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Research on Fingerprint Image Enhancement Algorithm Based on Adaptive Fractional Differential

Hao Pan[1], Kai Chang[1] and Shuang Pan[2]

[1]School of Computer Science and Technology, Wuhan University of Technology, Wuhan, China
2School of Economics, Wuhan University of Technology, Wuhan, China
panhaomail@163.com, changkai@whut.edu.cn

Abstract. Image enhancement is the most important part of fingerprint recognition. In order to improve the accuracy of fingerprint recognition, a fingerprint image enhancement algorithm based on fractional differential theory is proposed in this paper. This algorithm improves the traditional fractional differential form to improve the calculation accuracy and constructs a high-precision fractional differential mask. And the differential order is selected point by point according to the texture around the pixels. Compared with the methods in the references, the experimental results show that the enhancement effect is improved by about 7% in terms of average gradient.

1. Introduction

In recent years, fractional calculus theory, as a tool of image enhancement, has formed a huge system with broad application prospects. And many problems in physical science, electromagnetics, electrochemistry, diffusion and general theory can be solved by fractional calculus[1,2,3]. When fractional derivative is applied to fingerprint image enhancement, compared with traditional enhancement methods, image texture details are clearer, image edges are significantly enhanced, and the smoothing area information of the image is preserved nonlinearly [4,5]. In order to overcome the shortcomings of integer-order differential operator, Yang et al [6] extended the application of integer-order differential in image sharpening to fractional-order differential. An image enhancement Tiansi operator was constructed by the definition of G-L fractional-order differential. The theory of fractional-order differential was successfully applied to image enhancement, and the Tiansi algorithm was verified by experiments. The advantages of sub-operators over integer-order differential operators. Pu et al [7] proposed six high-precision differential and differential forms based on the definitions of G-L and R-L fractional differential, and established image enhancement operators respectively , which further verified the advantages of fractional differential operators. In reference [8,9], the image enhancement operator is constructed by using the traditional fractional differential form, and the operator structure is improved. Experiments show that the improved operator has better effect. And in reference [10,11], the fractional differential order is obtained by using gradient information, and an adaptive function is constructed to enhance it. However, this method only selects the image gradient and does not consider the local statistical information of the image.

In order to solve these problems, this paper chooses the fractional differential form with second order accuracy to construct the differential operator, and improves the operator structure accordingly. Then, using gradient information and local statistical information of the image, combined with the influence of the central pixel on the neighboring pixels, an adaptive fractional differential order adaptive function is constructed. In this method, fingerprint ridges and image texture details are preserved, and the noise reduction effect is achieved. This method is not only suitable for fingerprint quality improvement, but also has certain reference value for image texture detection.

2. Construction of Fractional Differential Operators

2.1 Construction of Second Order Precision RH Operators

The traditional Tiansi and R-L fractional order differential operators are established on the basis of classical fractional order differential approximation formulas, and their accuracy is not high. In this paper, a second-order fractional differential backward difference scheme proposed in reference [10] is selected to construct the differential operator. According to the error analysis of the literature experiment, it can be seen that the second-order fractional differential backward difference scheme based on R-L fractional differential is obviously more accurate than the traditional fractional differential method. Its second-order backward difference scheme is expressed as follows:

$$ {}^{RL}D_x^{\alpha} f(x) \approx \frac{1}{h^{\alpha}} \sum_{i=0}^{[t/h]} q_{i,2}^{(\alpha)} f(x-ih) . \tag{2.1} $$

$$ q_{i,2}^{(\alpha)} = (-1)^i (\frac{3}{2})^{\alpha} \sum_{i=0}^{i} \frac{1}{3^l} \binom{\alpha}{i-l} \binom{\alpha}{l} \quad l \ge 1 . \tag{2.2} $$

According to formula (2.1), for the fingerprint image $f(x,y),\ x\in[x_1,x_2], y\in[y_1,y_2]$, we can get the α-order partial differential backward difference approximation of $f(x,y)$ in x and y coordinates.

$$ \frac{\partial^{\alpha} f(x,y)}{\partial x^{\alpha}} \approx q_{0,2}^{(\alpha)} f(x,y) + q_{1,2}^{(\alpha)} f(x-1,y) + ... + q_{n,2}^{(\alpha)} f(x-n,y) . \tag{2.3} $$

$$ \frac{\partial^{\alpha} f(x,y)}{\partial y^{\alpha}} \approx q_{0,2}^{(\alpha)} f(x,y) + q_{1,2}^{(\alpha)} f(x-1,y) + ... + q_{n,2}^{(\alpha)} f(x-n,y) . \tag{2.4} $$

In this experiment, only the first three coefficients are obtained for calculation. According to formula (2.2), we can know:

$$ q_{0,2}^{(\alpha)} = (\frac{3}{2})^{\alpha},\ \ q_{1,2}^{(\alpha)} = (\frac{3}{2})^{\alpha}(-\frac{4}{3}\alpha),\ \ q_{2,2}^{(\alpha)} = (\frac{3}{2})^{\alpha} \frac{\alpha(8\alpha-5)}{9} . \tag{2.5} $$

As q_1, q_2, q_3 .

