Improved Sub-pixel Edge Location Based on Spatial Moment

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***Abstract*—In order to overcome the disadvantages of time consuming and high computational cost in spatial moment, an improved sub-pixel edge detection algorithm based on spatial moment is proposed. Firstly, region of interest and Canny operator is used to reduce the number of edge points in the moment template operation. Then a constraint is set up by using the space moment characteristic of the edge to determine whether the pixel is the edge point. Finally, Using linear equations instead of nonlinear equations to obtain edge parameter. Only a moment template is required to participate in the operation. The experimental results show that the proposed algorithm is simple, accurate and timesaving.**

Keywords- sub-pixel edge detection, spatial moment, moment template, Canny operator.

I. INTRODUCTION

Medical image analysis, remote sensing and other domains tend to have rigid requirements on the accuracy of edge location during the last few years. Such as the accuracy of medical image analysis needs to be achieved 1/5 to 1/10 pixel, the precision of satellite remote sensing technology is higher than previous one[1]. Pixel edge detection algorithm can't meet the practical requirements, so we have to sub-pixel edge location to improve the edge localization accuracy. At present, the sub-pixel edge detection mainly has three kinds of methods: fitting, interpolation method and moment method. Fitting based on edge model fitting image grey value to complete the sub-pixel edge detection, sub-pixel location is used B-spline curve fitting by Bouchara and other peoples, It has a high precision and large amount of time. The interpolation method is to obtain the edge by using the gray distribution and image gray interpolation. Interpolation method is to realize the sub pixel edge detection by interpolating the derivative of the gray or gray value of the pixel. Two time interpolation B spline interpolation and three spline interpolation have been researched and discussed in literary circles. These methods spend short time to compute. But they are also sensitive to noise. In all sub pixel edge detection algorithm, edge detection based moment method has the characteristics of high detection accuracy, relatively simple calculation process and good anti-noise performance. Tabatabai and Mitchell [8] is first used the method of moment to the sub-pixel edge detection, through calculating the edge of the four parameters of the model to obtain the accurate edge. After that, the sub-pixel extraction algorithm based on spatial moment (SGM) was put forward. Cheng and Wu [9] expand the method to the color image. However, the edge extraction methods based on spatial moment requires convolution operation of six moment template, which is time-consuming and not ideal. An improved spatial moment method is proposed by Lee et al [10], which first use histogram bimodal characteristics to calculate the gray scale of target and background, and the other two parameters only need to compute three moment template. Ghosal [11] proposed sub-pixel edge detection method based on orthogonal Zernike moment (ZOM), whose essence is that the edge of the four parameters can be calculated using the orthogonality and rotation invariance of the Zernike moment, needed to compute three moment template. Although ZOM method is simple and high positioning accuracy, the ZOM method is not suitable for describing the small targets in the images, and cannot fully extract the edge information. Bin et al. [12] complete sub-pixel edge detection using Fourier-Mellin orthogonal moment (OFMM) amplitude rotating invariance and lower radial moment order, which is higher than the positioning precision of ZOM, and has good resistance to noise, but has computational complexity and low efficiency.

Edge detection method based on moment has been widely used, because the moment method is integral operation, simple calculation, and not sensitive to image noise. In all the sub-pixel edge detection method based on the moment, the moment for the number of moment templates which are used for convolution operation is not less than three, so these methods take a large amount of time, have high calculation cost. In order to overcome these shortcomings, an improved sub-pixel edge detection method based on spatial moment is proposed in the paper, which just need a zero moment template to participate in the calculation, and make up for the defects of other moment method in the description of small images and noise sensitivity. And using the early image preprocessing and edge coarse location it save a large amount of computing time and obtain higher precision.

II. METHODOLOGY

In the visual servo system of mobile robot, it needs using the technology of image processing. The image information needed are get through image gray-scale transformation and edge extraction. Image processing technology using the computer for processing and recognizing 2D continuous image camera in the robot's head input, can determine the object's position, direction, and other state property. When the camera captures images, due to uneven ground and the changes of lighting conditions, so that it makes obtained image generated noise and distortion. image processing for the processing of target images, can remove random noise and distortion, improve the quality of the output image, and make the image clearer.

