Precise Locating Algorithm by Modified Least Square Method for CES Switch Operating

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***Abstract*—Accurate positioning method of three dimensional pose of space circle is a typical problem of binocular vision. The correlation algorithm is particularly important for the positioning accuracy in the case of strong interference of edge feature information. According to the precise positioning requirements of the distribution cabinet handcart in the distribution room, this paper establishes the elliptic curve optimization method based on the European distance minimization feature. Based on the least square method, the information model of the outside edge of the switch is established by using the circular contour of the cylindrical groove, and the three-dimensional pose positioning method of the spatial circle is studied. Finally, the effectiveness of the algorithm is verified by a case study.**

***Index Terms*—binocular vision, precise positioning of space circle, least square method**

I. Introduction

With the rapid development of robot technology, robot based automation has become a major development trend in all walks of life. Distribution room is an important part of power supply system [1]. Its operation and maintenance has always depended on the traditional mode of manpower. Fig.1 a) and Fig. 1b) are 2 typical Circular Earthing Switches (CES Switch), In operation and maintenance, such switches need to be precisely positioned to switch the grounding state of distribution unit. Based on the binocular vision positioning and robot technology, this paper establishes the automatic on duty operation system for the traditional power distribution cabinet as shown in Fig. 1c). The CES switch is precisely positioned through the vision system, and the relevant and maintenance operations are completed by the robot operation tools [2].

As shown in Fig. 1a), the CES switch has a clear edge profile, and the general edge processing algorithms can handle it well. As for Fig. 1b) CES switch, the edge is not clear, especially in the case of shadow and other interferences. There are more interferences and noises, so it is necessary to study the related algorithms.

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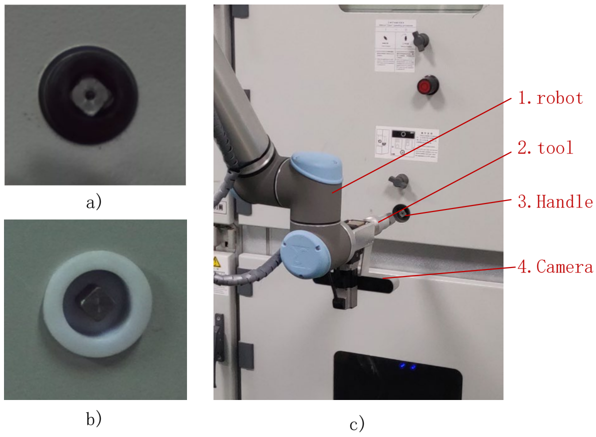

Figure 1. CES handle operating robot system.

II. Localization Algorithm of CES Switch

This paper adopts the method of binocular vision [3]. The overall flow of the precise positioning algorithm of CES switch is shown in Fig. 2. Firstly, the ellipse contour is extracted with binocular camera, and the contour points are fitted to ellipse. The pose of space circle is solved by two ellipse images [4]. Then calculate the rotation angle of the central square column by combining the side line of the square column, and the complete space attitude of the handcart is finally obtained.

For the precise positioning technology of space circle, Quan [5] proposes a method to solve the position and pose of circle in space by two conic parameters presented in different perspectives. In this method, the solution of space circular pose is transformed into algebraic solution of parameter equation. This process of algebraic solution relies strongly on the extraction of ellipse. The error of RANSAC algorithm used in the extraction process is further amplified when solve the set. Malassiotis proposed a positioning method based on three-dimensional hole model [6]. It is based on uniform sampling of 3D model. According to the projection matrix of camera and the projection of model pose in the left and right pictures, it calculates the sum of the distance between each contour point and the nearest projection point as the function to be optimized. And the gradient descent method is used to optimize the function

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to obtain the accurate pose parameters. But it needs to reconstruct KDtree in iteration and solve gradient by numerical differentiation. The calculation is time-consuming and lack of accuracy. In this paper, the algebraic solution method is used to screen the spatial curve of the image and establish the point set of the ellipse contour in the space. Based on the least square method, each degree of freedom and geometric parameters of general geometry including space circle are optimized. Finally, the space precise positioning of circular features is completed to meet the requirements of robot operation.

