Research on Calibration Technology of Five-Degrees-of-Freedom Tandem Robots

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Abstract. In the robot feedback control system of visual feedback, the calibration of the hand-eye system is very important, because it directly affects the accuracy of the robot. Aiming at the small operating space and compact structure of the micro-assembly robot system, a fixed-vision hand-eye calibration method is proposed. The method first obtains the coordinates of 15 spatial points in the robot base coordinate system, and then uses the camera pose measurement principle to obtain the coordinates of the corresponding spatial points in the camera coordinate system, and then establishes the calibration equations. Based on the least squares method, the coordinate transformation matrix between the hand-eye systems is calibrated. The experimental results show that the constructed hand-eye system coordinate transformation matrix is effective and reliable. The calibration accuracy and effectiveness of the method are verified by relevant grabbing experiments.

1. Introduction
Most of the existing robot systems use the vision system as the only or important means of target pose detection [1-3]. Due to the structural size limitations of micro-assembly robots and the strict precision requirements in precision assembly operations, the calibration methods of hand-eye systems commonly used in macro-operated robots is not useful. For example, in the calibration of the hand-eye system of the macro-operated robot, the binocular vision [4] and the structured light vision sensor scheme [5] are usually used to acquire the pose information of the object, and the three-dimensional coordinates of the operating object in the camera coordinate system are determined. However, in a micro-assembly robot system, it is very difficult to install two micro-cameras due to the size constraints of the assembly space structure. For other calibration methods of the hand-eye system, in recent years, many scholars have conducted a lot of research, and the literature proposed a calibration method based on binocular vision [6]. By changing the position of the robot end tool, the target point is measured in combination with the binocular vision system, and the coordinate conversion calculation is performed to solve the TCP coordinate system [7]. However, due to space constraints in the field of micro-assembly, this method is difficult to implement; the literature proposed to introduce stereoscopic 3D reconstruction technology into the hand-eye model of single-camera structured light scanning system, and proposed the calibration algorithm of phase matching technology [8]. The calibration of the vision system is realized, but the accuracy of the projector is high, and it is difficult to meet the requirements in actual operation [9].

At present, the calibration technique of the hand-eye system of micro-assembly robots is still immature, and many theoretical methods are in constant research and exploration. In this paper, the fixed visual hand-eye micro-assembly system is studied and its calibration method is studied. The method overcomes the problems in the calibration of the binocular camera and the error of the movement of the
stage, and the calibration of the hand-eye system of the robot can be completed by a simple operation of a single camera.

2. Camera imaging model

The pinhole camera model has four coordinate systems: world coordinate system, camera coordinate system, image physical coordinate system, and image pixel coordinate system. For the two-dimensional plane, the coordinates of the world coordinate system of the real world space point are \( P_w(X_w, Y_w, Z_w) \), the corresponding camera coordinate system coordinates are \( P_c(X_c, Y_c, Z_c) \), the coordinates of the corresponding image physical coordinate system are \( P'(X', Y') \), and the coordinates of the corresponding image pixel coordinate system are \( p(u, v) \), according to the pinhole Camera model.

The relationship between the camera coordinate system and image physical coordinate system is as shown in Figure 1 and equation (2-2):

\[
\frac{Z_c}{f} = \frac{X_c}{X'} = \frac{Y_c}{Y'}
\]

(2-2)

Image physical coordinate system to image pixel coordinate system. As shown in Figure 2, the relationship is as shown in equation (2-3):

\[
\frac{X_c}{X'} = \frac{Y_c}{Y'}
\]

(2-3)
\[
\begin{align*}
\begin{cases}
  u = \frac{x'}{dx} + u_0 \\
  v = \frac{y'}{dy} + v_0
\end{cases}
\end{align*}
\] (2-3)

After deformation, it can be transformed into a matrix form, as shown in equation (2-4):
\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix}
= 
\begin{bmatrix}
  1 & 0 & u_0 \\
  0 & 1 & v_0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x' \\
  y' \\
  1
\end{bmatrix}
\] (2-4)

\(dx\) represents the actual physical size of each pixel along the x-axis; \(dy\) represents the actual physical size of each pixel along the y-axis. \((u_0, v_0)\) indicates the coordinates of the optical center corresponding to the image pixel coordinate system.

The relationship between the world coordinate system and the image pixel coordinate system is obtained by the equation (2-1), (2-2), (2-3), (2-4), as shown in the equation (2-5):
\[
Z_c \begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix}
= K(RPw + t) = K \begin{bmatrix}
  X_w \\
  Y_w \\
  Z_w
\end{bmatrix} + t
\] (2-5)

K is the internal parameter matrix of the camera, and R and t are the external parameters of the camera.

3. Fixed visual hand-eye calibration algorithm

Hand-eye calibration refers to the transformation matrix between the camera coordinate system and the robot coordinate system. There are two main forms of hand-eye system installation: one is the Eye-in-Hand system (the camera is mounted directly at the end of the robot); the other is the Eye-to-Hand system (the camera is fixedly mounted and the position does not change with the movement of the robot). Due to the compact structure of the micro-assembly system, the mechanical arm load is small. Therefore, we chose to use a fixed installation of the camera.

