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A Multi-Strategy Method for Spot Center Localization and Error Measurement in Engineering Applications

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Abstract. To address the challenges of existing automatic spot-center positioning methods in engineering applications, namely the difficulty in simultaneously achieving real-time performance, positioning accuracy, and detection stability, this study proposes a multi-strategy approach for spot-center positioning and error measurement. This method integrates the center of mass approach, elliptical fitting, and two-dimensional Gaussian fitting. It selects strategies based on real-time and accuracy constraints for different detection scenarios, while introducing a unified error measurement model for the quantitative evaluation of positioning results. By establishing a pixel-to-physical coordinate mapping, a systematic evaluation of spot center localization and aiming error was achieved using metrics such as the root mean square error. Experiments demonstrated that under both static and dynamic conditions, this method exhibits excellent robustness and stability, meeting the comprehensive requirements for accuracy and real-time performance in engineering applications.

Keywords: *Multi-strategy Fusion; Spot Center Positioning; Error Measurement; Performance Trade-off; Deviation Calculation*

1. Introduction

Laser aiming technology is widely applied in industrial measurements and equipment calibrations, where its precision and stability directly impact system reliability and safety [1-2]. While existing methods have extensively studied theoretical accuracy, traditional single-positioning approaches struggle to balance precision, efficiency, and stability under complex lighting conditions, background interference, and variable spot shapes, which limits their engineering applications. Therefore, constructing a multi-strategy fusion positioning framework for complex engineering environments—enabling the complementary advantages of different positioning methods, dynamically adjusting weights to balance accuracy and computational efficiency, and integrating positioning results with target surface calibration for quantitative error measurement [3] has become a critical challenge for enhancing the practicality and robustness of visual inspection systems.

Existing automated spot center localization methods: Scholars worldwide have proposed various computer vision-based detection methods. Current laser spot center localization methods primarily fall into three categories: first, methods based on gray-level centroid calculation, which offer high computational efficiency but weak interference resistance [4]; second, methods based on contour geometric modeling, which exhibit good stability but rely on edge extraction quality [5]; and third, methods based on two-dimensional Gaussian distribution modeling, which offer high accuracy but involve complex computations [6-7]. Existing research primarily focuses on optimizing individual methods, lacking a systematic analysis of the trade-offs between accuracy, efficiency, and stability across different approaches, thereby limiting their application in complex engineering environments.

To address these issues, this study proposes a multi-strategy approach for engineering-oriented spot center localization and error measurement. The key contributions of this study are as:

(1) Establishing a multi-strategy localization framework that allows flexible selection based on engineering requirements, achieving an effective trade-off between detection accuracy and computational efficiency.

(2) Integrating a target surface calibration model to establish a unified laser aiming error measurement method, enabling the quantitative calculation of deviation distance and direction [8-9].

(3) Validating the robustness and stability of the proposed method under complex illumination conditions through comparative experiments [10].

2. Multi-Strategy Spot Center Localization and Error Measurement Method

2.1. System Design

To address the diverse requirements for detection accuracy and real-time performance in engineering applications, this study proposes a multi-strategy framework for spot-center positioning and error measurement. The overall system architecture is illustrated in Figure 1.

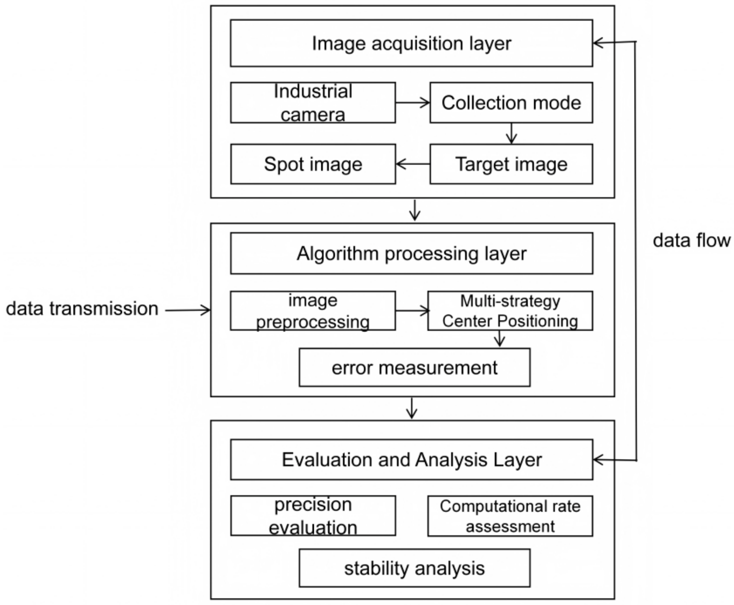

Figure 1. Framework of the multi-strategy spot center localization and error measurement system

