingerprint recognition is a promising approach.

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Using scene-change detection and multiple-thread background memory for efficient video coding

K. Zhang and J. Kittler

The use of background memory to improve coding efficiency has gained momentum recently due to the rapid decrease in the cost of memory chips. However, the associated computational costs still pose a problem for real time implementation. The authors propose a coding oriented scene-change detection algorithm and the use of multiple thread background memory to improve the coding efficiency of both scene-change frames and frames between two consecutive scene cuts. The experimental results show that the proposed scheme can improve the coding efficiency in both situations. The improvement is significant for scene-change frames.

Introduction: In many video applications, a scene or part of the scene may appear repeatedly such as in television news broadcasting and in multiple-point video conferencing. Such a change in the video scene will cause the scene cut frame to be encoded in the INTRA frame mode or create a large number of INTRA coded macroblocks. It is known that the INTRA mode will normally require a much higher bit consumption, manifesting itself in a burst of increased bit rate. In a fixed band low bit rate channel, such a burst of bits created by the scene cut frame will somehow have to be absorbed. There are three ways to deal with such frames: to increase the quantisation step dramatically so that the number of bits used to encode the frame can be reduced; drop out the following frames until the buffer content is below a given threshold; increase the buffer length so that the increase in number of bits can be absorbed gradually. The first option will result in a sharp drop in image quality and create unpleasant visual effects. The second option will result in a frozen picture for some time which is also unpleasant. The third option will lead to a long delay and, if the scene changes frequently, the scheme may not be able to absorb the increased number of bits in the following INTER frames. In practice, a combination of the first and second options is widely used to deal with scene-change frames. Recent developments employing more memory to achieve better coding efficiency provide another solution. The long term memory scheme [1] can significantly improve the coding efficiency of scene-change frames if the memory length is sufficient to cover the scene-change cycle. In practice, this approach may require thousands of frames of memory to achieve this objective. In news broadcasting, for instance, a scene cut is typically between a few seconds and a few minutes. The coverage of 1min of material will require 1800 frames to be stored. Therefore, it becomes impractical simply to increase the capacity of the long term memory to solve the problem. Here, we extend our previous work [2] and propose a new scheme targeted to this particular problem which uses scene-change detection and multiple thread background memory to improve the coding efficiency of scene-change frames.

Scene-change detection: The key part of the proposed scheme is a scene-change detector. Scene-change detection is not a difficult problem. Here, we propose a coding oriented scene-change detector which is capable of detecting a partial scene-change in the picture. The algorithm used in our approach is based on the observation that a scene-change (either part of the frame or the whole frame) will cause the number of macroblocks being coded in INTRA mode to substantially increase. However, any new region or object appearing in the scene will also cause the number of INTRA coded macroblocks to rise. Therefore, it is difficult to specify a fixed threshold to indicate that a scene-change has occurred. Through experimentation, we have observed that the number of INTRA coded macroblocks caused by moving objects is relatively stable for frames between two consecutive scene cuts. This is in contrast to the scene cut frame where the number of INTRA coded blocks increases suddenly and then falls back to a lower level in the following frames. The target for a scene-change detection algorithm is to detect a sudden significant increase in the number of INTRA coded macroblocks while tracking the general trend of INTRA coded macroblock numbers for frames between two consecutive scene cuts. This is achieved by tracking the moving exponential average count of INTRA coded macroblocks.