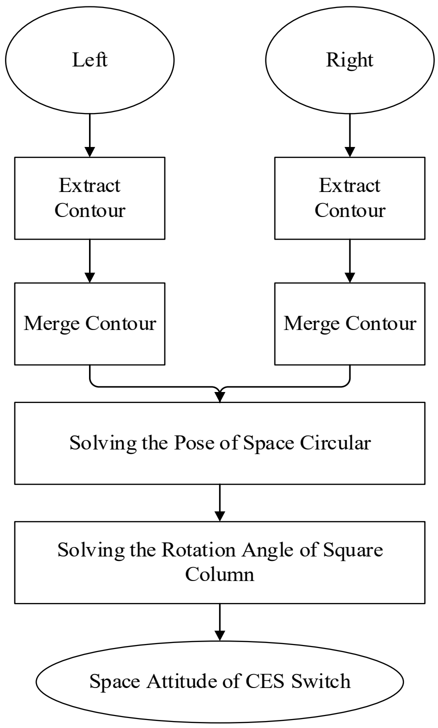


Figure 2. General process of CES switch positioning method.

A. Binocular Vision Location Based on Least Square Method

Take the image acquired by the left camera as an example, and name its projection matrix Proj_l. According to the projection method

$$\tilde{W}_l = \mathrm{Pr}oj_l \cdot X^{cam}, \quad W_l = \frac{\tilde{W}_l}{\tilde{W}_{l(3)}} \tag{1}$$

In (1), X^{cam} is the homogeneous coordinate of 3D point in camera coordinate system ($X^{cam}=[x,y,z,l]^{\mathrm{T}}$), W_l is the homogeneous pixel coordinate of the projection of the point in the graph($W_l=[u,v,l]^{\mathrm{T}}$). $\tilde{W}_{l(3)}$ is the value of the third column of vector $\tilde{W}_l$.

Let X^{circle} be the homogeneous coordinate of the three-dimensional point in the circular coordinate system. It can be converted into X^{cam} by changing matrix $T^{circle}_{cam}(\Theta)$. Because the point on the circle must be on the plane of the circle, the corresponding z value is 0. Therefore, the above formula can be expressed as

$$\tilde{W}_l = M_l(\Theta)\cdot X^{circle}$$

$$M_l(\Theta) = \mathrm{Pr}oj_l \cdot T^{cam}_{circle}(\Theta)\cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$W_l = \frac{\tilde{W}_l}{\tilde{W}_{l(3)}}$$

When the space circle plane is determined, the points on the space circle can be mapped one by one with the projection points in the picture. So M_l in (2) is reversible. X^{circle} can be expressed as

$$\tilde{X}^{circle} = M_l(\Theta)^{-1}\cdot W_l$$

$$X^{circle} = \frac{\tilde{X}^{circle}}{\tilde{X}^{circle}_{(4)}} \tag{3}$$

$\tilde{X}^{circle}_{(4)}$ is the value of the fourth column of vector $\tilde{X}^{circle}$. The process in (3) can be expressed as

$$X^{circle} = g_l(W_l,\Theta) \tag{4}$$

Mark $f_l(W_l,\Theta,r)$ as the projection point of the space circle. Substituting (4) into the representation of points on a circle in the coordinate system of a space circle:

$$f_l(W_l,\Theta,r) = g_l(W_l,\Theta)^T \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -r^2 \end{bmatrix} \cdot g_l(W_l,\Theta) = 0 \tag{5}$$

(5) is the equation that the projection point should satisfy. Thus, the model of spatial location can be established as:

$$\min_{\Theta,r}\Big(\sum_{W_l\in E_l}\left\|f_l(W_l,\Theta,r)\right\|^2\Big) \tag{6}$$

