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A New Robot Body Calibration Method of SCARA Based on Machine Vision

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Abstract: With the development of industrial automation, SCARA robot is widely used in industrial production because of its flexible action and fast speed. There is a certain error between the theoretical model and the actual model of SCARA robot due to the inconsistent in production and assembly process, which makes the robot positioning accuracy not guaranteed. At the same time, although the traditional calibration method like using laser tracker has high calibration accuracy, but the equipment is expensive and the calibration time is too long. In this paper, a calibration method based on machine vision for the SCARA robot is proposed, which uses the position error model to ensure the positioning accuracy of the robot's left-hand and right-hand systems. The calibration software is easy to use and the process is almost in automation. The experimental results show that the calibrating time is shorter and the positioning accuracy can be guaranteed.

Keywords: SCARA robot; calibration method; machine vision; position error model

I. INTRODUCTION

SCARA robot [1,2] is widely used in electronic industry, pharmaceutical industry, food industry and other fields because of its compact structure, flexible action, fast speed and high positioning accuracy. The robot positioning accuracy [3-5] is an important factor affecting the performance of the robot. The deviation of robot arm length and zero point are inevitably existed in the process of production and assembly, that resulting in the deviation between the kinematic theoretical model [6,7] and the actual model. Therefore, it is important to calibrate the robot body to improve the positioning accuracy of the robot. R. He [8] and W. Gao [9] used the exponential product model to model the robot, which can describe the rotating joint and the moving joint very well. Laser tracker was used to measure the position and attitude of the robot and calibrate the kinematic parameters of the robot [10-13]. Joubair. A [14] designed a special magnetic rod to fix it on the measuring plane and measured the position of each rod with a coordinate measuring machine [15], and designed a cap to match it and fixed it on the robot to obtain the positioning error of the robot. Joubair A [16] and Z. Qi [17] used the position error model to solve the kinematic parameters of the robot, but the calibration process was tedious. X. Li [18] and J. Zhang [19] proposed a calibration method of four-hole calibration plate based on singular value decomposition method. This method was simple and practical with high accuracy, but it required four holes of calibration plate in high machining accuracy.

The length error of the boom and arm and the zero-shift error caused by the boom and arm not in a straight line affect the positioning accuracy of SCARA robot. In order to improve the positioning accuracy, a position error calibration method based on machine vision is proposed to compute the length error and zero shift error. By using this method, the calibration process is simple and operation in automation. Finally, the data before and after calibration are analyzed to verify the positioning accuracy of the robot.

II. ROBOT CALIBRATION METHOD

A. *Calibration Principle*

The length error and zero shift error of SCARA robot are the main factors that affect its positioning accuracy. In order to analyze the error easily, the SCARA robot can be simplified to a planar two DOF (degree of freedom) robot. For any point P (x, y) in the robot workspace, two different attitudes of the robot can be used to reach point P. In order to distinguish, it is generally defined that the robot is in the left-hand system when θ_2<0, and when θ_2>0, the robot is in the right-hand system (when θ_2=0, the robot is in the singular position). When the origin position of the boom and arm is not in a straight line, the left-hand and right-hand systems generally do not coincide, resulting in absolute position error. As shown in Fig. 1, O and A are rotary joints, B is the end of the robot, XOY is the base standard system of SCARA, the length of the boom is l_1, the length of the arm is l_2, the angle of joint 1 is θ_1, the angle of joint 2 is θ_2, and the zero point offset value is $\Delta\theta_2$.

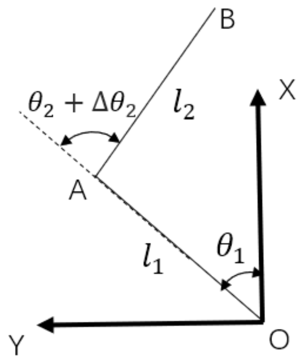

Fig. 1 Kinematics forward solution of SCARA robot after correction

The positive solution formula of robot is as follows:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} cos\theta_1 & cos(\theta_1 + \theta_2) \\ sin\theta_1 & sin\,(\theta_1 + \theta_2) \end{bmatrix} * \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \quad (1)$$

