Hand-eye calibration for flexible manipulator

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Abstract. This paper studies the determination of the pose relationship between camera which is embedded in the Barrett hand and end-effector of the UR5. It is fundamental for subsequent visual control. Least-square method and Lie group is used in this paper, and we also come up with an algorithm to increase the quantity of data for least-square to improve the accuracy of eye-in-hand calibration result. Firstly, through camera calibration, the intrinsic and external parameters of the camera are obtained. Secondly, we obtain equation of $CX = XD$ by eye-in-hand calibration, and $X$ not only is the matrix we want to compute but also represents the transformation relationship between camera and end-effector. Finally, to evaluate the proposed method, an experiment was designed, and the test result demonstrates the effectiveness of the proposed approach.

1. Introduction

Visual guided localization of industrial robots is an important part of industrial production intellectualization [1]. Accurately establishing the geometric position relationship between the visual sensor and the end-effector of the manipulator is the key to the precisely locating of the target by the manipulator. Hand-eye calibration methods fall into two different categories. One of the hand-eye calibration methods is eye-to-hand [2] and the mounting of camera is independent of the robot in this case. Another is eye-in-hand [3] calibration which means that camera is installed on board and moves with robot. The eye-to-hand configuration faces practical difficulties, such as fixed capture scenes, easy occlusion and so on [2].

This paper deals with the eye-in-hand configuration because it is more flexible for robots to actively grasp objects [4]. In the past decades, many researchers were devoted to studying eye-in-hand calibration. The basic method [5] of robotic eye-in-hand calibration is controlling a known calibration reference for robotic grippers in different observation spaces. Generally speaking, traditional eye-in-hand calibration solves the relative position between two coordinate systems by cumbersome procedures. We come up with a method to resolve this problem, by assembling different group of calibration images to new combinations. As noted in article [6], it is difficult to avoid singularity when computing the equation of matrix. Inspired by [7], if the camera move with a larger offset angle between the optical center during the camera calibration, the problem can be solved.

2. Methodology

2.1 Eye-in-hand calibration system
The goal of machine vision calibration is to compute the transformation relationship between image coordinate system and robotic coordinate system which is shown in Figure 1. Camera calibration provides the transformation relationship between the world coordinate system and the camera coordinate system. Hand-eye calibration offers the transformation relationship between the camera coordinate system and the robotic coordinate system, so we should divide the process of hand-eye calibration into two steps, camera calibration and eye-in-hand calibration.

![Figure 1. UR5 and Barrett Hand](image)

2.2 Camera calibration
The most popular camera calibration is Zhang’s method [8]. This method is highly accurate and easy to implement. Calibration results can be evaluated according the undistorted images via intrinsic parameters.

2.3 Eye-in-hand calibration
Owing to high cost and complex operation, direct measuring [8] approach has not been applied widely. An alternative solution is to compute the transformation parameters between the robot and the camera which is term with called eye-in-hand calibration.

The common method of eye-in-hand calibration is to construct and solve the $CX = XD$ equation by means of three or more pose transformations of the robotic end-effector [7]. The transformation of system coordinate can be demonstrated in Figure 2. Among them, $C_{obj}$ represents the world coordinate system, $C_{c1}$ and $C_{e1}$ represent the camera coordinate system and the end-effector coordinate system before the platform moving, $C_{c2}$ and $C_{e2}$ represent the two coordinate systems after platform moving. Camera can be calibrated with the fixed chessboard at the position of $C_{c1}$ and $C_{c2}$ respectively to obtain its internal and external parameters. The camera external parameter is the relative position between camera and chessboard in $C_{c1}$ and $C_{e1}$ positions, expressed by A and B. If relative transformation between $C_{c1}$ and $C_{c2}$ can be represented by $D$, the $D = BA^{-1}$.

Due to the matrix E and F of robotic motion parameters can be read by the feedback of controller, the relative position of $C_{e1}$ and $C_{e2}$ are known parameters represented by matrix C. We can acquire matrix E and F, and $C = F^{-1}E$. The matrix of X can be computed by equation of $CX = XD$.

![Figure 2. Transformation relationship of system coordinate](image)
The equation of \( CX = XD \) can be written as follows:

\[
\begin{bmatrix}
R_	ext{C} & t_	ext{C} \\
0^T & 1
\end{bmatrix}
\begin{bmatrix}
R & t \\
0^T & 1
\end{bmatrix}
= \begin{bmatrix}
R_	ext{D} & t_	ext{D} \\
0^T & 1
\end{bmatrix}
\]

(1)

As a result, the final expression can be obtained:

\[
R_	ext{C}R = RR_	ext{D} \\
R_	ext{C}t + t_	ext{C} = Rt_	ext{D} + t
\]

(2)

In the upper expression, \( R_	ext{C} \), \( R_	ext{D} \), \( t_	ext{C} \), \( t_	ext{D} \) are known parameters, and \( R, R_	ext{C}, R_	ext{D} \) are unit orthogonal matrix. \( R \) and \( t \) are parameters to be computed.

