

Article

Laser Spot Centering Algorithm of Double-Area Shrinking Iteration Based on Baseline Method

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Abstract: High-precision laser spot center detection occupies an important position in optical measurement technology. In this paper, we propose a laser spot centering method to improve positioning accuracy. This method is an iterative double-area shrinkage approach based on the baseline method. The background noise baseline is calculated from the noise statistics of multiple background image frames acquired, and then the background noise is subtracted during the calculation while retaining the effective information of the spot region. The real spot area is located in the end by double-area shrinkage iteration to calculate the position of the spot center. Simulation and experimental results showed that our proposed method has strong anti-background noise interference ability, as well as higher positioning accuracy in locating the spot center than commonly used approaches; the maximum localization accuracy could reach 0.05 pixels, meeting the real-time requirements of the algorithm. The fluctuation range of measurement results was small when continuously detecting the center of the same laser spot, which could reach 0.04 and 0.03 pixels in the x- and y-directions, respectively. The result indicates that the method can meet the requirements of laser high-precision positioning.

Keywords: laser spot center; baseline method; double-area shrinkage

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1. Introduction

With the development of industrial manufacturing and other industries, the process level has been improving, and measurement and positioning work as a guarantee of product quality has become more and more important, while the realization of high-precision automatic positioning has become a difficult research point. Compared with manual positioning, laser positioning has the advantages of high detection accuracy, good safety, and convenient operation, but the traditional laser center position detection algorithm does not meet the demand of high accuracy, and the calculation results may have large errors in a noisy environment. Therefore, there is a need to improve the accuracy of laser spot center detection in complex situations to ensure the smooth completion of the measurement work. Laser spot center location, which is widely applied in various measurement systems, including optical communication systems, optical path auto-collimation systems, and optical displacement angle measurement systems, is an important topic in the field of photoelectric detection and image processing [1–4]. The possible accurate positioning of the laser spot center directly determines the level of measurement accuracy.

Pixel-level centering was commonly used to locate the center to an image element early on, but the system could not achieve the required accuracy in some demanding situations. Therefore, a higher-accuracy center sub-pixel positioning algorithm is needed, which can position the result to sub-pixel level and, thus, greatly improve the measurement accuracy of the system. At present, algorithms that determine the laser spot center are divided into two categories: those based on edge detection and those based on gray values.

The edge detection-based algorithm assumes that the ideal spot geometry is a circle or an ellipse and largely adopts approaches, such as circle fitting [5–8]. The gray value-based algorithm mainly analyzes the surface characteristics of image intensity function to determine the laser spot center, which largely includes the centroid algorithm and the Gaussian fitting algorithm [9–11]. The aforementioned algorithms have some shortcomings in terms of positioning accuracy and computational complexity. The shape of the laser spot in practical measurements is often unpredictable. However, the circle fitting algorithm has high requirements for spot integrity, as well as poor interference resistance; the accuracy of the center operation is significantly reduced when in a noisy environment, and the obtained circle center may even produce obvious errors when encountering very strong external interference, representing serious limitations [12]. The Gaussian fitting method is computationally intensive, has high computational complexity, and exhibits poor real-time performance. In comparison, the gray centroid method, which does not require any prior knowledge about the spot shape, is widely used in various measurement systems because of its simplicity and robustness [13–17]. Based on the gray centroid method, many scholars have proposed improved methods, such as the square-weighted centroid method.

It is inevitable that the result is affected by the noise of the CCD and the environmental background noise in the process of laser spot center positioning, which has a certain impact on the spot image and results in relatively low positioning accuracy. The impact of CCD noise mainly comes from the discrete and incomplete sampling error of CCD, photon noise error, readout noise error, CCD background noise error, etc. Therefore, it is necessary to operate the image algorithm on the CCD acquired spot image before the measurement to reduce the influence of noise as much as possible. Image denoising is commonly used to improve the accuracy of spot center location [18]. Existing image denoising methods primarily include the threshold method, matching window method, and image interpolation method. Although these methods reduce the influence of noise to a certain extent, some limitations cannot be ignored. The threshold method is commonly used to reduce the effect of uniform noise, but it has the problem of manual parameter selection. The matching window method can eliminate the influence outside the matching window, but cannot reduce the noise inside the matching window. Processing with the image interpolation method can improve the signal-to-noise ratio of the image to a certain extent, but the measurement algorithm consumes more and more time and cannot meet the requirements of real-time detection as the interpolation accuracy increases [19–21].