A. Region of Interest.

In general, the geometric images that need to be extracted is only a small part of the whole image. So it is necessary to analyze in the region of interest and find the feature model, without the analysis of the whole image [13]. If we extract the region of interest that contains the desired target model at first, the pixels in the operation will be greatly reduced, which can significantly accelerate the speed of edge extraction algorithm, and meet the need of real-time detection.

B. Canny Edge Detection.

Canny operator is an optimal edge detection operator, whose essence is determining edge pixels in the image through finding maximum value of the signal function. It gives three criterions to measure the performance of edge detection: good detection performance, high positioning accuracy and the least number of edge response[14].

Firstly, Canny operator using Gaussian smoothing filter out the noise the image contains, and calculate the convolution of first order differential of Gaussian filter impulse response function and original image function. Then using non maxima suppression the width of the edge obtained by calculating gradient is decreased, and maximum points of gradient magnitude are removed. Finally, edges are connected using double threshold detection algorithm. Canny operator can produce good results of edge detection, and the influence of noise is small.

C. Sub-pixel Edge Extraction Based on SGM.

Define an ideal continuous two-dimensional edge model as shown in Fig 1.

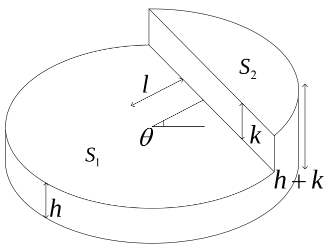

Figure 1. Ideal edge model

Ideal sampling area is a unit circle, where the background value of grey is h, target value of grey is $h+k$, the gray image contrast is k. And l is the vertical distance from the center of a circle to the actual edge. θ is the angle between the normal line of the edge and the horizontal direction(X-axis), whose range from $\left[-\pi/2, \pi/2\right]$, therefore, by the continuous two-dimensional grey function $f\left(x,y\right)$ the spatial moment is determined as shown in Eq.1[15]:

$$M_{pq} = \iint_{x^2+y^2\le 1} x^p y^q f\left(x,y\right) dxdy \tag{1}$$

To reduce the dimension of the edges, make the spatial moment M_{pq} rotate at any angle θ as shown in Eq. 2:

$$M'_{pq} = \sum_{r=0}^{p}\sum_{s=0}^{q}\binom{p}{r}\binom{q}{s}\left(-1\right)^{q-s}\left(\cos\varphi\right)^{p-r+s} * \left(\sin\varphi\right)^{q+r-s} M_{p+q-r-s,r+s} \tag{2}$$

Therefore, the relation of the two spatial moments M_{pq} and M_{pq} is as shown in Eq. 3:

$$\begin{cases} M'_{00} = M_{00} \\ M'_{10} = \cos\varphi M_{10} + \sin\varphi M_{01} \\ M'_{01} = -\sin\varphi M_{10} + \cos\varphi M_{01} \\ M'_{11} = \sin\varphi\cos\varphi\left(M_{02} - M_{20}\right) + M_{11}\left(\cos^2\varphi - \sin^2\varphi\right) \\ M'_{20} = \cos^2\varphi M_{20} + 2\cos\varphi\sin\varphi M_{11} + \sin^2\varphi M_{02} \\ M'_{02} = \sin^2\varphi M_{20} - 2\cos\varphi\sin\varphi M_{11} + \cos^2\varphi M_{02} \end{cases} \tag{3}$$

