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The Application of CCD Pixel Positioning Subdivision in the Reach of Laser Triangulation Measurement

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Abstract

During laser triangulation measurement, CCD image sensor is used to detect the laser spot with the measured information. Resolution and pixel size of CCD, directly affect the precision of laser scanning measurement. Based on the analysis of the gray centroid algorithm, the improvement gray centroid algorithm is proposed. By using the algorithm to solve the CCD location subdivision, the corresponding relationship between the spot position and the pixel is confirmed. The realization of the acquisition enhances the resolution through the segmentation, and the accuracy of laser triangulation measurement is improved.

Keywords*: Laser triangulation method; CCD positioning subdivision, Laser ranging; Gray centroid algorithm*

1. Introduction

Laser triangulation method can realize large range, high precision, rapid and non-contact shift measurement. Laser triangulation method can solve the contact pressure between the contact probe and the object to be measured, and reduce the damage of the object to be measured. It also can solve the lateral resolution issues that the large extending radius of contact probe brought, and effectively improve the speed of detection. Laser triangulation method has lower surface quality and material requirements to the object to be measured, and has broad application prospects. The CCD is used to detect the laser spot with the information of the shift to be measurement in laser triangulation measurements. Ranging results of laser triangulation probe can be calculated by the spot positions on the CCD. The range accuracy can be improved by the pixel location and subdivision on the CCD obtained in the spot position.

2. Linear Array CCD Pixel Location Subdivision Principle

Because the CCD is used to detect the laser spot, the reflected laser light from target enters the CCD acquisition optical system.

The influence of atmospheric jitter can be ignored due to the short distance, and it also won't produce aberratio by diffraction in the process of imaging. Therefore, the target spot imaging can approximately be regarded as Gaussian distribution diffuse plaques, and the illumination distribution function can be expressed as:

$$E(x) = \frac{\phi}{2\pi\sigma^2} \exp\left[-\frac{(x-x_0)^2}{2\sigma^2}\right] \tag{1.1}$$

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In the formula (1.1), x_0 is the centroid position calculated by the highest brightness central location in the diffuse plaques, and x_0 usually is used as the coordinate position of the target image. Φ is radiation power, which is reflected by the target on the CCD sensor. After the linear CCD sampling integral the spot formed by target, its gray distribution can be expressed as the followed mathematical model:

$$f(x) = k\left\{E(x) \cdot \mathrm{Re}\ ct\left(\frac{x}{a}\right) \cdot Comb\left(\frac{x}{b}\right)\right\} \tag{1.2}$$

In the formula (1.2), is a lateral dimension of the linear CCD sensor cells, b is the longitudinal dimension of the CCD photosensitive cell. By analyzing the formula (1.2), the images collected by the line array CCD is not continuous laser target mapping, but its discrete approximation. This system mainly measures the exact position of the image point reflected by the target. According to the characteristics of the above image gray distribution, it is necessary to calculate the center position of the original continuous image. Due to the limited resolution, it is required to determine and subdivide the central location of the target spot.

2. Gray Centroid Method

Gray centroid method is the most common location subdivision algorithm. Gray centroid method has a high sampling frequency to the part above the binarization threshold in the waveform, and the energy center is the center of the area. According to the law of CCD imaging, the reflected laser spot covers m pixels on the CCD photosensitive surface, and the envelope of the output signal waveform consistent with normal Gaussian distribution. The spot gray centroid is expressed by the formula (2.1):

$$X_c = \frac{X_1U_1 + X_2U_2 + \cdots + X_mU_m}{U_1 + U_2 + \cdots + U_m} \tag{2.1}$$

In the above formula X_c is spot gray centroid coordinates that the laser reflected by the target to the CCD. X_i is the coordinates of the i-th pixel in the normal Gaussian distribution, and U_i is pixel gray value which corresponding X_i.

