Home Position and Tool Coordinates Calibration for 6-DOF Robot Based on Fixed-point Constraint

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Abstract. In the application process of industrial robots, it is necessary to ensure that the home position is correct when the robot changes the end tool, so that the coordinate values of tool can be calculated more accurately and the accuracy of the robot's trajectory can be satisfied. A comprehensive calibration method of tool coordinates and home position of serial industrial robots based on fixed-point constraints is presented in this paper. Based on Denavit-Hartenberg (D-H) kinematics theory, the error models of tool coordinates and home position errors of 6-DOF serial industrial robots are established. By constraining the tool center point (TCP) of the robot with fixed points, the joint data of calibration points with different postures at the same position are collected, and the error value of the controlled object is identified by the least square algorithm. The calibration experiment results are basically consistent with the factory calibration parameters, which proves the feasibility of the calibration algorithm.

1. Introduction
In practical application, the trajectory of industrial robots is located at the tool center point (TCP) on the end of robot, so the accuracy of the tool coordinate system determines the accuracy of the robot trajectory [1]. Tool coordinate system of robot represents the transformation relationship between TCP and end-link coordinate system of robot. The deviation of the home position of the industrial robot will lead to the deviation of the end-link coordinate system in the transformation between the end-link coordinate system and the base coordinate system, which will lead to the error of the tool coordinate system [2]. Therefore, the accuracy of the home position of the robot should be considered when tool coordinate system is calibrated. There are many factors leading to the home deviation of the robot, such as the error in the assembly of the robot, the fault of the robot itself and the manual loading and unloading of robot [3]. At present, the calibration technology of tool coordinate system of robot has been very mature, which mainly includes external datum method and multi-point calibration method. External datum method is a fast and simple method to calibrate tool coordinates of robots by external datum points. It mainly includes the standard specimen calibration method and the fixed datum pilot method introduced in reference [4-5]. But in industrial application, most industrial robots use five-point method or seven-point method to calibrate tool coordinate system. These two methods belong to multi-point calibration method. They calculate the value of tool coordinate system through the position
coincidence of TCP and the orientation relationship of coordinate system [6]. In the aspect of home position calibration, the precise home position can be obtained by kinematic calibration based on pull-wire sensor or laser tracker, but it is limited by expensive equipment and complicated calibration process [7]. In addition, there are generally mechanical devices for positioning on the robot body to help the operator find its home position [8].

This paper presents a method which can simultaneously calibrate the deviation of tool coordinate system and home position of robot. It is a multi-point calibration method similar to the tool coordinate system calibration, which combines the kinematics model of robots. It can find out the dependence between the basic coordinate system and tool coordinate system, and calculates the deviation of tool coordinate system and home position of robots at the same time.

2. Modeling

2.1. D-H Kinematics Modeling of Robot

According to the D-H kinematics modeling rules of the robot [9], the kinematics model algorithm of the 6-DOF serial robot is to connect the link coordinate system on each joint in series by coordinate transformation. This process is called the forward kinematics solution of the robot. For different types of serial robots, the initial values of geometric parameters and home position are different. Taking the robot RB08 as the research object, the connecting rod coordinate system is established at the six rotating joints of the 6-DOF robot. After the robot connecting rod coordinate system is determined, the geometric parameters between the two coordinate systems can be determined according to the position of the connecting rod coordinate system. According to the principle of coordinate transformation, the transformation of two coordinate systems can be described by the product of homogeneous transformation matrix:

\[
^+T = \begin{bmatrix}
\cos \alpha_i & -\sin \alpha_i & 0 & a_{i-1} \\
\sin \alpha_i \cos \theta_i & \cos \alpha_i \cos \theta_i & \sin \alpha_i \sin \theta_i & d_i \\
\sin \alpha_i \sin \theta_i & \cos \alpha_i \sin \theta_i & \cos \alpha_i \cos \theta_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

Based on the linkage coordinate system of RB08 robot, the geometric parameters of RB08 robot are shown in table 1.

| Joints | \(a_{i-1}\) (mm) | \(\alpha_i\) (°) | \(d_i\) (mm) | \(\theta_i\) (°) |
|--------|------------------|-----------------|--------------|-----------------|
| 1      | 0                | 0               | 0            | 0               |
| 2      | 170              | -90             | -            | -90             |
| 3      | 560              | 0               | 0            | 0               |
| 4      | 155              | -90             | 640          | 0               |
| 5      | 0                | 90              | 0            | 0               |
| 6      | 0                | -90             | 110          | 0               |