After introducing $\Delta\theta_2$, according to (1), the forward solution formula of robot is rewritten as follows:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} cos\theta_1 & cos\,(\theta_1 + \theta_2 + \Delta\theta_2) \\ sin\theta_1 & sin\,(\theta_1 + \theta_2 + \Delta\theta_2) \end{bmatrix} * \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \quad (2)$$

Therefore, for a known length of segment between P1 and P2 in space, the angle of left-hand and right-hand system joints at P1 (X1, Y1) can be obtained as S1(θ_{11}, θ_{12}), and S2(θ_{21}, θ_{22}). Similarly, at P2 (X2, Y2), the angle of left-hand

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and right-hand system joints is S3(θ_{31}, θ_{32}), and S4(θ_{41}, θ_{42}). Inside, θ_{i1} represents the angle of joint 1 at the ith point, and θ_{i2} represents the angle of joint 2 at the ith point. According to equation (2), the left-hand system joint coordinate S1 and the right-hand system joint coordinate S2 can be used to get the same X1 and Y1 coordinates at point P1:

$$\begin{cases} l_1 \cos\theta_{11} + l_2 \cos(\theta_{11}+\theta_{12}+\Delta\theta_2) \\ = l_1 \cos\theta_{21} + l_2 \cos(\theta_{21}+\theta_{22}+\Delta\theta_2) \\ l_1 \sin\theta_{11} + l_2 \sin(\theta_{11}+\theta_{12}+\Delta\theta_2) \\ = l_1 \sin\theta_{21} + l_2 \sin(\theta_{21}+\theta_{22}+\Delta\theta_2) \end{cases} \tag{3}$$

To simplify symbols, equation (4) can be get:

$$\begin{cases} s_{i1} = \sin\theta_{i1} \\ c_{i1} = \cos\theta_{i1} \\ s_{i2} = \sin\theta_{i2} \\ s_{i12} = \sin(\theta_{i1}+\theta_{i2}) \\ c_{i12} = \cos(\theta_{i1}+\theta_{i2}) \\ i = 1,2,3\cdots \end{cases} \tag{4}$$

Use trigonometric identity and do variable substitution, equation (5) can be get:

$$\begin{cases} \lambda_1 = l_1 \\ \lambda_2 = l_2\cos\Delta\theta_2 \\ \lambda_3 = l_2\sin\Delta\theta_2 \end{cases} \tag{5}$$

Equation (3) can be written as:

$$\begin{cases} \lambda_1(c_{11}-c_{21}) + \lambda_2(c_{112}-c_{212}) + \lambda_3(s_{212}-s_{112}) = 0 \\ \lambda_1(s_{11}-s_{21}) + \lambda_2(s_{112}-s_{212}) + \lambda_3(c_{112}-c_{212}) = 0 \end{cases} \tag{6}$$

Similarly, P2 can be obtained:

$$\begin{cases} \lambda_1(c_{31}-c_{41}) + \lambda_2(c_{312}-c_{412}) + \lambda_3(s_{412}-s_{312}) = 0 \\ \lambda_1(s_{31}-s_{41}) + \lambda_2(s_{312}-s_{412}) + \lambda_3(c_{312}-c_{412}) = 0 \end{cases} \tag{7}$$

The hyper-static homogeneous linear equations can be obtained by equation (6) and (7). The singular value decomposition method (SVD) [18] is used to compute (6) and (7) and get the $[\lambda_1, \lambda_2, \lambda_3]$. After getting the result, the zero-point offset value can be calculated according to (5):

$$\Delta\theta_2 = \arctan\left(\frac{\lambda_3}{\lambda_2}\right) \tag{8}$$

Ratio value of boom to arm length:

$$K_l = \frac{l_2}{l_1} = \frac{\lambda_2/\cos\Delta\theta_2}{\lambda_1} = \frac{\lambda_2}{\lambda_1\cos\Delta\theta_2} \tag{9}$$

Since the length of P1 and P2 is known as D (mm), the actual value of robot arm length can be calculated by (2).

$$\begin{cases} \Delta x_1 = (\cos\theta_{11} - \cos\theta_{31}) \\ +K_l[\cos(\theta_{11}+\theta_{12}+\Delta\theta_2) \\ -\cos(\theta_{31}+\theta_{32}+\Delta\theta_2)] \\ \Delta y_1 = (\sin\theta_{11} - \sin\theta_{31}) \\ +K_l[\sin(\theta_{11}+\theta_{12}+\Delta\theta_2) \\ -\sin(\theta_{31}+\theta_{32}+\Delta\theta_2)] \\ l_{11} = \frac{D}{\sqrt{\Delta x_1^2+\Delta y_1^2}} \end{cases} \tag{10}$$

