RESEARCH ON SUBPIXEL CENTERLINE EXTRACTION METHOD OF LINE STRUCTURED LIGHT STRIPE

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In the process of using line structured light for measurement, it is an essential step to quickly and accurately extract the center position from the line structured light stripe to improve the accuracy of the line structured light measurement system. At present, it is difficult to reduce the extraction time while ensuring the extraction accuracy by the commonly used line structured light centerline extraction methods. In order to solve this problem, the article proposes a centerline extraction method based on extreme value method and gray gravity method. The experimental results show that this method can extract the light stripe centerline more accurately and quickly, which provides a solid guarantee for the next point cloud data acquisition.

Keywords: line structured light, centerline extraction, Sobel operator, extreme value method, gray gravity method

1. Introduction

With the development of modern industry, various measurement techniques provide data guarantee for engineering practice and offer sufficient bases for industrial production. The current measurement methods used in industrial production and engineering practice are divided into contact and non-contact measurements. Contact measurement is not suitable for industrial applications with high precision and special requirements because of the contact wear and tear between the measuring instruments and the measured workpiece during the measurement process [1]. With the development of computer science technology and machine vision, non-contact measurement is widely used in modern industry. As a branch of non-contact measurement, vision measurement technology based on line structured light is widely used in target tracking [2], defect detection [3], and other fields because of its non-contact [4], simple principle, and high measurement accuracy.

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The structured light 3D vision measurement platform is shown in Fig. 1. The line laser transmitter projects structured light onto the target object, forms a distorted line structured light stripe on the surface of the object, and image it in a CMOS/CCD camera. The computer converts 2D points on the photographic stripe image into 3D points in the world coordinate system according to the mathematical model of the measurement system [5].

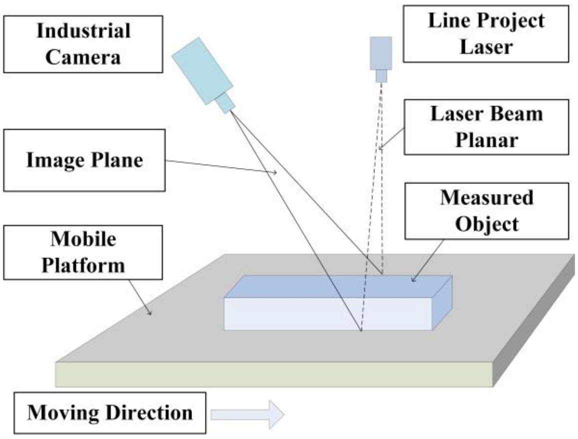


Fig. 1. Structured light 3D vision measurement platform

In the process of vision measurement using line structured light technology, the dimension parameters of the measured object are mainly contained in the centerline of the distortion light stripe. Because the stripe projected by the line structured light transmitter has a certain width [6], the collected stripe image needs to be processed to obtain an accurate centerline position [7]. Therefore, the accuracy of line structured light stripe centerline extraction directly determines the accuracy of line structured light measurement system [8]. At present, the common methods of extracting light stripe centerlines of line structure can be divided into traditional centerline extracting method and centerline extracting method based on deep learning. Among them, the centerline extraction method based on deep learning started late and has not been widely used in production practice [9]. Traditional centerline extraction methods can be divided into pixel-level and subpixel-level centerline extraction methods. Pixel-level extraction methods include extreme value method and direction template method. Subpixel-level centerline extraction methods include gray gravity method and Steger method based on the Hessian matrix [10]. The extreme value method is simple in principle, but it can only extract the centerline at the pixel-level[11]. Hu Bin proposed that the direction template method is quick in processing, but it is strongly affected by noise and has low robustness[12]. The Steger method based on the Hessian matrix has a high extraction accuracy, but it requires Gaussian convolution operations for each point 2 times on the image. In this way, it processes more data and is computationally expensive [13]. It is not easy to meet the real-time requirements of non-contact measurement. Zhang proposed an improved Kalman filter algorithm to quickly track and locate the area of interest of laser stripes in a sequence image and then extract the centerline [14]. Li proposed a method to extract the centerline of a line structured light stripe by using an internal push strategy to plan the search path and then move the search path forward or backward along the center of the light stripe [15]. The above extraction methods are challenging to meet both the accuracy and real-time requirements of non-contact measurement. Therefore, reducing the extraction time as much as possible while meeting the extraction accuracy has become a key factor in improving the efficiency of line structured light centerline extraction.