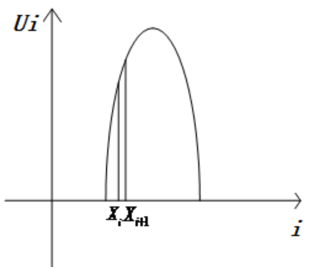

Figure 1. Schematic Diagram of the Centroid Method

Gray centroid method use the sub-pixel algorithm of centroid calculations. In the actual measurement, the collected CCD spot gray is easily interfered by various noise, after dealing the original signal should calculate the distribution of gray according to the algorithm. Otherwise it will bring large error, and affect the segmentation results.

3. Improved Gray Centroid Method

When measured with laser triangulation method, the measured surface roughness factors will bring some interference to the spot acquisition results. To solve this problem, an improved gray centroid method is put forward which is divided based on linear interpolation and the target region, to improve the measurement accuracy of the system.

3.1 CCD Imaging and Image Processing Algorithm

The frame grabber used by the system, is the black and white image acquisition card. The images obtained through this acquisition card are 256 grayscale images, so it is necessary to identify, analysis and process the collected gray images. In this paper, sub-pixel edge detection algorithm is used to process the CCD image, and the basic steps are as follows:

(1) First, the traditional edge detection operators are used to locate the laser spot.

The weight difference is up and down the adjacent gray of each pixel of the digital images $\{f(x,y)\}$ with the closest neighbor points' weights. Thus the $Sobel$ operator is obtained as follows:

$$\begin{aligned} s(i,j) &= \left|\Delta_x f\right| + \left|\Delta_y f\right| \\ &= \left|\begin{matrix} (f(i-1,j-1) + 2f(i-1,j) + f(i-1,j+1)) - \\ (f(i+1,j-1) + 2f(i+1,j) + f(i+1,j+1)) \end{matrix}\right| \\ &+ \left|\begin{matrix} ((f(i-1),j-1) + 2f(i,j-1) + f(i+1,j-1)) - \\ (f(i-1,j+1) + 2f(i,j+1) + f(i+1,j+1)) \end{matrix}\right| \end{aligned} \quad (3.1)$$

Convolution operators are as follows:

$$\Delta_x f = \begin{vmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{vmatrix}, \quad \Delta_y f = \begin{vmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{vmatrix} \quad (3.2)$$

Appropriate threshold TH is selected, whose judgment is as follows: if $s(i,j) > TH$. (i,j) is a step-like edge point, then $\{s(i,j)\}$ is the edges of the image.

(2)Because the extreme points are at the edges, the second derivative value is zero. For this feature, the points are taken in a small neighborhood of both sides of the edge points, the calculated gradient direction value about each point is in this small field. The formula is:

$$\theta(i,j) = \cot(f_y' / f_x') \quad (3.3)$$

Gradient direction values are got for each point in the chosen field. The center pixel gradient value is compared with the two pixel gradient values along the gradient direction. If the gradient magnitude at the center of the neighborhood is lager than the gradient magnitude of the two adjacent points along the direction of the gradient, this point is determined as an edge point value of 1, otherwise the point is determined as a non-point edge value of 0. Thereby the edge single-pixel image is obtained.

(3) Gradient values and gradient direction values of each edge pixel values are obtained by the above two steps. According the two above values Gaussian curve fitting along gradient direction is carried out. The Gaussian curve expression is as follows:

$$y = \frac{1}{\sqrt{2\pi\sigma}} \exp(\frac{-(x-\mu)^2}{2\sigma^2}) \tag{3.4}$$

The logarithm is taken to both sides of the equation (3.4) respectively, this formula is obtained:

$$\ln y = -\frac{(x-\mu)^2}{2\sigma^2} + \ln\frac{1}{\sqrt{2\pi\sigma}} \tag{3.5}$$

Formula (3.5) is a typical conic, so a binary quadratic polynomial is used to fit the pixel gradient logarithm values near the edge of the neighborhood firstly. In order to obtain the surface fitting function, the quadratic function is got through the surface fitting function. The quadratic surface fitting function is as follows:

$$f(x,y) = a_0 + a_1 x + a_2 x^2 + a_3 y + a_4 y^2 + a_5 xy \tag{3.6}$$

In formula (3.5), x and y are coordinate value of the pixel, and $f(x,y)$ is the logarithm value of the gradient magnitude of the (x,y) pixel. The pixels gray value near the edge of 3×3 neighborhood and the least squares are used to calculate the unknown factors in the fitting function. The solved equations are as follows:

$$\delta^2_{\min} = \sum_{x=i-1}^{x=i+1}\sum_{x=j-1}^{x=j+1}[f(x,y)-(a_0 + a_1 x + a_2 x^2 + a_3 y + a_4 y^2 + a_5 xy)]^2 \tag{3.7}$$

