Position Measurement of Laser Center by using 2-D PSD and Fixed-axis Rotating Device

PENGCHENG ZHANG¹, JIN LIU¹*, (Member, IEEE), HAIMA YANG²*, (Member IEEE), AND LUO YU¹
¹ School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai 201620, China
² School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
* Corresponding author: JIN LIU (e-mail: flyingpine@sina.com) and HAIMA YANG (e-mail: snowyhm@sina.com)

This work is supported by the National Natural Science Foundation of China under Grant No. U1831133 and 61701296, the Natural Science Foundation of Shanghai under Grant No. 17ZR1443500 and Shanghai Aerospace Science and Engineering Fund with the granted number SAST2017-062.

ABSTRACT Photoelectric non-contact measurement methods have been widely implemented in space target location, micro-displacement measurement and space optical communication. In term of the reliability and precision of measurement systems, it is a great significance to obtain the laser center location accurately. Since the two-dimensional position sensitive detector (2-D PSD) can continuously detects the gravity center position of the laser spot on its photosensitive surface, this paper provides a flexible method with high precision for the nonlinear correction of PSD as well as a new idea for PSD-based moving laser center positioning. Above all, a laser device system that rotating around a fixed-axis is designed, and the rotation angle can be controlled with the rotation accuracy of 0.5°. The trace of the gravity center of the rotating spot generated by the device on the PSD surface is detected, and the laser center location is obtained after further processing of data. In order to improve the detection accuracy of PSD, this research mainly focuses on the nonlinear correction method of the detector and the fitting method of the gravity center trace of the laser spot. Moreover, the effects of different sizes of light spots projected onto the 2-D PSD on the collected photocurrent and estimated coordinates were analyzed by experiments. From the experimental results, the non-linear error of PSD is corrected by the error curved surface interpolation method, the overall error is reduced by more than 32%, and the linearity of the positioning of the laser moving along the diagonal of PSD is 0.2%.

INDEX TERMS Position sensitive detector, Rotating laser, Curve surface fitting, Laser center location

I. INTRODUCTION

With the improvement of the monochromaticity and directionality of semiconductor lasers in recent years, the optical non-contact measurement techniques which aims at positioning and measuring have been extensively applied to such aspects of space optical communication, industrial inspection, optical positioning, laser alignment and target tracking, etc. [1]. The purpose of laser-based measurement system with photoelectric devices is to convert optical signals into electrical signals. Then, acquisition and processing of electrical signals indirectly obtain information of optical signals. Finally, we establish the geometric mathematical model between the optical signals and the target object, and solve the model to gain the position and attitude information of the measured object [2, 3].

Common photoelectric devices include charge coupled device (CCD), four-quadrant detector (QD), and position sensitive detector (PSD). Compared with other devices, PSD possesses great advantages in non-contact measurement field in light of its simplicity of signal processing, high position resolution, wide spectral response, excellent measurement continuity and the ability of simultaneous measurement of laser position and intensity [4, 5]. Xiao developed a flexible, high cost-effective and wide dynamic range photon beam position measurement (PBPM) system based on the PSD, and it has been used on Hefei Light Source (HLS) [6]. David presented an indoor positioning system (IPS) for detecting mobile agents based on a single position sensitive device sensor sited in the environment located on mobile agents [3, 7, 8]. The proposed IPS determined accurately position by the angle of arrival (AoA) of the beam signals received at the PSD.
sensor with lower cost, easier to install and low computational load. Tong proposed a technique and an automated system of measuring screw thread parameter based on the theory of laser measurement, which core is a laser triangulation method based on PSD to measure displacement [9]. However, PSD-based measurement system usually be faced with two problems: background light interference and sensor nonlinearity. For the former problem, We can apply the technique of light intensity modulation and band-pass filter to enhance the signal to noise ratio (S/N) [10, 11]. The latter problem mainly comes from the design structure of the sensor. Therefore, we are more concerned about how to improve the nonlinearity through computer algorithm. Calibration methods are mainly divided into two categories: linear interpolation and artificial neural network [12]. Zheng realizes partial correction of PSD by bilinear interpolation algorithm based on the platform of LABVIEW [13]. Yang introduced how to improve the nonlinearity of PSD by BP neural network and realized by MATLAB toolbox [14].