To solve this critical problem, based on the analysis of the stripe characteristics of line structured light, the article presents an improved stripe centerline extraction method for line structured light which combines extreme value method and gray gravity method. First, the method uses the extreme value method to preliminarily extract the stripe centerline of line structured light; Second, it uses the Sobel operator to extract the gradient of the initial center points and obtain the normal direction; Third, the method takes a number of subpixel points along both sides of the normal direction; Fourth, it uses the gray gravity method for each set of subpixel points; Finally, cubic spline interpolation is used to smooth the subpixel centerline. The experiment results show that the proposed method can improve the extraction speed and ensure extraction accuracy, which lays a foundation for the acquisition of 3D point cloud.

2. Fundamental Principles

2.1 Line Structured Light Stripe Properties

Line laser transmitters project line structured light onto the surface of the object, forming a light stripe with a certain width on it. The grayscale distribution on the cross-section of the light stripe at every position is approximately Gaussian distribution, as shown in equation (1), where σ is the standard deviation, A is the amplitude, and $f(x)$ is the intensity of the light stripe.

$$f(x) = Ae^{\frac{x^2}{-2\sigma^2}} \tag{1}$$

Fig. 2 (a) is a gray-scale image of a line laser transmitter with a wavelength of 650 nm, which emits structured light onto the surface of an object. Fig. 2 (b) shows the distribution of gray values corresponding to the cross-section of the image. It can be seen that, due to the influence of the material properties, the gray values along the cross-section of the line structured light stripe presented do not strictly follow the Gaussian distribution.

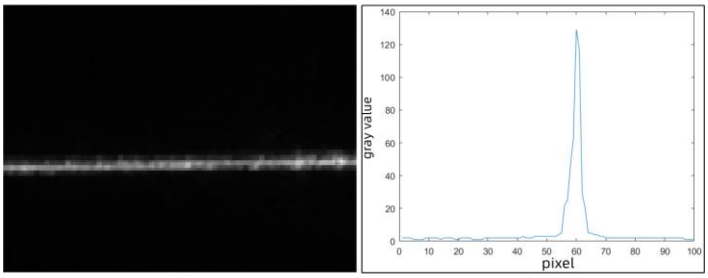


Fig. 2. (a) Line structured light stripe image;(b) Gray value distribution of light stripe cross section

2.2 Traditional Gray Gravity Method

Traditional gravity method is a common method to extract the centerline of line structured light. The basic principle is as follows: Calculate the gray center of gravity of each column (row) of a light stripe and use its coordinates as the center point coordinates of this column (row) light stripe. The calculation principle is shown in equation (2), where *I (i, j)* is the gray value of the pixel point *(i, j)*, and P *(i, y_j)* is the coordinate of the center point of the light stripe in column i.

$$p(i, y_j) = \left(i, \frac{\sum_{j=1}^{n} I(i, j) * j}{\sum_{j=1}^{n} I(i, j)} \right) \tag{2}$$

The traditional gray center of gravity method can quickly extract the subpixel centerline of a light stripe. The method is simple, fast, and accurate. But, the traditional gray gravity method can only calculate the center point of the light stripe in the column (row) direction, it is impossible to find the gray gravity in the normal direction of the light intensity of the light stripe. When the environmental impact is severe, the power of the light stripe tends to deviate significantly from the Gaussian distribution. For the above reasons, the traditional gray gravity method cannot guarantee extraction accuracy.

3. Line Structured Light Centerline Extraction

To solve the problem that the speed and accuracy of the mainstream light stripe centerline extraction methods are difficult to coexist, the paper proposes an improved centerline extraction method. The flowchart of the method is shown in Fig. 3, which is mainly composed of image preprocessing, getting subpixel point sets, extracting subpixel center points, and smoothing centerlines.

