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Low-Quality Fingerprint Image Enhancement on the Basis of Oriented Diffusion and Ridge Compensation

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***Abstract*—Fingerprint image enhancement is a key step in the Automated Fingerprint Identification System (AFIS). Because of different factors that affect the image, such as skin condition (very dry or moist, damaged or worn down skin, etc.), sensor noise, irregular print on the sensor, etc., the fingerprint image needs to be enhanced so that the structures of ridges and valleys are clearly visible. This paper presents fingerprint image enhancement with oriented linear anisotropic diffusion in the first stage and oriented local ridge compensation in the second stage. To control the process of oriented diffusion we have determined an orientation field from the previously established ridge orientation, which was additionally enhanced. Because the overall image contrast is decreased after the diffusion process, we have enhanced the contrast with block local normalization. In the second stage we have additionally enhanced ridge structure with oriented local ridge compensation. We have compared and combined our proposed algorithm with some of the state-of-the-art algorithms. The results of experiments, done on a public database FVC2004, show efficient fingerprint image enhancement.**

***Index Terms*—Image processing, image enhancement, fingerprint recognition, diffusion processes.**

I. INTRODUCTION

Fingerprint is a biometric physiological characteristic used for verification and identification of persons. Of all the biometric characteristics (iris, face, voice, hand), fingerprint has the highest degree of reliability [1]. The efficiency of fingerprint matching, and consequently of the automated fingerprint identification system, is highly dependent on the quality of the fingerprint image (Fig. 1). Because of different factors affecting the image (e.g. scratches, dust on the sensor, sweat, damaged skin, moisture or dryness of the skin, etc.) a fingerprint image can be marked as a low-quality image. All the above mentioned factors can cause incorrectly extracted features or minutiae. A fingerprint image must therefore be enhanced so that the structures of ridges and valleys constituting the fingerprint surface are clearly visible.

Many techniques have already been presented in the area of fingerprint image enhancement, both in spatial and in frequency domains [1]–[19]. This paper presents contextual filtering in the spatial domain with oriented anisotropic linear diffusion [5] and optimization of the local ridge compensation filter, which was presented in [4].

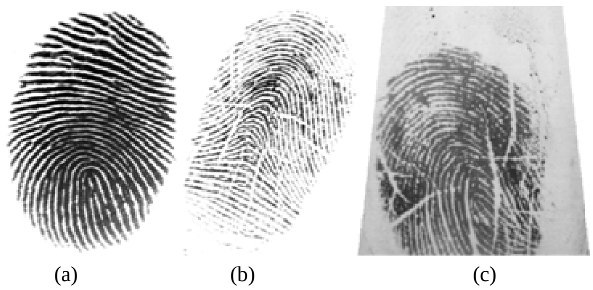

Fig. 1. Good-quality fingerprint a); Medium-quality fingerprint, damaged by scratches and noise b); Low-quality fingerprint with a lot of scratches and noise c).

Contextual filtering was presented by O'Gorman and Nickerson [20], and is the most often used technique for fingerprint image enhancement. With contextual filtering, filter characteristics change according to the local fingerprint image context. Filter parameters are usually precalculated and then selected for a particular image area. In a fingerprint image the context is most often defined with local ridge frequency and ridge orientation.

Diffusion can be defined as a physical process which equalizes concentration differences without creating or reducing mass. In the case of image processing, concentration of matter in a particular point is replaced by the brightness value of an image element, and the filtering process equalizes the differences in brightness of different image parts.

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To control oriented diffusion, we have first determined ridge orientation on the basis of gradient, which we have enhanced by multiplying the ridge orientation value by an empirically determined value. The diffusion process enhances a fingerprint image with smoothing along the local ridge; however, in doing so, it reduces the overall image contrast. We have therefore enhanced the contrast with block local normalization.

To control oriented local ridge compensation in the second stage, we have previously determined ridge orientation in the image enhanced in the first stage.