Considering the eight directions of the operator mask as shown in Figure. 2.1 and making the mask have a clear center, the size of the mask is odd. If the approximate fractional differential expressions of formulas (2.3) and (2.4) are used in all eight directions and the fractional differential mask with window size of 5×5 is used, the position of the upper half diameter of the operator mask is regarded as the same layer, and the weights of all coefficients are equal at each position of the same layer of the mask. A common operator mask (hereinafter referred to as RH operator) can be constructed as shown in Figure. 2.2.

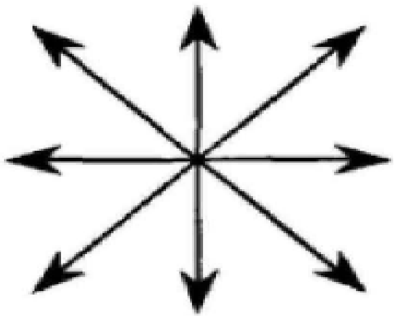

Figure. 2.1. Eight directions of the operator mask.

q_2	0	q_2	0	q_2
0	q_1	q_1	q_1	0
q_2	q_1	q_0	q_1	q_2
0	q_1	q_1	q_1	0
q_2	0	q_2	0	q_2

Figure. 2.2. 5×5 RH Operator.

2.2 Improvement of RH Operator

Because of many zero elements in RH operator, the pixels at these points do not contribute to the enhancement of central pixels, which obviously affects the image enhancement effect. The linear distance of two adjacent pixels is 1 and the oblique distance is $\sqrt{2}$, so the zero element position can be replaced by the following method:

$$q_3 = \sqrt{2}q_1, q_4 = \sqrt{2}(q_2 + q_3)/2, q_5 = \sqrt{2}q_4 . \tag{2.6}$$

A new mask can be constructed as shown in Figure. 2.3.

In order to increase the role of central pixels and reduce the role of surrounding pixels, the intensity factor $\gamma \in (0,1)$ is introduced to adjust the contribution of surrounding pixels to target pixels: $R_k = \gamma q_k, k = 1,2,...,5$. Obviously, the convolution of the new mask operator R and the original image is the process of image sharpening. In order to achieve better texture enhancement effect and make the sum of the weight of the mask R coefficients 1, the mask center coefficient $R_0 = 1 - 4(R_1 + R_2 + R_3 + R_5) - 8R_4$ can be made. The new operator is called IRH operator as shown in Figure. 2.4. γ=0.5 is selected in this paper.

q_5	q_4	q_2	q_4	q_5
q_4	q_3	q_1	q_3	q_4
q_2	q_1	q_0	q_1	q_2
q_4	q_3	q_1	q_3	q_4
q_5	q_4	q_2	q_4	q_5

Figure. 2.3. Improved RH Operator.

R_5	R_4	R_2	R_4	R_5
R_4	R_3	R_1	R_3	R_4
R_2	R_1	R_0	R_1	R_2
R_4	R_3	R_1	R_3	R_4
R_5	R_4	R_2	R_4	R_5

Figure. 2.4. Normalized IRH Operator.

3. Adaptive Fractional Differential Image Enhancement

It is difficult to artificially give the fractional differential order which makes the image enhancement best for the low-quality fingerprint images obtained in complex environments, and it is also difficult to filter the whole fingerprint image with a fixed fractional differential order to ensure that the information of the background pixels can be effectively retained while highlighting the target information [14]. In order to establish a more effective mechanism for selecting fractional differential order, so that every pixel in fingerprint image can obtain the best differential order for image enhancement. This paper chooses the appropriate order for each pixel in the image according to the image characteristics, in order to achieve better enhancement effect. Based on the principle of fractional differential enhancement, the magnitude of image edge and texture regions to be enhanced should be greater than that of smooth regions. Therefore, this paper constructs fractional differential order function by combining gradient and local information entropy of image.

3.1. Image gradient
The gradient of the image reflects the change rate of the gray level of the image. The gradient modes of image edge and texture regions are larger than those of smooth regions, so the magnitude of enhancement of image edge and texture regions is larger than that of smooth regions [8].