Considering the above solutions, in order to further improve the detection accuracy of PSD, this paper puts forward a proposal of a PSD-based positioning of laser center by the means of rotation. The method is divided into two main steps. The correction of nonlinearity is achieved first by the error curved surface interpolation approach and then the gravity center trace of the spot can be disposed by the Pratt method. In the end, the purpose of the high-precision center position of moving laser can be achieved. It should be noted that this method needs to consider the size of the spot projected onto the PSD photosensitive surface, and effect can be optimized by selecting the appropriate spot size.

Moreover, the rotating laser device can be employed in many fields. In the field of optical communication [15], high-quality linearly polarized light can be used to replace the laser. The effect can be optimized by selecting the appropriate spot size.

In view that the non-uniformity of the silicon wafer material used to produce the PSD exhibits a gradient change, therefore, the position error function $E(x, y)$ on the photosensitive surface can be deemed as a gradient surface. If the PSD photosensitive surface is discretized and the surface on the mesh is fitted by a binary high-order polynomial, the error value on the non-grid can be acquired by the surface interpolation method. By subtracting the error value from the measured value, the approximated position of the point can be obtained [4, 7]. The curved surface with position errors on the X and Y directions is expressed as:

$$E_{x}(x, y) = \sum_{i=0}^{n} \sum_{j=0}^{m} a_{ij} x^i y^j$$

$$E_{y}(x, y) = \sum_{i=0}^{n} \sum_{j=0}^{m} b_{ij} x^i y^j$$

$$E(x, y) = E_{x}(x, y) + E_{y}(x, y)$$  (2)

where $a_{ij}$ and $b_{ij}$ denote the surface parameters. The 2-D PSD photosensitive surface is discretized into equally-spaced square grids to obtain the measurement points of $k$.
coordinates \((x_k, y_k)\), where \(k > (n+1)(n+2)/2\) is required. The position error value on the X direction corresponding to each measurement point represented as \(e_{xi}\) and according to \(E_{x}(x, y)\), we have:

\[
\begin{bmatrix}
    e_{x1} \\
    e_{x2} \\
    \vdots \\
    e_{xn}
\end{bmatrix} =
\begin{bmatrix}
    1 & x_1 & y_1 & x_1^2 & y_1^2 & \cdots & x_1^k & y_1^k & \cdots & x_1^{n-k} & y_1^{n-k} & a_{m1} \\
    1 & x_2 & y_2 & x_2^2 & y_2^2 & \cdots & x_2^k & y_2^k & \cdots & x_2^{n-k} & y_2^{n-k} & a_{m2} \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots \\
    1 & x_n & y_n & x_n^2 & y_n^2 & \cdots & x_n^k & y_n^k & \cdots & x_n^{n-k} & y_n^{n-k} & a_{mn}
\end{bmatrix}
\]

The above equation can be abbreviated as:

\[e_{xi} = A_0^T x_i \]

Similarly, the linear equations with position error \(e_{yi}\) on the Y direction is as follows:

\[e_{yi} = B_0^T y_i \]

For the purpose of a better fitting effect, it is necessary to select the largest possible \(k\) to construct overdetermined equations [24]. The \(\alpha\) value obtained at this time satisfies that \(A_0^T\) is as close as possible in the sense of the least square error.

According to (4) and (5), we draw the conclusion of the equations of \(\alpha = A_0^T e_{xi}\) and \(\beta = A_0^T e_{yi}\). Under the condition of over-determination, we gained that \(A_0 = (A_0^T A_0)^{-1} A_0\), thereby calculating the values of \(\alpha\) and \(\beta\) [25, 26], and completing the fitting of the error curved surface.

III. Laser center positioning by rotating laser

A. Design of Rotating Laser System

As a typical Gaussian light source, the laser beam produces a light spot with uneven energy distribution when projected onto the photosensitive surface of PSD [27]. At steady state, PSD can continuously detect the gravity center position of the laser spot which is independent of the size of the spot and the energy distribution of the light source [5, 28]. When the laser rotates around a fixed axis, the continuous trace of PSD can be approximately circular curve and the center of the circle should be the actual center of the laser beam. Based on this reasoning, we propose a new method to detect the laser center.