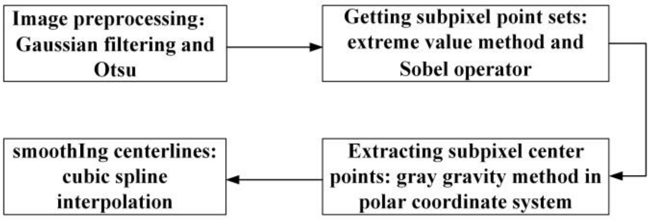


Fig. 3. Flowchart of the proposed method

3.1 Image Preprocessing

There is a series of noise in the light stripe image taken by an industrial camera, which will cause the center of the extracted light stripe to deviate from the side where there is noise, thus causing fluctuation of the centerline. To reduce the fluctuation, it is necessary to filter the original light stripe image. At the same time, eliminating these noises can reduce the computational load and improve the real-time performance of centerline extraction [16].

Gaussian filter is a linear smoothing filter. Its principle is to convolute the pixels on the image along the row (column) with the selected Gaussian template until all pixel points are convoluted [17]. After using a Gaussian filter with certain window width and corresponding deviation σ to remove noises. Fig. 4 (a) shows that the Gaussian filter is suitable for suppressing the Gaussian noise on the image and has a good effect on eliminating the noise that obeys the normal distribution.

After removing the noise that affects the accuracy of centerline extraction, the next step is to extract the region of interest (ROI) from the background. Otsu method can eliminate the influence of image background on the accuracy of stripe subpixel centerline extraction [18], and is not affected by image brightness and contrast [19], so it can select the best threshold image for segmentation adaptively. The principle of binarizing an image is shown in equation (3). Among them, $T(x, y)$ is the value of the binary pixel points, $I(x, y)$ is the gray value of the pixel points on the original stripe image, and t is the best threshold value for adaptive segmentation for different stripes using the Otsu method. Fig. 4 (b) is a binary stripe image.

$$T(x,y)=\begin{cases}1,(I(x,y)>t)\\0,(I(x,y)\le t)\end{cases} \tag{3}$$

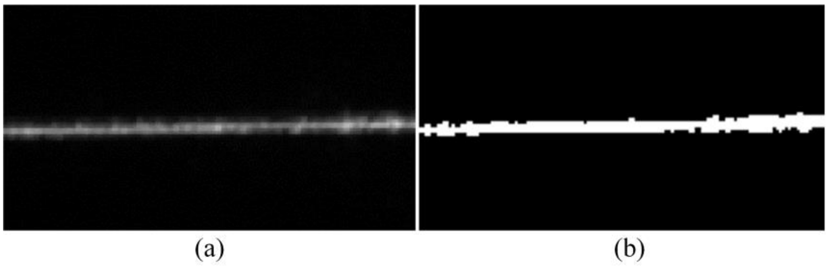


Fig. 4. (a) Gaussian filtered light stripe image; (b) Binary light stripe image

By observing Fig. 4 (a) and Fig. 4 (b), it can be seen that after image segmentation using Gaussian filter and adaptive threshold, the noises in the image are well suppressed, and the ROI obtained has better overlap with the original light stripe, and the light stripe outline is well preserved.

3.2 Getting Subpixel Point Sets

Firstly, after preprocessing the line structured light stripe, initial center points of the stripe extracted by the extreme value method. The gray distribution function of the cross-section of the light stripe is gradient calculated, and the pixel point P_0 (x_0, y_0) at the gradient value of 0 is taken as the initial center point of the light stripe.

Once the initial center point is obtained, Sobel operator is used to get the gradient x_t of the initial center points on the x-axis direction and the gradient y_t on the y-axis direction, ∇I is the gradient vector of the point (i, j). The calculation process is shown in system of equations (4). The initial centerline and the normal direction of some initial center points are shown in Fig. 5 (a) and Fig. 5 (b) respectively.

$$\begin{cases} x_t = \dfrac{\partial I(x,y)}{\partial x} \\ y_t = \dfrac{\partial I(x,y)}{\partial y} \\ \nabla I = \left[\dfrac{\partial I(x,y)}{\partial x}, \dfrac{\partial I(x,y)}{\partial y}\right] \end{cases} \tag{4}$$