Due to the observation noise in camera calibration process, it is necessary to solve the equation with multiple sets of expression of \( CX = XD \) by least squares method in practical measurement. In order to reduce the workload, we come up with an idea of assembling different group of calibration images to new combinations. And in this experiment, we define the left, middle and right orientations of calibration.

In each orientation, the 4 calibration images are collected which is shown in Figure 3, so we can get the 64 equation of \( CX = XD \) through 12 calibration results. For example, the No.1 left photo can match with the No.1 to No.4 middle photos and No.1 to No.4 right photos. This step can generate 16 outcomes of \( X \), the four left photos can get 64 outcomes. This method can generate 64 results of equation.

In order to obtain a unique solution to (11), two pairs of \((C_i, D_i)\) whose rotational parts satisfy certain conditions are required.

The previous sections assumed that in determining a unique solution to \( CX = XD \) no noise was present in the measured values for \( C \) and \( D \). Unfortunately, this assumption is physically unrealistic. A more practical approach is to find some type of "best-fit" solution from a set of noise measurements \( \{(C_1, D_1), \ldots, (C_i, D_i)\} \) and to find \( X \in \text{SE}(3) \) that minimizes an error criterion of the form

\[
\eta = \sum_{i=1}^{k} d(C_i X, XD_i)
\]

\( d \) represents the Euclidean distance. Using the knowledge of Lie group theory [9], the above minimization problem can be converted to the least squares fitting problem finally. When there are multiple sets of observations \((C_i, D_i)\), the solution of the \( R \) are more accurate.

3. Experiment

The experimental platform consists of the UR5 and Barrett Hand. As shown in Figure 1, the camera is embedded in the palm of Barrett Hand, and Barrett Hand is fixed on the end-effector of UR5. The resolution of captured image is 640 (H) \( \times \) 480 (V). The employed calibration board has 6 \( \times \) 4 corner points. Experiment platform is shown in Figure 4.
After 64 sets of equation of $CX = XD$ computing, we can get final result of $X$ matrix as follows:

$$TX = \begin{bmatrix} 3.065 & 20.566 & 90.568 \end{bmatrix}$$

$$RX = \begin{bmatrix} -0.0079 & -0.0091 & -0.0004 \\ 0.1225 & 0.0107 & 0.0059 \\ -0.0017 & -0.0002 & -9.8451 \end{bmatrix}$$

(3)

In order to prove the reliability of the experimental results, we choose one corner point of the chess board to locate its position in the UR5-base coordinate system. Firstly, we move the end-effector three times in different position to observe this point by corner matching, at the same time, we can get the distance from camera to this point by laser-range finder embedded in the Barrett Hand. Then we can establish three equations to compute this point that:

$$(x_1-x_0)^2+(y_1-y_0)^2+(z_1-z_0)^2 = d_1^2; \quad (x_2-x_0)^2+(y_2-y_0)^2+(z_2-z_0)^2 = d_2^2; \quad (x_3-x_0)^2+(y_3-y_0)^2+(z_3-z_0)^2 = d_3^2.$$

Among these equations, $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$ is the camera coordinate values in UR5-base coordinate system. $P(x_0, y_0, z_0)$ is selected coordinate frame origin, $d_1$, $d_2$, $d_3$ are values of the distance between camera and the P point. We can obtain P point coordinate value in UR5-base by the above three equation. Then we move camera in another position, comparing $d_4$ measured by laser-range finder to $d_5$ which can be computed by distance of camera coordinate point and P coordinate point. We define the $\Delta d$ as the distance error. We also use the point P coordinate value with camera external parameters to compute the P pixel value in camera, comparing it with the P pixel coordinate value of observation. In Table 1, the left column list is number of equations of $CX = XD$, we also define the $\Delta x$, $\Delta y$, $\Delta z$ as the error of each axis.

| △x(mm) | △y(mm) | △z(mm) | △d(mm) |
|--------|--------|--------|--------|
| 8      | 2.65   | -10.195 | -12.28 | 16.18  |
| 16     | 13.39  | 3.797  | -7.333 | 15.73  |
| 24     | -1.67  | 8.593  | -5.976 | 10.60  |
| 32     | -3.41  | 1.332  | -7.68  | 8.51   |
| 40     | 1.23   | 1.4    | -4.6   | 4.96   |
| 48     | -0.1   | 2.507  | -3.876 | 4.62   |
| 56     | 4.06   | 1.098  | -3.505 | 5.14   |
| 64     | 1.74   | 1.9    | -3.4   | 4.26   |

4. Conclusion

Through eye-in-hand calibration, we can get the position relationship between the camera and the end-effector of UR5, which can better realize the active detection in the grasping process and better make us understand the coordinate transformation relationship between the target object and the UR5. In the process of solving the error problem, we use least squares method and Lie group to eliminate the errors caused by camera calibration. According to the experimental results, we can obtain more accurate values of $X$ by more equation of $CX = XD$ which is shown in Figure 5.
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