Inspired by the laser shaft alignment instrument [29, 30] and the coaxiality measurement instrument [31], we designed a rotating laser device which can obtain rotating stable light spot.

The rotating laser device consists of a semiconductor laser, a diaphragm coupling and a hollow shaft stepping motor, as shown in Fig. 2. The metal diaphragm coupling is used to compensate the axial, radial and angular deviation between the stepping motor and the laser to improve the alignment accuracy of the device. The power cord pass through the hollow shaft.

The composition of the rotating laser control system is given in Fig. 3. The control of the rotating laser unit is composed by the STM32 microcontroller and the DC stepper motor driver. The software interacts with the microcontroller through the computer serial port to accomplish the open-loop control of the stepper motor. Moreover, the repeatability experiment shows that the rotation resolution of the system is \(0.001^\circ\), the accuracy is \(0.5^\circ\), the rotation range is \(360^\circ\), and the response speed is \(10\, ms\).

When the rotating laser device is operated, the total energy change of the projected spot can be measured by an optical power meter. Note that the laser beam is projected vertically onto the light power meter surface. It can be seen from Fig. 4 that the variation of the optical power is small and stable within \(\pm 1\, \mu W\).

When the rotating laser device is operated, the total energy change of the projected spot can be measured by an optical power meter. Note that the laser beam is projected vertically onto the light power meter surface. It can be seen from Fig. 4 that the variation of the optical power is small and stable within \(\pm 1\, \mu W\).

Inspired by the laser shaft alignment instrument [29, 30] and the coaxiality measurement instrument [31], we designed a rotating laser device which can obtain rotating stable light spot.
Next, Fig. 5 shows the changes in the rotation of a laser spot, and supposes that the red dot indicates the gravity center position of the spot. The digital image of the spot clearly shows that the energy distribution is not uniform and the shape is not an ideal circle. However, the energy distribution of the spot does not change significantly during the rotation.

**FIGURE 6.** Distribution of spot energy on the X-axis and Y-axis.

In addition, we measured the energy distribution of the spot in the orthogonal direction, as shown in Fig. 6. The energy in the X and Y directions is approximately in accordance with the Gaussian distribution of the laser energy, but the difference between them is still apparent, which means that the energy center of gravity and the center of the spot do not coincide. Therefore, the traditional digital image processing method is difficult to obtain an ideal laser center position under the case of non-uniform spot [32]. However, the proposed positioning method is to utilize the PSD to detect the gravity center of the light spot, which greatly reduces the requirements for the spot.

### B. Principle of Laser Center Positioning

After describing the designed device, the process of rotating laser spot center location is introduced in Fig. 7. The rotating laser device rotates counterclockwise for one circle to obtain continuous trace coordinates \((x_i, y_i)(i = 1, 2, \ldots, l)\). Then the trace data are processed by fitting algorithm, and the center coordinate \((X_c, Y_c)\) and the radius length \(r\) are obtained.

**FIGURE 7.** Principle of rotating laser spot center location.

Considering the important index of positioning system with response speed, we adopt the Pratt algorithm based on algebraic fitting to process the trace data. The traditional geometric algorithm requires multiple rounds of iteration to solve the parameters of the circular curve, while the Pratt algorithm is able to obtain them by minimizing the objective function. Therefore, the Pratt algorithm calculates simpler and faster than the geometric one. Besides, it still shares approximate accuracy with geometric fitting methods [33, 34]. The algebraic equation of the circular curve is:

\[
A\left(x^2 + y^2\right) + Bx + Cy + D = 0
\]  

(6)

If the unknown parameters in the above equation are expressed as \(z = [x^2 + y^2, x, y, 1]^T\), and the algebraic parameter vector is represented by \(P = [A, B, C, D]\), then the above equation can be written as \(Z^T P = 0\) [33]. Therefore, the problem of solving the parameter vector can be transformed into a minimization problem with constraints:

\[
\min g_c = P^TJP
\]

\[
\begin{bmatrix}
\sum_{i=1}^{l} x_i^2 & \sum_{i=1}^{l} x_i y_i & \sum_{i=1}^{l} y_i^2 & \sum_{i=1}^{l} x_i & \sum_{i=1}^{l} y_i & \sum_{i=1}^{l} z_i
\end{bmatrix}
\begin{bmatrix}
A \\
B \\
C \\
D
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
-2
\end{bmatrix}
\]

\[
s.t. \quad P^TQP = [A, B, C, D]
\]