An iterative double-area shrinkage method based on the baseline method, which can determine the exact location of the laser spot center, is presented in this paper. The proposed method eliminates the effect of noise by calculating the background noise baseline from multiple background images. Subsequently, the real spot area is located using double-area shrinkage iteration to calculate the spot center. Section 2 describes the traditional center positioning method. Section 3 introduces the realization principle of this approach. Section 4 conducts simulations, experiments, and comparisons with typical algorithms to verify the effectiveness of the proposed method. Lastly, Section 5 summarizes the conclusion.

2. Traditional Central Positioning Method

2.1. Circle Fitting Algorithm

The laser spot can be regarded as a circle under ideal conditions, and the center of laser spot is the circle's center. However, it will cause the asymmetry of the laser spot distribution, and the obtained spot is often not a standard circle due to the presence of scatter, uneven reflection from the measured object surface, and the influence of the optical system in the actual optical measurement. The laser spot center detection algorithm based on circle fitting uses a circle to approximate the contour of the laser spot according to the principle of least squares, such that the center of the spot, as well as the radius, can be calculated.

The least squares circle fitting curve is

$$R^2 = (x - \bar{x})^2 + (y - \bar{y})^2. \quad (1)$$

It can be expanded to obtain

$$R^2 = x^2 - 2\bar{x}x + \bar{x}^2 + y^2 - 2\bar{y}y + \bar{y}^2, \quad (2)$$

where R is the radius of the circle; $\bar{x}$ and $\bar{y}$ are constants. Another expression for the circle is

$$x^2 + y^2 + ax + bx + c = 0. \quad (3)$$

Let $a = -2\bar{x}$, $b = -2\bar{y}$, $c = \bar{x}^2 + \bar{y}^2 - R^2$; then, only the parameters a , b , and c are needed to find the center and radius of the circle.

2.2. Gray Centroid Method

The gray centroid method is a sub-pixel algorithm commonly used for high-precision localization of regular or irregular targets in images. In optical measurement systems, the gray centroid method is commonly used to calculate the laser spot center position. Suppose that the size of the spot image is $m \times n$, and the gray value of each pixel point is $G(i, j)$. The centroid of the laser spot is calculated using the following formula:

$$x_c = \frac{\sum_{i=1}^m \sum_{j=1}^n i \times G(i, j)}{\sum_{i=1}^m \sum_{j=1}^n G(i, j)}, \quad y_c = \frac{\sum_{i=1}^m \sum_{j=1}^n j \times G(i, j)}{\sum_{i=1}^m \sum_{j=1}^n G(i, j)}. \quad (4)$$

The processing of the gray centroid method is simple and requires only a small amount of calculation. However, it is susceptible to the influence of noise, leading to large errors. The gray centroid algorithm can produce high localization accuracy for images with uniform distribution and a high signal-to-noise ratio.

2.3. Gaussian Fitting Method

The energy of the laser spot imaged by the CCD is dispersed from the center of the spot to the surrounding area under ideal conditions, which is expressed as a two-dimensional Gaussian surface distribution of gray values. The Gaussian fitting method can be used to locate the center of the spot accurately for Gaussian-shaped spots. The formula is as follows:

$$I(x, y) = A \exp \left[-\frac{(x - x_0)^2}{\sigma_x^2} - \frac{(y - y_0)^2}{\sigma_y^2} \right], \quad (5)$$

where $I(x, y)$ is the intensity value when the coordinates of the image element are (x, y) , A is the amplitude of the spot, x_0 and y_0 are the center coordinates of the laser spot, and σ_x and σ_y are the standard deviations in the x - and y -directions, respectively.

