Calibration of Dual Industrial Robot System Based on Hand-Eye Calibration Algorithm

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Abstract: In order to improve the cladding efficiency and quality, the dual industrial robots are used to work together to achieve the task of repairing the industrial drill. However, the calibration accuracy of the base coordinates of the dual robot system is low, which directly affects the cladding quality. In order to solve this problem, a hand-eye calibration algorithm based on fixed calibration cone is proposed to calibrate the camera installed on the flange plate at the end of the machine arm, which improves the determination of the coordinate of the feature points of the calibration object. Based on the coordinate system of the calibration object as a link, the base coordinate relationship between the two robots with high accuracy is obtained.

1. Introduction
The dual industrial robot system is mainly composed of two KUKA six-degree-of-freedom industrial robots with the models of KR-60 and KR-20. The purpose is to coordinate and coordinate the two industrial robots to complete scanning, welding and other work, and realize the automatic bit repair task. The scanning robot first scans the three-dimensional point cloud at the damaged position, and then repairs the damaged position by the welding robot. Therefore, it is necessary to calibrate the base coordinates of the two industrial robots. In the system calibration, the coordinate points of the calibration object are often manually aligned in the process of reading by the robot, resulting in large errors. In order to meet the accuracy requirements, it is necessary to increase the calculation amount of the optimization algorithm. In this paper, the camera is calibrated first and then the hand-eye calibration is carried out, which will greatly improve the progress of the calibration object coordinate system.

2. Calibration of dual-robot system
In robot vision applications, hand-eye calibration is a very basic and key issue. Simply speaking, the purpose of hand-eye calibration is to obtain the relationship between robot coordinate system and camera coordinate system, and finally transfer the results of visual recognition to the robot coordinate system\textsuperscript{[1]}. The hand-eye calibration industry is divided into two forms. According to the different places where the camera is fixed, if the camera and the end of the robot are fixed together, it is called ‘eyes in
hand '. If the camera is fixed on the base outside the robot, it is called 'eyes outside' \([2]\). And the camera is installed on the mechanical hand, moving along with the manipulator. More commonly used. This is actually similar to eye-in-hand. It can quickly and effectively calibrate the coordinates of the measured object. When the camera takes photos, the manipulator moves to the position when the camera is calibrated, and then the camera takes photos to obtain the coordinates of the target.

2.1. The establishment of coordinate system and the calibration principle of hand-eye calibration

The hand-eye calibration model of binocular camera measurement system is shown in Figure 1. In order to facilitate the calibration of hand-eye relationship, the following coordinate system is first established: \(O_b - x_by_bz_b\) is coordinate system for manipulator base; \(O_t - x_ty_tz_t\) is flange coordinate system for machine arm end. The z axis is the rotation center axis of the flange, and the origin of the coordinate system is in the center of the flange. The attitude is determined by the forward kinematics of the robot. \(O_c - x_cy_cz_c\) is the camera coordinate system, whose x-axis is perpendicular to the light plane, and the attitude is unknown; \(O_m - x_my_mz_m\) is the calibration object coordinate system composed of three calibration cones.

![Figure 1 Coordinates and transformation of the robotic arm](image)

\(b_T\): it represents the conversion relationship between the flange coordinate system at the end of the manipulator and the basic coordinate system, which can be obtained from the forward kinematics calculation of the robot\([3]\).

\(t_c\): it represents the conversion relationship between camera coordinate system and manipulator end flange coordinate system; This transformation relationship is constant in the process of manipulator movement.

\(m_c\): it represents the relationship between the camera coordinate system and the calibration plate coordinate system (camera external parameters), which can be obtained by camera calibration.

\(b_m\): it represents the transformation from the calibration plate coordinate system to the basic coordinate system. As long as the relative position of the manipulator and the calibration plate remains unchanged, this transformation matrix does not change.

Control the manipulator to move to the position 1 above the measured calibration cone, the points above the measured calibration cone meet the following relationship:

\[X_b = b_T \cdot X_{t1}\]  \(1\)

\[X_{t1} = T_c \cdot X_{c1}\]  \(2\)
Combined the above three formulas:

\[
X_{cl} = \left( ^mT_{cl} \right)^{-1} \cdot X_m
\]

(3)

The mobile manipulator moves to position 2 with the following:

\[
X_b = bT_{t1} \cdot ^mT_{c1}^{-1} \cdot X_m
\]

(4)

Since the base coordinate of the machine arm and the position of the calibration cone are fixed, \(bT_m\) does not change, so it can be obtained:

\[
bT_m = bT_{t1} \cdot ^mT_{c1}^{-1} = bT_{t2} \cdot ^mT_{c2}^{-1}
\]

(5)

2.2. Solving Rotation Matrix \(R_c\)

Expand the \(bT_m = bT_{t1} \cdot ^mT_{c1}^{-1}\) into matrix form:

\[
\begin{bmatrix}
X_m \\
1
\end{bmatrix} = 
\begin{bmatrix}
R_{t1} & T_{t1} \\
0 & 1
\end{bmatrix} \cdot 
\begin{bmatrix}
R_c & T_c \\
0 & 1
\end{bmatrix} \cdot 
\begin{bmatrix}
X_c \\
1
\end{bmatrix}
\]