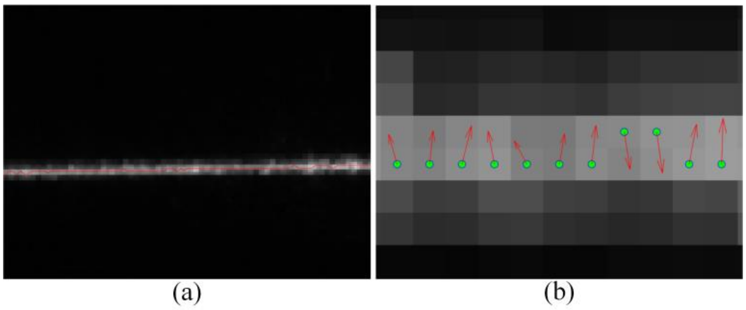


Fig. 5. (a) Initial centerline of the light stripe; (b) Normal direction of some initial center points

Since the light intensity in the normal direction of the initial center point best conforms to the Gaussian distribution characteristics of line structured light, n subpixel points of the initial center point in the positive and minus directions respectively of the normal direction of the initial center point are found, and each $2n+1$ subpixel points form a subpixel point set. Among them, the value of n is determined according to the ROI width obtained by Otsu method.

The coordinate calculation method for each subpixel point P_i (x_i, y_i) in the normal direction is shown in system of equations (5). In which, $i \in [-n, n]$, l is unit length 1, α is the angle between the normal direction of the initial center point P_0 (x_0, y_0) and the x-axis. P_0 and the relative positions and polar coordinates of the $2n$ subpixel points $P_{\pm1}$, $P_{\pm2}$, ..., $P{\pm}n$ taken in the normal direction are shown in Fig. 6.

$$\begin{cases} x_i = x_0 + i * l * \cos(\alpha) \\ y_i = y_0 + i * l * \sin(\alpha) \end{cases} \tag{5}$$

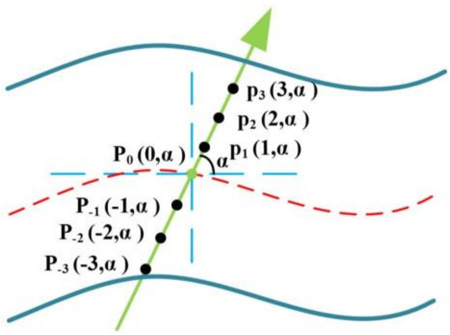


Fig. 6. Relative position and polar coordinates of points

3.3 Extracting Subpixel Centerlines of Light Stripes

It is obvious that the pixel coordinates of subpixel points are mostly non-integers, so taking the integer values of the horizontal and vertical coordinates of the subpixel points to get the gray value $I(i, \alpha)$ of each subpixel point.

For each set of subpixel points, the gray gravity method are used to extract the center points of light stripes until all the subpixel point sets have been traversed. Different from the pixel coordinate system, the principle of using gray gravity method to calculating the coordinate of subpixel center point P(p_c, α) in polar coordinate system is shown in equation (6). Fig. 7 shows the exact position of the subpixel center point P(p_c, α) in the polar coordinate system by using the gray gravity method.

$$p_c = \frac{\sum_{i=-n}^{n} I(i,\alpha) * i * l}{\sum_{i=-n}^{n} I(i,\alpha)} \tag{6}$$

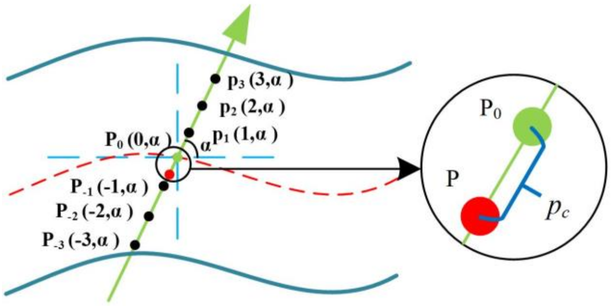
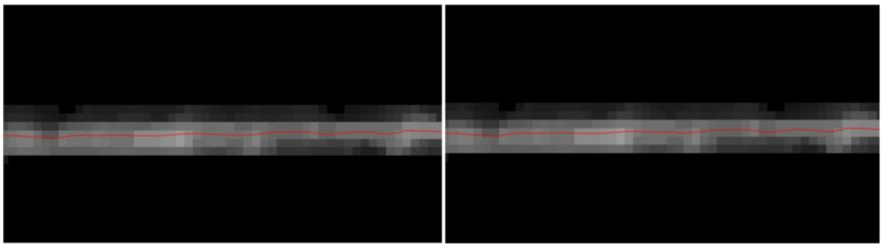