In (6), $\left\|f_l(W_l,\Theta,r)\right\|$ uses L2 norm as the distance to be optimized. Its physical meaning is the Euclidean distance between the point in the plane corresponding to the projection point and the circle. The advantage is that the calculation steps only include inverse and linear processes，Therefore, the Jacobian matrix of f_l can be directly solved by the chain derivation method. (6) is also applicable to the image acquired by the right camera, so the function of binocular camera to be optimized is

$$\min_{\Theta,r}\Big(\sum_{W_l\in E_l}\left\|f_l(W_l,\Theta,r)\right\|^2 + \sum_{W_r\in E_r}\left\|f_r(W_r,\Theta,r)\right\|^2\Big) \tag{7}$$

Using Levenberg-Marquardt iterative method [7] to solve (7). Combining the advantages of Gauss Newton method [8] and gradient descent method, the step length of gradient descent is adjusted dynamically to converge to the minimum value quickly. Because space rotation is involved in the optimization process, the representation of three parameters of space rotation has deadlock problem [9]. For example, axis angle representation, Euler angle representation, etc. Therefore, in order to avoid deadlock in optimization process, quaternion can be used, like $q=(q_x,q_y,q_z,q_w)$, $\Theta=(x,y,z, q_x,q_y,q_z,q_w)$. This method is over parametric, representing three degrees of freedom with four parameters. It needs to meet the constraints:

$$q_x^2+q_y^2+q_z^2+q_w^2=1 \tag{8}$$

Therefore, the four parameters cannot be regarded as the parameters to be optimized, so the local parameterization method is used in the iterative process [10].

B. Precise Positioning Method of CES Switch

Based on the above model, this paper uses the method of binocular vision to extract the contour of ellipse and fit the contour points to ellipse. The pose of the space circle is solved by two ellipse images on the left and right, and the rotation angle of the center is calculated by combining with the edge line of the square column, so as to achieve the precise positioning of the space pose of the CES switch. It includes:

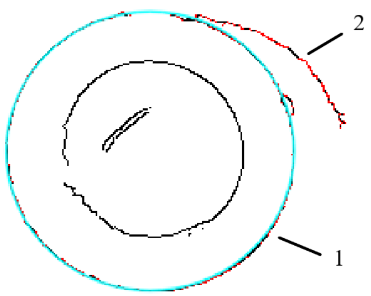


Figure 3. Ellipse fitting results from RANSAC algorithm.

1) Ellipse contour extraction

First, after the left and right images are obtained by binocular camera, the edge image is obtained by Canny operator. Because there are many noise points in the image, and the contour points are scattered when the light conditions are poor, it is necessary to conduct dilation and erosion treatment. Then use the algorithm proposed by Suzuki[11], Its output is a contour tree, and the contour of the child node is contained in the outer contour. However, the extraction of ellipse contour does not need structured information, and other contours in the outside contain the possibility of real contour. Therefore, this method ignores the structured information returned by Suzuki algorithm, regards each contour as a part of the target contour, and discards the too short contour caused by discrete points. Next, use RANSAC algorithm for the acquired contour points. The ellipse fitted by this method has high robustness and enough accuracy. The fitting result is shown in Fig. 3. Curve 1 is the extracted ellipse contour and curve 2 is the discarded non-circular contour. It can be seen that it fits the actual edge of the ellipse well, and RANSAC algorithm can filter out the contour points that do not belong to the edge of the ellipse.

2) Ellipse contour merge

Under the influence of light and shadow, the ellipse contour extracted by Canny operator is usually composed of several discontinuous contours. For the actual ellipse edge, if it is divided into m contours, then m ellipse equations will be obtained. And only one section of contour is used in any ellipse fitting, so the accuracy is poor. Therefore, it is necessary to merge the contours that may belong to the same ellipse. In this paper, an efficient ellipse merging algorithm is proposed, which fully considers the distribution of ellipse contour points

Set the fitting parameters of two profiles as A_0, A_1. P_{in}^0, P_{in}^1 represents the set of contour points on A_0, A_1 respectively. If A_0, A_1 belong to the same ellipse, then P_{in}^0 and P_{in}^1 do not overlap in orientation. Fig. 4 shows a situation where two profiles (curve 1, curve 2) overlap in orientation. Abandoning this kind of contour combination can remove most cases from different ellipses and greatly speed up the calculation.