Taking the logarithm of both sides of Equation (5) and simplifying it to a polynomial, we obtain

$$z = ax^2 + by^2 + cx + dy + f. \quad (6)$$

The coefficients corresponding to the polynomial can be calculated using the least squares method, and then the coordinates of the center of the laser spot can be calculated as follows:

$$x_0 = -c/2a, \quad y_0 = -d/2b. \quad (7)$$

Although the overall accuracy of this method is high, some uncertainty bias occurs after the background noise is removed due to the CCD having a certain degree of background noise and a complicated calculation.

3. Realization Principle of Proposed Approach

An optical system that consists of a laser, laser attenuator, lens, and CCD camera was built to collect the laser spot image (Figure 1). The realization of spot center detection is

shown in Figure 2. To eliminate the influence of noise on the laser spot, the method is divided into two steps. The first step is to calculate the background noise baseline using multi-frame background images acquired by the CCD, and the other locates the center of the laser spot after removing noise.

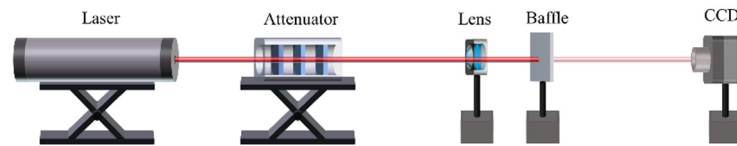


Figure 1. Image acquisition.



Figure 2. Realization of spot center detection.

3.1. Statistics of Background Noise Baseline

The laser spot is not disturbed by noise when collected under ideal conditions. However, it is inevitably affected by various noises in actual laser spot collection. The traditional method is setting a fixed threshold to remove the influence of background noise. Thus, the purpose of eliminating noise effectively is not achieved. In this paper, the baseline method based on the statistical characteristics of noise can be used to calculate the noise distribution from multiple background image frames to obtain the background noise baseline adaptively. The specific process is shown in Figure 3.

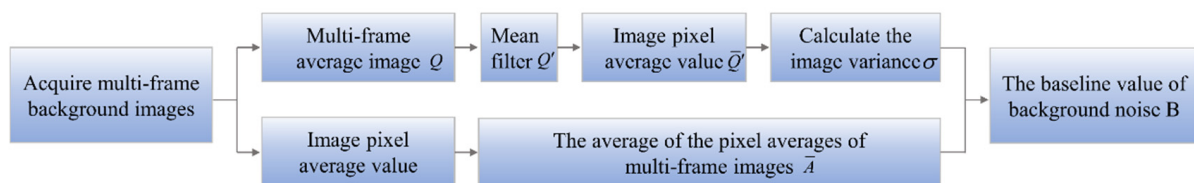


Figure 3. Calculation of the background noise baseline.

After collecting multiple background image frames using a camera, the image gray average and the image gray variance can be calculated using Equations (10) and (11), respectively; subsequently, the background noise baseline can be computed according to Equation (8).

$$B = \bar{A} + \frac{2 \times \sigma}{\sqrt{\text{mask}_x \times \text{mask}_y}}, \quad (8)$$

where B is the calculation result of the background noise baseline, $\bar{A}$ is the overall average pixel value of multiple image frames, and mask_x and mask_y are the sizes of the filter template, set to 0.05 times of the image. If the size of the image is $M \times N$ and the pixel value of the k -th background image at the pixel (i, j) is $f_k(i, j)$, then

$$Q = \frac{1}{n} \sum_{k=1}^n f_k, \quad (9)$$

$$\bar{A} = \frac{1}{n} \sum_{k=1}^n \left(\frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} f_k(i, j)}{M \times N} \right), \quad (10)$$

$$\sigma = \sqrt{\frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} (Q'(i,j) - \overline{Q'})^2}{M \times N - 1}}, \quad (11)$$

where n is the background image frame, Q' is the mean filtering result on the average image Q , in which multi-frame background images are superimposed, and $\overline{Q'}$ is the average pixel value of Q' .

3.2. Spot Center Locating Method

In accordance with the definition of ISO standards, the laser spot centroid and beam width can be calculated using the first-order moment and the second-order moment, respectively [22]. Our method makes improvements on this basis to search for the effective spot area iteratively under the premise of eliminating background noise effectively to enable a more precise computation of spot center.