To compare the efficiency of image enhancement, we have compared and combined our two-stage algorithm with some of the state-of-the-art algorithms (Gabor filter [2], Short Time Fourier Transform – STFT [9], and Yang two-stage enhancement algorithm on the basis of learning from image [3]).

Gabor filter was presented by Hong [2] and is the most popular contextual filter. Filtering of a normalized image is based on predetermined internal image contexts, such as ridge orientation and frequency.

Chikkerur [6] proposed STFT for enhancing a fingerprint image. This procedure determines ridge orientation and ridge frequency for each block individually, and then uses this information for image filtering in the Fourier domain. Because of the complex content of a low-quality fingerprint image, not all areas are enhanced. Certain filter parameters are also difficult to precisely determine with STFT analysis. However, STFT enhances curved areas better than a traditional Gabor filter.

Yang [3] presented a two-stage algorithm for low-quality fingerprint image enhancement with learning from image. The image is first enhanced in the first stage (in the spatial domain), and then also in the second stage (in the frequency domain) with learning from the original image and from the image enhanced in the first stage.

The paper includes the following sections: Section II presents first stage enhancement, which includes determining ridge orientation, diffusion process and contrast enhancement with block local normalization. Section III describes fingerprint image enhancement in the second stage, which includes determining ridge orientation in the image enhanced in the first stage, and the process of oriented local ridge compensation. Section IV shows experimental results and Section V sums up the conclusions.

II. FIRST STAGE ENHANCEMENT

Fingerprint image enhancement in the first stage consists of the following steps: 1) determining the orientation field; 2) oriented linear anisotropic diffusion filtering; 3) image contrast enhancement with block local normalization.

A. Determining the Orientation Field

Determining ridge orientation (1) is based on a gradient procedure with Gaussian mask of size 7×7. To determine the orientation field and to precisely control the oriented diffusion filter, we have additionally enhanced ridge orientation by multiplying the ridge orientation value by factor M = 55, which was determined empirically (Fig. 2).

The procedure for determining the orientation field is the following:

1. Dividing the original fingerprint image $I(i, j)$ into blocks of size $w \times w$.
2. Determining the horizontal gradient $G_x(u,v)$ and the vertical gradient $G_y(u,v)$ for an individual pixel in a block with the use of Gaussian gradient operator.
3. Determining ridge orientation with the following

$$-_{ij} = \frac{1}{2}\tan^{-1}\left(\frac{\sum_{u=i-(w/2)}^{i+(w/2)}\sum_{v=j-(w/2)}^{j+(w/2)} 2G_x(u,v)G_y(u,v)}{\sum_{u=i-(w/2)}^{i+(w/2)}\sum_{v=j-(w/2)}^{j+(w/2)} (G_x^2(u,v)-G_y^2(u,v)}\right). \quad (1)$$

4. Determining orientation field OF by multiplying the ridgeorientation value $-_{ij}$ by an empirically determined factor $M = 55$

$$OF(i, j) = -_{ij} \times M. \quad (2)$$

B. Oriented Linear Anisotropic Diffusion Filtering

The process of oriented linear anisotropic diffusion [5] (6) is controlled with a diffusion tensor D, which depends on a structure tensor $^{2}\circ$ and on the previously determined oriented field OF.

The structure tensor $^{2}\circ$ is determined on the basis of gradients G_x and G_y, which were previously determined with the use of Gaussian gradient operator for an individual pixel

$$^{2}\circ = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \begin{bmatrix} G_x * G_x & G_x * G_y \\ G_x * G_y & G_y * G_y \end{bmatrix}. \quad (3)$$