Similarly, l_{21},l_{31},$l_{41}$and the length of the boom and arm can be obtained:

$$\begin{cases} l_1 = \frac{l_{11}+l_{21}+l_{31}+l_{41}}{4} \\ l_2 = K_l l_1 \end{cases} \tag{11}$$

B. *Calibration system and software design*

As shown in Fig. 2 and 3, the whole calibration system includes SCARA robot system, machine vision system and computer. In order to improve the position accuracy of the robot, a circular marker is installed at the end of the screw to obtain the position information of the robot. The machine vision system adopts the 6-megapixel black-and-white camera of Hikvision with a resolution of 3072 * 2048, a camera lens with a focal length of 25 mm and a red-light source with a diameter of 150 mm.

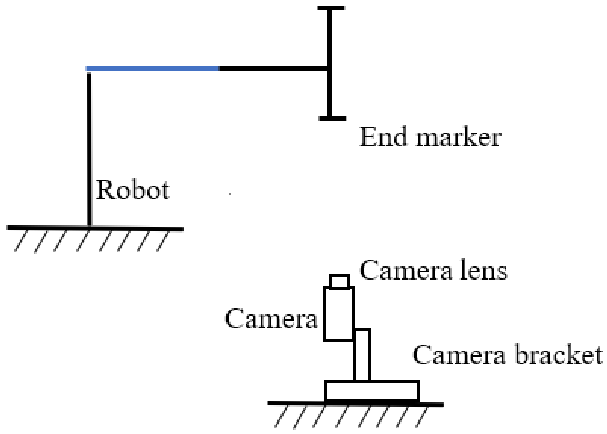

Fig. 2 Calibration system schematic

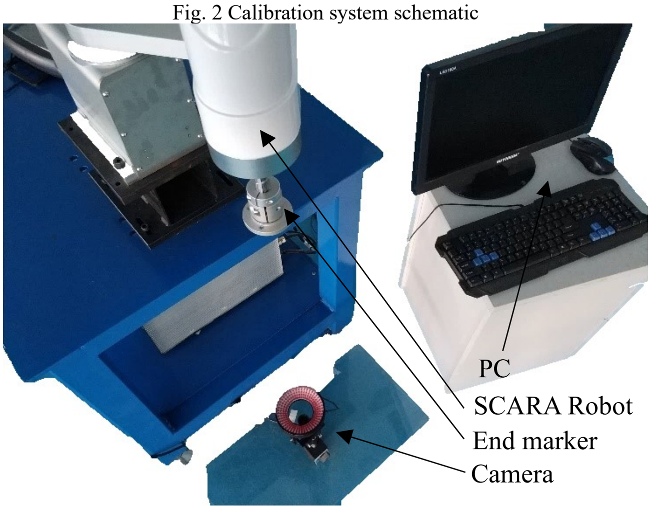

Fig. 3 Physical diagram of calibration system

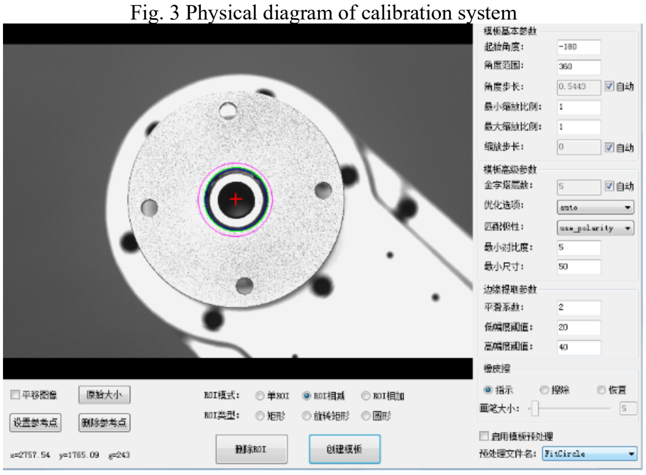
Fig. 4 template matching interface

In this paper, Halcon visual processing software is used to build template matching module in C#, using shape-based template matching method, as shown in Fig. 4. First, define a ROI area to be identified manually in the image, and then adjust the relevant parameters on the right side of Figure 4 to make the created template more accurate. Because Canny operator is a better detector for edge detection. The basic idea is: firstly, Gaussian filter is used to smooth the image, then the gradient amplitude and gradient direction matrix of the image are calculated, then non maximum suppression is applied to the gradient amplitude image, and finally the edge is detected and connected by double threshold processing and connection analysis. In this paper, Canny operator is used to get the edge contour, and the smoothing coefficient and threshold are adjusted to get more accurate edge information. The edge template preliminarily extracted is shown in Fig. 5, Among them, the blue and red lines are the selected ROI area contours, and the green lines are the extracted edge contours. and there are some small interfere (Fig. 6). In order to simplify the preprocessing process, the "eraser" function is used to remove some interference contours, only keep the contour information of the outer circle, and the center of the fitted circle is taken as the reference point.

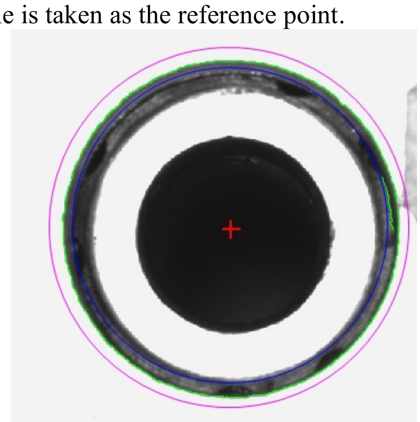

Fig. 5 edge extraction

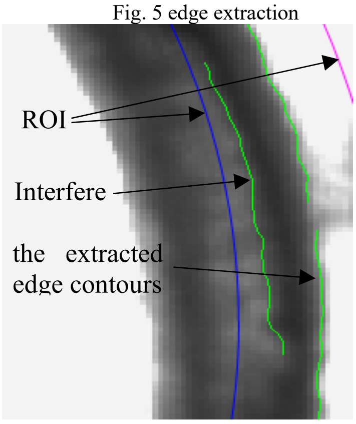

Fig. 6 interference edge