Fig. 7. Exact position of the subpixel center point P

The conversion from the subpixel center point P(p_c, α) in polar coordinate system to the subpixel center point P(x_p, y_p) in pixel coordinate system is shown in system of equations (7).

$$\begin{cases} x_p = x_0 + p_c * \cos(\alpha) \\ y_p = y_0 + p_c * sin(\alpha) \end{cases} \tag{7}$$

The exact centerline extracted by this method has a slight fluctuation due to the distortion of light stripes, so the obtained centerline is fitted with cubic spline interpolation. Fig. 8 is a comparison before and after smoothing the extracted centerline. It can be seen that cubic spline interpolation has a significant smoothing effect on the curve.



(a) (b)

Fig.8. (a) Centerline before cubic spline interpolation; (b) Centerline after cubic spline interpolation

4. Analysis of Experimental Results

The paper uses a line structured light vision system as shown in Fig. 9 to collect images. The line laser transmitter has a wavelength of 650 nm, the industrial camera is a Daheng MER2-160-75GM CMOS industrial camera, the camera lens is Computar M0814-MP2, the focal length is 8mm, and the filter type on the lens is AZURE-BP635 +30nm. Line laser emitters produce line structured light and project it onto the measured object to form line structured light stripes. The mobile platform can move on the guide rail in one dimension. CMOS industrial camera and fixed focus lens can collect continuous light stripe images of the measured object at a certain frame rate.

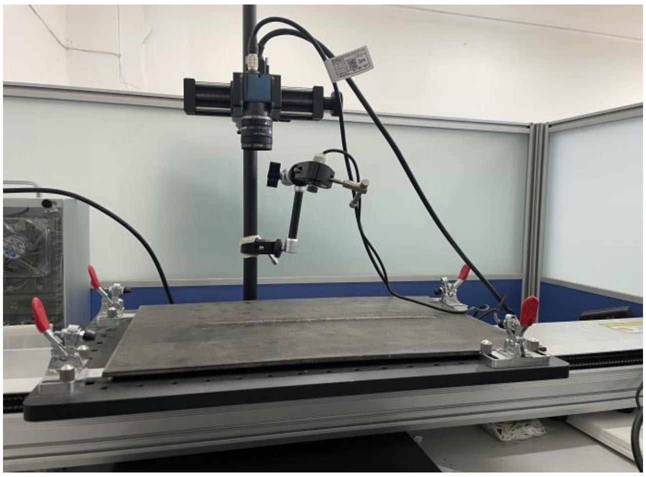


Fig. 9. line structured light vision system

4.1 Accuracy Analysis of Light Stripe Centerline Extraction

In the paper, to validate this centerline extraction method, 25 centerlines of different line structured light stripes are extracted using the proposed method. In Fig. 10, 6 representative light stripe pictures are selected to observe the effect of centerline extraction.

