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DETERMINATION OF THE DIRECTIONAL FIELD OF FINGERPRINTS PAPILLARY LINES IN AUTOMATED BIOMETRIC IDENTIFICATION SYSTEMS

Abstract. This paper presents a new method, based on the gradient characteristics analysis, to estimate the directional field of fingerprints. The method computes the smoothed orientation image of papillary lines. Its main component consists in the analysis of the local histogram of the directions taking into account the gradient module in a square neighborhood which size is commensurable with the average inter-ridges distance on the fingerprint image. Experimental verification of this method for fingerprints of different quality showed that it yields better results in comparison with the known methods based on the analysis of gray-scale levels along the selected directions.
Keywords: biometric identification, fingerprints, papillary lines, ridges, gradient field, directional field.

WYZNACZANIE POLA KIERUNKÓW LINII PAPILARNYCH ODCISKÓW PALCÓW W AUTOMATYCZNYCH SYSTEMACH IDENTYFIKACJI BIOMETRYCZNEJ

Streszczenie. W pracy przedstawiono nową metodę opartą na analizie cech gradientu, aby wyznaczyć pole kierunków odcisków palców. Metoda ta oblicza wygładzony obraz orientacji linii papilarnych. Jej głównym elementem jest analiza lokalnego histogramu kierunków, biorąc pod uwagę moduł gradientu w kwadratowym obszarze, którego rozmiar jest współmierny ze średnią odległością między grzbietami na obrazie odcisku palca. Weryfikacja doświadczalna tej metody dla odcisków palców różnej jakości wy-

kazała, że uzyskuje się lepsze wyniki w porównaniu ze znanymi metodami opartymi na analizie poziomów szarości wzdłuż wybranych kierunków.
Słowa kluczowe: identyfikacja biometryczna, odciski palców, linie papilarne, grzbiety, pole gradientu, pole kierunków.

Introduction

The systems based on the unique person characteristics unchanged during human life (fingerprints, retina, iris, etc.) hold a central position in systems of personal identification. Biometric data cannot easily be changed, forged, duplicated unlike the traditional systems that are based on knowledge (password, PIN) or possession (keys). Hence, biometric data provide a higher level of safety, security, convenience and productivity.

In the last few years, the method of identification of an individual based on biometric characteristics contained in fingerprints has found new spheres of application. The means of fingerprints identification are successfully used not only by criminalistics experts but also for the organization of a reliable control of access to material values, information, forbidden zones and rooms, secret facilities, protection of computers and computer networks, bank transactions, verification of persons in the social welfare bodies, monitoring of prisoners, etc.

The complex solution of a wide spectrum of problems arising when developing fingerprint processing techniques demands special methodological, algorithmic and software means. It is necessary within these means to take optimally into account the specific character and features of space-topological structure and geometry of the papillary lines of fingerprints [1, 3, 7, 8].

The method of formation of the directional field of papillary lines proposed in the present article is based on the analysis of gradient characteristics of input fingerprints. Experimental verification of this method for different quality of fingerprints showed that it yields better results in comparison with the known methods based on the analysis of grayscale levels along the selected directions.

Preliminary stage of fingerprint direction field estimation

Let us consider the input fingerprint image $F = \{f(m,n)\}_{(m,n) \in M \times N}$, where $f(m,n) \in \{0, 1, \dots, 2^b - 1\}$, $m = \{0, 1, \dots, M-1\}, n = \{0, 1, \dots, N-1\}$; b is the bitmap depth; M and N are the dimension parameters of image. The index m increases from the top to the bottom (an image line), the index n increases from the left to the right (an image column).

The most simple and natural method of determining a local orientation of fingerprint papillary lines is based on calculation of the gradient at image points. If we have a continuous scalar function, the gradient vector specifies the direction in which the derivative of this function is maximal, and it is equal to the gradient module. Processing the digital fingerprint images, we have a discrete function $f(m,n)$, i.e. the changing value is brightness at the image points. The angle determining the orientation of a papillary line is orthogonal to the direction of the gradient. Therefore, having calculated the gradient at each specific point of the image, it is possible to calculate also the local directions of papillary lines. Approximation of partial derivatives by the corresponding differential ratios is used for calculation of the gradient [2].