After obtaining the coefficient of quadratic surface function from the equation (11), a polar coordinates is set up to the edge point as the center. a quadratic equation is obtained with $\rho\cos(\theta)$, $\rho\sin(\theta)$ respectively replacing the x, y in the surface function (3.6). Because this equation is about the change in curvature at the gradient direction, its maximum value is the exact coordinates of the edge points. Quadratic equation is as follows:

$$\rho = -\frac{a_1\cos(\theta) + a_3\sin(\theta)}{2[a_2\cos^2(\theta) + a_5\cos(\theta)\sin(\theta) + a_4\sin^2(\theta)]} \tag{3.8}$$

The sub-pixel edge point coordinates is:

$$x = \rho_g\cos(\theta) \quad y = \rho_g\sin(\theta) \tag{3.9}$$

3.2 Spot Image Preprocessing

In order to effective solve the problem of edge jumps, before calculating the spot centroid, the method of multiple linear interpolation is used firstly to the spot image obtained in data process. This will increase the spot gray information, which improves the calculation accuracy and stability of the central coordinates of the spot. The advantage of this method is the small calculation and large advantageous to hardware implementation.

Set $0 < x < 1$, then the gray value of interpolation points is explained by the following formula:

$$g(i+x) = g(i) + x[g(i+1) - g(i)] \quad (3.10)$$

As interpolation at the 1/4 position of every two pixels, that is calculating in the case of $x = 0.25$.

3.3 Use the Sobel Operator to Realize the Goal of Regional Division

Using the Sobel operator to divide the laser spot area into the edge pixel region and the inside pixel region. The pixels point in target region is represented as $s1$, and the number of pixels is $n1$. Among them, $x_{s1,i}$, $g_{s1,i}$ is respectively represent the coordinates of the i-th pixel and the corresponding gray value of the coordinates. Similarly, the edge pixels points of the target areas are represented as $s2$, and the number of pixels is $n2$. Among them $x_{s2,j}$, $g_{s2,j}$ is respectively represent the coordinates of the j-th pixel and the corresponding gray value of the coordinates.

Then, the calculation formula of gray centroid method is:

$$X_c = \frac{\sum_{i=1}^{n1} x_{s1,i} g_{s1,i} + \sum_{j=1}^{n2} x_{s2,j} g_{s2,j}}{\sum_{i=1}^{n1} g_{s1,i} + \sum_{i=1}^{n2} g_{s2,j}} \quad (3.11)$$

In order to achieve the purpose of inhibiting the interior noise in the target area, reducing the gray uncertainty effect that brought by gray centroid method and meaning the inside pixel grayscale of the target region, can get higher anti-noise performance than the original gray centroid method. The gray value is:

$$g_{s1} = \frac{1}{n1} \sum_{i=1}^{n1} g_{s1,i} \quad (3.12)$$

The above formula represents the gray weights of the pixel inside the target region, and the improved gradation center algorithm can be expressed as:

$$X_c = \frac{g_{s1} \sum_{i=1}^{n1} x_{s1,i} + \sum_{j=1}^{n2} x_{s2,j} g_{s2,j}}{n_1 g_{s1} + \sum_{j=1}^{n2} g_{s2,j}} \quad (3.13)$$

3.4 Target Pixel Threshold Overall Parallel

In the gray centroid method, because its inherent principle makes them susceptible to interference from ambient background light, the result of interference will make the calculated results shift to the center of the window. It directly lead to reduce the positioning accuracy. Therefore, it can use the image gray value that greater than the threshold value to minus the threshold value G of system settings. It can set the other gray value that less than the threshold value to a value of 0, which is based on the thoughts of parallel moving down all the effective signal. The direct result is to increase the weight of central pixel, and to improve the measurement accuracy of the spot. The improved algorithm of parallel moves down the target pixel threshold value.