Plugging geometric parameters into equation (1), a general formula for coordinate transformation of connecting rods can be obtained:

\[
^T = \begin{bmatrix}
\cos \theta_1 & -\sin \theta_1 & 0 & a_{i-1} \\
\sin \theta_1 \cos \alpha_{i-1} & \cos \theta_1 \cos \alpha_{i-1} & -\sin \alpha_{i-1} & d_i \\
\sin \theta_1 \sin \alpha_{i-1} & \cos \theta_1 \sin \alpha_{i-1} & \cos \alpha_{i-1} & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)

Finally, the position of the end coordinate system relative to the base coordinate system of the robot can be obtained by multiplying the homogeneous transformation matrices between the six adjacent coordinate systems in turn.

\[
^T = ^0T_6^5T_5^4T_4^3T_3^2T_2^1T_1^0T_0^1T_0^1P = \begin{bmatrix}
^T_N \\
0 \\
1
\end{bmatrix}
\]

(3)
The matrix $^6T_0$ represents the conversion relationship between the end link coordinate system and the base coordinate system, wherein the sub-matrix $^6N_0$ represents the attitude information of the end-link coordinate system in the base coordinate system of robot, and the sub-matrix $^6P_0$ represents the position information of the end-link coordinate system in the base coordinate system of robot.

2.2. Tool coordinate system

The tool installed on the end-link of the robot is the actuator of the robot. The tool coordinate system is the coordinate system fixed at the end of the tool. Its origin is the tool end center, called TCP point. The relationship among the base coordinate system, the end-link coordinate system and the tool coordinate system of the robot is shown in Figure 1.

Through the kinematics model, it can be concluded that the representation of the end-link coordinate system $E$ in the base coordinate system $B$ can be represented by the transformation matrix $^6T_0$, while $^6T_{tool}$ is the transformation matrix of the tool coordinate system $T$ relative to the end coordinate system $E$. If the effect of attitude is discarded, that is to say, the direction of tool coordinate system $T$ and end coordinate system $E$ is the same, and only the position relationship is different. The transformation matrix can be expressed as:

$$^6T_{tool} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: $x$, $y$ and $Z$ represent the translation distance between TCP and the end-link coordinate system $X$, $Y$ and $Z$ axes respectively. The transformation matrix between the tool coordinate system and the base coordinate system of robot can be expressed as: $^6T_{tool} = ^6T_{base} * ^6T_{end}$. If only the position relation of the tool coordinate is considered, the transformation relation between the end center of the robot tool and the base coordinate system is expressed as follows: $^6P_{tool} = ^6N_{tool} * ^6P_{end}$

2.3. Basic Principles of Calibration

Controlling TCP to contacts a fixed point from different directions to ensure that the TCP position was fixed when computer collects data, as shown in Figure 2. In this case, different calibration points have different joint angles because of different orientations, but the actual position of TCP is unchanged.

![Figure 1. Relations between robot coordinate systems.](image1)

![Figure 2. Calibration principle.](image2)
The position error between two calibration points is expressed by 
\[ \Delta P = P_{i} - P_{j} = \cdots = P_{i} - P_{j+1} = 0. \]

However, there is a deviation in the TCP position obtained by forward kinematics solution of the joint angle data from the perspective of the theoretical model, which is not consistent with the actual position of TCP. The position error between the two TCP position values obtained from the joint angle forward kinematics solution of the calibration points is expressed by 
\[ \Delta P_{n} = P_{n}^{\text{base'}} - P_{n}^{\text{tool'}}. \]

The TCP position obtained by forward kinematics solution does not match the actual TCP position, which is considered to be caused by the error of home position \((\theta_{1} - \theta_{6})\) and tool coordinate position \(P_{6}\) of the robot. The error between the actual position error and the model position error can be approximately replaced by the differential equation, as shown below.

\[ d(\Delta P_{n}) = \Delta P_{n} - \Delta P_{n} = -\Delta P_{n} \quad (4) \]

The differentiation of Matrix with respect to the home position \((\theta_{1} - \theta_{6})\) and tool coordinate position \(P_{6}\) as shown below.

