RESEARCH ON HIGH PRECISION AND ZERO-COST FOR ROBOT ZERO-POSITION PARAMETER IDENTIFICATION METHOD

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Abstract

This paper introduces a robot zero position parameter identification and calibration method based on high precision and zero cost, in order to solve the shortcomings of the traditional axis pin calibration and laser tracker calibration algorithms. The nonlinear least-squares iterative method proposed in this paper is used to identify the zero position parameters of the robot, and can effectively analyse and correct the kinematic errors of the robot. This method needs to collect 20 – 25 different pose data points of the robot in a fixed position, to determine the unknown deviation parameters in the zero-position model of the robot. At the same time, the four-point tool coordinate system calibration method is used to replace the existing five-point tool coordinate system calibration method. The experimental results show that the accuracy of the calibration method using zero position parameter identification is 69.847% higher than that of the most used shaft pin calibration method. Compared with the laser tracker calibration method with the highest accuracy, its time efficiency is improved by 80%. This method considers the calibration accuracy and efficiency, and significantly improves the adaptability of the zero-position calibration method to the calibration environment.

Key Words

Nonlinear least-squares iterative, industrial robot, parameter identification, zero-positioncalibration, intelligent computing

1. Introduction

Modern production processes require more complex manufacturing processes, which promotes the robot calibration technology [1]–[3]. Robot calibration is an indispensable part of robot technology. Its purpose is to determine the kinematics and posture parameters of the robot, so that the robot can be more accurately controlled when performing tasks. The process of robot calibration usually involves measuring the angle of the robot joints and the pose of the end effector relative to the reference coordinate system. Through robot calibration, it is possible to reduce the error of the robot during task execution and improves its accuracy and reliability. There are two types of robot calibration: internal calibration and external calibration. Internal calibration refers to determining the angle of robot joints and the relative position between joints, usually completed by measuring the rotation axis of joints and the position of end effectors. External calibration is the process of determining the pose of the robot's end effector in the reference coordinate system, which can ensure the accuracy and reliability of the robot during task execution. The specific steps of external calibration include establishing a reference coordinate system, selecting calibration tools, and conducting measurements and calculations, *etc.* The importance of robot calibration is self-evident, as it can significantly improve the accuracy and reliability of robots. However, robot calibration is also one of the bottlenecks in robot applications. Methods for improving the accuracy of industrial robots have been demonstrated in many literatures. Wang *et al.* [4] proposed a new Tool Center Point (TCP) calibration method for industrial robots. The proposed method provides fully automated robotic TCP calibration within a defined cycle time. It was found that the traditional manual robot TCP calibration process takes approximately 15 min and takes more time in high-precision situations. The proposed method reduces this time to less than 3 min without operator support. Li *et al.* [5] proposed a calibration method for industrial robots based on the principle of perigon error close, aiming at the problem that the self error of the industrial robot calibration device affects the calibration accuracy. The model parameter identification experiment verifies the feasibility of this method for industrial robot calibration. Zhao *et al.* [6] proposed a robot zero calibration device and method based on spatial parameter clustering recognition to overcome the shortcomings of traditional axis pin and laser tracker calibration. The clustering module identifies multiple groups of zero position training parameters,

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Recommended by Howard Li
(DOI: 10.2316/J.2024.206-1072)

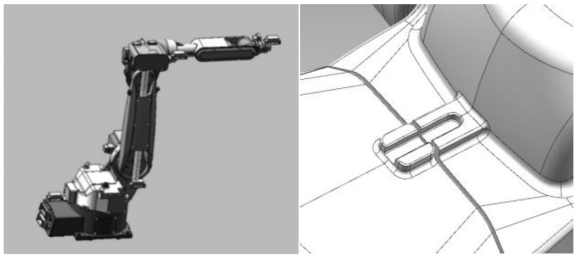

Figure 1. Installation diagram of each shaft pin.

and solves the optimal zero position parameters of each joint. This method considers the calibration accuracy and efficiency, and significantly improves the adaptability to the calibration environment. Although relevant scholars have done in-depth research on the robot zero calibration algorithm, because of the time-consuming and accuracy problems of the algorithm, it still cannot be widely used in practical engineering.

This paper summarises the shortcomings and deficiencies of traditional axis pin calibration and laser tracker calibration algorithms. For the most extensive laser tracker calibration algorithms, this paper establishes a zero-position parameter error model of robot kinematics. This paper uses nonlinear least-squares iterative method to solve the zero position parameters of the robot kinematics. At the same time, the four-point tool coordinate system calibration method is used instead of the existing five-point tool coordinate system calibration method. This paper proposes zero-position parameter identification calibration, which can satisfy short time, high precision, and zero-cost calibration.

2. Zero Position Parameter Calibration of Traditional Robot

Robot zero calibration is to accurately define the initial position of the robot arm and joint as the origin of the robot coordinate system.

2.1 Calibration Algorithm of Traditional Axis Pin

Figure 1 shows the installation diagram for each shaft pin. Move the robot so the shaft pin can be smoothly inserted into the calibration hole to complete the calibration. The principle of calibration algorithm of traditional axis pin method is that the zero-point position can be considered to have been reached by aligning the shaft pin. However, due to the low accuracy of this method, it is only suitable for occasions where the absolute positioning accuracy of the robot is not high. When calibrating the shaft pin, it is necessary to pay attention to the accuracy and error of the measuring tool, as well as the stability of the robot itself. Therefore, it is necessary to select the appropriate zero-point calibration method according to the specific situation in practical application.