(7)

By using the Lagrange multiplication method, the minimum problem can be addressed and the Lagrange function is constructed as follows [35]:

\[
\min h_c(P, \lambda) = P^TJP - \lambda(P^TQP - 1)
\]  

(8)

where \(\lambda\) indicates the Lagrange multiplier. Differentiating with respect to \(P\) gives the first order necessary condition:

\[
JP - \lambda QP = 0
\]  

(9)

In light of the invertibility of \(Q\) [33], we have:

\[
Q^{-1}JP = \lambda P
\]  

(10)

Then \(\lambda\) and \(P\) denote the eigenvalues and eigenvectors of the matrix \(Q^{-1}J\), respectively. According to (9), the equation \(P^TJP - \lambda P^TQP = P^TJP - \lambda = 0\) is deduced, and further the extreme value of \(P^TJP\) is \(\lambda\). The symmetric matrix \(Q^{-1}J\) has four real eigenvalues, and \(P^TJP < 0\) indicates no practical meaning. Therefore the values of \(\lambda\) and \(P\) should be the minimum positive eigenvalue of the matrix \(Q^{-1}J\) and its corresponding eigenvector, respectively [33, 35, 36]. After tackling the minimum value problem, the standard equation of the circular curve is expressed as:

\[
\left(x - \frac{B}{2A}\right)^2 + \left(y - \frac{C}{2A}\right)^2 = \frac{B^2 + C^2 - 4AD}{4A^2}
\]  

(11)
where \((B12A,C12A)\) means the center position \((x_i, y_i)\) of the circle, and \((B_i + C_i - 4AD)/4A^2\) indicates the radius \(r\) of the circle curve. Moreover, the fitted center represents the position of the laser center.

In addition, we define the accuracy of the trace curve fitting. Suppose the variation in the radial direction of any point in the trace relative to the circular curve is given by:

\[
ed_i = (x_i - x)^2 + (y_i - y)^2 - r^2
\]

Then, the fitting accuracy is expressed by the roundness value \(Ce\):

\[
Ce = \max\{\epsilon_i\} - \min\{\epsilon_i\}
\]

IV. Experiment and result analysis

To verify the feasibility of the proposed rotating laser location method, an experimental platform is designed, as displayed in Fig. 8. The experimental setup consists of a 2-D pincushion PSD from Hamamatsu Photonics, a semiconductor laser tube with wavelength of 650 nm and adjustable beam size, a fixed-axis rotating device and a three-dimensional numerically-controlled platform. Pincushion PSD is more likely to reach the specified positioning of moving rotating laser center by Pratt method.

A. Nonlinear correction by error curved surface interpolation method

In order to validate the effectiveness of the error curved surface interpolation method, the experiment of scanning the photosensitive surface is conducted. Before the experiment, it is necessary to choose the appropriate spot size. Considering that the photosensitive surface of PSD is a limited range, we focus on the positional changes of the vertex coordinates of the sensor surface under different spot sizes. We first control the displacement platform to move the laser beam to the reference position. Then, we can adjust the optical lens set inside the laser tube to change the size of the laser beam that projected onto the surface of the PSD, and the measured results are recorded in Table 1.