(7)

where \(X_m\) is the expansion matrix of the calibration cone vertex in the robot base coordinate, \(X_c\) is the expansion matrix of calibration cone vertex in camera coordinate system, \(R_{t1}\) and \(T_{t1}\) are the rotation matrix and translation matrix of the flange coordinate system relative to the base coordinate system, It can be obtained by the forward kinematics of the robot, \(R_c\) and \(T_c\) are the rotation matrix and translation matrix of the camera coordinate system relative to the flange coordinate system at the end of the machine arm. It is solved by hand-eye calibration, and because the hand-eye calibration method uses the 'eye in hand' form, the relative pose of the camera coordinate system relative to the flange coordinate system is unchanged [4], that is, \(R_c\) and \(T_c\) do not change when moving to two different positions.

For ease of calculation, convert (7) to:

\[
\begin{bmatrix}
X_{m1} \\
X_{m2} \\
\vdots
\end{bmatrix} = 
\begin{bmatrix}
R_{t1} & T_{t1} \\
0 & 1
\end{bmatrix} \cdot 
\begin{bmatrix}
R_c & T_c \\
0 & 1
\end{bmatrix} \cdot 
\begin{bmatrix}
X_{c1} \\
X_{c2} \\
\vdots
\end{bmatrix}
\]

(8)

Since the manipulator needs to move from position 1 to position 2, substituting Equation (8) into Equation (6) can further obtain:

\[
\begin{bmatrix}
X_{m1} \\
X_{m2} \\
\vdots
\end{bmatrix} = 
\begin{bmatrix}
R_{t1} \cdot T_c + R_{t1} \cdot R_c \cdot X_{c1} + T_{t1} \\
R_{t2} \cdot T_c + R_{t2} \cdot R_c \cdot X_{c2} + T_{t2}
\end{bmatrix}
\]

(9)

If the manipulator is controlled to move only from position 1 to position 2, then in formula (9) is \(R_{t1} = R_{t2}\). And the rotation matrix \(R_c\) is orthogonal matrix. Therefore, it is further obtained from (9):

\[
R_c (X_{c1} - X_{c2}) = R_{t1} (T_{t2} - T_{t1})
\]

(10)

Make \(\alpha = R_{t1}^T (T_{t2} - T_{t1}) \cdot X = R_c \cdot \beta = (X_{c1} - X_{c2})\), Then (10) can be written as a matrix equation \(\alpha = X \cdot \beta\), Due to the noise in the actual measurement, it is not stable when the camera is used to collect data, and the result of direct right division of \(\beta\) is not ideal. Therefore, the two sides of the equation are transposed to obtain:

\[
\beta^T \cdot X^T = \alpha^T
\]

Where \(R_c\) is the rotation matrix to be solved, the matrix has nine unknown parameters, which are expressed as:

\[
X^T = [R_{t11} \text{ } R_{t12} \text{ } R_{t13} \text{ } R_{t21} \text{ } R_{t22} \text{ } R_{t23} \text{ } R_{t31} \text{ } R_{t32} \text{ } R_{t33}]^T
\]
Where $R_{ij}$ is the data of the $i$ row $j$ column in the rotation matrix $R$. Let $(X_{c1} - X_{c2})$ in (10) be expanded to a matrix of $3 \times 9$ by $[\Delta X_c, \Delta Y_c, \Delta Z_c]$, so there is:

$$\beta^T = \begin{bmatrix} \Delta X_c & \Delta Y_c & \Delta Z_c & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta X_c & \Delta Y_c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta X_c & \Delta Y_c & \Delta Z_c \end{bmatrix}$$

The $\alpha=X \cdot \beta$ system composed of such a set of data has only three independent equations and cannot solve all unknowns of $X$. Therefore, at least the number of collections met $n \geq 3$. To make equation $\beta^T \cdot X^T = \alpha^T$ a well-posed or over-determined full rank matrix equation. Then, the least square principle can be used to solve $X^T = (\beta \beta^T)^{-1} \beta \alpha^T$. The required matrix can be obtained by recombining the obtained $X^T$ with $3 \times 3$. Because of the above calculation process, let $R_c = X$. Therefore, the required rotation matrix $R_c$ can be solved by inversion of $X^T$ matrix.

$$R_c = \alpha \beta^T (\beta^T \beta)^{-1}.$$  

2.3. Solving translation matrix $T_c$

Control the manipulator to change any position, make two shots of the calibration cone to obtain the feature points to ensure $R_{t1} \neq R_{t2}$, From formula (9):

$$(R_{t1} - R_{t1})T_c^T + (R_{t1}R_{c1} - R_{t2}R_{c2}) + (T_{t1} - T_{t2}) = 0 \quad (11)$$

Make $A = (R_{t1} - R_{t1})$; $B = (R_{t1}R_{c1} - R_{t2}R_{c2}) + (T_{t1} - T_{t2})$, Formula (11) may be expressed as $AT_1 + B = 0$.