The calibration test steps are as follows:

1) Rough zero of each axis of the robot.
2) Installation of pin adapter for each axis of robot.
3) Adjust the robot joint so that the shaft pin is installed on axis 1, and axis 1 is reset to zero.
4) Adjust the robot joint so that the shaft pin is installed on the 2-axis, and the 2-axis resets to the zero position.
5) Adjust the robot joint so that the shaft pin is installed on the 3-axis, the 3-axis resets to the zero position, and fix the 2 and 3-axis.
6) Adjust the robot joint so that the shaft pin is installed on the 4-axis, the 4-axis resets to zero, and the 2, 3, and 4-axis are fixed.
7) Adjust the robot joint so that the shaft pin is installed on the 5th axis, the 5th axis is reset to zero, and the 2nd to 5th axes are fixed.
8) Adjust the robot joint so that the shaft pin is installed on the 6-axis, the 6-axis resets to the zero position, and the 2nd to 6th axis is fixed.

So far, the robot shaft pin calibration algorithm has been completed. The shaft pin calibration method has the disadvantages of poor accuracy and difficult popularisation, and has been gradually eliminated.

2.2 Laser Tracker Calibration Algorithm

Robot zero calibration based on laser tracker can improve the accuracy of the standard robot, but it is difficult to use in the manufacturing workshop due to cost and flexibility [7]–[9]. The calibration algorithm of laser tracker requires one adapter flange, one target ball mounting base, and several screws on the robot body. The adapter flange and target ball mounting base are installed as shown in Fig. 2. The positioning pins should be aligned during installation. The *Radius* formed by the target ball installation center and the flange center is greater than 0, and it is related to the measurement of error.

Robot tool coordinate system is T_7; Base coordinate system is O; The coordinate system of the laser tracker is M; The Z-axis, X-axis, and Y-axis directions of each link coordinate system of the robot are modified according to the following figure.

2.2.1 Data Acquisition and Measurement Steps

The axis of each axis ($J_1 \sim J_6$) of the robot body is measured in turn by using a laser tracker. The method is to install the target ball at the end of the robot, rotate each joint axis separately in sequence, and let the laser tracker pick up points every certain angle interval. In order to make the measurement more accurate, the rotation range of each axis should be as large as possible, and ensure that at least 20 points can be picked up.

2.2.2 Calibration Algorithm of Parameter Identification Tracker

This section describes the algorithm process of laser tracker calibration using the least square method to identify the zero position parameters. Figure 3 is the flow chart of the laser tracker calibration algorithm.

1) The calibration algorithm of parameter identification tracker requires static acquisition for each axis of the robot, once every 2°. The acquisition requires at least 20

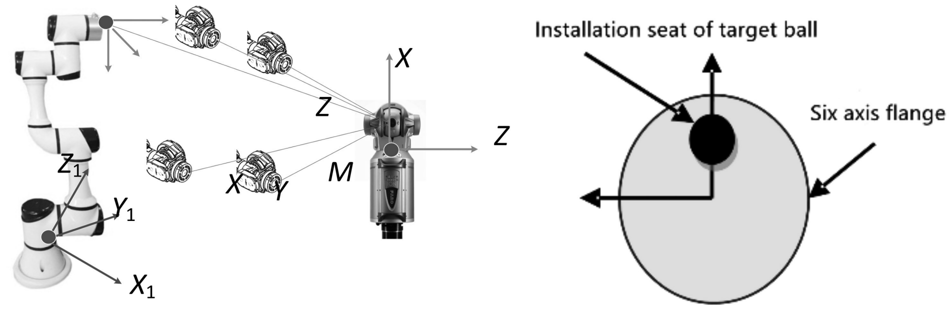

Figure 2. Installation diagram of adapter and target ball flange required for zero calibration.

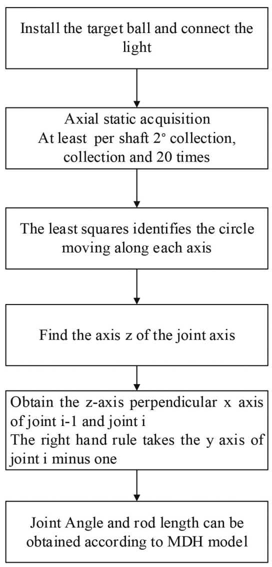

Figure 3. Flow chart of laser tracker calibration algorithm.

points, and the joint axis requires a motion range of at least 40°. For data acquisition of each axis, it is necessary to keep the other axes stationary and return to zero.

2) The circle of the end track of each moving joint axis is identified by the least square method, and the center of the circle is fitted. The optimal parameters can be fitted by the least squares of the data. The form of the least squares problem is as follows: $f(x) = min\|Ax - b\|^2$, then, the optimal solution $\widehat{x}$ of f(x) must satisfy:

$$\begin{cases} \frac{\partial f}{\partial x_k}(\widehat{x}) = \nabla f(\widehat{x})_k = 0, k = 1, \ldots, n \\ \widehat{x} = \left(A^T A\right)^{-1} A^T b = A^{\dagger} b \end{cases} \tag{1}$$

The column vectors of the matrix $A \in R_{m \times n}$ are independent of each other. Therefore, A can be decomposed into $A = \mathrm{QR}$, where $Q \in R_{m \times n}$ is an orthogonal matrix ($Q^T Q = I$), and $R \in R_{n \times n}$ is an upper triangular matrix. So:

$$\begin{cases} A^T A = (\mathrm{QR})^T (\mathrm{QR}) = R^T Q^T \mathrm{QR} = R^T R \\ A^{\dagger} = \left(A^T A\right)^{-1} A^T = \left(R^T R\right)^{-1} (\mathrm{QR})^T = R^{-1} Q^T \end{cases} \tag{2}$$

Solve for $R\widehat{x} = Q^T b$ to get $\widehat{x}$. Multiple measurements are required in the identification, and the data can be expanded.