<table>
<thead>
<tr>
<th>Spot size</th>
<th>Reference values</th>
<th>(V_{x1})</th>
<th>(V_{x2})</th>
<th>(V_{y1})</th>
<th>(V_{y2})</th>
<th>Coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>((-4, 4))</td>
<td>1mm</td>
<td>0.603</td>
<td>0.608</td>
<td>0.270</td>
<td>4.353</td>
<td>((-3.774, 3.784))</td>
</tr>
<tr>
<td></td>
<td>2mm</td>
<td>0.494</td>
<td>0.502</td>
<td>0.228</td>
<td>3.444</td>
<td>((-3.710, 3.723))</td>
</tr>
<tr>
<td></td>
<td>3mm</td>
<td>0.550</td>
<td>0.552</td>
<td>0.276</td>
<td>3.605</td>
<td>((-3.607, 3.610))</td>
</tr>
<tr>
<td></td>
<td>4mm</td>
<td>0.473</td>
<td>0.505</td>
<td>0.247</td>
<td>3.102</td>
<td>((-3.533, 3.603))</td>
</tr>
<tr>
<td></td>
<td>5mm</td>
<td>0.500</td>
<td>0.546</td>
<td>0.293</td>
<td>2.519</td>
<td>((-3.012, 3.191))</td>
</tr>
<tr>
<td>((-2, 2))</td>
<td>1mm</td>
<td>0.267</td>
<td>4.261</td>
<td>0.572</td>
<td>0.611</td>
<td>((-3.740, 3.814))</td>
</tr>
<tr>
<td></td>
<td>2mm</td>
<td>0.230</td>
<td>3.427</td>
<td>0.488</td>
<td>0.498</td>
<td>((-3.708, 3.731))</td>
</tr>
<tr>
<td></td>
<td>3mm</td>
<td>0.291</td>
<td>3.592</td>
<td>0.549</td>
<td>0.574</td>
<td>((-3.534, 3.587))</td>
</tr>
<tr>
<td></td>
<td>4mm</td>
<td>0.254</td>
<td>3.117</td>
<td>0.472</td>
<td>0.516</td>
<td>((-3.492, 3.602))</td>
</tr>
<tr>
<td></td>
<td>5mm</td>
<td>0.303</td>
<td>2.555</td>
<td>0.523</td>
<td>0.596</td>
<td>((-2.959, 3.157))</td>
</tr>
<tr>
<td>((-4, 4))</td>
<td>1mm</td>
<td>3.899</td>
<td>0.240</td>
<td>0.562</td>
<td>0.551</td>
<td>((-3.751, 3.772))</td>
</tr>
<tr>
<td></td>
<td>2mm</td>
<td>3.412</td>
<td>0.233</td>
<td>0.520</td>
<td>0.592</td>
<td>((-3.658, 3.698))</td>
</tr>
<tr>
<td></td>
<td>3mm</td>
<td>3.459</td>
<td>0.245</td>
<td>0.528</td>
<td>0.533</td>
<td>((-3.646, 3.656))</td>
</tr>
<tr>
<td></td>
<td>4mm</td>
<td>3.298</td>
<td>0.251</td>
<td>0.535</td>
<td>0.524</td>
<td>((-3.558, 3.583))</td>
</tr>
<tr>
<td></td>
<td>5mm</td>
<td>2.586</td>
<td>0.275</td>
<td>0.587</td>
<td>0.511</td>
<td>((-3.049, 3.256))</td>
</tr>
<tr>
<td>((-2, 2))</td>
<td>1mm</td>
<td>0.524</td>
<td>0.532</td>
<td>3.501</td>
<td>0.225</td>
<td>((-3.706, 3.709))</td>
</tr>
<tr>
<td></td>
<td>2mm</td>
<td>0.516</td>
<td>0.515</td>
<td>3.413</td>
<td>0.227</td>
<td>((-3.684, 3.684))</td>
</tr>
<tr>
<td></td>
<td>3mm</td>
<td>0.534</td>
<td>0.530</td>
<td>3.423</td>
<td>0.234</td>
<td>((-3.642, 3.653))</td>
</tr>
<tr>
<td></td>
<td>4mm</td>
<td>0.538</td>
<td>0.526</td>
<td>3.242</td>
<td>0.236</td>
<td>((-3.558, 3.588))</td>
</tr>
<tr>
<td></td>
<td>5mm</td>
<td>0.576</td>
<td>0.489</td>
<td>2.619</td>
<td>0.252</td>
<td>((-3.128, 3.366))</td>
</tr>
</tbody>
</table>

where \(V_{x1}, V_{x2}, V_{y1}\), and \(V_{y2}\) represent the electrode signals after current-voltage conversion, amplification and reverse processing. We select the appropriate linear constant \(\lambda = 1.2\) to calculate the estimated coordinates. The selection of \(\lambda\) should satisfy the requirement of small overall position error and the linear range is extended as far as possible. Analysis of
data in Table 1, we find that the total optical energy of PSD decreases slowly with the increase of spot size. In addition, the position errors between the estimated coordinates and the reference coordinates increases gradually. Therefore, it is reasonable to infer that the smaller the spot, the more concentrated the energy, and the more accurate the PSD position detection. Considering that the spot will rotate at the boundary of the PSD surface, we finally choose the spot with a diameter of 1 mm to carry out the experiment.