The approach uses the background noise baseline and the OTSU method to binarize the collected laser spot image. Then, the eight-neighbor connectivity algorithm is used to process the binary image and define the connected domain with the largest area as the first spot area I_1 and the second spot area I_2 . D_x and D_y are the spot area diameters in the x- and y-directions, respectively. The result is shown in Figure 4.

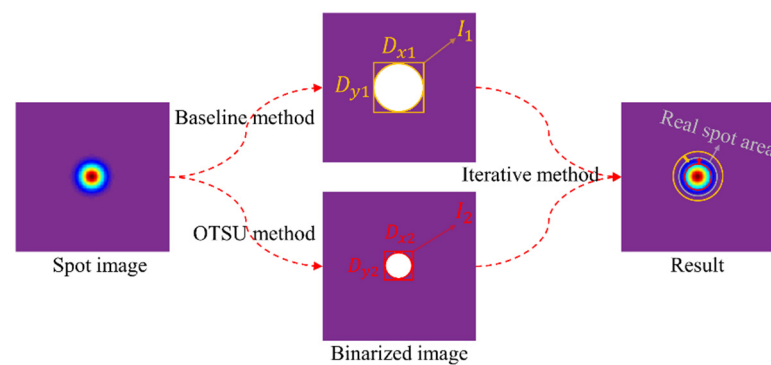


Figure 4. Center location method of laser spot area shrinking iteration.

The initial spot center and radius can be obtained by calculating the pixels in the spot area according to Equations (12) and (13) after determining the initial spot area.

$$\begin{cases} C_{xk} = \frac{\sum_{i=1}^m \sum_{j=1}^n i \times (I_k(i,j) - S_k)}{\sum_{i=1}^m \sum_{j=1}^n I_k(i,j)} \\ C_{yk} = \frac{\sum_{i=1}^m \sum_{j=1}^n j \times (I_k(i,j) - S_k)}{\sum_{i=1}^m \sum_{j=1}^n I_k(i,j)} \end{cases}, \quad (12)$$

$$\begin{cases} R_{xk} = 2 \times \sqrt{\frac{\sum_{i=1}^m \sum_{j=1}^n (i - C_{xk})^2 \times (I_k(i,j) - S_k)}{\sum_{i=1}^m \sum_{j=1}^n (I_k(i,j) - S_k)}} \\ R_{yk} = 2 \times \sqrt{\frac{\sum_{i=1}^m \sum_{j=1}^n (j - C_{yk})^2 \times (I_k(i,j) - S_k)}{\sum_{i=1}^m \sum_{j=1}^n (I_k(i,j) - S_k)}} \end{cases}, \quad (13)$$

where $k = 1$ represents the first spot area, and $k = 2$ represents the second spot area. (C_{xk}, C_{yk}) represents the center coordinates. R_{xk} is the spot radius in the x-axis direction, and R_{yk} is the spot radius in the y-axis direction. S_k is the spot noise baseline. The first

spot noise baseline is the background noise baseline (i.e., $S_1 = B$). The second spot noise baseline is the average value of all the pixel values that are lower than the background noise baseline in the effective area obtained after doubling the second spot area, and, if no pixel value exists below the background noise baseline in the effective area of the light spot, then $S_2 = B$.

Given an initial value ζ , if $R_{x1} - R_{x2} > \zeta$, $R_{y1} - R_{y2} > \zeta$, then the x-axis direction of the first spot area is reduced by $R_{x1} - \frac{D_{x1}}{4}$, and the y-axis direction of the first spot area is reduced by $R_{y1} - \frac{D_{y1}}{4}$, the x-axis direction of the second spot area is extended by $R_{x2} - \frac{D_{x2}}{4}$, and the y-axis direction of the second spot area is extended by $R_{y2} - \frac{D_{y2}}{4}$. When the spot area is changed, the spot center and radius are recalculated iteratively until the radius difference between the two spots is less than ζ , then the iterative convergence condition is met, and the final real spot center is obtained. The real spot center takes the mean value that corresponds to the center of the two spot areas. The same result can be obtained, and, if $R_{x2} - R_{x1} > \zeta$, $R_{y2} - R_{y1} > \zeta$, then the principle is the same.