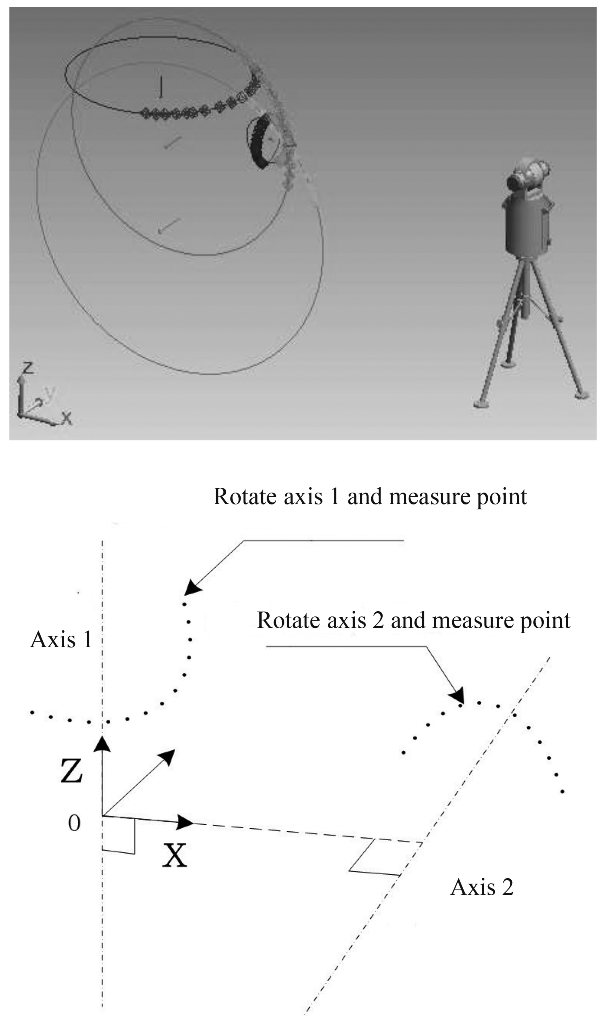

Figure 4. Establish the axis of each axis of the robot.

3) Figure 4 shows the establishment of the axis of each axis of the robot, and the normal vector (vertical circle) of the circle can be obtained from the data. The line between the center of the circle and the point on the normal vector is the axis (Z axis) of the moving joint. The X-axis can be obtained by the common perpendicular line between the Z-axis of joint $i-1$ and joint$i$. The common vertical line between Z-axis and X-axis is Y-axis (right-hand rule). The coordinate system of each joint axis can be established by this method, so that the a_{i-1} to a_i can also be calculated.

4) First, the point H_{i-1} in the $i-1$ axis of the connecting rod is projected onto the i-axis straight line L_i to obtain the intersection H_i. Obtained two projection points H_i and H_{i-1}, establish a straight line to obtain an approximate common perpendicular a_{i-1}. Find an approximate solution, project the axis of the $i-1$ axis directly onto the i-axis, and approximately obtain a_{i-1} value. Given the position of the relevant axis of the robot in space, all the connecting rod parameters of the robot can be obtained according to the MDH model. The zero-position error of each axis can be obtained by calculating theta value. At this point, the zero calibration of the laser tracker is solved.

3. Robot Zero Parameter Identification

Parameter identification refers to the process of determining the parameters of the system mathematical model by analysing the input and output data of the system. This process usually includes data collection, preprocessing, model selection, parameter estimation, and model validation. This paper uses the variable attitude to collect the values of 20–25 groups of different attitudes under a fixed position, and the joint value is calculated by the inverse solution to 20–25 groups of pose values. Because the robot's position is fixed, zero position parameter identification makes the joint value error of these 20 to 25 groups 0.

3.1 Zero Position Parameter Identification of Multi-Point Robot Kinematics

In the zero-position parameter identification, sensors are usually used to measure the joint angle or pose [10]–[13] of the robot, and then, these measured values are compared with the predicted values of the robot model, to determine the unknown parameters in the model. Thesemodify Denavit-Hartenberg (MDH)parameters include joint length, offset, position and direction of rotation axis, *etc*. The final identification parameters can be used in the controller of the robot to achieve high-precision control of the robot.

In the zero-position parameter identification of multi-point robot kinematics, it is necessary to collect the method of observing and measuring the position and the end effector pose of the robot in a fixed position to identify the zero-position of the robot. It is only needed to calibrate 20–25 points to derive the zero-position error and tool coordinate system of each joint. Figure 5 shows the solution process of robot zero parameter identification. Robot zero parameter identification is essentially an algorithm of robot joint zero deviation parameter identification.