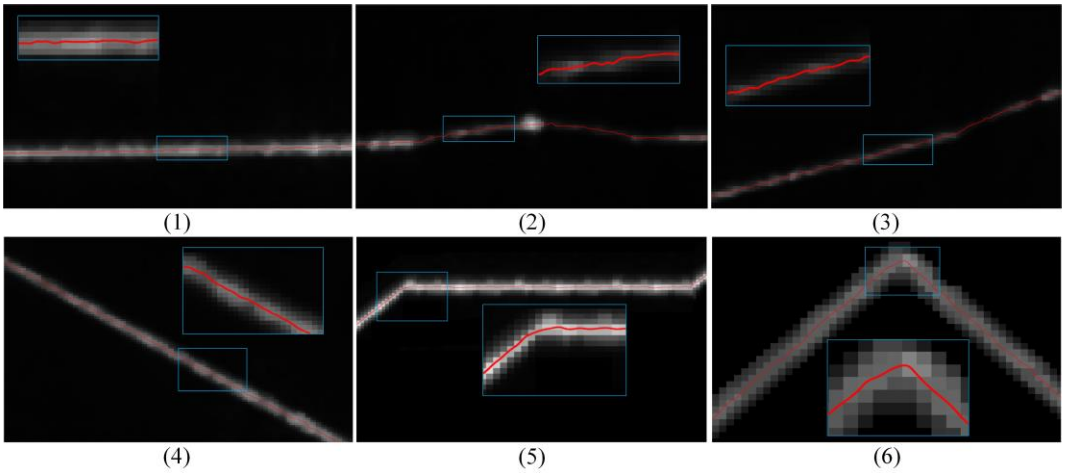


Fig. 10. Centerlines extracted using the proposed method

The Steger method based on the Hessian matrix extracts the centerline of a light stripe with high accuracy, but slower speed; The gray gravity method is fast in extracting the centerline, but it is susceptible to noise, which results in lower accuracy. To validate the proposed method, extracting the centerline of the light stripe in Fig. 10 (1) by gray gravity, Steger and the proposed method respectively. The overall effect is shown in Fig. 11 (a), and the partial comparison diagram of the results of the three methods is shown in Fig. 11 (b). As shown in Fig. 11 (b), the center points extracted by the proposed method are closer to that obtained by Steger method than by gray gravity method.

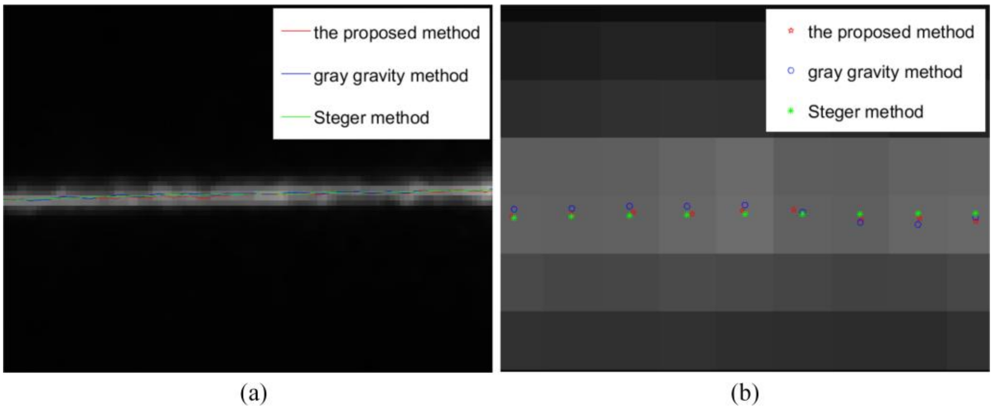


Fig. 11. (a) Centerlines extracted by the 3 methods; (b) Comparison of centerlines extracted by the 3 methods

In order to further evaluate the accuracy of the proposed method, the standard deviation of the extracted y-axis coordinate of the center points of the light stripe to the y-axis coordinate of the real center points can be used to represent the accuracy of the proposed method's centerline extraction. Because the real center points of the light stripe cannot be measured, the standard deviation is calculated using the residual instead of the actual errors[20]. Since the proposed method finds the final center point in the normal direction of the initial center point, and the gray value of the light stripe changes most significantly in the normal direction, the center points extracted by the proposed method in a small length range will fluctuate more in the y-axis direction than the center point extracted by the other two methods. Therefore, if the standard deviation of the center points extracted by these three methods is compared in a small length range, the proposed method will be slightly larger than the other two methods. However, a more comprehensive and accurate way to assess the accuracy of centerline extraction should be to calculate the standard deviation of all center points extracted on a light stripe. The principle for calculating the standard deviation is shown in equation (8). Where k is the number of center points, y_j is the y-axis coordinate of the center point, $\bar{y}$ is the average of y_j, $(y_j - \bar{y})$ is residual error.

$$s = \sqrt{\frac{\sum_{j=1}^{k}(y_j - \bar{y})^2}{k-1}} \tag{8}$$

The centerlines of 25 different line structured light stripe images mentioned above are extracted using the three centerline extraction methods, and their respective standard deviations are shown in Table 1.