4. Results and Discussion

4.1. Simulation

The human eye can recognize gray images much less well than color due to the special structure of the human eye; thus, it is necessary to make some pseudo-color processing of gray images to improve people's ability to distinguish the details of images. A certain pseudo-color image processing process is needed for the gray image for a Gaussian distribution of the spot in order to display the details of the spot image in a gradient, in which each gray level of the image is mapped one by one according to a linear or nonlinear function, and different gray levels correspond to different pseudo-colors, so as to achieve the purpose of image enhancement to some extent.

As shown in Figure 5, MATLAB was used for simulation to generate ideal laser spot images with the radius of 20 pixels on the center of a size of 256×256 pixels. The central position was (128, 128). The CCD camera's own noise has a large impact on the image of the laser spot. In order to simulate a noisy environment, random noise was added to the laser spot image using a given signal-to-noise ratio (SNR) according to the random noise characteristics of the CCD. As shown in Figure 6, to imitate the real environment and to verify the feasibility of the method in this paper, we added random noise with different SNRs to the laser spot images, which reflect the changes in the images from low to high SNRs. We generate 10 background noise images for each of the different SNRs, and then an optimal baseline value is calculated using the statistical method of background noise baseline proposed in this paper, which makes it possible to effectively filter out the background noise in the spot image while retaining the true spot information of the laser as much as possible. After the effective elimination of background noise, the threshold value of the difference between the radii of the two spot areas is set $\zeta = 0.1$, iterative area shrinkage is performed based on the difference between the radii of the two newly obtained spot areas, and the real spot area is located until the end-of-iteration condition is satisfied, allowing the center of the spot to be calculated.

As shown in Figure 7, the method proposed in this paper and some popular algorithms were used to compare the deviation of the detected spot center from the true spot center after the corresponding denoising of the spot image. With the gradual increase in image SNR, the deviation between the detected spot center and the real spot center determined using the Gaussian fitting algorithm, traditional centroid method, and square-weighted centroid method decreases rapidly, and the center localization accuracy improves. However, these methods are easily affected by background noise. The deviation between the center positioning results of x-axis and y-axis and the true center is more than 0.2 pixels when the interference from background noise is large (SNR = 12.5), and the fluctuation range of the center positioning results is larger as the SNR of the image increases. In contrast, the method proposed in this paper could find the center of the laser spot accurately under

the interference of background noise, with the maximum centering accuracy reaching 0.05 pixels, and the deviation of the spot centering results fluctuated slightly.

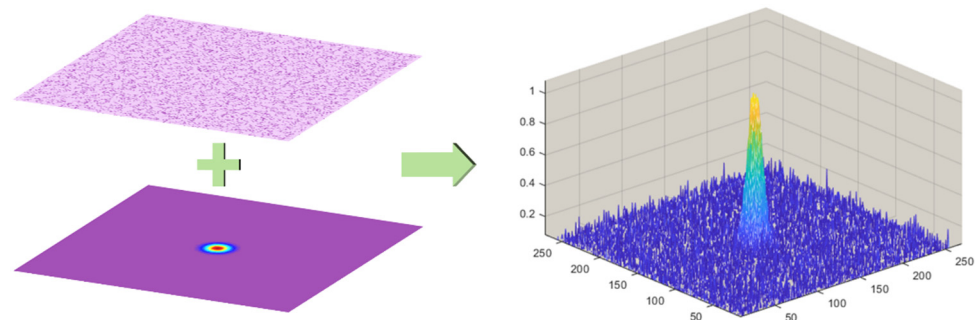


Figure 5. Simulation of noise generation in laser spot image.