After the rotation angle θ, the edges are perpendicular to X-axis, then

$$M'_{01} = \int_{-1}^{+1}\int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} y f'\left(x,y\right) dxdy = 0 \tag{4}$$

$$M'_{01} = M_{01}\cos\theta - M_{10}\sin\theta \tag{5}$$

By Eq. 4 and Eq. 5 , we get

$$\theta = arc\tan\frac{M_{01}}{M_{10}} \tag{6}$$

$$\begin{aligned} M'_{00} &= 2\int_{-1}^{1}\int_{0}^{\sqrt{1-x^2}} h_1 dydx + 2\int_{l}^{1}\int_{0}^{\sqrt{1-x^2}} kdydx \\ &= h\pi + \frac{k}{2}\pi - k\sin^{-1}l - kl\sqrt{1-l^2} \end{aligned} \tag{7}$$

$$\begin{aligned} M'_{10} &= 2\int_{-1}^{1}\int_{0}^{\sqrt{1-x^2}} h_1 xdydx + 2\int_{l}^{1}\int_{0}^{\sqrt{1-x^2}} kxdydx \\ &= \frac{2}{3}k\sqrt{\left(1-l^2\right)^3} \end{aligned} \tag{8}$$

$$\begin{aligned} M'_{20} &= 2\int_{-1}^{1}\int_{0}^{\sqrt{1-x^2}} hx^2 dydx + 2\int_{l}^{1}\int_{0}^{\sqrt{1-x^2}} kx^2 dydx \\ &= \frac{h}{4}\pi + \frac{k}{8}\pi + \frac{k}{2}l\sqrt{\left(1-l^2\right)^3} - \frac{k}{4}l\sqrt{1-l^2} - \frac{k}{4}\sin^{-1}l \end{aligned} \tag{9}$$

$$\begin{aligned} M'_{02} &= 2\int_{-1}^{1}\int_{0}^{\sqrt{1-x^2}} hy^2 dydx + 2\int_{l}^{1}\int_{0}^{\sqrt{1-x^2}} ky^2 dydx \\ &= \frac{h}{4}\pi + \frac{k}{8}\pi - \frac{k}{6}l\sqrt{\left(1-l^2\right)^3} - \frac{k}{4}\sin^{-1}l - \frac{k}{4}l\sqrt{1-l^2} \end{aligned} \tag{10}$$

By Eq. 7, Eq. 8 and Eq. 9, we can get

$$l = \frac{4M'_{20} - M'_{00}}{3M'_{10}} \tag{11}$$

$$k = \frac{3M'_{10}}{2\sqrt{\left(1-l^2\right)^3}} \tag{12}$$

$$h = \frac{M'_{00} - k\left(\frac{\pi}{2} - \arcsin l - l\sqrt{1-l^2}\right)}{\pi} \quad (13)$$

According to the edge model, the Equation of sub-pixel edge detection is

$$\begin{cases} x' = x + \frac{N}{2} l\cos\theta \\ y' = y + \frac{N}{2} l\sin\theta \end{cases} \quad (14)$$

Where (x', y') represent sub-pixel coordinates of edge points, and (x, y) represent image coordinates of edge points.

Through Eq. 7 ~ Eq. 10, we can get:

$$2\left(M'_{20} - M'_{02}\right) - M'_{00} = \frac{2}{3} kl\sqrt{\left(1-l^2\right)^3} \quad (15)$$

$$M'_{20} - M'_{02} = \frac{2}{3} kl\sqrt{\left(1-l^2\right)^3} \quad (16)$$

Let $S(x,y) = 2\left(M'_{20} - M'_{02}\right) - M'_{00}$. it is the Plan of the edge model as shown in Fig. 2, where the radius of the two circles are 0.5 and 1 respectively. In the black area $2\left(x^2+y^2\right)-1<0$ is less than 0, but in the gray area $2\left(x^2+y^2\right)-1>0$ is more than 0. For Fig.2, $\iint\left[2\left(x^2+y^2\right)-1\right]dxdy$ are not equal in these two regions ， so when The gray level of the two regions is equal, we get it：

$$\iint\left[2\left(x^2+y^2\right)-1\right] f(x,y)dxdy \neq 0 \quad (17)$$

$$S(x,y) \neq 0 \quad (18)$$

So, make

$$g(x,y) = \frac{\left|M'_{20} - M'_{02}\right|}{S(x,y)} \quad (19)$$

Therefore, when the pixels are the edge points, $g(x,y)=1$, then we can use the function $g(x,y)$ to make sub-pixel edge extraction.