After the template is created, in order to detect the matching effect of the template, the camera is used to continuously collect 10 images, and the coordinates of the center reference point are shown in Table I. The average value of the center coordinate u is 1455.6187 pixel, the standard deviation of the center coordinate u is 0.0751 pixel, the average value of the center coordinate v is 998.5138 pixel, and the standard deviation of the center coordinate v is 0.0806 pixel. From the standard deviation point of view, the algorithm has high stability and small error, which can meet the application of this paper.

TABLE I
PIXEL COORDINATES OF THE CENTER OF THE CONTINUOUS ACQUISITION TEMPLATE

number	center coordinate u/ pixel	center coordinate v pixel	score
1	1455.5438	998.6526	98.9
2	1455.6948	998.5391	99.1
3	1455.7347	998.3928	99.4
4	1455.6665	998.4561	98.9
5	1455.7041	998.4321	98.7
6	1455.5364	998.5765	99.1
7	1455.5904	998.5422	99.1
8	1455.5384	998.5483	98.7
9	1455.5733	998.5603	99.0
10	1455.6045	998.4375	98.8

C. *Calibration process*

In this paper, the robot with the length of the boom and arm of 200 mm is selected. The robot position is obtained by gathering the end position information from the camera. First, move the end of robot to the center of the camera's field of view. Record the manipulator position P0 (X0, Y0) and the center pixel coordinate Q0 (U0, V0). Then the robot is controlled to move a certain distance along the X direction, and the robot end coordinates P1 (X1, Y1) and pixel coordinates Q1 (U1, V1) are recorded. Then move a certain distance along the Y direction, and record the robot end coordinates P2 (X2, Y2) and pixel coordinates Q2 (U2, V2). Through point Q0 and Q1, the rotation angle of X axis of pixel coordinate and X axis of robot can be calculated as (12):

$$tan\theta = \left(\frac{V1-Vo}{U1-U0}\right) \tag{12}$$

If U1 > U0, the rotation angle is θ, if U1 < U0, the rotation angle is (θ-π). After obtaining the rotation angle, new points Q3 (U3, V3), Q4 (U4, V4) and Q5 (U5, V5) can be obtained by rotation transformation matrix. Then the pixel equivalent in X direction is KX = A / U4-U3, and the pixel equivalent in Y direction is KY = A / V5-V4. Then the average pixel equivalent K = (KX + KY) / 2, the unit is mm / pixel. In the experiment of this paper, the movement distance of the robot in XY direction is 20 mm. Finally, KX = 0.039761, KY = 0.040529, K = 0.04015 are calculated.