Diffusion tensor D is defined with the following:

$$\text{A}=\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} \text{ª}_1 + \text{ª}_2 + \left[\left(\text{ª}_2 - \text{ª}_1\right)\times\left(s11 - s22\right)\right]/a \\ \left(\text{ª}_2 - \text{ª}_1\right)\times s12/a \end{bmatrix}, \quad (4)$$

$$\text{B}=\begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \begin{bmatrix} \left(\text{ª}_2 - \text{ª}_1\right)\times s12/a \\ \text{ª}_1 + \text{ª}_2 + \left[\left(\text{ª}_2 - \text{ª}_1\right)\times\left(s11 - s22\right)/a\right] \end{bmatrix}, \quad (5)$$

$$D(S) = \begin{bmatrix} m_1 & n_1 \\ m_2 & n_2 \end{bmatrix}, \quad (6)$$

where ª_1 and ª_2 represent proper values, chosen with the following procedure:

$$\text{ª}_1 = a, \quad (7)$$

$$\text{ª}_2 = \begin{cases} a, & \text{if orientation is not determined in I(x,y)}, \\ 1, & \text{if orientation is determined in I(x,y)}, \end{cases} \quad (8)$$

$$\begin{cases} \dfrac{\partial u}{\partial t} = div(D(^{2}\circ(\nabla u_{\pm}), OF)\nabla u), & \text{on } \Omega\times\left(0,\infty\right), \\ u\left(x,\ 0\right) = f(x), & \text{on } \Omega, \\ \left\langle D(^{2}\circ(\nabla u_{\pm}),\ \text{OF})\nabla u,\ \text{n}\right\rangle = 0, & \text{on } \partial\Omega\times\left(0,\infty\right). \end{cases} \quad (9)$$

(a) (b) (c) (d) (e)

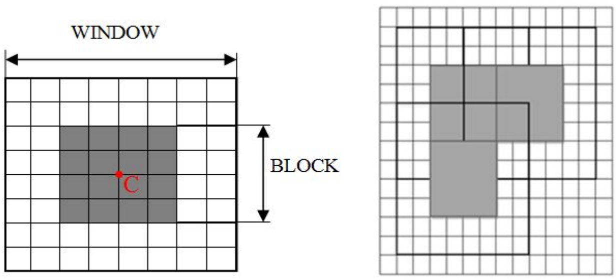
Fig. 2. Original image (FVC_2004 DB1_a 1.6.tif) (a); Image enhanced with the diffusion process (~ = 0.01 , stepsize = 0.25 , nonsteps = 40) with field orientation for M=0 (b); M=65 (c); M=55 (d); M=45 (e);

Figure 2 shows a fingerprint image enhanced with oriented anisotropic diffusion filter with field orientation for different factor values M. We can observe that the M factor has a very high influence on the control of oriented diffusion filtering, and consequently on the fingerprint image enhancement. As we can see in Fig. 2(a) and Fig. 2(c), the diffusion process can correctly connect disconnected ridges.

C. Fingerprint Image Contrast Enhancement

Efficient fingerprint image contrast enhancement is achieved with a block local normalization algorithm, which is more efficient than global [2] or local normalization [3].

Similarly as with local normalization, which is determined for each pixel individually, block local normalization is calculated for each block of a fingerprint image. We have previously divided a greyscale image into non-overlapping blocks BLOCK of size $w = 4$, which have common the centre points C with windows WINDOW of size $w = 8$, (Fig. 3), where the windows partially overlap. Normalization is determined for an entire block according to the default mean value ($M_0 = 128$) and variance ($V_0 = 128 \times 128$) of the window WINDOW.



(a) (b)

Fig. 3. Presentation of block BLOCK of the size 4×4, where we have calculated the local normalization of window WINDOW (a); Presentation of an analysis of the movement of blocks and corresponding windows (b).

III. Second Stage Enhancement

In the second stage we have enhanced the fingerprint image with oriented local ridge compensation filter, which is controlled with ridge orientation determined from the image enhanced in the first stage. Determining ridge orientation is the same as in subsection II.A in steps 1 to 3.

A. Oriented Local Ridge Compensation

With optimisation of the local ridge compensation filter [8], where we have decreased the processed window width, we have achieved faster and more efficient fingerprint image enhancement.