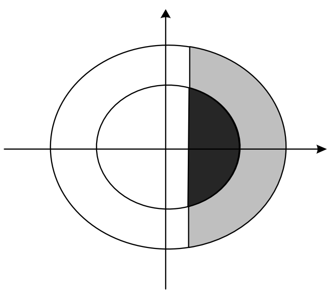

Figure 2. Edge model plane

D. Improved Sub-pixel Edge Extraction.

According to Eq.19，we need to use a moment template to participate in the operation, the sub-pixel edge extraction can be performed only by taking out the parameters.

Due to $M'_{00} = M_{00}$ whose moment templates are the same, calculating equation of the continuous two-dimensional edge model is

$$M_{00} = \iint f(x,y)dxdy \quad (20)$$

According to figure 1, the area of background region and target region area in the edge model are S_1 and S_2 respectively. Eq. 20 can be converted into

$$\begin{aligned} M_{00} &= S_1 h + S_2(h+k) \\ &= (\pi - S_2)h + S_2(h+k) \\ &= \pi h + S_2 k \end{aligned} \quad (21)$$

As shown in Fig.3,it is the Plan of the edge model after the rotation of θ. From geometric knowledge, we get:

$$S_2 = \alpha - \frac{1}{2}\sin 2\alpha \quad (22)$$

$$l = \cos\alpha \quad (23)$$

When solving Eq. 22, the process need to solve the nonlinear equations. In actual situation, Eq. 22 can be instead of a linear equation. Discrete the edge model of the unit circle for a $N \times N$ template form, whose specific process is as shown in Fig. 4.

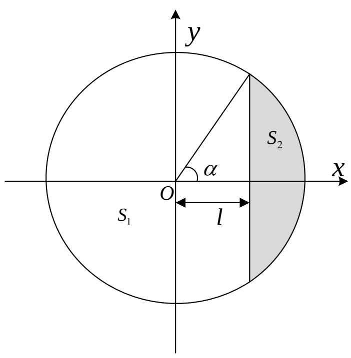

Figure 3. The plan of edge model after the rotation of

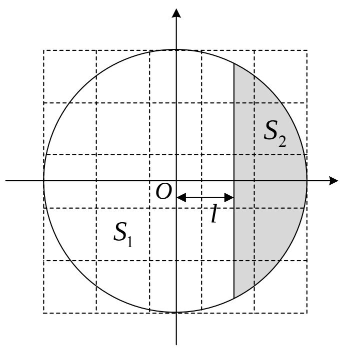

Figure 4. Edge model of discretization

The $N \times N$ template in Fig. 4 is indicated by a solid frame, which represents a pixel unit. According to the gray distribution of the image, the sub-pixel position of the pixel edge points should be in the middle of the small box. And 5×5 moment template of M_{00} is as shown in Tab. 1.

In a word, when the dimension of the moment template equals to 5, the minimum and maximum value of the area S_2 of the target region can be obtained by using simple geometric knowledge. And when l is 0.5 pixels, S_2 take the minimum; when l is -0.5 pixels, S_2 take the maximum. So, according to Numerical value of moment template M_{00}, we can calculate the values range of S_2 is $[1.1735, 1.9681]$.