The algorithm processing layer of this framework undergoes a focused design comprising three key steps:

(1) Spot image preprocessing: Denoising, enhancement, and segmentation are performed on the raw target surface image to obtain a stable spot region [11-12].

① Noise reduction: Employ a 3×3 median filter to eliminate isolated noise and salt-and-pepper noise while preserving edge structures; in dynamic scenes, overlay a 5×5 Gaussian filter $(\sigma = 1.0 - 1.5)$ to suppress random noise, ensuring continuous grey-level distribution and facilitating subsequent Gaussian fitting.

② Image enhancement: Performed grey-level normalisation, mapping pixels to [0,255]; employed Contrast-Enhancing Localised Adaptive Histogram Equalisation (CLAHE) to boost local contrast, followed by γ correction $(\gamma = 0.8 - 1.2)$to accentuate the difference between the light spot core and background, thereby improving segmentation stability.

③ Threshold Segmentation: Under static, uniform illumination conditions, employ Otsu's global threshold segmentation. For dynamic or fluctuating illumination scenarios, utilise local mean adaptive threshold segmentation $(\text{window size } 21 \times 21, \text{C} = 5 - 10)$. Following binarisation, perform 3×3 structural element opening operations and connected component analysis, retaining the largest connected region as the valid light spot area.

(2) Multi-strategy spot center localization: Select an appropriate center localization strategy based on engineering application requirements to extract the spot center [13-14]. Upon obtaining a stable spot region, the system enters the multi-strategy centre localisation phase.

Unlike traditional methods employing a single fixed algorithm, this approach supports three centre localisation strategies: grey-level centroid method, elliptical least-squares fitting, and two-dimensional Gaussian fitting.

(3) Error visual measurement: The target surface calibration model is combined to convert pixel coordinates to physical coordinates to calculate aiming error offsets [15].

Through this framework, different center positioning strategies can be flexibly switched under a unified data flow and error model, thereby adapting to the comprehensive demands of accuracy, efficiency, and stability in various engineering inspection scenarios.

2.2. Related Methods

2.2.1. Multi-Strategy Spot Center Localization

To address the diverse spot center localization demands across inspection scenarios, this study proposes a multi-strategy approach. This method integrates three common localization algorithms—centroid-based, elliptical fitting, and two-dimensional (2D) Gaussian fitting—within a unified framework. By selecting strategies based on real-time and accuracy constraints for different scenarios, optimal localization precision and robustness are ensured while maintaining real-time performance.

(1) Gray-Scale Centroid Method

The gray-level centroid method treats the laser spot as a two-dimensional distribution. The "center of mass" of the spot is calculated by performing a weighted average of the gray-level values of pixels within the spot region, using this as the spot center position.

Since the spot brightness follows a Gaussian-like distribution, its center can be obtained through brightness-weighted summation: Let the spot region be Ω, the pixel coordinates in the image be (x, y), and the corresponding grayscale value be $I(x, y)$. The spot center coordinates can be expressed as

$$x_c = \frac{\sum_{(x,y)\in\Omega} x \cdot I(x,y)}{\sum_{(x,y)\in\Omega} I\,(x,y)}, \quad y_c = \frac{\sum_{(x,y)\in\Omega} y \cdot I(x,y)}{\sum_{(x,y)\in\Omega} I\,(x,y)}$$

In the image coordinate system, (x, y) represents the horizontal and vertical coordinates of a pixel. The value $I(x, y)$ indicates the gray level of the corresponding pixel, showcasing its light intensity. Additionally, Ω defines the spot region obtained through threshold segmentation or preprocessing.