For each pixel in a normalized image *norIm* (i, j) we have determined the weighted sum of neighbouring pixels according to the following:

$$\mathrm{enhIm}(i, j) = \sum_{m=-(w-1)/2}^{(w-1/2)} \sum_{n=-(h-1)/2}^{(h-1)/2} mask \times$$

$$\times \mathrm{norIm}(i', j), \tag{10}$$

$$i' = i + m\cos\big(oimg\,(i, j)\big) + n\sin\big(oimg\,(i, j)\big), \tag{11}$$

$$j' = j - m\sin\big(oimg\,(i, j)\big) + n\cos\big(oimg\,(i, j)\big), \tag{12}$$

where *i'* and *j'* mark the new coordinates of the normalized image, translated with affine transformation [21] according to the following:

$$\begin{pmatrix} i' \\ j' \end{pmatrix} = \begin{pmatrix} \cos\big(oimg\,(i, j)\big)\sin\big(oimg\,(i, j)\big) \\ -\sin\big(oimg\,(i, j)\big)\cos\big(oimg\,(i, j)\big) \end{pmatrix} \times \begin{pmatrix} m \\ n \end{pmatrix} + \begin{pmatrix} i \\ j \end{pmatrix}, \tag{13}$$

where $oimg\,(i, j)$ determines pixel (i, j) orientation in a normalized image. Value (i', j') was calculated with bilinear interpolation as a function of four coefficients of the original window close to (i, j).

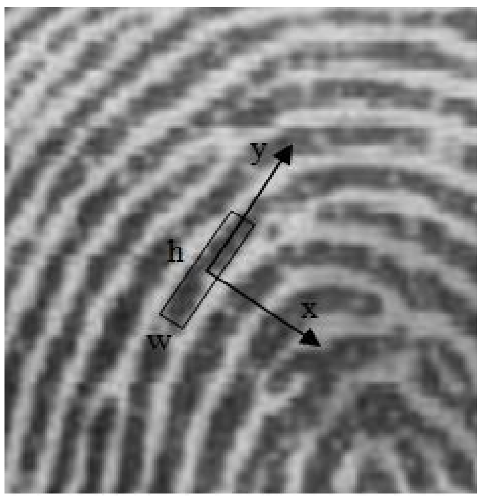
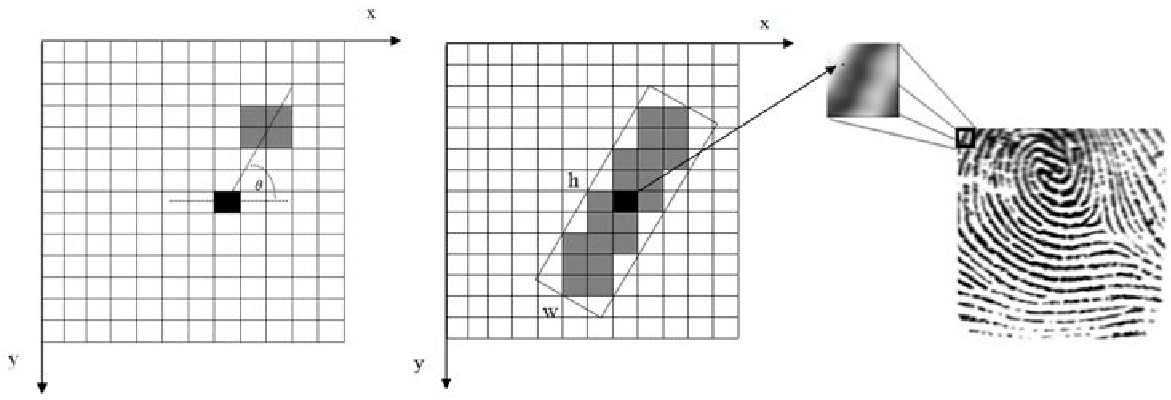


Fig. 4. Oriented ridge compensation.



(a) (b)

Fig. 5. The beginning of directional interpolation with the sampling of point 4 neighbouring pixels in the direction of the pixel or the ridge (a); Pixel (black square) is the sum of the values of points of the entire interpolation (b).