The zero-position parameter identification of multi-point robot kinematics is a method to identify the zero-position of the robot by collecting different poses of the robot in a fixed position, observing, and measuring the position and pose of the end effector, to derive the unknown deviation parameters of the zero-position relationship angle in the robot kinematics model [14]–[17]. These data are used to derive the unknown parameters in the robot

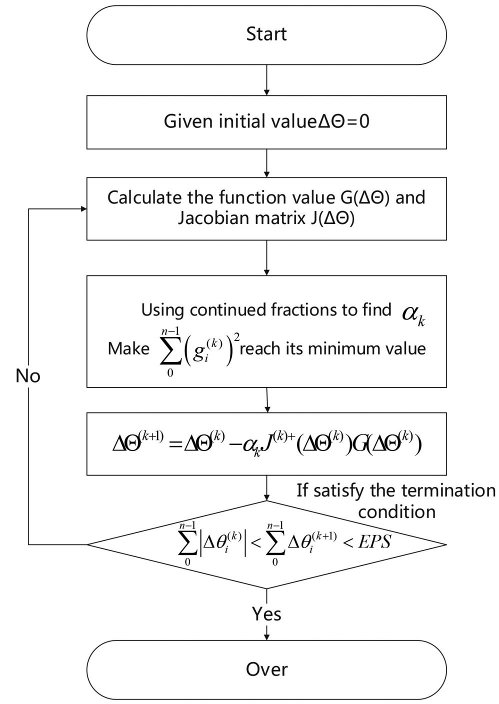

Figure 5. Algorithm flow of robot zero parameter identification.

kinematics zero-position model. Using the method of parameter identification to calculate the robot joint angle under the position and orientation of the end effector of the robot, and comparing with the actual measured end effector pose to calculate the error.

As shown in Fig. 6, the robot kinematics model describes the mathematical form of the robot motion law. The base coordinate system of the robot is $\{B\}$, the measurement position coordinate system of $20 \sim 25$ points calibrated by the robot is $\{P\}$, which means that the end of the manipulator contacts a fixed point in different poses, and the end coordinate system of the robot is $\{E\}$. As the robot end $\{E\}$ is always in contact with the $\{P\}$ point in the fixed coordinate system, the position of the robot end point in the $\{P\}$ coordinate system is $(0, 0, 0)^T$.

The position and pose of the robot base coordinate system in $\{P\}$ coordinate system is determined as ${}^P_BT$ in some way, and the position and pose of the robot end in $\{P\}$ coordinate system can be deduced as ${}^P_ET = {}^P_BT \cdot {}^B_ET$. Then, the attitude ${}^B_ET$ of the end effector in the robot base coordinate system can be calculated by using the forward kinematics formula.

$$ {}^B_ET = f(\Gamma, \Theta) \tag{3} $$

Γ is the rod length parameter of the robot. This shows that in the process of robot motion, the end point is always maintained at the origin in the $\{P\}$ coordinate system. Set the joint space vector of a robot as:

$$ \Theta = \left[\theta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5 \ \theta_6\right]^T \tag{4} $$

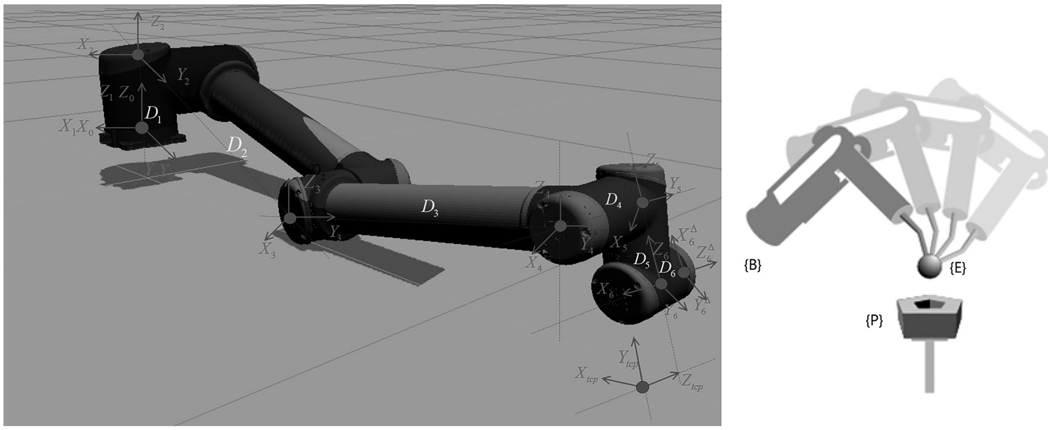

Figure 6. Robot joint coordinate system and calibration multipoint attitude acquisition.

The joint error vector is:

$$\Delta\Theta = \begin{bmatrix}\Delta\theta_1 & \Delta\theta_2 & \Delta\theta_3 & \Delta\theta_4 & \Delta\theta_5 & \Delta\theta_6\end{bmatrix}^T \quad (5)$$

Where, $\overline{\theta_i}$ is the theoretical zero value of the robot; θ_i is the joint that the robot rotates, $\overrightarrow{\Delta\theta_i}$ is the zero-position deviation, so it is necessary to carry out parameter identification for the zero-position deviation of the robot.

