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Static Hand-eye Calibration Method of Industrial Robot

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***Abstract*—*Due to the complicated calculation of hand-eye relation between industrial robot and camera by traditional methods, a static hand-eye calibration method was proposed. Determined by optical measuring equipment, the transform matrix between the measuring coordinate system and the world coordinate system as well as the flange coordinate system was easily obtained respectively; After the calibration plate being imaged with an industrial camera, the transform matrix between the camera coordinate system and the calibration plate coordinate system was also achieved, so that the hand-eye relation of robot and camera was fast calculated with four matrices. The experiment showed that the error was less than 1.5mm while comparing the calibration result with that obtained by traditional method. It is not necessary to operate or run the robot during the whole calibration process. This method is reliable, simple and accurate, and provides an alternative to examine the calibration accuracy by general calibration method.*

***Keywords*—*Eye-in-hand:industrial robot:optical measuring equipment:static calibration*

I. INTRODUCTION

Computer vision plays an important role in making industrial robots work intelligently. The visual sensor or industrial camera, in practical engineering application, is usually mounted at the end of robot manipulator. This relationship is called eye-in-hand[1-2]. The target position and orientation can be measured in real time by camera and then transformed to robot, determining the next motion of robot manipulator. But before that, the hand-eye relation between the industrial robot and camera must be calibrated.

Methods of calibrating the relation between industrial robot and camera by now can be mainly divided into three categories: traditional method, autonomous method, and active vision method[4]. The traditional method initially was proposed by Tsai[5] and Shiu[6]. The industrial robot must move at least to 3 different poses to capture the images of a calibrating plate and then a traditional equation was established to solve the hand-eye matrix, but the solution process was very complicated. The process methods like quaternion, direct product of matrixes[3,7] were later put forward to calculate the equation. For the autonomous method, it was unnecessary to use calibration plate, because different images were captured from the same scene or object instead of calibration plate, and by matching these images, there existed constraint relation between hand-eye parameters and the matching information[8-9], but this method generally performed weak robustness. Active vision method was aimed at driving the industrial robot as well as camera to make several special movements, with which the movement of extracted point in captured images corresponded[10]. Active vision method had an advantage of convenient calculation and good robustness, however, it required a platform with high precision, while there was always errors between theoretical mechanical parameters of industrial robot and the real ones, so this method performed low accuracy.

For the disadvantages of calibration methods described above, this paper will propose a static calibration method to solve hand-eye relation of robot. Using an optical measurement equipment, the relation between the world coordinate system, the flange coordinate system and the measuring coordinate system can be respectively determined. After the calibration plate being imaged with an industrial camera, the transform matrix between the camera coordinate system and the calibration plate coordinate system can also be achieved, so that the hand-eye relation of robot will be calculated easily with four matrices.

II. CAMERA IMAGING MODEL

In order to obtain the 3D position of target object from the images captured by the industrial camera, it is essential to determine the imaging geometric model of camera. The typical pinhole model is used, as is shown in Fig.1.

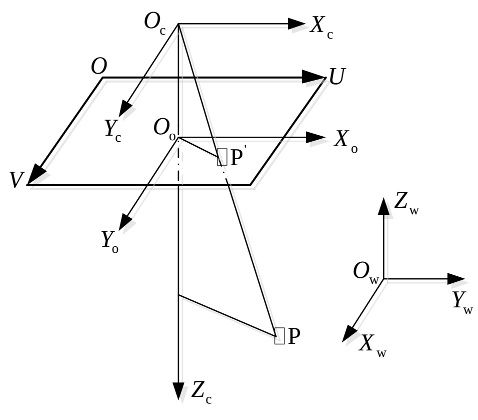

Fig. 1. Pinhole model of camera imaging.

In Fig.1, $O_wX_wY_wZ_w$ represents the world coordinate system, while $O_cX_cY_cZ_c$ the camera coordinate system, $X_oO_oY_o$ the image physical coordinate system and UOV the image pixel coordinate system. Supposing P is the target point in physical space whose coordinate in $O_wX_wY_wZ_w$ is (x_w, y_w, z_w),

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and P' is the corresponding image point whose coordinate in UOV is (u, v), the relation between them can be described as:.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = k \begin{bmatrix} f_u & 0 & u_0 & 0 \\ 0 & f_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{R} & \boldsymbol{T} \\ \boldsymbol{O} & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} \quad (1)$$

k is the proportionality coefficient; f_u, f_v are the scale factors respectively in the direction of axis U and V, (u_0, v_0) is the coordinate in *UOV*, representing the projection point of optical axis in camera imaging plane, f_u, f_v, u_0, and v_0 are the intrinsic parameters of the camera; $\boldsymbol{R}$ and $\boldsymbol{T}$ are respectively the rotation matrix and the translation vector composed of the extrinsic parameters, that is, the rotating part and the translation part of the homogeneous matrix describing the pose of $O_w X_w Y_w Z_w$ in $O_c X_c Y_c Z_c$.