Let us consider some point (m,n) in the fingerprint image. The local orientation at this point is the angle $d(m,n)$ which a papillary line extending in the neighborhood of the point forms with a horizontal axis. The matrix $D = \{d(m,n)\}_{(m,n)\in M\times N}$, where $d(m,n)\in [0,\pi)$, will be understood as a directional field. It is assumed that the angles are counted from the abscissa axis in the counterclockwise direction.

The problem of constructing the pointwise direction field can be formulated as a problem of converting the input fingerprint image $F = \{f(m,n)\}_{(m,n)\in M\times N}$ into the two-dimensional discrete function $D = \{d(m,n)\}_{(m,n)\in M\times N}$ possessing the values from the set of possible directions [0, π).

The pointwise fields $\Phi = \{\varphi(m,n)\}_{(m,n)\in M\times N}$ and $G = \{g(m,n)\}_{(m,n)\in M\times N}$ constitute the basis of the proposed method of creating a fingerprint direction field, where $\varphi(m,n)$ and $g(m,n)$ represent the gradient direction and the gradient module at the image point (m,n), respectively:

$$\varphi(m,n) = \mathrm{arctg}\left({}^{\Delta_n}/_{\Delta_m}\right), g(m,n) = \sqrt[2]{(\Delta_m^2 + \Delta_n^2)};$$

$$\Delta_m = f(m,n+1) - f(m,n-1), \Delta_n = f(m+1,n) - f(m-1,n).$$

The classical Previtt and Sobel operators [2, 6] can also be used for local noise reduction when determining partial derivatives of grayscale function $f(m,n)$.

Since the direction of a papillary line is orthogonal to the gradient direction, then

$$d(m,n) = (\varphi(m,n) + \tfrac{\pi}{2}) + \pi S\left(\varphi(m,n) + \tfrac{\pi}{2}\right),$$

where $S(x)$ is the sign function of the form

$$S(x) = \begin{cases} 0, \text{if } x \geq 0, \\ 1, \text{if } x < 0. \end{cases}$$

Further, on the basis of the pointwise directional field $D = \{d(m,n)\}_{(m,n) \in M \times N}$, the converted directional field $D_\nu = \{d_\nu(m,n)\}_{(m,n) \in M \times N}$ is formed in order to reduce the information redundancy and speed up the fingerprint processing. For representation of directions $d_\nu(m,n) \in \{0, 1, \ldots \nu - 1\}$ we use ν identical intervals at a range of angles [0; π), the value π/ν is the selected sampling step.

Thus, $d_\nu(m,n) = \left\lfloor d(m,n)\nu/_\pi \right\rfloor$; the integer part of a real number x is designated by $\lfloor x \rfloor$. If the direction $d(m,n)$ at a point (m,n) is undefined $(g(m,n) = 0)$ or the gradient module is less than some selected threshold $(g(m,n) < T_g)$, then in this case the direction $d_\nu(m,n)$ is equal to ν.

Fingerprint direction field estimation

An approach, in which a fingerprint image is divided into segments of the set size and the direction of papillary lines is calculated blockwise, is used in most of fingerprint processing methods. A choice of the segment size is guided by considerations of high-speed performance, a volume of the received information, as well as by accuracy of the image description.

The first stage of creation of a segmented directional field consists in allocation of informative part of fingerprints. The known approaches to implementation of this step are based on the fact that in informative part of a fingerprint there is an oriented pattern while the image background has isotropic character [1, 3, 8, 10].

Thus, a key element of procedure of forming a directional field of papillary lines is segmentation of fingerprint image $F = \{f(m,n)\}_{(m,n) \in M \times N}$ into $M_s \times N_s$ non-overlapping square blocks with the side length of $l > 1$ points, where $M_s = \lceil M/l \rceil, N_s = \lceil N/l \rceil$; the least integer no less than a real number x is designated by $\lceil x \rceil$.

The pointwise directional field $D_\nu = \{d_\nu(m,n)\}_{(m,n) \in M \times N}$ formed at a preliminary stage is the basis for the formation a segmented directional field $D_s = \{d_s(m_s, n_s)\}_{(m_s,n_s) \in M_s \times N_s}$.