According to the size of the end circular marker in the camera field of vision, this experiment sets a regular hexagon with a distance of 20 mm from the end of the robot to the point, and the center of the hexagon is P0 point, so the Cartesian coordinates of the six points are P1-P6, as shown in the Fig.7.

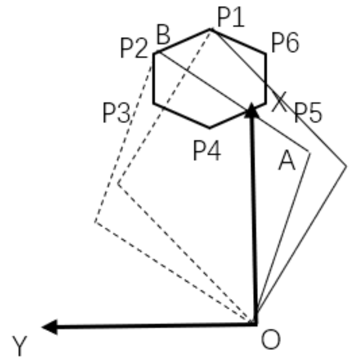

Fig. 7 calibration diagram of robot arm length and zero point

When the robot moves to the reference point P1(X1,Y1) in the left-hand system, record the joint coordinates S1(θ_{11}, θ_{12}), and set out to take photos with the camera, record the pixel coordinates Q1(U1,V1) of the center of the circle at this time, then move to P1 in the right-hand system, and trigger the camera to take photos, record the pixel coordinates Q2(U2,V2) of the center of the circle at this time, compare and calculate the pixel coordinate errors of the center of the circle twice, and it can be found that the two points do not coincide. Therefore, it is necessary to transform the pixel coordinates through the rotation matrix to find out the deviation of the X and Y directions of the machine.

According to the formula, the position of the robot can be adjusted to make the left-hand and right-hand systems coincide.

$$\begin{bmatrix}\Delta X\\ \Delta Y\end{bmatrix} = \begin{bmatrix}cos\theta & -sin\theta\\ sin\theta & cos\theta\end{bmatrix} * \begin{bmatrix}U2-U1\\ V2-V1\end{bmatrix} * \mathrm{K} \tag{13}$$

The calibration procedure is as follows:

Step 1: move to the center of camera field of view, establish the center circle template and calculate its center coordinates.

Step 2: move 20 mm along the X and Y directions to calculate the average pixel equivalent.

Step 3: Under the left-hand system, control the robot end to move to P1 point, record the pixel coordinates of point P1 in the left-hand system.

Step 4: Under the right-hand system, control the robot end to move to point P1, record the pixel coordinates of point P1 in the right-hand system, calculate the position error and correct the current position according to (13).

Step 5: take pictures repeatedly and get the current pixel coordinates, calculate the position error and correct the current position. After 5 times of continuous execution, take the joint coordinates of the 5th point P1 right-hand system.

Step 6: move to point P2 and record the joint coordinates, and repeat steps 4 and 5 to get the joint coordinates of point P2 of the other hand system. According to the algorithm in this paper, a group of zeros and robot arm lengths are automatically calculated from P1P2. Repeat the steps to find the zero-point and robot arm length of P2P3, P3P4, P4P5 and P5P6, and calculate the average value of each parameter.

III. Experimental Analysis

According to the calibration process, the left-hand and right-hand system joint coordinates of each point can be obtained. As shown in Table II.

TABLE II.
VALUES OF JOINTS 1 AND 2 IN THE LEFT-HAND AND RIGHT-HAND SYSTEM

position	Left hand system	Left hand system
P1	(36.582, -69.77)	(-32.292,68.198)
P2	(35.953, -74.645)	(-37.836,73.055)
P3	(40.358, -83.642)	(-42.42,82.038)
P4	(45.843, -87.84)	(-41.195,86.258)
P5	(46.761, -83.585)	(-35.56,81.585)
P6	(41.94, -74.151)	(-31.32,72.485)

According to (10) and (11), the five results of robot arm length and zero-point calibration are shown in Table III. Take the average value of calibration results, and the average value of the boom is 200.143mm, the average value of the arm is 199.689mm, and the average value of zero-point deviation is -0.812 °. In this paper, the calibration process is automatic, easy to operate and takes about 1 minute, while in reference [18], the calibration process is manual teaching and takes about 20 minutes.

