A low illumination image enhancement algorithm based on adaptive fractional differentiation

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Abstract. Using fixed order fractional differential for image enhancement, some regions of the image may not achieve the desired enhancement effect. According to the characteristics of human vision and low illumination image, an adaptive order fractional differential enhancement algorithm is proposed. Three different differential orders are selected for enhancement, and one of them is adaptively selected for each pixel according to the comparison results of gradient values. The experimental results show that the adaptive order can not only enhance the image with high gradient value such as the edge, but also reduce the noise interference in the flat area, which has better visual effect than fixed order enhancement.

1. Introduction
The captured images are usually indistinct in the night or under illumination environment. Image enhancement algorithms can improve image quality. The main purpose of image enhancement is to highlight the area of interest to the user and suppress other unimportant information, thereby improving the overall visual effect of the image. Image sharpening is the most widely used method in traditional image enhancement. The most commonly used algorithms are sharpening by integer order differentiation in the space domain and high-pass filtering in the frequency domain.

Integer order differential operators such as Robert operator and Laplacian operator are widely used in image enhancement. Many improved algorithms[1-3] further enhance the enhancement effect of integer order differential. However, it is still sensitive to noise and easy to suppress the texture details in the image.

In recent years, fractional differential has been introduced into the field of image processing and applied to image edge detection and image enhancement. Fractional order differential can effectively solve the problems existing in integer order differential, and has achieved very good results in image enhancement.

2. Fractional differential image enhancement
In terms of image enhancement, differential operations have a boosting effect on the high-frequency components of the image. Fractional differential and integer differential have different degrees of improvement to the image. With the increase of the order, the integer-order differential increases the high-frequency component rapidly, but it has a significant weakening effect on the very low-frequency signal. Although the fractional order differential does not improve the high-frequency components as much as the integer order differentials, it also has a substantial increase. It also enhances the
intermediate frequency signal and retains the nonlinearity of the very low frequency component of the signal.

Fractional order differentiation can effectively improve the edge and texture details while preserving the texture details of smooth areas[4-6], and effectively solve the problem of integer order differential sensitive to noise.

According to the visual characteristics of the human eye[7], structural regions with large image changes, such as edges, are most likely to attract human attention. These parts mainly correspond to the high-frequency components of the image. The rich texture area is also easy to attract human attention, these are mainly concentrated in the intermediate frequency part. The areas that change gently belong to low-frequency components, which are generally not easy to attract human attention. The enhancement effect of the fractional differential is basically in line with the visual characteristics of the human eye, and the most high-frequency enhancement, followed by the intermediate frequency, the low frequency is retained, so the enhanced visual effect is better.

However, there is no unified definition form for fractional differentials. Riemann-Liouville (R-L), Grunwald-Letnikov (G-L), and Caputo definitions are more famous[8-10]. The definition of G-L can be derived from the definition of R-L. The definition of R-L is to simplify the calculation of fractional derivatives. The definition of Caputo is to make the Laplacian transformation more concise, which is convenient for solving fractional differential equations. Since the G-L definition is more accurate in the numerical realization of signals, the fractional order differential operator is derived from the definition.

2.1. difference definition of fractional differential

The definition of fractional calculus G-L is as follows: let the function have order continuous derivative, for at least the integral part obtained, then the order G-L derivative is defined as [9]:

\[
 d^\nu f(t) = \lim_{h \to 0} h^{-\nu} \sum_{m=0}^{t-v} (-1)^m \frac{\Gamma(v+1)}{m!\Gamma(v-m+1)} f(t-mh) 
\]  

(1)

In this expression, \( \Gamma(n) = \int_0^{\infty} t^{n-1} e^{-t} dt = (n-1)! \).

If the duration of the unitary signal is \( t \in [a, t] \), the interval is divided equally according to the unit interval \( h = 1 \) to get \( n = \frac{t-a}{h} = t-a \). Thus, the difference expression of fractional differential of one variable signal \( f(t) \) is derived as follows:

\[
 \frac{d^\nu f(t)}{dt^\nu} \approx f(t) + (-v)f(t-1) + \frac{(-v)(-v+1)}{2!} f(t-2) + \cdots + \frac{\Gamma(-v+1)}{n!\Gamma(-v+n+1)} f(t-n) 
\]  

(2)

2.2. fractional differential mask operator

The Tiiasi differential operator constructed in reference [11] is used for image enhancement. The differential operator extracts the first N-term multipliers from the difference equation and constructs an eight direction isotropic filter. A 5*5 filter is used to extract the first three multipliers in the difference equation. The first three multipliers are as follows:

\[
a_0 = 1, \quad a_1 = -v, \quad a_2 = \frac{(-v)(-v+1)}{2}
\]  

(3)

The filter template is derived as follows:
The results show that the enhancement effect is closely related to the differential order. When the order is small, the enhancement effect is not obvious; with the increase of order, the enhancement effect is closer to the enhancement effect of integer order differential. The enhancement effect is the best when the order is between 0.4 and 0.6[11]. Due to the different brightness of different images, the optimal differential order is different, and the most suitable differential order is different in different regions of the image. If a fixed order is used to strengthen an image, when the order is large, the flat area may be over enhanced; when the order is small, the enhancement of edge detail area may not achieve the desired effect. Therefore, better enhancement effect can be achieved by adaptive differential order enhancement.