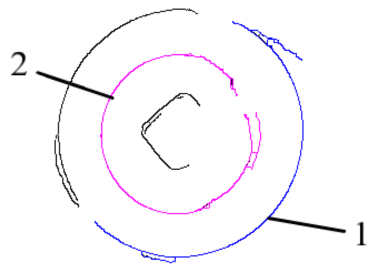


Figure 4. Two curves overlapping in orientation.

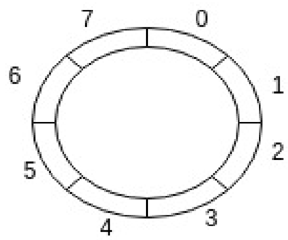


Figure 5. Ellipse divided by orientation.

The ellipse is divided into 8 parts according to Fig. 5 in order to judge whether it overlaps in orientation or not. Represent the coverage as an 8-bit binary value *b*. Take P_{in}^0 as an example, if points in P_{in}^0 cover orientation 2, 3, 4, express it as b_0=0b00111000. Similarly, the coverage corresponding to P_{in}^1 is expressed as b_1. Sum b_0 and b_1 by bits, and count the number *n* of 1 in the obtained result. If the orientations of the contours at both ends do not overlap, the two contours at most cover the joint part at the same time, thus $n \leqq 1$. In special cases, the two profiles are connected end to end, $n = 2$. At this time, the number n_0 and n_1 of 1 in b_0 and b_1 need to meet $n_0+n_1=10$, otherwise they will overlap in orientation.

After these redundant contours are removed, an ellipse *E* is obtained by fitting two sets of points of the remaining contour. If *E* satisfies most of the points in the two contour point sets, the two contour point sets can be considered to belong to the same circle and can be combined.

3) Solution of space circular pose

By merging ellipses, a small number of left and right ellipse profiles can be obtained. Then the least square method can be used to solve the space circular pose. First, the left and right ellipse contours are algebraic solved one by one, and the contours that really belong to the space circle are screened out. Then the least square algorithm is used to get the pose of the space circle. And find out the coordinate transfer matrix T_{circle}^{cam} between the space circle and the camera.

III. Performance Evaluation

In order to test the positioning algorithm proposed in this paper, a distribution station duty robot is used as the experimental platform to evaluate its accuracy and stability.

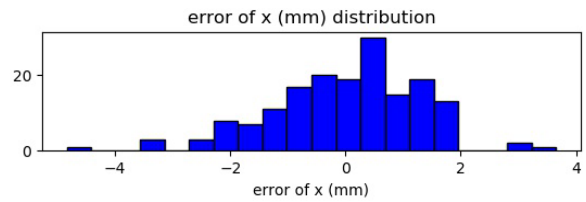
In the experiment, the sampling space is set to $x \in [-200, 200]mm$, $y \in [-200, 200]mm$, $z \in [300, 700]mm$. Sample 200 times evenly to calculate $\tilde{T}_{cuboid}^{cam}$. According to the attitude of the camera in the robot coordinate system, the coordinate transformation matrix $\tilde{T}_{cuboid}^{rob}$ between the robot and the square cylinder is derived. Because the positioning error of robot is far less than that of vision algorithm, the error and stability of positioning algorithm can be evaluated by analyzing $\tilde{T}_{cuboid}^{rob}$. Table I shows the parameters adopted by the algorithm in the experiment.

According to 200 sampling analysis, the error of positioning results in six degrees of freedom is decomposed into *x*, *y*, *z*, *roll*, *pitch*, *yaw*. The relative error of each component is as shown in Fig. 6.