Through Eq. 22, when $S_2 \in [0, \pi]$, relation graph of and is shown in Fig.5, where the solid line represents the true relation curve between and when the relation curve S_2 and α can be approximated as a straight line. The straight line is calculated as shown:

$$\alpha = 0.5114 S_2 + 0.7674 \quad (24)$$

$$l = \cos(0.5114 S_2 + 0.7674) \quad (25)$$

TABLE I 5×5 SPATIAL MOMENT TEMPLATE OF M_{00}

0.0219	0.1231	0.1573	0.1231	0.0219
0.1231	0.1600	0.1600	0.1600	0.1231
0.1573	0.1600	0.1600	0.1600	0.1573
0.1231	0.1600	0.1600	0.1600	0.1231
0.0219	0.1231	0.1573	0.1231	0.0219

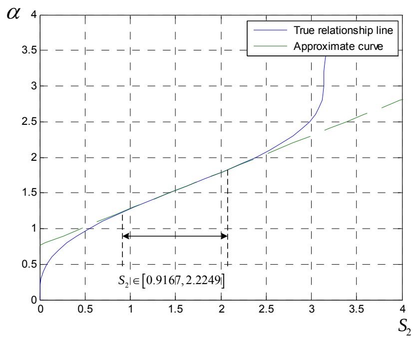

Figure 5. The relation graph of S_2 and α

By the Eq. 22 and Eq.24 can get two relation curve. As shown in Fig.5, when $S_2 \in [1.1735, 1.9681]$, the two curve overlap approximately. And when value interval of S_2 is 0.001 pixels, mean difference of α is $6.0549e \times 10^{-5}$ pixels , which can be neglected. Based on rotation invariance of moment template, that solving the following equations can calculate edge parameters l and k :

$$\begin{cases} M_{00} = \pi h + S_2 k \\ l = \cos(0.5114 S_2 + 0.7674) \\ h = \dfrac{M_{00} - k\left(\dfrac{\pi}{2} - \arcsin l - l\sqrt{1-l^2}\right)}{\pi} \end{cases} \quad (26)$$

And the background gray h in Eq. 26, we use the literature [10] about the whole picture to use histogram method to calculate the double peak, to calculate separately. At this time if the value of $g(x, y)$ is 1, we can make sub-pixel edge location.

The steps of improved sub-pixel edge detection based on spatial moment are as follows:

Get on the image preprocessing, extracting the interested region and edge detection of the Canny operator;

Take the coordinates of the pixel edge a Canny operator and generate a moment template;

Using the Eq.(26) to calculate the parameters h, l and k of the edge model.

(4)By the Eq.(19), calculate sub-pixel edge location, then return to the second step and take the next pixel.

E. Real-time Analysis.

In the method, the computation time is saved by the following steps. Firstly, the region of interest is extracted, which can reduce the number of pixels participate in calculation. Second, the edge points are extracted by using the Canny operator, which saves a lot of computation time

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and improves the extraction efficiency. Finally, when Seeking parameters l, the number of moments template participate in calculation to be reduced to one of the five. The running time of sub pixel edge extraction based on moment method can be regarded as the convolution operation time of the pixel gray level. Taking 5×5 moment template as an example, if the number of the edge points located through Canny operator and region of interest is P, and the number of the required templates is N, the operation times of the method are $25\times P$,which is less than SGM and ZOM, which shows that the method is high efficiency and time saving.

III. Results and Discussion

In order to evaluate the accuracy and validity of the algorithm, considering the geometric distribution of the edge model and the accuracy of the contrast, in the following experiments, the dimension of each rectangular template is 5, and the evaluation criteria is fitting error..

A. Simulation Experiment.

In order to verify the accuracy and robustness of the algorithm, in this paper, the simulation experiment is carried out. Firstly, produce a simulation image of edge model which is added with different levels of Gauss noise, whose noise means is 0, the variance range is 0 to 1 pixels, and the step size is 0.05 pixels. SGM method, ZOM method and the proposed method were used to carry out the sub-pixel edge extraction respectively. the fitting error of three methods is shown in Fig.6. Obviously, the fitting error of the proposed methods is smaller than the other two methods, which shows that the method has good accuracy and robustness to noise.