$$X_c = \frac{(g_{s1} - G)\sum_{i=1}^{n1} x_{s1,i} + \sum_{j=1}^{n2} x_{s2,j}(g_{s2,j} - G)}{n_1(g_{s1} - G) + \sum_{j=1}^{n2}(g_{s2,j} - G)} \quad (3.14)$$

According to the above linear CCD pixel subdivision location algorithm analysis, we can know that because the gray centroid method can make full use of the gray value of each point in the symmetrical distribution spot target. Therefore, it can effectively overcome the influence of wave asymmetry, and haves high positioning accuracy and stability. However, due to the diversity of the targets, the CCD used in the object surface to be measured is rough. The CCD output signal may appear double peak phenomenon, and the system measurement accuracy will be decreased. At the same time, the spot collected by CCD will introduce all kinds of interference noise. It needs a correction on gray centroid method in order to get better results. Therefore, this paper proposes a method of using the target region division, linear interpolation and moving down the all threshold value to correct. According to the CCD pixel location subdivision theory we can know that the more number of effective pixel gray spot, the higher localization accuracy of gray centroid method. But in the laser triangulation measurement, the CCD pixel covered by laser spot is rarely. The improved gray centroid method not only can improve the measurement accuracy of the spot, but also can enhance the stability of the system at the same time.

4 The Analysis of Experiments and Results

In this paper, the laser triangulation method is used to measure the eccentricity parameter of projectiles, and the laser spot image in CCD image sensor is affected by the noise under the same condition. The gray centroid method and the improved centroid method are realized. The average value, standard deviation and the limit error of the same projectile eccentricity are got after numerical analysis. The measuring results of two kinds of methods are shown in Table 4-1 and Table 4-2:

Table 4-1. The Results of Gray Centroid Location

	threshold of 0	threshold of 10	threshold of 20	threshold of 30	threshold of 40	threshold of 50	threshold of 60
average value	502.24	502.27	502.3	502.32	502.33	502.35	502.37
standard deviation σ	0.09	0.07	0.07	0.07	0.09	0.11	0.12
limit error σ	0.27	0.21	0.21	0.21	0.21	0.33	0.36

Table 4-2. The Results of the Improved Gray Centroid Location

	threshold of 0	threshold of 10	threshold of 20	threshold of 30	threshold of 40	threshold of 50	threshold of 60
average value	502.61	502.64	502.67	502.61	502.65	502.79	502.74
standard deviation σ	0.08	0.07	0.08	0.08	0.08	0.08	0.08
limit error σ	0.23	0.19	0.20	0.20	0.20	0.26	0.23

According to the above data, the effect on the positioning accuracy is analyzed from the different thresholds value. The target image is collected by CCD, which will be accompanied by a noise. The noise can be removed by the method of setting the threshold. The selected threshold is too large, and the window is smaller. The image information of the small part will be shielded by the threshold, and this will reduce the effective information. In this condition the reduced information is just the details of measurement, and will result in the decrease of ranging accuracy. If the selected threshold value is too small, the windows are larger. Some larger noise will be introduced into the image data, and this will also result in the decrease of ranging accuracy. Therefore, it is very important to select the threshold. Select the appropriate threshold value according to the size and height of the target pixel value, with the change of the target value and dynamic adjustment. The regional background of the image is measured firstly, and regard the average value of the collected images of all gray values cumulative obtained as regional background. In order to be able to adapt to the complex measurement environment, the regional background is got from the target point of the image. It is more meaningful to contrasting the regional background and the global background positive the measurement point, and the gray value of the regional background is treated as the threshold value. Step length is as interval in the experiment according to the different selected threshold window, it analysis and compare the gray centroid method and the improved gray centroid method. The average value of projectile eccentricity distance is got and the standard deviation changed curve that change with the threshold value is as shown in Figure 4.1 and Figure 4.2.