This method features a simple algorithmic structure and high computational efficiency, enabling rapid spot-center localization with a low computational overhead. It is suitable for engineering scenarios that demand high real-time performance, where the spot shape is regular and background interference is minimal. However, it is sensitive to grayscale distribution and may exhibit positioning shifts under conditions of noise interference, spot asymmetry, or local saturation, which limits its robustness and accuracy.

(2) Elliptical Least Squares Fitting

The elliptical least-squares fitting method first extracts the edges of the spot, approximates the spot contour as an elliptical model, fits the elliptical parameters using the least-squares method, and uses the center of the ellipse as the spot center.

Fitting a quadratic curve:

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0$$

Solve for parameters $\mathrm{A, B, C, D, E, F}$ via least squares. Under elliptical constraints, the center coordinates are given by

$$x_c = \frac{2CD - BE}{B^2 - 4AC}, \quad y_c = \frac{2AE - BD}{B^2 - 4AC}$$

In this context, x and y denote the pixel coordinates of the spot's edge points. The parameters $A{\sim}F$ represent the ellipse model parameters derived from fitting the set of edge points.

This method determines the center position by geometrically modeling the spot edges, thereby reducing the dependence on a uniform light intensity distribution. It maintains good positioning stability even under spot deformation or center grayscale saturation, making it suitable for detection scenarios with slightly irregular spot contours or elliptical deformations. However, it relies heavily on edge extraction quality and has high computational complexity, potentially leading to reduced positioning accuracy in complex backgrounds or under blurred edge conditions.

(3) Two-Dimensional Gaussian Fitting

The 2D Gaussian fitting method assumes that the intensity distribution of the laser spot approximates a 2D Gaussian function. This distribution was fitted using nonlinear least squares, with the center of the fitted function representing the center of the spot.

The 2D Gaussian model can be expressed as

$$I(x, y) = I_0 \exp\left(-\frac{(x - x_0)^2}{2\sigma_x^2} - \frac{(y - y_0)^2}{2\sigma_y^2}\right) + I_b$$

In this context, $I(x, y)$ represents the gray value at pixel coordinates (x, y). The variable I_0 denotes the peak intensity of the spot, while (x_t, y_t) indicates the center of the Gaussian distribution, marking the coordinates of the spot's center. The parameters σ_x and σ_Y define the expansion scales of the spot in the x and y directions, respectively. Lastly, I_b refers to the background gray value bias term.

This method, based on a two-dimensional Gaussian distribution model approximation of the spot, exhibits strong noise resistance and high positioning accuracy. It enables sub-pixel-level center extraction and is suitable for high-precision detection and calibration scenarios. However, its computational complexity and sensitivity to initial parameters limit its engineering applicability when the spot deviates from the Gaussian assumption or when a high real-time performance is required.

2.2.2. Error Measurement

To enable the comparability and quantitative analysis of laser aiming errors across different spot-center positioning strategies, this study establishes a unified error measurement method based on multi-strategy positioning results. This method uses target calibration to establish a mapping relationship between the pixel and physical coordinates, providing a unified description of the deviation of the spot center relative to the target center.

The method first obtains the pixel-to-physical coordinate scaling factor k through calibration. It then converts the pixel coordinates of the spot center (x_c, y_c) to a physical coordinate system with the target center as the origin (X, Y). The conversion relationship is as follows:

$$X = k(x_c - x_t), \quad Y = k(y_c - y_t)$$

where (x_t, y_t) denotes the target center pixel coordinate system.

Based on this, the aiming errors are uniformly described in terms of their magnitude and direction as follows:

① Deviation Distance: The magnitude of the offset between the spot center and the target center is introduced as the deviation distance d, defined as the "Euclidean distance" between the spot center and the target center in the physical coordinate system:

$$d = \sqrt{(X)^2 + (Y)^2}$$

where: X, Y are the coordinate components of the spot center in the physical coordinate system.

② Deviation Angle: The directional characteristic of the spot center's offset. The deviation angle θ is defined as the azimuth angle of the spot center relative to the target center in the physical coordinate system:

$$\theta = \arctan\left(\frac{Y}{X}\right)$$

where: θ denotes the angle between the offset direction of the spot center and the X − axis; X and Y represent the coordinate components of the spot center in the physical coordinate system.