During the experiment, the three-dimensional displacement platform is first adjusted to make the laser beam projected onto the central area of the PSD surface. Then, we fine-tune the two-axis displacement platform used for fixing PSD until the estimated position calculated by the voltage signals is at the origin of the coordinates. Finally, we adopt spiral rectangular scanning method to scan the photosensitive surface, with step size of 1 mm and sampling frequency of 200 Hz. We collected 500 sets of data at each reference position, and used the average of each set of data to represent the estimated coordinates of this point, as shown in Fig. 9.

FIGURE 9. The trace of laser scanning on the photosensitive surface of the PSD. The red dot ‘*’ denotes the reference positions of PSD after grid discretization, and the blue line visualizes the scan path.

FIGURE 10. Bivariate quintic polynomial fitting effect.

We use the bivariate quintic polynomial to fit the position error data obtained by deviation of coordinates in the X direction. The reason for choosing the fifth order is that the appropriate order is more accord with the variation of the error. For different types of PSDs, we can flexibly change the order of polynomial to have better fitting results. The intensity diagram in Fig. 10 visually indicates that the error at both ends is significantly higher than central region.

FIGURE 11. The original position error fitting curved surface of PSD.

Similarly, we can process the error data in the Y direction and finally gain the position error fitting surface \( E(x, y) \). The result of the processing is a conical surface, with a gradient descending trend from the periphery to the center, as shown in Fig. 11. The average errors in X and Y directions are 0.0642 mm and 0.1105 mm, respectively.

FIGURE 12. The corrected trace after surface error curved interpolation.

Next, the nonlinear distortion of the PSD is corrected using the error curved surface interpolation method. From Fig. 12, it can be seen that the position deviation of the estimated coordinates is corrected and the linearity of the trace is greatly improved. Obviously, the output error of the PSD in the range of effective 9 mm \( \times \) 9 mm is significantly reduced.

FIGURE 13. The corrected position error curved surface.
From Fig. 13, it can be intuitively seen that the corrected curved surface transform from the original conical gradient surface to a gentle small-gradient surface. The position error is greatly reduced and it becomes irregular. It is worth noting that the average error in X and Y directions are reduced to 0.0033 mm and 0.0088 mm, respectively. In addition, the overall position error decrease by more than 32%. Therefore, the correction method effectively improves the positioning accuracy and extends the detection range of the PSD.

B. Moving laser center positioning by Pratt method

The moving laser positioning experiment is carried out to verify validity of the proposed method. In the experiment, 9 positions on the diagonal of the 9 mm × 9 mm photosensitive surface are selected as the reference measurement points. First, we adjust the three-dimensional displacement platform to move the laser beam that aligned with the coordinate origin to the starting position (-4, -4). Next, we control the fixed-axis rotating device to rotate three times counterclockwise and process and record the sensor’s electrode signal. For other locations, we move the laser beam along the diagonal of the photosensitive surface to repeat the acquisition process. After all the positions have been measured, we obtain 9 sets of trace data and reduced the measurement error by averaging. Finally, the modified trace is shown in Fig. 11 by using error curved surface interpolation method.

When the spot rotates in the boundary area of the PSD, the gravity center position beyond the effective detection range of the PSD, which leads to huge abnormal positional distortion. We refer to this phenomenon as the edge effect, and Fig. 14 also validates this theory. The edge effect cannot be optimized by nonlinear correction, but we can improve the positioning accuracy by selecting a smaller diameter spot or sacrificing a tiny effective detection area of the boundary.