(a) (b) (c) (d) (e)

Fig. 6. Original image (FVC_2004 DB1_a 1.6.tif) (a); image enhanced with Yang algorithm (b); image enhanced with Gabor filter (c); image enhanced with STFT (d); presented algorithm (e).

Figure 5(a) shows the beginning of interpolation in the direction of the temporary pixel with sampling of an individual pixel according to the width and length of the window and its four neighbours. Figure 5(b) shows a window with length h and width w, in which an entire interpolation for the temporary pixel (black square) is performed in the direction of the ridge or the temporary pixel. The window width is $w = 1$ pixel, and the window height is $h = 9$ pixels.

Figure 6 shows a fingerprint image enhanced with Yang two-stage algorithm [3], Gabor filter [2], STFT [9] and our algorithm.

IV. Experimental Results

Experiments were performed on a public database FVC2004 consisting of four sub-bases: DB1_A, DB2_A, DB3_A and DB4_A. Each sub-base includes 800 fingerprints, out of which 8 are of the same person.

To assess the efficiency of an algorithm and thus of the automated fingerprint identification system, Equal Error Rate (EER) needs to be established. EER marks the point in which FNMR and FMR are equal [1].

$$\mathrm{EER} = \frac{\mathrm{FMR} + \mathrm{FNMR}}{2}, \text{ if } FMR = FNMR, \quad (14)$$

FMR (Fals Match Rate) and FNMR (False Non Match Rate) are determined with the following:

$$FMR = \frac{\text{Number of acepted imposter atempts}}{\text{Total number of imposter accesses}} \times 100\%, \quad (15)$$

$$FNMR = \frac{\text{Number of rejected genuine attempts}}{\text{Total number of genuine accesses}} \times 100\%. \quad (16)$$

– Genuine recognition attempts: the template of each fingerprint image is compared with other images of the same fingerprint. Symmetric matching is excluded (if, for example, the template of image *j* matches image *k*, image *k* is not compared to image *j* again).

– Impostor recognition attempts: the template of the first fingerprint image is compared with first images of other fingerprints, and symmetric matching is also excluded here.

To evaluate the equal error rate EER (%), we have used a matching algorithm, presented by Medina-Pérez et.al [22]. The original code was downloaded from the following website: (http://www.codeproject.com/Articles/97590/A-Framework-in-C-for-Fingerprint-Verification).

Table I shows a comparison of enhancement algorithms and a combination of our two-stage algorithm in both stages (in the Table marked as ODRC - oriented diffusion ridge compensation) and in individual stages (in the Table marked as oriented diffusion for first stage and ridge compensation for second stage), with some other enhancement algorithms (Gabor [2], STFT [9], Yang [3]).

TABLE I. A COMPARISON AND COMBINATION OF OUR TWO-STAGE ALGORITHM (BOTH STAGES ARE MARKED AS ODRC – ORIENTED DUFFUSION + RIDGE COMPENSATION, FIRST STAGE ENHANCEMENT IS MARKED AS ORIENTED DIFFUSION AND SECOND STAGE ENHANCEMENT AS RIDGE COMPENSATION) WITH GABOR FILTER, STFT AND YANG TWO-STAGE ALGORITHM.