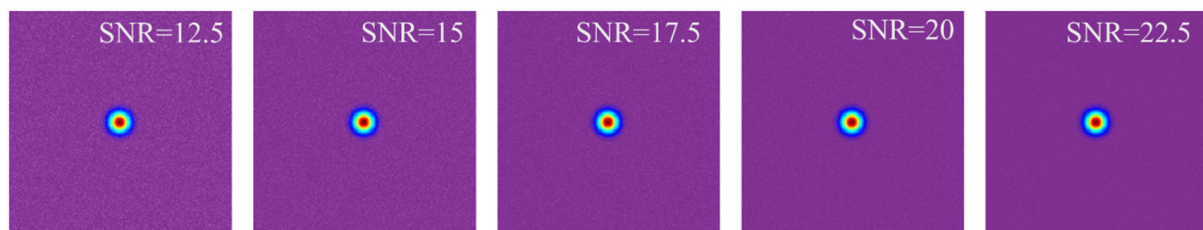


Figure 6. Laser spot after adding noise with different SNRs.

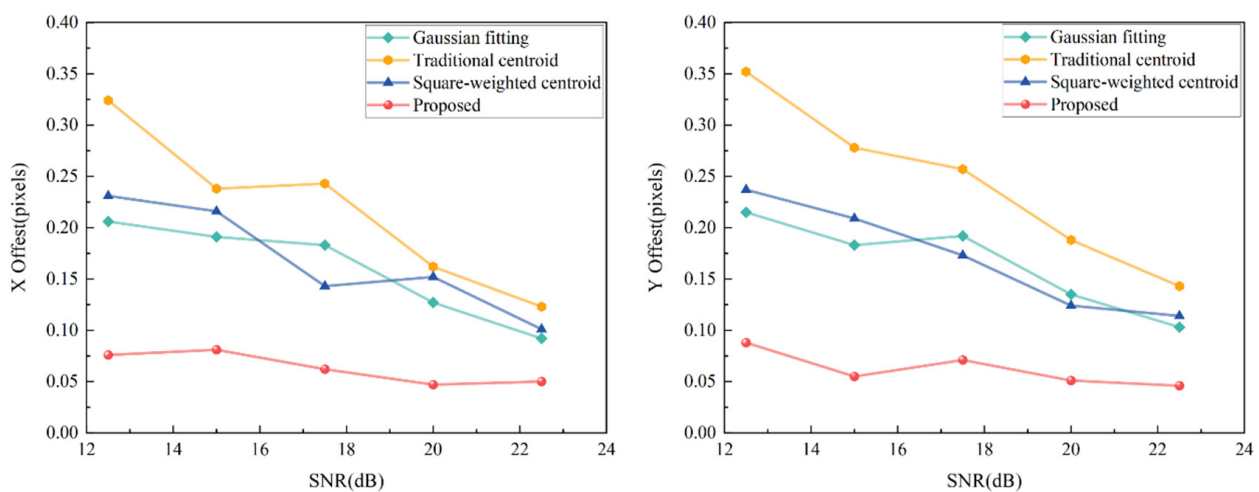


Figure 7. Deviation of the center locating results of several algorithms from the true center in the x- and y-directions.

The iterative convergence of the spot area in this paper is shown in Figure 8. The spot area stabilized at the third–fourth iterations, and the final spot center was calculated. Figure 9 shows the comparison of the running time of different algorithms. Although the computational complexity of this paper’s algorithm is higher than that of the traditional and square-weighted centroid methods, our algorithm was less complex than that of the Gaussian fitting algorithm, and our average running time was 0.061 s, thus meeting the real-time requirement. Therefore, the positioning accuracy and running efficiency of the spot center localization method in this paper could obtain better results.

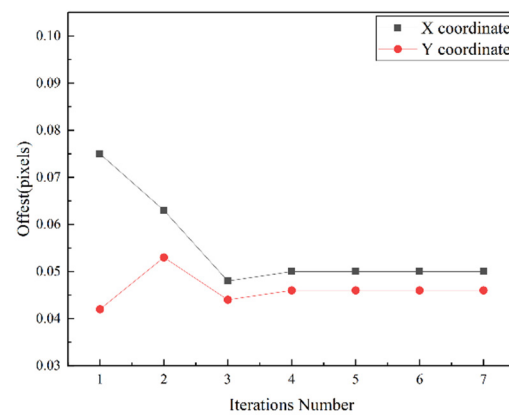


Figure 8. Iterative convergence process of spot area.