This measurement is independent of specific localization strategies and applies to different localization results, such as the gray-level centroid, elliptical fitting, and two-dimensional Gaussian fitting methods, providing a unified evaluation basis for comparing the performance of multi-strategy approaches.

2.3. Adaptive Spot Localization Strategy Selection

Strategy selection is critical for multi-strategy localization methods. Based on the distinct characteristics of the application scenarios, the most suitable strategy selection mechanism must be identified. The system automatically presets the selection prior to operation, according to the engineering application requirements. The specific selection principles were as follows:

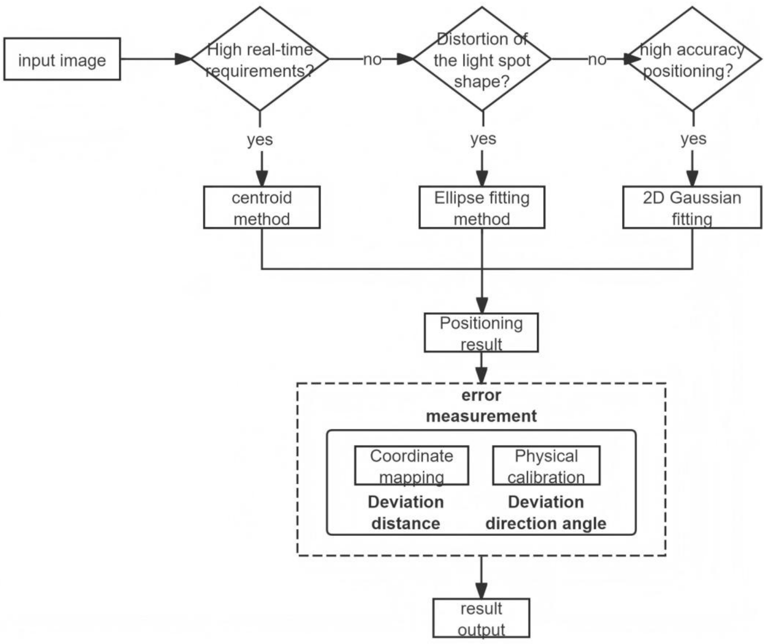

Figure 2. Multi-strategy spot center localization selection architecture

① Scenarios with high real-time requirements: For dynamic monitoring (e.g., moving laser targeting), the centroid method is recommended. This approach calculates the center of gravity of the spot using grayscale weighting, enabling millisecond-level positioning to meet real-time detection demands.

② Scenarios with spot shape distortion: When the spot becomes distorted owing to the imaging angles or optical system effects, the elliptical fitting method is recommended. This technique enhances the positioning accuracy by fitting the spot contour with an ellipse, thereby improving the system robustness under suboptimal conditions.

③ High-precision static scenarios: For static detection or calibration requiring extreme accuracy, the 2D Gaussian fitting method is recommended. This technique establishes a 2D Gaussian model based on the brightness distribution of the light spot, achieving sub-pixel positioning accuracy suitable for static high-precision calibration. The specific architecture is illustrated in Figure 2.

3. Experimental Design and Validation

3.1. Experimental Scenario Design

Existing research predominantly focuses on single-spot center localization algorithms or compares multiple algorithms in parallel to analyze performance differences. However, studies lacking a unified system framework for achieving algorithmic cooperative scheduling and adaptive selection remain scarce [16-17]. Consequently, although such methods are effective under ideal experimental conditions, they struggle to simultaneously meet real-time, accuracy, and stability requirements in complex engineering scenarios.