FVC_2004	**Compared algoritms**	**EER (%)**	**Time processing**
DB1_A	Original image	16.06 %	
	STFT	13.67 %	0.38 s
	Gabor filter	11.35 %	0.60 s
	Ridge compensation	9.31 %	12.76 s
	Oriented diffusion	9.02 %	4.15 s
	ODRC	8.21 %	15.49 s
	ODRC + Gabor	7.74 %	16.55 s
	Ridge compensation + Gabor	7.41 %	11.27 s
	ODRC + STFT	7.15 %	14.88 s
	Ridge compensation + Yang_second enhance	7.24 %	12.88 s
	Yang	7.23 %	46.32 s
	Oriented diffusion + Yang_second enhance	7.22 %	38.09 s
	ODRC + Yang_second enhance	6.89%	16.63 s
	Oriented diffusion + STFT_	6.80 %	4.22 s
	Ridge compensation + STFT	6.52 %	15,44 s
DB2_A	Original image	15.73 %	
	Oriented diffusion +Gabor	13.56 %	1.48 s
	Oriented diffusion + Yang_second enhance	12.42 %	17.34 s
	ODRC + Gabor	12.17 %	6.27 s
	STFT	11.61 %	0.44 s
	Ridge compensation	11.43 %	5.66 s
	Oriented diffusion	10.53 %	1.91 s
	Ridge compensation + STFT	10.42 %	1,65 s
	ODRC	9.85 %	6.27 s
	Ridge compensation + Yang_ second enhance	9.80 %	4.98 s
	ODRC + STFT	9.71 %	5.96 s
	Gabor	9.61 %	0.34 s
	Ridge compensation + Gabor	9.32 %	4.94 s
	Oriented diffusion +STFT	9.05 %	1.92 s
	ODRC + Yang _ second enhance	7.69 %	8.19 s
	Yang	7.33 %	17.86 s
DB3_A	Ridge compensation	12.27 %	6.60 s
	Gabor	9.70 %	0.41 s
	ODRC	9.68 %	7.34 s
	Oriented diffusion	9.56 %	1.49 s
	Ridge compensation + Yang_ second enhance	9.46 %	6.61 s
	Ridge compensation + STFT	9.17 %	7,01s
	STFT	8.10 %	0.25 s
	Yang	8.76 %	34.25 s
	Original image	8.67 %	
	Oriented diffusion + Gabor	8.56 %	1.83 s
	Oriented diffusion + STFT	8.55 %	2.36 s
	ODRC + Gabor	8.47 %	8.66 s
	ODRC + STFT	8.35 %	7.61 s
	Oriented diffusion + Yang_second enhance	8.19 %	20.50 s
	Ridge compensation + Gabor	7.71 %	7,00 s
	ODRC + Yang_ second enhance	7.20 %	8.19 s
DB4_A	Original image	16.08 %	
	Gabor	12.98 %	0.29 s
	Oriented diffusion	10.55 %	1.03 s
	ODRC	10.35 %	5.85 s
	Yang	10.09 %	25.96 s
	STFT	9.91 %	0.30 s
	Ridge compensation	9.78 %	5.25 s
	Ridge compensation + STFT	9.45 %	5,23 s
	ODRC + Gabor	9.32 %	6.86 s
	Ridge compensation + Yang_ second enhance	8.92 %	4.96 s
	Oriented diffusion + STFT	8.47 %	1.78 s
	ODRC + STFT	8.44 %	5.22 s
	ODRC + Yang_ second enhance	7.98 %	6.35 s
	Ridge compensation + Gabor	7.79 %	6.16 s
	Oriented diffusion + Yang_second enhance	7.69 %	16.20 s

Table I shows that our algorithm in both stages and in individual stages provides the lowest EER (in almost all sub-bases of FVC_2004) in combination with some other enhancement algorithms (Gabor, STFT, Yang). A lower EER means a better automated fingerprint identification system.

For example, in sub-base DB1_A, we have managed to achieve better image enhancement with a combination of our and Yang algorithm in comparison to the original Yang algorithm, and the processing was even faster by 33.3 %.

V. CONCLUSIONS

This paper presents efficient two-stage fingerprint image enhancement. The image is first enhanced with oriented diffusion in the first stage and then with oriented local ridge compensation in the second stage. In determining the orientation field, we had to additionally enhance the ridge orientation value by multiplying it by factor 55 to achieve efficient ridge smoothing with oriented diffusion. After the diffusion process, we had to enhance the contrast of the fingerprint image. This was done with block local normalization with block size 4×4, which provides better results than 2×2 or 8×8 block sizes. Table I shows that a combination of our algorithm in both stages and in individual stages with some other algorithms (Gabor, STFT, Yang) can additionally lower the equal error rate EER, and even speeds up processing when a combination with Yang algorithm is used.

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