For a robot without deviation, its forward kinematics shall be:

$$T = f(\Theta, \Gamma) = \begin{bmatrix} r(\Theta) & p(\Theta, \Gamma) \\ 0 & 1 \end{bmatrix} \quad (6)$$

For a robot with deviation, its forward kinematics shall be:

$$T = f(\Theta + \Delta\Theta, \Gamma) = \begin{bmatrix} r(\Theta + \Delta\Theta) & p(\Theta + \Delta\theta, \Gamma) \\ 0 & 1 \end{bmatrix} \quad (7)$$

The essence of zero calibration is to obtain the vector $\Delta\Theta$, and modify the zero-position of each axis to $[\Delta\theta_1, \Delta\theta_2, \Delta\theta_3,\ \Delta\theta_4,\ \Delta\theta_5,\ \Delta\theta_6]$. Through the joint function, the angle is converted into the code disk value and written into ferroelectric memory. Combined with the experience of laser instrument calibration method, $\Delta\theta_1$, and $\Delta\theta_6$ can be set arbitrarily, which is consistent with the case that the two columns corresponding to $\Delta\theta_1$, and $\Delta\theta_6$ in the Jacobian matrix are 0 in the identification process.

Due to the common error of the robot body, and the positive solution of robot is calculated according to the formula, the position p and attitude r in the result are not accurate. Combined with the "fixed-point and variable posture" operation in teaching, we can easily associate it with changing the posture of the robot while ensuring that the end is aligned with a fixed point in space. It is easy to obtain a series of position vectors:

$$p_0(\Theta + \Delta\Theta, \Gamma), p_1(\Theta + \Delta\Theta, \Gamma), \ldots, p_i(\Theta + \Delta\Theta, \Gamma) \\ (i = 1, 2, 3, \ldots, 25) \quad (8)$$

Based on this, the following equations can be constructed:

$$\begin{cases} g_0(\Delta\Theta) = p_0(\Theta + \Delta\Theta, \Gamma) - p_1(\Theta + \Delta\Theta, \Gamma) = 0 \\ g_1(\Delta\Theta) = p_1(\Theta + \Delta\Theta, \Gamma) - p_2(\Theta + \Delta\Theta, \Gamma) = 0 \\ \vdots \\ g_{n-1}(\Delta\Theta) = p_{n-1}(\Theta + \Delta\Theta, \Gamma) - p_n(\Theta + \Delta\Theta, \Gamma) = 0 \end{cases} \\ (n = 1, 2, 3, \ldots, 25) \quad (9)$$

As Θ and Γ are known, the above equation is equivalent to the following matrix equation.

$$G(\Delta\Theta) = \begin{bmatrix} g_0(\Delta\Theta) \\ g_1(\Delta\Theta) \\ \vdots \\ g_{n-1}(\Delta\Theta) \end{bmatrix} = 0 \quad (10)$$

The solution of the problem is the generalised inverse of the least-square solution of the system of equations (10), and the Jacobian matrix is defined:

$$J(\Delta\Theta) = \partial G(\Delta\Theta)/\partial\Theta \\ = \begin{bmatrix} \partial g_0/\partial\theta_0 & \partial g_0/\partial\theta_1 & \cdots & \partial g_0/\partial\theta_6 \\ \partial g_1/\partial\theta_0 & \partial g_1/\partial\theta_1 & \cdots & \partial g_1/\partial\theta_6 \\ \vdots & \vdots & & \vdots \\ \partial g_{n-1}/\partial\theta_0 & \partial g_{n-1}/\partial\theta_1 & \cdots & \partial g_{n-1}/\partial\theta_6 \end{bmatrix} \quad (11)$$

In the problem of robot zero-position parameter identification, it is challenging to solve the nonlinear equations due to a large number of parameters and complex value range [18]–[20]. In this paper, using the nonlinear least-squares iterative method to solve the robot zero-position joint deviation value:

$$\begin{cases} Z^{(k)} = \alpha_k J^{(k)+}\left(\Delta\Theta^{(k)}\right) G\left(\Delta\Theta^{(k)}\right) \\ \Delta\Theta^{(k+1)} = \Delta\Theta^{(k)} - \alpha_k Z^{(k)} \end{cases} \quad (12)$$

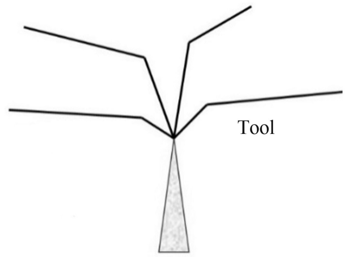

Figure 7. Four-point calibration diagram.

Where $Z^{(k)}$ is the linear least-square solution of the linear algebraic equation system $G^{(k)}Z^{(k)} = F^{(k)}$. α_k is the point at which the function $\sum_{i=0}^{n-1}\left(p_i^{(k)}\right)^2$ reaches the minimum, and the rational extreme value method is used to calculate α_k. In the iteration process, it is necessary to consider the influence of various parameters and the relationship between different iteration steps. Keep iterating and updating until $\overrightarrow{\Delta\Theta}$ is small enough. The efficiency and accuracy of calculating the zero-position parameters of the robot can be effectively improved by reasonable iterative formula.

At this point, the deviation $\Delta\Theta$ of the robot zero-position parameters can be obtained. In practical applications, in order to improve the accuracy and efficiency of robot motion, various optimisation methods can be used to improve the solving process of kinematic parameters.

3.2 Calibration Principle of Four-Point Tool Coordinate System

The four-point tool coordinate system calibration method is used to replace the existing five-point tool coordinate system calibration method. The basic principle of the method is that the welding torch tip approaches the target tip in four different poses as shown in Fig. 7, and the coordinate system between the welding torch tip and the center of the robot flange is achieved by the following calculation process.