For the calibration of the Eye-to-Hand system, the homogeneous coordinate transformation relationship between the world coordinate system and the image pixel coordinate system is as shown in equation (3-1):
\[
\begin{bmatrix}
  x', y', 1 \\
  m & n & 0 \\
  \alpha & \rho & 0 \\
  t_1 & t_2 & 1
\end{bmatrix}
\] (3-1)

\([x', y', 1]\) is the coordinate of the target point in the image pixel coordinate system, \([x, y, 1]\) is the coordinate of the target point in the world coordinate system, \([m, n, 0]\) is a 3×3 orthogonal matrix rotated by the world coordinate system relative to the image pixel coordinate system.

Therefore, the relationship can be obtained as (3-2):
\[
\begin{align*}
  x' &= x \cdot m + y \cdot \alpha + t_1 \\
  y' &= x \cdot n + y \cdot \rho + t_2
\end{align*}
\] (3-2)

An expression obtained by amplifying the above expression (3-3)
\[ x' = x \times m + 0 \times n + y \times o + 0 \times p + 1 \times t_1 + 0 \times t_2 \]
\[ y' = 0 \times m + x \times n + 0 \times o + y \times p + 0 \times t_1 + 1 \times t_2 \]  
(3-3)

The matrix representation is as shown in equation (3-4)

\[
\begin{bmatrix}
    x' \\
    y'
\end{bmatrix} =
\begin{bmatrix}
    x & 0 & y & 0 & 1 \\
    0 & x & 0 & y & 0 & 1
\end{bmatrix} \begin{bmatrix}
    m \\
    n \\
    o \\
    p \\
    t_1 \\
    t_2
\end{bmatrix}
\]  
(3-4)

Amplify the matrix to obtain the equation (3-5)

\[
\begin{bmatrix}
    x_1' \\
    y_1' \\
    x_2' \\
    y_2' \\
    \vdots \\
    x_n' \\
    y_n'
\end{bmatrix} =
\begin{bmatrix}
    x_1 & 0 & y_1 & 0 & 1 \\
    0 & x_1 & 0 & y_1 & 0 & 1 \\
    x_2 & 0 & y_2 & 0 & 1 \\
    0 & x_2 & 0 & y_2 & 1 & 0 \\
    \vdots \\
    x_n & 0 & y_n & 0 & 1 \\
    0 & x_n & 0 & y_n & 0 & 1
\end{bmatrix} \begin{bmatrix}
    m \\
    n \\
    o \\
    p \\
    t_1 \\
    t_2
\end{bmatrix}
\]  
(3-5)

Finishing the equation (3-6):

\[
\begin{bmatrix}
    x_1' \\
    x_2' \\
    \vdots \\
    x_n' \\
    y_1' \\
    y_2' \\
    \vdots \\
    y_n'
\end{bmatrix} =
\begin{bmatrix}
    x_1 & 0 & y_1 & 0 & 1 \\
    x_2 & 0 & y_2 & 0 & 1 \\
    \vdots \\
    x_n & 0 & y_n & 0 & 1 \\
    0 & x_1 & 0 & y_1 & 0 & 1 \\
    0 & x_2 & 0 & y_2 & 0 & 1 \\
    \vdots \\
    0 & x_n & 0 & y_n & 0 & 1
\end{bmatrix} \begin{bmatrix}
    m \\
    n \\
    o \\
    p \\
    t_1 \\
    t_2
\end{bmatrix}
\]  
(3-6)

Find the least squares solution with MATLAB

\[
\begin{bmatrix}
    m \\
    n \\
    o \\
    p \\
    t_1 \\
    t_2
\end{bmatrix} =
\begin{bmatrix}
    x_1 & 0 & y_1 & 0 & 1 \\
    x_2 & 0 & y_2 & 0 & 1 \\
    \vdots \\
    x_n & 0 & y_n & 0 & 1 \\
    0 & x_1 & 0 & y_1 & 0 & 1 \\
    0 & x_2 & 0 & y_2 & 0 & 1 \\
    \vdots \\
    0 & x_n & 0 & y_n & 0 & 1
\end{bmatrix}^{-1} \begin{bmatrix}
    x_1' \\
    x_2' \\
    \vdots \\
    x_n' \\
    y_1' \\
    y_2' \\
    \vdots \\
    y_n'
\end{bmatrix}
\]  
(3-7)

4. Experimental design
The robotic hand-eye system calibration experiment device includes: auto focus camera, five-degree-of-freedom tandem robot.

The experimental steps are as follows: First, a hexahedral base is installed at the end of the robot, a fixture is mounted on the base-a three-jaw chuck, and then a standard cylinder is clamped with a three-jaw chuck, and one end of the standard cylinder is dyed with a red dye. And put a white paper on the tray position.