To address these limitations, this study introduces the concept of "multi-strategy unified validation" during the experimental design phase. This approach systematically evaluates the performance of different positioning algorithms under static and dynamic conditions, providing an experimental foundation for the subsequent development of automated multi-strategy selection mechanisms. In static experiments, the laser maintained a fixed orientation while continuously capturing multiple frames to analyze spot extraction stability and the repeatability of different center-based positioning algorithms, thereby verifying their positioning accuracy under ideal conditions. In the dynamic experiments, spot offsets of varying magnitudes and directions were generated by adjusting the laser orientation. Corresponding deviation distances and direction angles are calculated to evaluate the system's adaptability and detection stability under multiple aiming states. The experimental system comprises a laser emission module, target surface apparatus, and image processing module. It employs a violet laser and a violet photosensitive target surface. A mark was placed at the target center, with concentric circles of radii 2/4/6/8/10 cm drawn for pixel-to-physical coordinate mapping and deviation calculation

[18].

3.2. Evaluation Metrics

This study constructs an experimental evaluation metric system based on three dimensions: detection accuracy, computational efficiency, and result stability. This metric system aims to comprehensively reflect the performance differences and engineering adaptability of different positioning strategies in practical-detection scenarios.

(1) Positioning Accuracy Metric

Positioning accuracy measures the deviation between the center of the laser spot and its true position, serving as a core metric for evaluating the laser aiming detection performance. This study uses the calibrated physical coordinates of the target surface as a reference and adopts the deviation distance of the laser spot center as the primary accuracy evaluation indicator.

Under static experimental conditions, multiple consecutive frames were captured to compute the deviation distance of the spot center relative to the target center. The root mean square error (RMSE) serves as a quantitative evaluation metric for positioning accuracy and is calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} d_i^2}$$

Among these,d_i represents the deviation distance of the spot center in the i frame image, where Ndenotes the number of sampled frames. RMSE comprehensively reflects the overall level of positioning error and is suitable for precision comparison analysis between different positioning strategies.

(2) Computational Efficiency Metric

Computational efficiency measures the real-time processing capability of different spot-center localization strategies in engineering applications. This study uses the average processing time per frame as the efficiency evaluation metric, encompassing two primary computational processes: image preprocessing and spot center localization.

Under identical hardware and software conditions, the average processing time required by each positioning strategy for a single frame was statistically recorded to reflect the differences in computational complexity. This metric provides an intuitive indication of the suitability of each method for real-time requirements, serving as a crucial basis for flexible multi-strategy selection.

(3) Stability and Repeatability Metrics

Stability evaluates the fluctuation of the spot center positioning results under repeated measurements, serving as a key indicator for assessing reliability in engineering applications. This study analyzes the statistical characteristics of the spot center deviation distance using multi-frame continuous acquisition results from static experiments.

Specifically, the standard deviation (SD) of the deviation distance was adopted as the stability evaluation metric, calculated as follows:

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(d_i - \bar{d})^2}$$

where $\bar{d}$ is the mean deviation distance; d_i represents the deviation distance of the spot center in the i frame image; and N denotes the number of sampled frames. A smaller standard deviation indicates less fluctuation in positioning results and better system stability.

In the dynamic experiments, the consistency of the deviation calculations under varying offset magnitudes and directions was analyzed to further validate the adaptability and robustness of the proposed method in complex detection scenarios.

3.3. Experimental Results and Analysis

Table 1. Performance Comparison of Different Spot Center Localization Algorithms (Static)

Algorithm Type	**Mean Square Error/ mm**	**Maximum Deviation/ mm**	**RMSE /mm**	**Single Frame Processing Time / ms**	**Standard Deviation SD /mm**
Gray-scale Centroid Method	0.082	0.137	0.094	3.1	0.031
Elliptical approximation method	0.041	0.089	0.052	8.6	0.018
Two-dimensional Gaussian fit	0.028	0.061	0.036	21.3	0.021
Gray-scale Centroid Method	0.082	0.137	0.094	3.1	0.031

Under identical experimental conditions, the detection performance of the system in static scenarios was analyzed comparatively. As shown in Table 1., the three spot-center localization algorithms exhibit distinct strengths. The gray-level centroid method achieves the shortest single-frame computation time, making it suitable for high-realtime scenarios. However, its mean error and RMSE are relatively large, and its positioning accuracy is significantly affected by spot morphology and noise. The elliptical fitting method outperforms the gray-level centroid method across all error metrics, demonstrating stability against spot deformation with moderate computation time. The 2D Gaussian fitting method achieves the highest positioning accuracy and best error control; however, its computation is time-consuming, making it unsuitable for direct application in high-real-time scenarios.