T_m^6: calibration object matrix. $T_{6,1}^0$ is the first measurement T_6 matrix; $T_{6,2}^0$ is the second measurement T_6 matrix; $T_{6,3}^0$ is the third measurement T_6 matrix; $T_{6,4}^0$ is the fourth measurement T_6 matrix.

The relationship between four measurements:

$$\begin{cases} T_m^6 = \begin{bmatrix} R_m^6 & P_m^6 \\ 0\,0\,0 & 1 \end{bmatrix} \\ T_{6,1}^0 T_m^6 = T_{6,2}^0 T_m^6 = T_{6,3}^0 T_m^6 = T_{6,3}^0 T_m^0 \end{cases} \tag{13}$$

According to relation (13), there are:

$$\begin{cases} \left(T_{6,2}^0 - T_{6,1}^0\right) T_m^6 = 0 \\ \left(T_{6,3}^0 - T_{6,1}^0\right) T_m^6 = 0 \\ \left(T_{6,4}^0 - T_{6,1}^0\right) T_m^6 = 0 \end{cases} \tag{14}$$

Expand the above formula, as follows:

$$\begin{cases} [R_{6,2}^0 - R_{6,1}^0 P_{6,2}^0 - P_{6,1}^0] * [P_m^6; 1] = 0 \\ [R_{6,3}^0 - R_{6,1}^0 P_{6,3}^0 - P_{6,1}^0] * [P_m^6; 1] = 0 \\ [R_{6,4}^0 - R_{6,1}^0 P_{6,4}^0 - P_{6,1}^0] * [P_m^6; 1] = 0 \end{cases} \tag{15}$$

Let,

$$\begin{cases} P_{6,2}^0 - P_{6,1}^0 = b_1 \\ P_{6,3}^0 - P_{6,1}^0 = b_2 \\ P_{6,4}^0 - P_{6,1}^0 = b_3 \\ A = \left[R_{6,2}^0 - R_{6,1}^0; R_{6,3}^0 - R_{6,1}^0; R_{6,4}^0 - R_{6,1}^0\right] \\ b = [-b_1; -b_2; -b_3] \end{cases} \tag{16}$$

Solve the over determined linear equations using the least-square method:

$$P_m^6 = \left(A^T A\right)^{-1} A^T * b \tag{17}$$

Tool coordinate system settings:

$$p_x = P_m^6\,(1)\,, p_y = P_m^6\,(2)\,, p_z = P_m^6\,(3) \tag{18}$$

Note: (1) semicolon ";" refers to linefeed; (2) The default vector is the column vector.

4. Experimental Results and Analysis

Figure 8 shows the experimental procedure framework of zero calibration. The robot position accuracy is tested according to the national standard "GB/T 12642-2001 Industrial Robot Performance Specifications and Test Methods" to compare the effects of the three calibration methods.

Experiments are carried out on different robots to verify the accuracy of zero position parameter identification. Figure 9 shows the different experimental environments of zero-position calibration.

4.1 Calibration Algorithm of Axis Pin

This experiment uses the shaft pin method to calibrate the zero-position of the robot, and verifies it by comparing the angle value of the robot with the angle value of the theoretical robot. However, it can be seen from Table 1 that there is a large gap between theoretical value and shaft pin calibration value. The theoretical zero value of the robot is the initial value of the joint coordinate system of the robot. This is because the algorithm does not consider the compensation of robot arm length, link offset, torsion angle, and other parameters, and the actual calibration results are related to the machining accuracy, which leads to the actual error of the robot. Therefore, in the field, where high-precision calibration is required, a more accurate calibration method should be adopted to ensure the motion accuracy and stability of the robot.

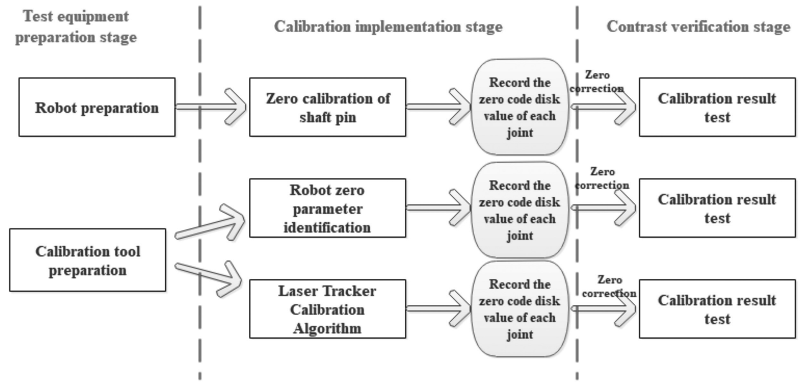

Figure 8. Experimental step frame diagram.

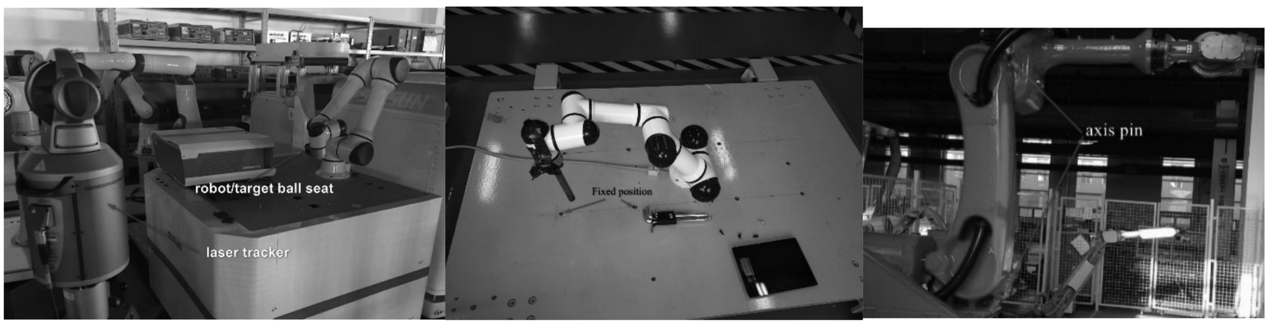

Figure 9. Different experimental environments of zero-position calibration.