For more precise determining the direction of the papillary ridges at a segment it is necessary to analyze the local pointwise directions $d_\nu(m,n)$ in the area slightly larger than the segment itself. The size of this area has to be selected according to the average inter-ridges distance on the fingerprint image. A square aperture $A(m_s^c, n_s^c; h_g \times h_g)$ having the side length of $h_g > l$ points and the centerpoint (m_s^c, n_s^c), which is the central point of the corresponding segment $(m_s,\ n_s)$, is used to form an array D_s; $A(\propto,\beta;\ h \times h) = \{x,y \mid -{}^{h}/_{2} \le x {-} \propto \le {}^{h}/_{2}, -{}^{h}/_{2} \le x - \beta \le {}^{h}/_{2}\}$.

At first, a histogram $Hist(d_v(m,n))$ of the local directions is formed taking into account the gradient value $g(m\ ,n)$

$$Hist(d_v(m,n)) = \sum_{(m,n)} \xi(m,n)\, g(m,n), (m\ ,n) \in A(m_s^c,\ n_s^c;\ h_g \times h_g),$$

where $\xi(m,n) \in \{0, 1\}$ is a two-digit sign possessing the unit value if the direction at a point (m,n) matches up with $d_v(m,n)$.

The estimated direction $d_s(m_s,\ n_s)$ is determined by the maximum sum of values of the weighed histogram $Hist(d_v(m,n))$ in the $(2\Delta + 1)$ adjacent samples, in this case the analyzed direction corresponds to the central sample, $\Delta \in \{1,2,\ldots,\lfloor \nu / 8 \rfloor\}$. Thus, the direction $d_s(m_s,\ n_s) = \delta_s \in \{0,\ 1,\ \ldots,\ \nu - 1\}$ for which the sum

$$Q = \sum_{\delta = |\delta_s - \Delta|_\nu}^{|\delta_s + \Delta|_\nu} Hist(\delta)$$

has a maximum value is appropriated to the selected segment; the smallest nonnegative residue modulo p is designated by $|x|_p$. When calculating the sum of the histogram values, a modulo operation is required because the index $\delta \in \{0, 1, \ldots, \nu - 1\}$ is looped, i.e. the direction $\delta_s - \Delta < 0$ is identical to the direction $\nu + (\delta_s - \Delta)$ and the direction $(\delta_s + \Delta) > \nu$ is identical to the direction $(\delta_s + \Delta) - \nu$.

Accounting of the gradient value $g(m\ ,n)$ allows us to exclude the impact of those points of a fingerprint image which do not belong to the boundaries of the papillary ridges and do not contain reliable information about the direction of a lines flow in the considered neighborhood. The average thickness of the papillary line in the fingerprint image is approximately from 3 to 15 points at the typical resolution of 500 dpi. Therefore, at least one ridge will be located in a square aperture with a side length of $h_d = 15$ points. This allows us to reliably determine the direction of the papillary lines on the segment under consideration. The accuracy of detecting the direction of ridge flow has a decisive impact on the key qualitative characteristics of the further fingerprint processing [1, 3, 8, 9].

The advantage of this method consists in its flexibility. It is possible to vary both the size of the considered area and the number of the selected directions. This allows us to achieve the greatest accuracy.

Fingerprint direction field optimization

After formation of the directional field $D_s = \{d_s(m_s,\ n_s)\}_{(m_s,n_s)\,\in\, M_s \times N_s}$ there arises a problem of elimination of the inaccuracies that have appeared at the stage of its estimation. The necessary result is attained by smoothing the directional field. This approach is based on the fact that the fingerprint ridges are continuous curves. It is required to make correction of the directional field so that the direction at the segment under consideration was similar to the directions of neighboring segments. The correction procedure of the direction field belongs to a class of the so-called relaxation procedures and significantly reduces the impact of wrongly detected directions caused by skin defects on initial fingerprint image [1, 3-5, 8].

Let us consider how the recursive correction of the directions field $D_s = \{d_s(m_s,\ n_s)\}_{(m_s,n_s)\,\in\, M_s \times N_s}$ is executed. The direction in each segment is replaced with the value computed taking into account the directions of neighboring segments in the square aperture$A(m_s,\ n_s;\ 5 \times 5)$. For this purpose the matrix of weighting coefficient $W_s = \{w_s(m_s,\ n_s)\}_{(m_s,n_s)\,\in\, M_s \times N_s}$ is formed, where

$$w_s(m_s,\ n_s) = \left]\frac{\nu}{2} - \frac{1}{24}\sum_{h_m=-2}^{2}\sum_{h_n=-2}^{2}|\delta_s(h_m,\ h_n)|\right[,$$