3. Adaptive order fractional differential image enhancement

According to the characteristics of human vision, the resolution of human eye to gray level is very poor when the gray level of image is very high or low. When the gray level of the image is moderate, the resolution of the human eye is the strongest. For the gray image, the human eye will focus on the area where the gray value changes greatly. The change of gray level is reflected in the gradient value of pixels. The more obvious the change is, the greater the gradient value is.

For low illumination pictures taken at night, due to insufficient illumination, there are usually more dark areas. The average gradient value of dark areas is usually small, while the parts illuminated by light will show details such as edge texture of objects, and the gradient value is larger. If a small fixed differential order enhancement is used, the important information on the image may not achieve the desired enhancement effect. If a larger differential order enhancement is used, noise will easily appear in large flat areas such as sky and ground. Because the features of different regions of an image are different, it is not appropriate to simply use the same differential order for an image[12].

Therefore, an adaptive fractional order differential enhancement algorithm is proposed. In this algorithm, the pixels with different gradient values are enhanced by selecting different differential orders. The edge with larger gradient is enhanced with larger differential order, the texture details are enhanced with medium order, the flat area is enhanced with small differential order, and the original gray value is reserved for the very smooth area. The specific algorithm is as follows:

Firstly, three fractional orders $d_1$, $d_2$ and $d_3$ with certain difference are selected, among which $d_1 < d_2 < d_3$. Using these three orders to enhance the image, three enhanced images $f_1$, $f_2$ and $f_3$ are obtained. The gradient value $r_0$ of each pixel of the original image and the average gradient $T_1$, $T_2$ and $T_3$ of the three images are calculated. Then $r_0$ was compared with $T_1$, $T_2$ and $T_3$. According to the comparison results, the best pixel value of the three images is selected. The selection principle is that, for the gradient value $r_0(i, j)$ in the original image, if $r_0(i, j) > T_3$, the value of $f_3(i, j)$ is selected; if $r_0(i, j) > T_2$, the value of $f_2(i, j)$ is selected; if $r_0(i, j) > T_1$, the value of $f_1(i, j)$ is selected; otherwise, the original pixel value remains unchanged.
4. Experimental results and analysis

The experiment was conducted with road traffic pictures taken at night. Different differential orders $d_1 = 0.3$, $d_2 = 0.5$ and $d_3 = 0.7$ were selected for fixed order differential enhancement and adaptive order differential enhancement.

![Comparison of three kinds of fixed order enhancement and mixed order enhancement in the first image](image)

Figure 1. Comparison of three kinds of fixed order enhancement and mixed order enhancement in the first image

Figure 1 shows the experimental results of the first image. From the experimental results, the enhancement effect with 0.3 differential order is not enough, and the important information on the vehicle is fuzzy; the enhancement effect with 0.7 differential order is very obvious, but there is noise in the flat area. The enhancement effect of 0.5 differential order is the best. Figure 2 shows the contrast effect after enlarging the enhanced image. By observing the important information of the vehicle tail, it can be seen that the enhancement effect of adaptive order is better than that of 0.5 differential order, and the noise in flat area is lower.

![Contrast of enhancement effect of the first image after local area enlargement](image)

Figure 2. Contrast of enhancement effect of the first image after local area enlargement
Figure 3 shows the contrast of enhancement effect of the second image. For the edge enhancement, the enhancement effect of adaptive order is close to that of 0.7. Figure 4 shows the enlarged result of local area. It can be seen that the order of 0.7 produces very obvious noise on the flat area of the road, while the adaptive algorithm has almost no noise. By comparing the information entropy, the information entropy of adaptive algorithm is higher than 0.3 and 0.5 order, close to 0.7 order, but the comprehensive visual effect is better than 0.7 order.

From the comprehensive experimental results, the enhancement effect of adaptive order is better than that of using a fixed order alone.

Table 1. Comparison of information entropy of different orders.

| differential order | Original picture | 0.3  | 0.5  | 0.7  | adaptive order |
|--------------------|------------------|------|------|------|----------------|
| information entropy| 5.854            | 5.900| 5.930| 5.965| 5.949          |

5. Conclusion

By analyzing the characteristics of human vision and low illumination image, a low illumination image enhancement algorithm based on Adaptive Fractional Differential is proposed. This algorithm can not only keep good enhancement effect on the region with larger gradient value, but also remove the noise produced by the flat area. Compared with fixed order differential enhancement, adaptive fractional differential has better visual effect.

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