All the intrinsic and extrinsic parameters can be easily achieved using the calibration toolbox by Zhengyou ZHANG.

III. Principle of Static Calibration

A. Building Hand-eye Calibration System

The hand-eye calibration system is made up of industrial robot as well as the controlling system, industrial camera, calibration plate, extern optical measuring equipment, and some relevant parts. The calibration site is shown in Fig.2.

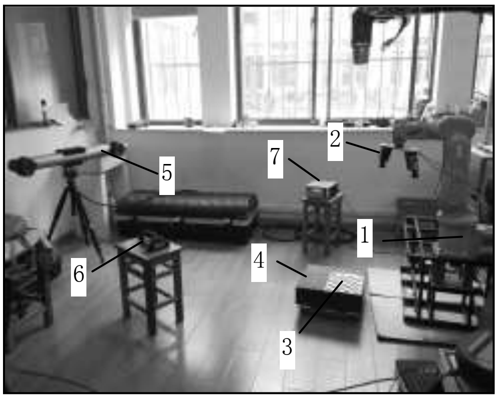

Fig. 2. The site of hand-eye calibration system.

In Fig. 2, 1 is the industrial robot; 2 is the industrial camera; 3 is the calibration plate; 4 is the marble block; 5 is the optical measuring equipment; 6 is the hand-held probe; 7 is the controller of the measuring equipment.

B. Determining Each Coordinate System

As a matter of fact, several kinds of measuring equipment can be adopted to assist in hand-eye calibration. Although there may be differences between the use of various measuring equipment, the idea and purpose are consistent. In this paper, the optical measuring equipment designed by Creaform in Canada, Vxtrack Ctrack-380, is taken as an example to illustrate the role played in the calibration process.

Besides the coordinate systems built in Fig.1, there should also be some other ones while using the method proposed by this paper, as is shown in Fig.3.

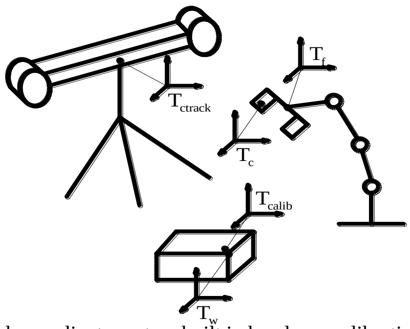

Fig. 3. Each coordinate system built in hand-eye calibration system.

In Fig.3, T_{ctrack} is the measuring coordinate system which is the intrinsic reference of Ctrack-380, and the origin is the center of Ctrack-380. All the position of point or the pose of object measured by Ctrack-380 are relative to T_{ctrack}; T_w, that is $O_w X_w Y_w Z_w$ in section Ⅱ, is the world coordinate system. Several points are measured respectively on three planes adjacent to each other of the marble block by the hand-held probe which is called Handyprobe and is the supporting equipment of Ctrack-380, and these three planes are fitted in sequence, whose normal vectors and intersection are respecttively chosen to be the axes and the origin of T_{ctrack}; T_{calib} is the calibration plate coordinate system, which is built when calibrating the extrinsic parameters of industrial camera. The origin of T_{calib} is generally chosen at one corner of the checkerboard; T_c, that is $O_c X_c Y_c Z_c$ in section Ⅱ, is the camera coordinate system, which is the intrinsic reference of the industrial camera, whose optic center is generally chosen as the origin of T_c; T_f is the flange coordinate system of the industrial robot. Several points are measured on the cylindrical surface of flange and projected to flanged end, then a circle can be fitted, whose center and normal vector are respectively chosen to be the origin and Z axis of T_f.

In the first place, several target marks need to be attached uniformly to the surface of flange and marble block separately, making sure that at least 3 market targets are always in the sight of Ctrack-380. T_w and T_f then can be respectively built according to the description above using Ctrack-380 and the corresponding software Vxelement. At the same time, the homogeneous matrices ${}^{ctrack}\boldsymbol{T}_w$, ${}^{ctrack}\boldsymbol{T}_f$, respectively between the coordinate systems T_w, T_f and T_{ctrack}, can be obtained.

Then, the homogeneous matrix ${}^{w}\boldsymbol{T}_{calib}$, between the coordinate systems T_w and T_{calib}, can be obtained by measuring directly.

Therefore, the homogeneous matrix ${}^{ctrack}\boldsymbol{T}_{calib}$, between the coordinate systems T_{calib} and T_{ctrack}, can be calculated as the equation below.

$${}^{ctrack}\boldsymbol{T}_{calib} = {}^{ctrack}\boldsymbol{T}_w \cdot {}^{w}\boldsymbol{T}_{calib} \quad (2)$$

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The calibration plate is used to be imaged once by the industrial camera, and the extrinsic parameters, that is the homogeneous matrix ${}^{c}\boldsymbol{T}_{calib}$ between the coordinate systems T_{calib} and T_c, can be obtained by using the calibration toolbox by Zhengyou ZHANG.