$\delta_s(h_m,\ h_n) = |d_s(m_s, n_s) - d_s(m_s + h_m,\ n_s + h_n)|_\nu^-$; the absolutely least residue of an integer number x modulo p is designated as $|x|_p^-$; the approximate value of a real number y is designated as $]y[$ and is formed by the rule

$$]y[= \begin{cases} \lfloor y \rfloor, \text{if } y < \lfloor y \rfloor + 0{,}5; \\ \lceil y \rceil, \text{if } y \geq \lfloor y \rfloor + 0{,}5. \end{cases}$$

The difference $\delta_s(h_m,\ h_n)$ is understood as the minimum angle between the respective directions.

The obtained values of weighting coefficients are averaged taking into account the neighboring elements in the aperture $A(m_s,\ n_s;\ 3 \times 3)$:

$$\widetilde{w}_s(m_s,\ n_s) = \left]\frac{1}{9}\sum_{h_m=-1}^{1}\sum_{h_n=-1}^{1} w_s(m_s + h_m,\ n_s + h_n)\right[.$$

Correction of the direction $d_s(m_s,\ n_s)$ in the segment $(m_s, n_s) \in M_s \times N_s$ consists in the calculation of the new direction

$$\hat{d}_s(m_s,\ n_s) = |d_s(m_s,\ n_s) + \Delta_s(m_s,\ n_s)\,|_\nu\ .$$

The direction correction $\Delta_s(m_s,\ n_s)$ is calculated by the formula

$$\Delta_s(m_s,\ n_s) = \frac{\sum_{h_m=-1}^{1} \sum_{h_n=-1}^{1} \widetilde{w}_s(m_s + h_m,\ n_s + h_n)\ \delta_s'(h_m,\ h_n)}{\sum_{h_m=-1}^{1} \sum_{h_n=-1}^{1} \widetilde{w}_s(m_s + h_m,\ n_s + h_n)}\ .$$

Here, the difference $\delta_s'(h_m,\ h_n) = |d_s'(m_s,\ n_s) - d_s(m_s + h_m,\ n_s + h_n)|_{\bar{\nu}}^{-}$, where the direction $d_s'(m_s,\ n_s)$ is the direction for which the sum of squared differences between the considered direction and the directions in the neighboring segments taking into account corresponding weighting coefficient, i.e.

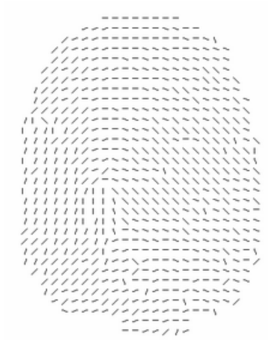
$$\sum_{h_m=-1}^{1} \sum_{h_n=-1}^{1} \widetilde{w}_s(m_s + h_m,\ n_s + h_n)\ \left(\delta_s'(h_m,\ h_n)\right)^2,$$

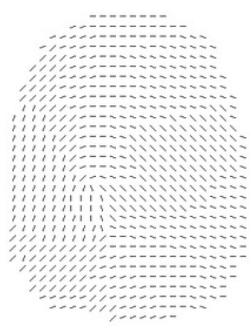
has a minimum value.

The optimization of the directional field is repeated iteratively and is finished if there is no more correction of the direction in any segment. Due to the high speed of process convergence the required number of iterations does not exceed 3 ÷ 5. The received directional field $\widehat{D}_s = \{\ \hat{d}_s(m_s,\ n_s)\}_{(m_s, n_s)\,\in\, M_s \times N_s}$ represents the smoothed fingerprint orientation image.

The figure below shows a fingerprint (a), an estimated directional field (b) and a smoothed directional field (c).


(a) Fingerprint


(b) Directional field


(c) Smoothed directional field

Conclusion

In this paper a new method of forming the fingerprint directional field is proposed. Its main component consists in the analysis of the local histogram of the pointwise directions taking into account the gradient module in a square neighborhood which size is commensurable with the average inter-ridges distance on the fingerprint image. The developed method showed the high efficiency and passed detailed approbation in the automated dactyloscopic identification systems using the large-volume fingerprint databases as well as the fingerprints received by the real-time optical scanner with resolution of 500 dpi.

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