In order to reflect the change of gray scale magnitude between the central and neighboring pixels in more detail, the gradient modes $G_i(i=0,1,...,7)$ are calculated in eight directions of the pixel points (x, y), and the gradient modulus variation characteristics in eight directions of each pixel point are obtained. The maximum values of the eight directional gradient modes are approximated as the gradient modes at the pixel points (x, y).

$$G(x,y) \approx \max\{G_0, G_1, G_2, G_3, G_4, G_5, G_6, G_7\}. \tag{3.1}$$

3.2. Image Local Information Entropy
The information entropy of image indicates the richness of image texture. The change of pixel value of image edge and texture part is greater than that of smooth part, so the information entropy of image edge and texture part is larger [8]. In order to show the richness of local information, this paper calculates the local information entropy (expressed in E).

Let Ω(x, y) be a set of image pixel values in a rectangular window with the pixel point (x, y) as the center and the size of d×d, where d is odd and d≥3. $p(j)$ is the frequency when the pixel value in Ω(x, y) is j, then the local information entropy at (x, y) is defined as:

$$E(x,y) = -\sum_{j\in\Omega(x,y)} p(j)\log_2 p(j). \tag{3.2}$$

In order to more accurately count the relationship between each pixel in the image and the neighborhood pixels, the parameter d is set to be 3.

3.3. Determination of Adaptive Fractional Differential Order
According to the principle of fractional differential image enhancement, the larger the gradient mode and local information entropy of the image, the more likely the local region belongs to the edge and texture of the image. So the larger differential order is needed in the region. The smaller the gradient mode and local information entropy of the image, the greater the possibility that the local area is the smoothing part of the image. A smaller differential order should be used to preserve the information of the smoothing area.

It can be seen that the differential order is proportional to the gradient modulus and the local information entropy at the point. Therefore, the functional relationship between the fractional differential order and the gradient modulus and the local information entropy of the image can be constructed as:

$$v(x,y) = w_1 G'(x,y) + w_2 E'(x,y) + w_3. \tag{3.3}$$

Where w_1, w_2, w_3 is the weighted coefficient, v(x, y) is the required adaptive fractional differential order, G'(x, y) and E'(x, y) represent the normalized values of gradient G(x, y) and information entropy E(x, y), respectively. In order to ensure that the differential order v(x, y) does not exceed 1, we have $w_1 = 0.6, w_2 = 0.3, w_3 = 0.1$.

Two positive parameter delta and theta are added to G (x, y) normalization to ensure G (x, y) self-adaptive change. When G (x, y) >40, delta = 2, theta = 0.49; when G (x, y) ≤ 40, delta = 3, theta = 0.66; m and n are the minimum and maximum values of the gray scale modulus of the image, respectively. G'(x, y) can be obtained as follows:

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$$G'(x,y)=\frac{G(x,y)-m}{\delta(n-m)}+\theta=\begin{cases}\dfrac{G(x,y)-m}{2(n-m)}+0.49, G(x,y)>40\\ \dfrac{G(x,y)-m}{3(n-m)}+0.66, G(x,y)\le 40\end{cases}. \quad (3.4)$$

The normalization process of information entropy E is as follows:

$$E'(x,y)=\frac{E(x,y)-E_{\min}}{E_{\max}-E_{\min}}. \quad (3.5)$$

4. Experiment

In order to verify the efficiency of the fingerprint image enhancement algorithm proposed in this paper, experiments were carried out in the standard libraries FVC2002 and FVC2004 [15] of the International Fingerprint Verification Competition. In the experiment, the selection of image enhancement operator includes traditional Tiansi operator, RH operator and IRH operator. And the selection of fractional differential order function includes fixed order, segmentation-based adaptive differential order [10-11] and texture-based adaptive differential order proposed in this paper. In this paper, a comparative analysis of experiments was carried out for the combinations of different operators and orders. And in order to objectively evaluate the effectiveness of this paper's algorithm, information entropy (AE) and average gradient (AG) are introduced to evaluate the image quality after enhancement.

Information entropy reflects the texture richness of an image. The larger the value, the richer the information contained in the image. The formula for calculating information entropy is as follows:

$$AE=-\sum_{i=0}^{255}p(i)\log_2 p(i). \quad (4.1)$$

Where $p(i)$ is the probability of the occurrence of the pixel value *i* in the image.

The average gradient represents the clarity of the image. The larger the value, the clearer the texture details in the image. The formula is:

$$AG=\frac{1}{(M-1)(N-1)}\sum_{x=1}^{M-1}\sum_{y=1}^{N-1}\sqrt{\frac{(f(x,y)-f(x-1,y))^2+(f(x,y)-f(x,y-1))^2}{2}}. \quad (4.2)$$

Where M and N are image dimensions.

For fingerprint image in DB1 database of FVC2004 database, different combinations of algorithms are used to enhance the image. According to the evaluation criteria, the processed image is calculated to judge the specific enhancement effect of the image. The specific data are shown in Table 4.1.