Change different postures for multiple acquisition, making acquisition times $n \geq 3$. According to the principle of least squares:

$$T_c = (A^T A)^{-1} A^T B.$$  

So far, the algorithm completes the calibration of rotation matrix $R_c$ and translation matrix $T_c$ of camera coordinate system relative to flange coordinate system.

3. Specific calibration method

The method of calibrating dual industrial robots based on the hand-eye relationship mainly describes the transformation matrix of the camera mounted on the robot relative to the end flange of the robot, and based on the new coordinate system composed of three conical calibration cones as a link, The base coordinate systems of the two robots are linked. The specific method is as shown in Figure 2[5].

First scan the three calibration cones with the binocular sensor camera, get the coordinates of the three cone vertices, use these three points to establish a tie coordinate system in space. Then based on the hand-eye calibration algorithm to obtain the relationship between the camera coordinates and the flange coordinates. Finally, the relationship between the flange coordinate system and the robot coordinate system is calculated through the forward kinematics of the robot. The transformation matrix between the base coordinate system of the main robot and the tie coordinate system is obtained by combining the above three sets of relations.

In the same way, the transformation matrix between the robot base coordinate system and the tie coordinate system can be obtained according to the above operation. Finally, according to these two transformation matrices, the transformation relationship matrix between the master and slave robots can be obtained, so as to complete the calibration of the dual robot system.
Figure 2 Base coordinate conversion of dual robot system

Install binocular vision sensors on the end flanges of the two robots, and place three non-collinear calibration cones between the two robots, adjust the angles of each joint of the left robot arm, and make the camera at a suitable position. Position points and scan the three calibration cones to obtain the three coordinate values p1, p2, and p3 of the three cone points under the camera. Since these three points are not collinear, these three points can form one Tie coordinate system: Select the feature point p1 as the origin, the vector formed by the feature points p1 and p2 as the x axis direction, x axis direction vector calculated as $x = \frac{p_1 - p_3}{|p_1 - p_3|}$; The plane direction through p1 and perpendicular to three feature points is z axis; The direction of the y axis is calculated by the difference between the x axis and the z axis, so we can get the coordinate system of the calibration object in the camera $O_c - x_c y_c z_c$. By reading the calibration data of the camera, the transformation matrix $^cT_c$ from the camera coordinate system to the calibration cone coordinate system can be obtained.

Conversion matrix from camera coordinate system to flange coordinate system at the end of manipulator can be obtained by hand-eye calibration algorithm $^cT_c$.

The kinematics model is established according to the known D-H parameters of the robot. The conversion relationship between the adjacent D-H link coordinate system is:

$$(i-1)T_i = \text{Trans}(a_{i-1},0,0)\text{Rot}(\alpha_{i-1})\text{Trans}(0,0,d_i)\text{Rot}(\theta_i)$$

Where $^0T_1$ represents the pose transformation matrix from joint 0 coordinate system to joint 1 coordinate system, Similarly, the transformation matrix $^{b}T_i$ from the flange coordinate system to the base coordinate system can be obtained by solving the forward kinematics.

By substituting the above three transformation matrices into the formula (6) $^{b}T_m = \frac{b}{a}T_a^{-1}$, the transformation matrix from the base coordinate system of the main manipulator to the calibration object coordinate system can be obtained.
Repeat the above steps, the transformation matrix $b^2T_m^r$ from the base coordinate system of the right arm to the calibration coordinate system is calculated.

Finally, by the transformation matrix $b^1T_m^l$ of the left arm and the transformation matrix $b^2T_m^r$ of the right arm, it can be substituted into the formula $b^1T_{b2} = b^1T_m^l \cdot \text{inv}(b^2T_m^r)$, The transformation matrix $b^1T_{b2}$ between left and right manipulators is obtained.

4. Conclusion
In this paper, a non-contact hand-eye calibration method for dual robot vision system is proposed. The binocular camera scanning method is used to obtain the coordinates of the calibration cone feature points in the camera. Based on the link sensor composed of the calibration points, the coordinate transformation matrix between the base coordinates of the left and right manipulator is obtained. The hand-eye calibration method is used by both machines to improve the accuracy of coordinate reading, that is, to further improve the calibration accuracy, which is easy to operate and easy to implement. In summary, the proposed calibration method of dual-robot system can meet the requirements of high experimental accuracy and has high industrial application value.

References
[1] Ma Xianghua, Qu Jiarui, Zhao Yang. (2020) Research on target grasping of seven-axis manipulator based on visual positioning. Journal of Applied Technology, 20 (2): 153-157.
[2] Hou Maosheng, Wang Qiang, Ma Guoqing. (2018) The calibration method and verification of three-dimensional morphology flexible measurement system. Application optics, 39 (3): 385-391.
[3] Ma Hongwei. (2020) Research on industrial robot positioning system based on machine vision. Manufacturing automation, 2020, v.42: 63-67.
[4] Deng Zhihao. (2018) Development of automatic filling system for liquefied natural gas for vehicles. Guangdong: Guangdong University of Technology: 18-22.
[5] Guangdong. (2014) Research on coordination technology of dual industrial robots. Heilongjiang: Harbin Institute of Technology: 31-32.