\[ d(\Delta P_{n}) = \sum_{i=1}^{6} \frac{\partial(\Delta P_{n})}{\partial \theta_{i}} d\theta_{i} + \frac{\partial(\Delta P_{n})}{\partial x} dx + \frac{\partial(\Delta P_{n})}{\partial y} dy + \frac{\partial(\Delta P_{n})}{\partial z} dz \quad (5) \]

The error model of tool coordinate and home position of 6-DOF serial robot is obtained by substituting equation (4) into equation (5)

\[ -\Delta P_{n} = \sum_{i=1}^{6} \frac{\partial(\Delta P_{n})}{\partial \theta_{i}} \Delta \theta_{i} + \frac{\partial(\Delta P_{n})}{\partial x} \Delta x + \frac{\partial(\Delta P_{n})}{\partial y} \Delta y + \frac{\partial(\Delta P_{n})}{\partial z} \Delta z \quad (6) \]

The model can be expressed in matrix equation:

\[ -\Delta P_{n} = K \omega \quad (7) \]

The matrix \(K = [q_{1}, q_{2}, q_{3}, q_{4}]\) is a matrix with 3 rows and 9 columns, which is called error coefficient matrix. The three rows represent the position information of X, Y and Z directions respectively. The number of matrix columns is the number of error parameters involved in the calculation.

The matrix \(\omega = (\Delta \theta_{1}, \Delta \theta_{6}, \Delta x, \Delta y, \Delta z)^{T}\) is a column vector consisting of nine error parameters that need to be identified.

3. Calibration algorithm

In equation (7), \(K\) and \(\Delta P_{n}\) are known quantities that can be calculated. As unknown quantities that need to be identified, matrix \(\Delta \omega\) containing nine parameter errors can be identified by corresponding identification algorithms as long as there are enough data of the calibration points to make the number of equations larger than the number of error parameters. To obtain the value of matrix \(\Delta \omega\), the generalized inverse matrix \(K^{+}\) of the error coefficient matrix \(K\) should be obtained firstly. As shown below.

\[ \Delta \omega = K^{+}(\Delta P_{n}) = (K^{T}K)^{-1}K^{T}(-\Delta P_{n}) \quad (9) \]
The equation (9) is the general formula for solving linear equations by least square method. The obtained error parameters are continuously compensated to the kinematics model and solved again in the identification. In this way, the parameter errors are kept close to the accurate values by iteration. The specific parameter identification process is shown in Figure 3.

4. Experiment
A factory-calibrated RB08 6-DOF serial robot is taken as the research object. As shown in Figure 4, a TCP tool is installed at the end of the end-link of the robot, and the cusp position of another TCP tool is used as a fixed reference point. The tool coordinate values of current TCP are calibrated by using the three-point method of robot system. The home position values and tool coordinates values are recorded as test benchmarks, and the specific data are: \( Q_1=Q_2=\ldots=Q_6=0^\circ, \ x=9.71\text{mm}, \ y=6.24\text{mm}, \ y=155.33\text{mm} \).
Then reset the home position and tool coordinate value manually through the robot teaching device, as the initial value of home position and tool coordinate calibration, and the specific data are: Q1=Q6=0°, Q2=1.68°, Q3=0.76°, Q4=-1.40°, Q5=-1.00°, x=9mm, y=6mm, y=155mm. Next, controlling the TCP of the robot to contacts the fixed point from different directions and record joint angle data. Twenty sets of joint angle data were recorded as calibration data. Finally, the calibration data are substituted into the error model, and the results are identified in Matlab by using least squares algorithm as shown in Figure 5.

The results show that the home position values and tool coordinate values of the robot are basically the same as standard data after compensating the identified error parameters to the initial value. The residual of 20 sets of calibration data is 0.38 mm, which is significantly smaller than 2.01 mm before calibration. It also shown that the algorithm with a significant convergence occurs is reliable. If the residual error is large than before, it is necessary to re-select the calibration points and re-calibrate the robot.

5. Conclusion
The research content of this paper is the comprehensive calibration of home position and tool coordinates of 6-DOF serial robot. The data of calibration points are obtained by fixing the TCP position of the robot and changing its attitude. The error model is established by the error of the calibration points between the model deviation and the actual deviation. The home position and tool coordinates of the robot are identified simultaneously by the least square method. The results show that the calibration algorithm can accurately calibrate the home position and tool coordinates of the robot.

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