Table 1

The standard deviation S of extraction method of the light stripe line

light stripe	Steger method/pixel	gray centroid method/pixel	the proposed method/pixel
1	0.7909	0.7985	0.7634
2	2.2753	2.4141	2.4023
3	11.1689	11.6856	11.2975
4	26.4225	24.4011	23.6184
5	14.6470	14.0697	13.5756
6	21.4171	21.6846	20.7106
7	16.8860	16.9573	16.9054
8	16.9675	17.4505	16.8827
9	16.2924	16.9487	16.3961
10	104.3738	104.8153	104.4206
11	19.3895	19.9820	18.9880
12	21.9946	22.1113	22.0282
13	138.6009	138.0919	137.3342
14	134.0852	136.0478	135.5181
15	132.3741	136.1677	135.5574
16	105.1711	104.4591	104.2124
17	61.6268	61.3052	61.0072
18	38.1365	38.5133	38.0035
19	31.4916	32.7928	32.7160
20	87.6597	90.9903	88.6342

21	105.4407	105.8386	105.4597
22	25.0104	25.1118	24.9157
23	25.3884	25.4795	25.4414
24	67.7999	68.1506	67.5331
25	17.0130	17.8373	17.3004

The smaller the standard deviation, the higher the accuracy of the extracted centerline and vice versa. From the data in Table 1, it is obvious that the standard deviation of centerlines extracted with the proposed method is smaller than that of centerlines extracted with traditional gray gravity method. This shows that the extraction accuracy of the proposed method is better than that of traditional gray gravity method.

4.2 Speed Analysis of Light Stripe Centerline Extraction

The computer used for image processing is a Dell OptiPlex 7080 workstation; The CPU is Intel(R) Core (TM) i7-10700; the RAM is 64G; the image processing software used is MATLAB 2021a. The centerlines of 25 different line structured light stripe images mentioned above are extracted using the three centerline extraction methods and repeated three times. Their respective average extraction times are shown in Table 2.

Table 2

Average running time of extraction methods of light stripe centerline

light stripe	Steger method/s	gray gravity method/s	the proposed method/s
1	0.1527	0.0179	0.0036
2	0.1684	0.0091	0.0030
3	0.1385	0.0156	0.0039
4	0.1691	0.0176	0.0044
5	0.1708	0.0266	0.0146
6	0.1754	0.0249	0.0154
7	0.3473	0.0606	0.0051
8	0.3709	0.0589	0.0059
9	0.3460	0.0607	0.0044
10	0.3572	0.0597	0.0068
11	0.3475	0.0598	0.0060
12	0.3548	0.0595	0.0062
13	0.3922	0.0585	0.0038
14	0.3667	0.0577	0.0039
15	0.3621	0.0582	0.0041
16	0.3493	0.0601	0.0065
17	0.2472	0.0450	0.0029
18	0.1187	0.0093	0.0018
19	0.1467	0.0125	0.0018
20	0.2650	0.0176	0.0064
21	0.3716	0.0641	0.0070

22	0.3351	0.0210	0.0044
23	0.3031	0.0160	0.0059
24	0.2969	0.0153	0.0045
25	0.2810	0.0487	0.0056

Table 2 shows that the speed of the proposed method is the fastest compared with gray gravity method and Steger method, which is several times faster than traditional gray gravity method and more than 10 times faster than Steger method. The proposed method uses the extreme method to get the initial center points, determines the number of subpixel points in the positive and negative direction of the normal direction of the initial center points according to the width of the light stripe, and then the exact center points of each set of subpixel points are calculated using the gray gravity method. However, the traditional gray gravity method obtains the center point of each column by calculating the all-pixel points of each column in the image. This inevitably makes the calculation amount of the proposed method less than that of the traditional gray gravity method, which makes the calculation speed of the proposed method faster. Experiments show that the centerline extraction method proposed in this paper is fast, can meet the real-time requirements of non-contact measurement based on-line structured light, and provides technical support for the subsequent fast acquisition of 3D point cloud.

5. Conclusions

Under the background of the broad application of non-contact measurement technology, this paper presents a centerline extraction method for line structured light stripes based on extreme value and gray gravity methods. Experiments show that the proposed method has high accuracy in centerline extraction, fast computing program and can meet the accuracy and real-time requirements of non-contact measurement, which has certain engineering practice value.

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