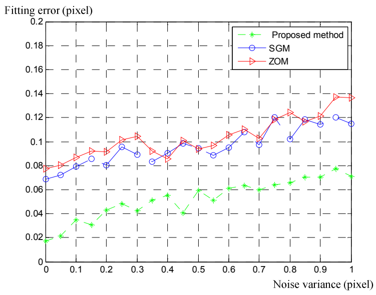


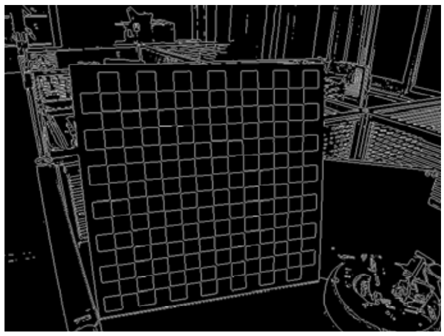
Fig. 6. Fitting error of sub-pixel edge extraction under different noise levels

B. Physical Experiment.

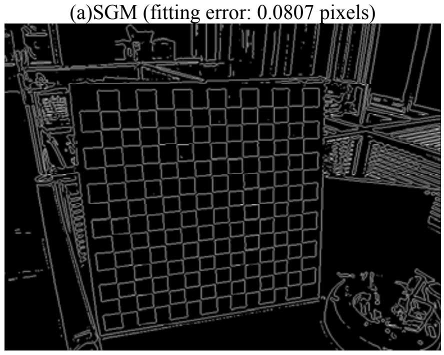
In order to verify the accuracy and robustness of the sub-pixel edge detection method, SGM method, ZOM method and the proposed method were used to carry out the sub-pixel edge extraction for Physical image respectively. The original image is the planar image of the camera calibration template, as shown in Fig. 7 . The results of sub-pixel edge extraction using SGM, ZOM and Proposed method respectively are shown in Fig.8.

As as shown in Fig. 8(a), many details of the image edge are not detected. many edges are not continuous, not complete and clear, and the details are not smooth . The detection time is 10.2s and longer. The sub-pixel edge detection using ZOM is as shown in Fig. 8(b), whose detection time is 6.8s. The detection time is faster, but the fitting error is large. While all the edges of the image are detected, there is no flaw in the edge and the edge of the fault is very few, the details are complete, clear and continuous. The proposed method not only maintain a high positioning accuracy, but also the detection effect is significant. The time spent on the method is 6s，which is 4 times of traditional SGM algorithm. This is due to the use of the Canny operator and the region of interest to reduce the number of pixels in the moment template calculation, and each time only needs to calculate a moment template M_{00} , which not only conducive to the removal of noise, but also greatly reduce the calculation of invalid sampling. Therefore, the proposed method has obvious advantages over the other two methods in both detection accuracy and detection time.

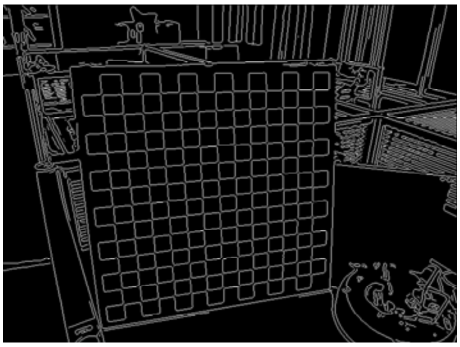
Figure. 7 The plane pattern of camera calibration



(a)SGM (fitting error: 0.0807 pixels)



(b) ZOM (fitting error: 0.0998 pixels)



(c) Proposed method (fitting error: 0.0259 pixels)

Figure 8. The results of sub-pixel edge location

IV. CONCLUSION

In the paper, we propose an improved the sub-pixel edge extraction based on spatial moment. Firstly, the region of interest and the Canny operator is used to reduce the number of edge points. Then, a moment template is used to perform the high precision sub-pixel edge detection. The experimental results and analysis show that the method is more accurate and more economical time. Meanwhile, the method is not only easy to be applied to the visual measurement, but also the parameters of the geometric model and the operation of camera calibration and matching in some cases.

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