Fig. 15 visualizes the change trend of fitting results. We calculate that the average roundness value and the average trace centrifugal variation are 0.0137 mm and 0.0046 mm, respectively. Considering the ideal case of eliminating the distortion trace at both ends, the two values can be reduced to 0.0095 mm and 0.0033 mm, respectively. Therefore, within the range of effective detection surface, the proposed method has strong robustness and high fitting accuracy.

FIGURE 15. The result of trace fitting by Pratt method. The blue solid line and the red dashed line represent the trace and the fitted circular curve respectively. The red dot '*' denotes the center of circular.
where \( Y_{op} \) denotes the position model of the original point, \( Y_{cp} \) means the position model after the nonlinear correction and \( Y_{lcp} \) indicates the position model of the laser spot center (the center of the fitted trace). The SSE (sum of squared errors) of the three regression models reach 36.799 \( \times 10^{-4} \) and 31.32 \( \times 10^{-4} \), respectively.

Furthermore, we adopt the Bisquare method to perform linear regression analysis on the position coordinates to check the positioning accuracy. After analysis, the regression model is as follows:

\[
\begin{align*}
Y_{op} &= 0.9816 \times X + 0.01296 \\
Y_{cp} &= 0.9966 \times X + 0.001917 \\
Y_{lcp} &= 1.002 \times X + 0.4119
\end{align*}
\]

(14)

where \( Y_{op} \) and \( Y_{cp} \), respectively. Finally, we attempt to locate the laser center that is moving along the diagonal of the PSD. We verify the effects about different sizes of light spots projected onto the 2-D PSD on the collected photocurrent and estimated coordinates. Experiments have shown that the accuracy of proposed method can be effectively improved by selecting a smaller size spot. For the inherent nonlinearity of PSD, we adopt the error curved surface interpolation method to optimize the measurement data, and then the overall position error is reduced by approximately 32%. Moreover, the trace of the gravity center of the laser spot is processed by Pratt algorithm based on algebraic fitting, the mean and standard deviation of the fitted radius reach 0.2928 mm and 0.0055 mm, respectively.

REFERENCES


[8] D. Rodriguez-Navarro et al., “Indoor Positioning System Based on a PSD Detector, Precise Positioning of Agents in Motion can be satisfied with the requirements of laser-based non-contact measurement.

V. CONCLUSION

In conclusion, we have investigated a technology and system to improve the accuracy of laser center positioning by 2-D PSD. Specifically, this paper provides a simple and flexible method with high precision for the nonlinear correction of PSD as well as a new idea for PSD-based moving laser center positioning. We deduce the calculation process about the whole method and design laser rotating device with stable spot. We verify the effects about different sizes of light spots projected onto the 2-D PSD on the collected photocurrent and estimated coordinates. Experiments have shown that the accuracy of proposed method can be effectively improved by selecting a smaller size spot. For the inherent nonlinearity of PSD, we adopt the error curved surface interpolation method to optimize the measurement data, and then the overall position error is reduced by approximately 32%. Moreover, the trace of the gravity center of the laser spot is processed by Pratt algorithm based on algebraic fitting, the mean and standard deviation of the fitted radius reach 0.2928 mm and 0.0055 mm, respectively. Finally, we attempt to locate the laser center that is moving along the diagonal of the PSD. The experimental results prove that we have achieved the satisfying accuracy with a linearity of 0.2%.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/.


PENGCHENG ZHANG was born in 1996. He is currently pursuing the M.S. degree with the School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai, China. His research interests include sensor technology, photodetection, embedded systems and intelligent control.

JIN LIU was born in 1978. She is currently an Associate Professor with the School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai, China, where she is also an Associate Dean. Her research interests include intelligent detection and control technology, distributed sensor networks, and test information acquisition and processing.

HAIMA YANG was born in 1979. He received the Ph.D. degree in signal and information processing from the Xi’an Institute of Optics and Precision Mechanics, Chinese Academy of Science, Xi’an, China, in 2015. He is currently an Associate Professor with the Instrument Science and Technology, School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, China. His research interests include digital signal analysis and processing, SPR sensor mechanism and simulation, pattern recognition system development, and symbolic slider variable structure control.

LUO YU was born in 1995. She is currently pursuing the M.S. degree with the School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai, China. Her current research interests include digital signal processing and sensor fusion.