Table 1. Average evaluation parameters of fingerprint images in DB1 database in FVC2004 database.

evaluation criterion / ***image***	***AE***	***AG***
original image	7.22	26.50
Tiansi Operator, Differential Order v=0.5	7.60	34.82
RH Operator, Differential Order v=0.5	7.74	39.66
IRH Operator, Differential Order v=0.5	7.87	43.14
IRH Operator, Segmentation-Based	7.93	48.76

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Adaptive Algorithm		
IRH Operator, the Adaptive Algorithm in this paper	7.98	52.09

As can be seen from Table 4.1, when using fixed differential order, the image enhancement effect of IRH enhancement operator is obviously higher than that of traditional Tiansi operator and RH operator. When all the IRH enhancement operators are used, the image enhancement effect of the adaptive fractional order algorithm is higher than that of the fixed order algorithm, and the adaptive algorithm proposed in this paper is better than the adaptive algorithm based on segmentation. In general, the algorithm proposed in this paper is superior to other methods in information entropy and average gradient, which further reflects the effectiveness of the proposed algorithm. Compared with the methods in the references[10], the experimental results show that the enhancement effect is improved by about 7% in terms of average gradient.

In the image enhancement experiments, one fingerprint image is enhanced by different algorithms, and the result is shown in Figure. 4.1. Figure. 4.1(a) shows the original fingerprint image, and the definition of fingerprint image is not very high. Figure. 4.1(b), Figure. 4.1(c) and Figure. 4.1(d) respectively show the processing results of fingerprint image enhancement using Tiansi, RH and IRH operators when using fixed differential order (v=0.5). The enhanced images in Figure. 4.1(b) and (c) are blurred and the enhancement effect is not obvious. In Figure. 4.1(d), it can be seen that the image texture detail clarity after IRH operator processing has been enhanced to some extent, and the overall brightness has also increased. Figure. 4.1 (e) and Figure. 4.1 (f) both use IRH enhancement operators. The former uses the adaptive differential order enhancement method in reference [10-11], and the latter uses the adaptive differential order function calculation proposed in this paper. Compared with Figure. 4.1 (d), both of them have the overall effect of enhancement. However, it can be seen that the method proposed in this paper is better than the method in reference [10-11] in the enhancement effect of fingerprint image edge region.

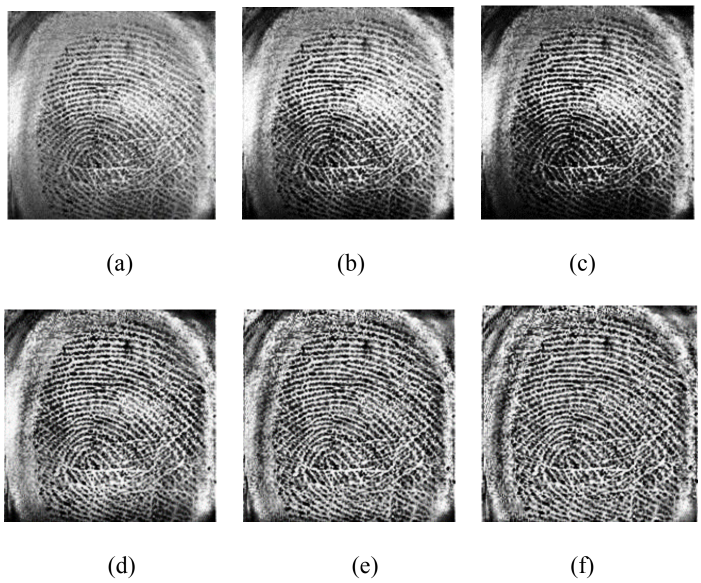

Figure. 4.1. Experimental results obtained by different experimental methods. (a): the original fingerprint image; (b): Tiansi operator, differential order v=0.5; (c): RH operator, differential order v=0.5; (d): IRH operator, differential order v=0.5; (e): IRH operator, segmentation-based adaptive algorithm; (f): IRH operator, the adaptive algorithm in this paper.

5. Conclusion

Fractional differential is widely used in fingerprint image enhancement, especially when the quality of fingerprint image is not high. In this paper, an improved IRH operator is constructed by using fractional differential form with second order accuracy. Considering the local characteristics of image enhancement and the diversity and complexity of the internal structure of the image, we construct a characteristic differential order at each pixel of the image, construct an adaptive IRH operator, and make a new exploration on the selection method of fractional differential order in image enhancement. Experiments show that the proposed algorithm has great advantages in texture detail clarity and fingerprint edge texture processing. However, due to the requirement of calculation accuracy, the processing time will increase, which will be a problem for further research.

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