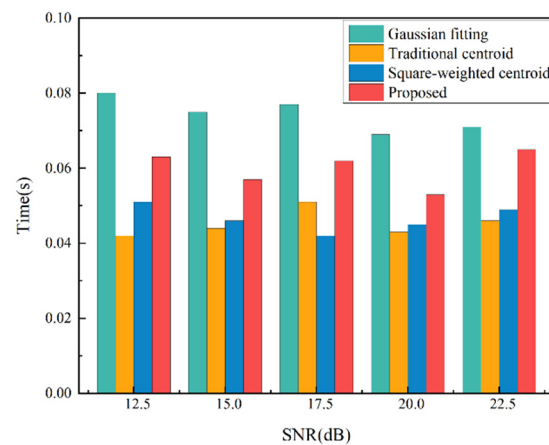


Figure 9. Running time of different algorithms.

4.2. Experiment

We performed a specific practical experiment to further testify the validity of our proposed method. Figure 10a shows the experimental platform of the CCD-based laser beam measurement system built to acquire the laser spot. First, the laser light is generated by the GY-10 He–Ne laser which has better stability and reliability. Then, the attenuator is added to attenuate the laser beam energy incident on the photosensitive surface of the CCD camera in order for the CCD to receive energy without oversaturation to protect the CCD camera, considering that the energy of the laser beam may far exceed the saturation energy value of the CCD detector or even exceed the damage threshold of the CCD image element, which may damage the CCD device. The laser beam enters the lens after attenuation, which is used to ensure that the laser beam is within the measurable range. Finally, the beam is passed into the CCD camera, which completes the acquisition of the laser spot image.

Table 1 presents the device parameters used for the experiment. We used a masking plate to mask the laser so that 10 consecutive background images were acquired for background noise baseline statistics. Then, we acquired the laser spot to obtain a 1626×1236 pixel gray image. Since we cannot know the exact true spot center of the real acquired laser spot, multiple frames of spot images were acquired continuously for centering to perform stability analysis of the algorithm. Figure 10b shows that we continuously collected 10 frames of laser spot images displayed in pseudo-color in the same location. Table 2 displays the center positioning results of different algorithms for 10 consecutive laser spot image frames. Table 2 depicts that the location accuracy of several methods for comparison could reach the sub-pixel level.

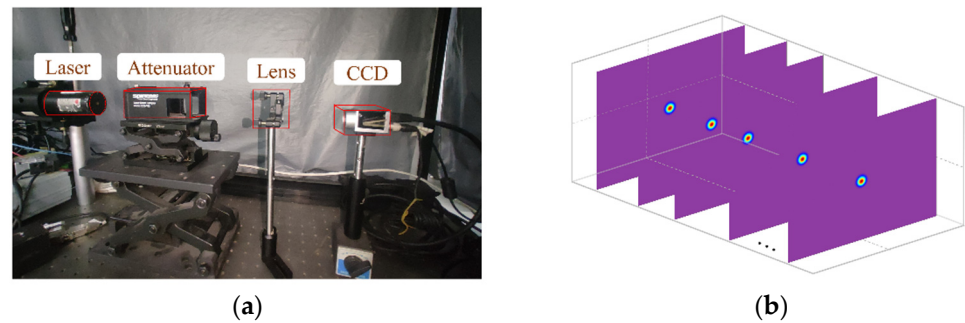


Figure 10. Laser spot images are collected by CCD: (a) experimental platform; (b) continuous image acquisition.

Table 1. Device parameters used for the experiment.

Equipment Name	Equipment Parameter	Value
Laser	Type	GY-10 He–Ne
	Wavelength	632.8 nm
	Power	1.5 mw
CCD	Type	BASLER ACA1600-20GM
	Max resolution	1626 × 1236
	Pixel size	4.4 μm × 4.4 μm
	Output format	Mono 8-bit

Table 2. Laser spot center located by different algorithms.