The control robot points a red dot on the white paper, records the coordinates in the robot coordinate system, and then moves to a different position and repeats 10 times. After completion, the camera takes
a picture and the resulting experimental image is shown in Figure 3.

![Figure 3](image)

The coordinates of the center of each point in the graph are extracted according to the Hough transform. The extracted target points are in the world coordinate system, and the coordinates in the image pixel coordinate system are shown as Table 1.

Table 1 World coordinate system, original coordinates in the image pixel coordinate system

| Serial number | Coordinates in the world coordinate system | Coordinates in the Image pixel coordinate system |
|---------------|---------------------------------------------|-----------------------------------------------|
| 1             | -13.0167, 295.2323                           | 1635.8636, 414.0444                           |
| 2             | -9.312, 295.2159                             | 1846.4604, 411.9381                           |
| 3             | -9.7094, 269.3443                           | 1678.0402, 836.6050                           |
| 4             | 11.3305, 261.219                             | 1654.8481, 978.2444                           |
| 5             | -8.5305, 217.2812                           | 1706.5456, 727.8610                           |
| 6             | -6.6071, 195.0013                           | 1729.6037, 108.1503                           |
| 7             | 3.6713, 190.171                             | 1915.6967, 91.7871                            |
| 8             | 33.1817, 300.9095                           | 2407.0381, 1.488                             |
| 9             | 44.3605, 298.2609                           | 2610.1980, 2.5299                             |
| 10            | 35.5652, 278.8685                           | 2421.6405, 7.2489                             |
| 11            | 44.9946, 275.0712                           | 2590.3613, 5.7392                             |
| 12            | 34.6878, 234.7774                           | 2333.6303, 0.18452                            |
| 13            | 47.0987, 230.1313                           | 2561.1963, 83.6319                            |
| 14            | 38.1771, 209.0045                           | 2369.8713, 46.3625                            |
| 15            | 48.3348, 204.6028                           | 2557.4551, 22.7496                            |

The resulting transformation matrix \( R = \begin{bmatrix} 0.0629 & 0.0117 & 0 \\ -0.0023 & 0.0584 & 0 \\ -118.3451 & 298.4684 & 1 \end{bmatrix} \)

The error \( e = [x', y'] - R^{-1} [x, y, 1] \), \( [x', y', 1] \) is the coordinate of the target point in the image pixel coordinate system, which is the coordinate of the target point in the world coordinate system, and \( R \) is the 3×3 orthogonal matrix of the world coordinate system rotated relative to the image pixel coordinate system. Furthermore, the error of the position coordinates of each point based on the current rotation transformation matrix robot in the world coordinate system is \([0.3681, 0.1377, 0.1987, 0.1840, 0.3733, 0.2858, 0.0907, 0.0793, 0.2482, 0.1238, 0.1929, 0.2420, 0.0389, 0.3243, 0.1451] \), the maximum error is 0.3681 mm.

5. Conclusion

In this paper, a calibration method for the hand-eye system of a micro-assembly robot is proposed, and the transformation matrix between the micro-assembly hand-eye systems is obtained. The validity and accuracy of the calibration results were verified by the prototype system. Compared with other calibration methods, the calibration process of the method is simple and convenient. Besides, it doesn’t require complicated auxiliary equipment and has good practicability.
References

[1] Ji ZHU Z, JI Q. Novel eye gaze tracking techniques under natural head movement [J]. IEEE Transactions on Bio-Medical Engineering, 2007, 54(12): 2246-2260.

[2] Xu X, Zhu D, Zhang H, et al. TCP-based calibration in robot-assisted belt grinding of aero-engine blades using scanner measurements [J]. The International Journal of Advanced Manufacturing Technology, 2017, 90(1-4): 635-647.

[3] PRIBANIC T, CIFREK M, PEHAREC S. Light plane position determination for the purpose of structured light scanning [C]. IEEE ISIE 2005, Dubrovnik, Croatia, USA, 2005: 1315-1320.

[4] MUIS A, OHNISHI K. Eye-to-hand approach on eye-in-hand configuration within real-time visual serving [J]. IEEE/ASME Trans on Robotics, 2005, 10(4): 404-410.

[5] MEDIONIG, KANG S B. Emerging topics in computer vision [M]. New Jersey, USA: Pearson Prentice Hall, 2005: 215-245.

[6] JIMENEZ R, CERES R, PONS J L. A survey of computer vision methods for locating fruit on trees [J]. Transactions of the ASAE, 2003, 43(6): 1911-1920.

[7] Roth Z, Mooring B, Ravani B. An overview of robot calibration [J]. IEEE Journal on Robotics and Automation, 1987, 3(5): 377-385.

[8] He Q X, You Z, Kong X D. Positioning Error Compensation Method of Industrial Robot Based on Closed-loop Feedback of Position and Orientation[J]. China Mechanical Engineering, 2016, 27(07): 872-876 (in Chinese).

[9] Tan J, Xi N, Wang Y. A singularity-free motion control algorithm for robot manipulators—a hybrid system approach [J]. Automatica, 2004, 40(7): 1239-1245.