Table 1
Comparison between Theoretical Value and Shaft Pin Calibration Value

Joint	Theoretical value of zero position	Shaft pin calibration value
$J1$	$0°$	$0.141°$
$J2$	$0°$	$-0.370°$
$J3$	$0°$	$-0.249°$
$J4$	$0°$	$0.216°$
$J5$	$-90°$	$-90.039°$
$J6$	$0°$	$-0.165°$

Table 2
Comparison between Theoretical Calculation Value and Calibration Value of Laser Tracer

Joint	Theoretical value of zero position	Calibration value of laser tracker
$J1$	$0°$	$0°$
$J2$	$0°$	$-0.0011°$
$J3$	$0°$	$-0.0043°$
$J4$	$0°$	$-0.0193°$
$J5$	$-90°$	$-90.0035°$
$J6$	$0°$	$0°$

4.2 Calibration Experiment of Laser Tracker

In this experiment, ION-type tracker produced by FARO Company is selected. The measurement range of this tracker can reach 40 m, and the measurement accuracy is $10\mu m \pm 8\mu m/m$, considering the sphericity error of the target ball and the spatial distance between the tracker and the robot during measurement, the accuracy of the tracker is $\pm 25\mu m$. It is far lower than the repeated positioning accuracy of the robot, so it meets the requirements of absolute positioning accuracy measurement.

In order to determine the spatial position of each axis of the robot, the laser calibration method and laser tracker can be used to measure the three-dimensional space. By fitting these points with the parameter identification algorithm, the position of each axis of the robot in space can be determined. Next, the error of the zero position of each axis can be calculated through the spatial geometric relationship between the axes. Table 2 shows that the difference between the angle calculated by the laser tracker and the actual angle of the robot is minimal, which indicates that the accuracy and reliability of this method are high.

When using the laser tracker for calibration, in order to save time, because axis 1 no longer has the previous axis and axis 6 no longer has the next axis, the two axes have no constraint relationship, so it is not necessary to calibrate them and set them directly to 0. It is set by the

Table 3
Robot Joint Values based on 25 Points

$J1$	$J2$	$J3$	$J4$	$J5$	$J6$
17.0000°	0°	8.0000°	6.5000°	6.0000°	5.0000°
16.8473°	0.0037°	7.9969°	0.7536°	5.8648°	11.2339°
16.6945°	0.0044°	7.9964°	−5.0911°	5.8394°	17.5662°
16.5418°	0.0021°	7.9983°	−10.8988°	5.9249°	23.8613°
16.3891°	−0.0033°	8.0027°	−16.5387°	6.1182°	29.9887°
16.2366°	−0.0118°	8.0097°	−21.9008°	6.4135°	35.8385°
16.0843°	−0.0232°	8.0191°	−26.9061°	6.8022°	41.3315°
15.9323°	−0.0378°	8.0311°	−31.5083°	7.2745°	46.4216°
15.7807°	−0.0553°	8.0455°	−35.6908°	7.8204°	51.0923°
15.6296°	−0.0759°	8.0624°	−39.4597°	8.4299°	55.3496°
15.4789°	−0.0995°	8.0819°	−42.8363°	9.0941°	59.2147°
15.3288°	−0.126°	8.1038°	−45.8503°	9.8049°	62.7177°
15.1794°	−0.1556°	8.1282°	−48.5353°	10.5551°	65.892°
15.0306°	−0.1882°	8.1551°	−50.9257°	11.339°	68.772°
14.8826°	−0.2237°	8.1844°	−53.054°	12.1513°	71.3904°
14.7355°	−0.2622°	8.2162°	−54.9503°	12.9877°	73.7774°
14.5893°	−0.3037°	8.2505°	−56.6419°	13.8447°	75.9601°
14.444°	−0.348°	8.2873°	−58.1529°	14.7192°	77.9627°
14.2998°	−0.3953°	8.3264°	−59.5045°	15.6085°	79.8065°
14.1567°	−0.4455°	8.3681°	−60.7152°	16.5106°	81.5101°
14.0147°	−0.4985°	8.4121°	−61.8011°	17.4236°	83.0897°
13.8739°	−0.5544°	8.4586°	−62.7764°	18.3459°	84.5592°
13.7344°	−0.6131°	8.5075°	−63.6531°	19.2762°	85.9311°
13.5963°	−0.6746°	8.5588°	−64.442°	20.2132°	87.2159°
13.4595°	−0.7389°	8.6124°	−65.1523°	21.156°	88.423°
14.1567°	−0.4455°	8.3681°	−60.7152°	16.5106°	81.5101°
14.0147°	−0.4985°	8.4121°	−61.8011°	17.4236°	83.0897°

on-site station and working condition, so the default value is consistent with the theoretical value.