Table 2. Performance Comparison of Spot Center Localization Algorithms (Dynamic)

Algorithm Type	Mean Absolute Distance Error/mm	Azimuth Angle Error/°	Single Frame Time Fluctuation/ms	Maximum Transient Deviation / mm	Algorithm Type
Gray-scale Centroid Method	0.035	2.7	±0.4	0.152	Gray-scale Centroid Method
Ellipse Fitting Method	0.022	1.8	±0.7	0.098	Ellipse Fitting Method
Two-dimensional Gaussian fitting	0.019	1.5	±1.2	0.074	Two-dimensional Gaussian fitting
Gray-scale Centroid Method	0.035	2.7	±0.4	0.152	Gray-scale Centroid Method

Table 3. Relationship Between Application Scenario Requirements and Automatic Spot Positioning Strategy Selection

Application Scenario Type	Primary Requirements	System-Automatically Selected Positioning Strategy
Dynamic Real-Time Monitoring	High real-time performance, rapid response	Gray-scale Centroid Method
Spot morphology distortion	Robustness and Stability	Ellipse Fitting Method
Static high-precision detection	High Accuracy, Low Fluctuation	2D Gaussian fitting method
Dynamic Real-Time Monitoring	High real-time performance, rapid response	Gray-scale Centroid Method

Under identical experimental conditions, the detection performance of the system in dynamic scenarios was compared and analyzed. As shown in Table 2., all three spot-center localization algorithms demonstrated excellent adaptability and robustness in dynamic-targeting scenarios. The gray-level centroid method offers significant advantages in terms of computational speed and real-time performance, making it suitable for high-real-time dynamic tracking applications.

The elliptical fitting method demonstrated good robustness against spot deformation and exhibited stable direction and deviation control. The two-dimensional Gaussian fitting method maintains optimal accuracy and is suitable for high-precision slow-change processes.

The combined results of the static and dynamic experiments revealed that the performance advantages of different spot-center localization algorithms under varying operating conditions exhibited significant scenario dependency. Therefore, within a unified detection framework, the system dynamically selects localization strategies based on real-time requirements, spot characteristics, and accuracy demands, as listed in Table 3. The system automatically selects the corresponding localization strategy prior to the operation according to the predefined application scenario requirements and maintains consistency throughout the experiment.

4. Conclusions

4.1. Research Summary

The multi-strategy spot center localization and error measurement method proposed in this study for engineering applications integrates geometric center methods, centroid methods, and Gaussian distribution modeling. By dynamically adjusting the strategy weights, it overcomes the limitations of single strategies under complex conditions, such as varying illumination and background interference. In addition, combined with the target surface calibration model, the proposed error measurement method enables the quantitative calculation of spot localization errors, thereby enhancing the overall accuracy and robustness of the system.

4.2. Limitations of the Current Approach

Although the multi-strategy spot center localization method proposed in this study demonstrated good performance in experiments, it still has some shortcomings and limitations, mainly reflected in the following aspects:

(1) Insufficient Intelligent Strategy Selection: Current strategy selection and weight adjustment rely on preset rules and simple error models, lacking intelligent optimization in dynamic or unknown environments.

(2) Adaptive Error Compensation: Error compensation based on target surface calibration models may be affected by target surface variations and equipment wear in practical applications, necessitating solutions for dynamic corrections and calibration updates.

(3) Robustness in Complex Noise Environments: While proposed method performs well in conventional scenarios, its robustness in extreme noise conditions requires improvement. Enhancing the noise suppression capabilities is a key focus of future research.

4.3. Future Outlook

Future research will focus on exploring intelligent strategy selection mechanisms based on machine learning or adaptive control to further enhance the adaptability and accuracy of the system. Additionally, the introduction of dynamic calibration and adaptive error compensation mechanisms significantly improved long-term stability and precision. Moving forward, we will expand the application scope of this method, exploring its potential in fields such as Unmanned Aerial Vehicles (UAVs), autonomous driving, and robotic vision navigation. We will also strengthen its robustness in extremely noisy environments to accommodate more complex engineering scenarios.

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