Method	Gaussian Fitting		Traditional Centroid		Square-Weighted Centroid		Proposed	
Number	x (Pixels)	y (Pixels)	x (Pixels)	y (Pixels)	x (Pixels)	y (Pixels)	x (Pixels)	y (Pixels)
1	800.536	631.156	800.581	631.218	800.483	631.241	800.522	631.199
2	800.419	631.208	800.498	631.272	800.542	631.149	800.499	631.206
3	800.466	631.218	800.685	631.192	800.547	631.195	800.488	631.220
4	800.504	631.168	800.487	631.207	800.612	631.234	800.526	631.196
5	800.548	631.210	800.453	631.118	800.371	631.318	800.532	631.208
6	800.344	631.345	800.547	631.394	800.501	631.118	800.492	631.221
7	800.514	631.168	800.582	631.245	800.484	631.215	800.514	631.216
8	800.489	631.262	800.391	631.247	800.625	631.307	800.497	631.195
9	800.461	631.233	800.347	631.195	800.521	631.165	800.503	631.215
10	800.525	631.192	800.476	631.290	800.393	631.197	800.511	631.198

After the corresponding denoising of the spot images, Table 3 shows the accuracy analysis and comparison of different center positioning algorithms in the x- and y-directions. The difference between the maximum positioning result and the minimum positioning result in the x and y directions was compared when centering 10 frames of spot images in succession. The results show that 0.204 and 0.189 pixels were reached for the Gaussian fitting method, 0.338 and 0.276 pixels were reached for the traditional centroid method, and 0.254 and 0.2 pixels were reached for the square-weighted centroid method, respectively. This shows that the fluctuation range of the center location results of these three methods exceeded 0.1 pixels. In comparison, the proposed method had the best results among other methods, regardless of whether it was the fluctuation range of the center positioning coordinates in the x-direction or y-direction, reaching 0.044 and 0.026 pixels, respectively, and the average standard deviation (SD) was even lower at 0.015 pixels on x and 0.01 pixels on y (Table 3), proving good stability.

Table 3. Analysis and comparison of different algorithm results.

Method	Max _x	Min _x	Δx	Max _y	Min _y	Δy	SD _x	SD _y
Gaussian fitting	800.548	800.344	0.204	631.345	631.156	0.189	0.062	0.056
Traditional centroid	800.685	800.347	0.338	631.394	631.118	0.276	0.099	0.073
Square-weighted centroid	800.625	800.371	0.254	631.318	631.118	0.200	0.082	0.064
Proposed	800.532	800.488	0.044	631.221	631.195	0.026	0.015	0.010

The experimental findings show that the fluctuation range of the center positioning result of the proposed method was small when the center of the same laser spot was detected continuously. The locating stability for laser spot using the proposed method was improved sevenfold compared with the traditional centroid method and improved five-fold compared with the Gaussian fitting algorithm. It should be noted that this study had some shortcomings. We only focused on cases where the intensity distribution of the laser beam was Gaussian, while ignoring the beam distortion, top-hat beam, etc. Theoretically, the method is not affected by the spot morphology, which we will verify in future experiments.

5. Conclusions

The gray centroid method is usually used in laser spot center positioning systems. However, it cannot achieve satisfying accuracy because of its susceptibility to background noise. Thus, on the basis of gray centroid method, we proposed an iterative double-area shrinkage method based on the baseline method to improve the spot center localization performance. The laser spot image acquired by CCD is mixed with many random noise components, the influence of noise can be effectively suppressed through the noise baseline statistics, and then the real spot area can be located so as to calculate the spot center through the double area iteration. In this paper, the effectiveness of the method was verified from two perspectives: simulation and real experiments. The simulation experiments were mainly used to verify the detection accuracy and robustness of the algorithm to noise and analyze the time complexity of the algorithm. The real experiments were mainly used to verify the usability of the algorithm and the stability of continuous measurement under a real environment. The experimental results on simulated and real laser spot images show that our proposed method could achieve more accurate center localization than the commonly used methods. In the simulation experiments, the maximum localization accuracy of the proposed method could reach 0.05 pixels, while meeting the real-time requirements of the algorithm. The fluctuation range of the measurement results could reach 0.04 and 0.03 pixels in the x- and y-directions, respectively, with excellent stability when the center of the same laser spot was detected continuously. Therefore, this method can meet the requirements of laser high-precision positioning.

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