4.3 Experiment of Robot Zero-Position Parameter Identification Algorithm

The zero-position of the robot can be identified by observing and measuring the position and pose of the end effector in a fixed position. The zero-position error of each joint and the tool coordinate system can be derived by calibrating 20–25 points without a laser tracker. Table 3 shows the robot joint values recorded based on 25 points as the inputs of the nonlinear least-squares iterative method.

Figure 10 shows the curve of the joint offset value. These two joints have no constraint relationship, so can set them directly to 0 without calibrating them. The zero-position parameter identification equation requires five cycles to converge.

According to the nonlinear least-squares iterative method, the zero-position value as shown in Table 4 can be calculated. The difference between the zero-position parameter identification calibration value and the actual angle value of the robot is small, and the actual error is better than the shaft pin calibration algorithm.

4.4 Experiment of Time Efficiency and Position Repeatability

The time efficiency of robot zero calibration is obtained by using three calibration methods, *i.e.,* shaft pin, zero parameter identification, and laser tracker. Table 5 shows

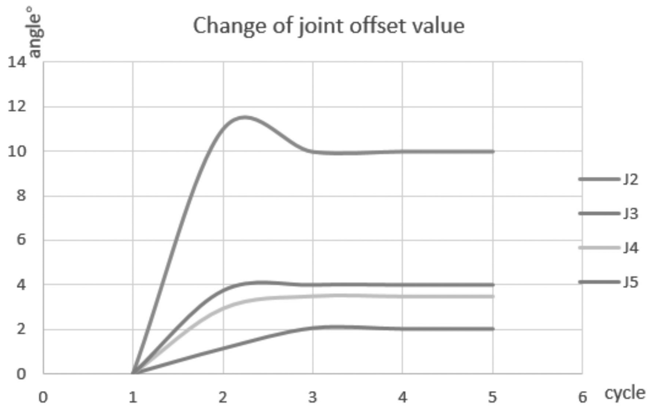

Figure 10. Joint offset value curve.

Table 4
Comparison between Theoretical Value and Zero-Position Parameter Identification Calibration Value

Joint	Theoretical value of zero position	Calibration value of zero-position parameter identification
$J1$	0°	0°
$J2$	0°	0.067°
$J3$	0°	−0.0235°
$J4$	0°	−0.1387°
$J5$	−90°	−90.008°
$J6$	0°	0°

Table 5
Calibration Relative Error and Time Efficiency

Method	Shaft pin calibration	Calibration of laser tracker	Zero position parameter identification and calibration
Time/min	20	120	24

the calibration relative error and time efficiency. The robot shaft pin calibration takes about 20 min, the laser tracker calibration takes about 120 min (because the heat engine of the laser tracker needs 60 min), and the zero-position parameter identification calibration takes about 24 min.

In this study, the zero-position parameter identification method is used to calibrate the robot, and the position accuracy and repeatability of the calibrated robot are calculated. As shown in Table 6, the position repeatability of the robot includes the average error and standard deviation.

The experimental results show that the positioning error of the robot is significantly reduced after zero calibration, which provides a powerful guarantee for the accurate positioning of the robot. At the same time, compared with the traditional zero calibration method, the method proposed in this paper has higher efficiency and operability, saves the installation and calibration time of the zero-calibration tool, shortens the calibration time by about half, and greatly improves the efficiency and accuracy of calibration, but the accuracy is slightly lower than the laser tracker calibration algorithm. Therefore, when selecting the calibration method, it is necessary to weigh the factors of speed and accuracy, and select the appropriate calibration method according to the actual situation. The proposal and application of this method provide useful support and help for the application and development of robots. The statistical results show the effectiveness of the proposed method.

Table 6
Robot Position Repeatability Experiment

Comprehensive error	P1	P2	P3	P4	P5
10% speed average err	0.011	0.017	0.017	0.010	0.010
10% speedstandard-deviation	0.006	0.010	0.006	0.003	0.002
50% speed average err	0.007	0.013	0.008	0.009	0.012
50% speedstandard-deviation	0.003	0.008	0.006	0.006	0.006
100% speed average err	0.015	0.013	0.010	0.012	0.010
100% speedstandard-deviation	0.011	0.008	0.005	0.004	0.005

5. Conclusion

The main way to improve the accuracy of the robot is to identify and compensate the flexible parameters in the zero position parameters, kinematic parameters, and non-geometric parameters of the robot. This paper discusses the zero-position calibration and accuracy evaluation method of industrial robot, and proposes a new zero position parameter identification and calibration method of robot and a zero-position parameter error model of robot kinematics. The model includes joint length, offset, rotation axis position and direction, and other parameters, which can more accurately describe the kinematic characteristics of the robot. By collecting multiple groups of different pose values of the robot in fixed position, the zero position parameters of the robot are identified by using the nonlinear least-squares iterative method, to determine the unknown parameters in the zero-position model of the robot, and can effectively analyse and correct the kinematic errors of the robot. At the same time, the four-point tool coordinate system calibration method is used to replace the existing five-point tool coordinate system calibration method.

The robot zero position parameter identification and calibration method proposed in this paper is suitable for high-precision application scenarios and meets the needs of various industrial manufacturing scenarios. However, the influence of flexible parameters on the positioning error of the robot has not been fully studied, which is the focus of future research. It is necessary to further study the influence of flexible parameters and incorporate them into the robot model to improve the positioning accuracy of the robot.

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