TABLE. III
ROBOT ARM LENGTH AND ZERO POINT FROM EXPERIMENT

number	L1/mm	L2/mm	$\Delta\theta_2$/°
1	200.146	199.661	-0.820
2	200.130	199.691	-0.810
3	200.137	199.687	-0.810
4	200.152	199.700	-0.808
5	200.149	199.708	-0.816

In order to test the positioning accuracy of the robot, 20 points are selected evenly in the working area of the robot for error test, and the position errors of the left-hand and right-hand systems before and after each point calibration are calculated. As shown in Fig. 8, the maximum position error before calibration is 3.069mm, the average error is 2.663mm, and the standard deviation is 0.251mm. As shown in Fig. 9, the maximum position error after calibration is 0.118mm, the average error is 0.058mm, and the standard deviation is 0.034mm. The average error before and after calibration is reduced from 2.663mm to 0.058mm, and the accuracy is increased by 97.8%. In terms of standard deviation, the robot position error in the working range is relatively stable, which shows that the calibration method in this paper has achieved good calibration results. Compared with reference [18], although the calibration accuracy can reach 0.05mm, its positioning accuracy depends heavily on the machining accuracy of the calibration plate and the proficiency of the operator. With the increase of the use of the calibration plate, its calibration accuracy will be worse and worse.

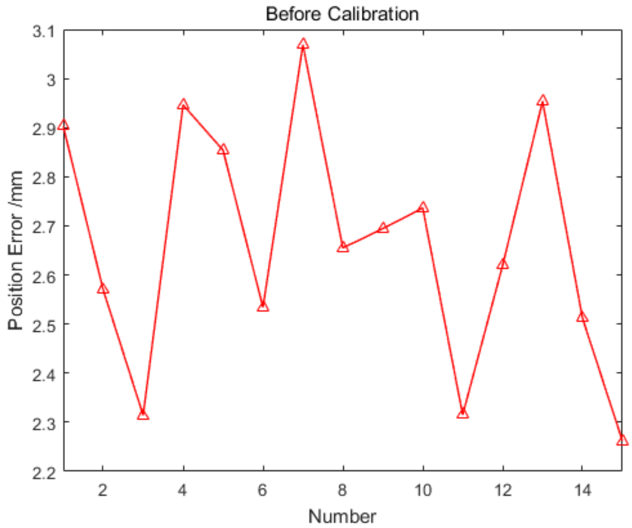

Fig. 8 position error before calibration

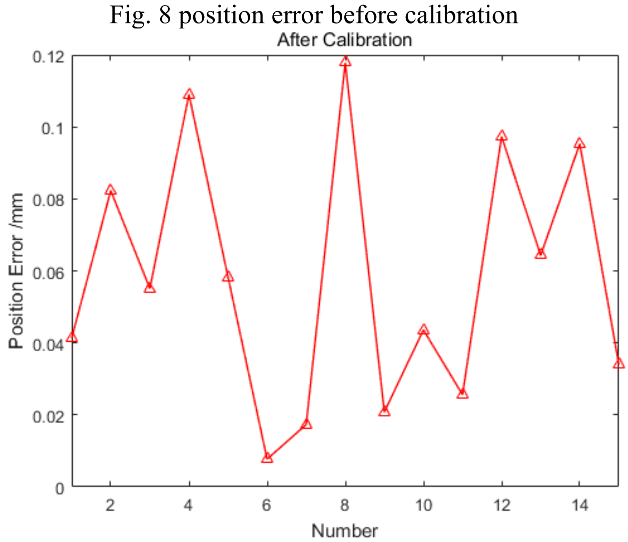

Fig. 9 Position error after calibration

IV. Conclusion

In this paper, a body calibration method of SCARA robot based on machine vision is proposed. Compared with the traditional calibration method like using laser tracker, which requires expensive measuring equipment and complicated calibration process, this new method with the designed calibration system and software is easy to operation and time saving. The experimental process and results show that the calibration time of one SCARA robot is about 1 minute and almost in automation process. IF the robot is in good condition, the average positioning error at the same point in both left-hand and right-hand coordinate systems of the robot after calibration is less than 0.06mm.

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