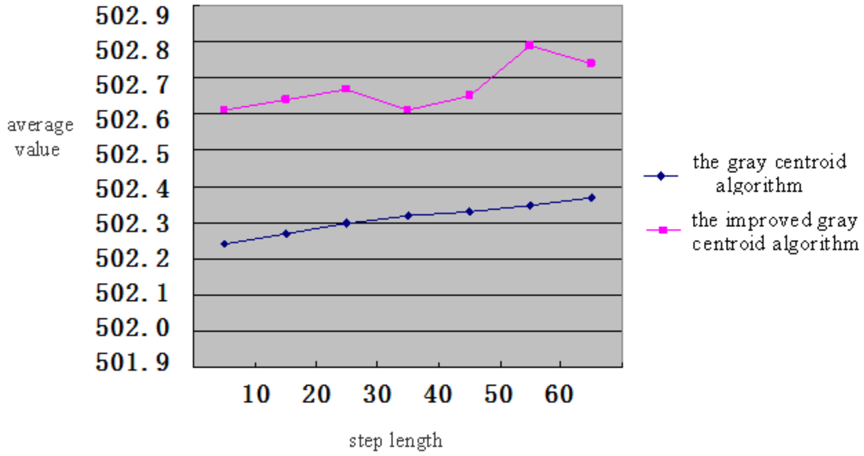

Figure 4.1. Changed Curve of Centroid Average Value

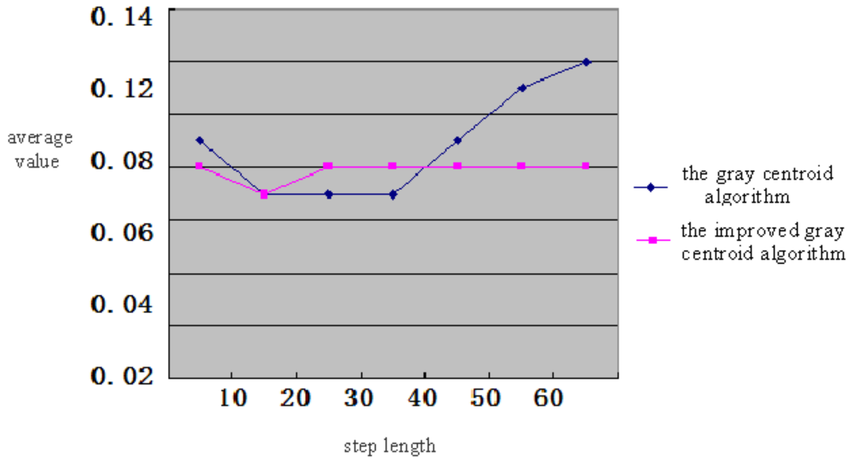

Figure 4.2. Standard Deviation Changed Curve of Centroid

From the above figures, the spot centroid position increases with the increase of the threshold because of the asymmetric distribution of the spot in the centroid method and the improved centroid method. Its standard deviation increases with the increase of the threshold value, because the selected threshold is too large. That results in the decrease of the effective spot pixel through the window and the signal to noise ratio, and reduces the resolution of the image sensor accuracy. It can be seen from the following data that the calculated standard deviation and the centroid average value is less affected by the change of threshold value. The method can be positioned location of the target image point in the sub-pixel level to improve the resolution of the CCD image sensor, and this will directly affect the accuracy of the measurement system. Because the responded location information on the CCD is equivalent to the projectile eccentricity information measured by the laser triangulation probe, three-dimensional geometry is obtained from the coordinate conversion. Under the measuring conditions of the same object morphology, high measurement accuracy and stability by improving the centroid method are achieved.

5. Conclusion

This paper presents the laser triangulation measurement method based on subdivision technology of CCD positioning. The resolution of CCD directly affects the precision of laser scanning measurement. This paper proposes an improved gray centroid algorithm based on the analysis of the centroid algorithm. The algorithm used to locate subdivision CCD can locate the position of the target image point in the sub-pixel level, and solve the correspondence between the spot position and pixel. In the measurement of projectile eccentricity by laser triangulation, the laser spot is imaged on the CCD image sensor. When the spot shape is affected by the noise under the same condition, gray centroid method and improved gray centroid are realized to get the average value, standard deviation and limit errors of the same projectile eccentricity. The results show that the improved gray centroid algorithm can increase the accuracy and measurement stability.

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