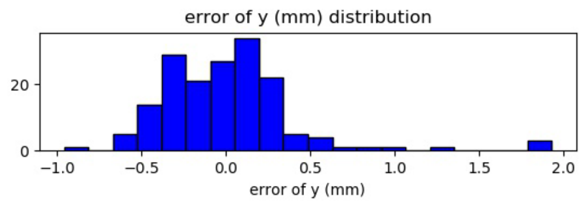
Because the camera is placed horizontally, the *x* error is much higher than the *y* error. The *yaw* angle in Fig. 6 is mainly obtained by the rotation of the square column in the middle of CES switch, so it is different from the calculation principle of *roll* angle and *pitch* angle. It can be seen from Fig. 6 that the overall translation error is controlled within 2mm, and the rotation error is controlled within 2°, which meets the use requirements of the on duty robot in the power distribution station.

TABLE I. Parameters of CES Switch Positioning Algorithm Used in the Experiment

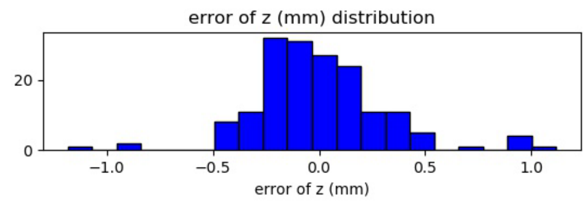
Symbol	Interpretation	*Value*
th_{canny}^{l}	Low threshold of Canny operator	500
th_{canny}^{h}	High threshold of Canny operator	1500
$th_{ellipse}$	Threshold of ellipse RANSAC fitting	5
th_{fuse}	Fitting quality of merging ellipses	0.9cm
th_{Δ}	Maximum value of Δ	0.01
th_{ρ}	Threshold value of distance in linear NMS algorithm	10pix
th_{θ}	Threshold value of angle in line NMS algorithm	5°
th_{θ}^{ransac}	Threshold value of extracting rotation angle of square cylinder by RANSAC algorithm	5°



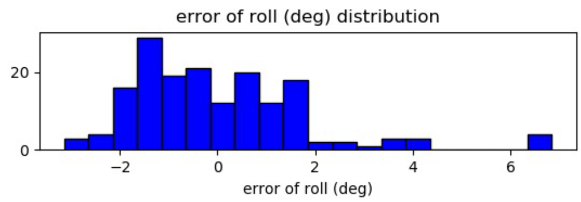
(a) relative error of *x*



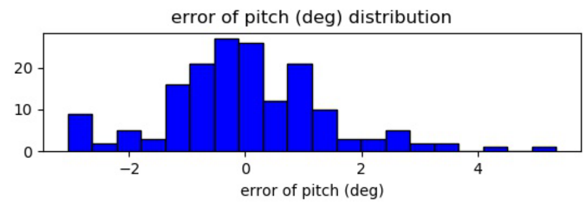
(b) relative error of y



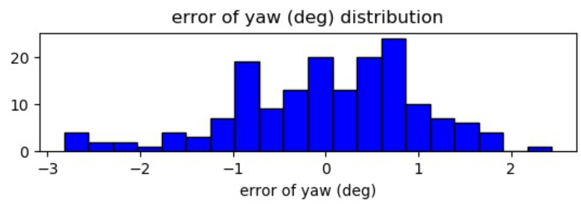
(c) relative error of *z*



(d) relative error of *roll*



(e) relative error of *pitch*



(f) relative error of y*aw*

Figure 6. Distribution of relative positioning error of circular handcart.

IV. Discussion and Conclusion

This paper introduces the principle of the least square algorithm and the specific process of positioning the CES switch by this positioning method. It is generally based on the analysis of the shape of the CES switch. The circular outer edge of the CES switch is used as an auxiliary feature to determine the spatial pose of the circle. The distribution station on duty robot is used as the experimental platform to verify the experiment. Experimental results show that the translation accuracy and rotation accuracy of this method can reach 2 mm and 2° respectively, verifies the effectiveness of the algorithm. Our future work is to apply this precision algorithm to more parts of CES switch positioning, such as line detection. We believe that this will further improve the accuracy of CES switch locating.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Chen Zhen and Guo Zihan put forward innovative points and write papers. Xu Jing, Xu Wenhui and Qin Chuan do the experiment.

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