Therefore, the homogeneous matrix ${}^{ctrack}\boldsymbol{T}_{calib}$ can be calculated in another way as the equation below.

$$ {}^{ctrack}\boldsymbol{T}_{calib} = {}^{ctrack}\boldsymbol{T}_{f} \cdot {}^{f}\boldsymbol{T}_{c} \cdot {}^{c}\boldsymbol{T}_{calib} \tag{3} $$

Based on (2) and (3), the hand-eye matrix, that is the homogeneous matrix ${}^{f}\boldsymbol{T}_{c}$ between the coordinate systems T_c and T_f, can be calculated as the equation below.

$$ {}^{f}\boldsymbol{T}_{c} = ({}^{ctrack}\boldsymbol{T}_{f})^{-1} \cdot {}^{ctrack}\boldsymbol{T}_{w} \cdot {}^{w}\boldsymbol{T}_{calib} \cdot ({}^{c}\boldsymbol{T}_{calib})^{-1} \tag{4} $$

This is the principle of proposed static hand-eye calibration. It is very easy and fast in terms of calculation, which has an advantage over the traditional calibration method. And during the whole calibration process, there is no need for industrial robot to move, avoiding the error causing by the deviation of robot structure size. By the way, this method can be used to get relation between the industrial camera and any base, namely, it can not only be applied to deal with robot hand-eye calibration.

IV. Experimental Procedure and Result Analysis

A. Experimental Facilities

The hand-eye calibration experiment proposed in this paper is carried out on the self-developed robot system. The industrial camera is mounted together with adapter flange to the end of robot. The experiment system uses Imaging DFK 23GV024 camera, Computar M0814-MP2 lensand, PCIe-PoE2+ image capture card which has two mutually independent network communication interface used to connect cameras and it can supply power for cameras when transmitting data. A black and white checkboard which has 9×7 squares, is chosen as the calibration plate which is attached to a marble block with high plane precision. The optical measurement equipment is Vxtrack Ctrack-380 developed by Creaform Canada. The supporting equipment Handyprobe is used to measure surface and the precision is up to 0.05mm. The process of hand-eye calibration is mainly based on Matlab and Vxelement.

B. Experimental Steps

(1) Using the industrial camera to capture 16 images of the calibration plate, and applying the calibration toolbox by Zhengyou ZHANG to calibrate the intrinsic parameters, the final result is as shown in Tab.I.

TABLE I. Intrinsic parameters of industrial camera.

Parameters	X Direction	Y Direction
Focal Length(fc)	1404.7	1392.6
Principal Point(cc)	315.3	228.7

(2) Attaching several target marks uniformly to the surface of flange and marble block separately, using Ctrack-380 and the corresponding software Vxelement to build the coordinate systems T_w and T_f, and the homogeneous matrices ${}^{ctrack}\boldsymbol{T}_{w}$, ${}^{ctrack}\boldsymbol{T}_{f}$ are obtained, the result is as following.

$$ {}^{ctrack}\boldsymbol{T}_{w} = \begin{bmatrix} -0.9891 & 0.1418 & -0.0405 & 70.79 \\ 0.0490 & 0.0572 & -0.9972 & 529.6 \\ -0.1391 & -0.9882 & -0.0636 & 2329 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

$$ {}^{ctrack}\boldsymbol{T}_{f} = \begin{bmatrix} 0.1383 & 0.9038 & 0.4049 & -262.9 \\ 0.0412 & -0.4138 & 0.9094 & -320.8 \\ 0.9895 & -0.1091 & -0.0945 & 2351 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

(3) Measuring directly, and the homogeneous matrices ${}^{w}\boldsymbol{T}_{calib}$ is obtained, as below.

$$ {}^{w}\boldsymbol{T}_{calib} = \begin{bmatrix} 1 & 0 & 0 & 51.5 \\ 0 & 1 & 0 & 51.5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

(4) Using the industrial camera to just once capture the image of calibration plate, and the homogeneous matrices ${}^{c}\boldsymbol{T}_{calib}$ is obtained by using the calibration toolbox, as below.

$$ {}^{c}\boldsymbol{T}_{calib} = \begin{bmatrix} 0.2903 & -0.9175 & -0.2718 & -9.238 \\ -0.9030 & -0.3566 & 0.2395 & 108.6 \\ -0.3167 & 0.1759 & -0.9321 & 777.8 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8} $$

C. Experimental Data Disposal

The hand-eye matrix ${}^{f}\boldsymbol{T}_{c}$ is calculated by substituting (5)-(8) to (4), the result is as following.

$$ {}^{f}\boldsymbol{T}_{c1} = \begin{bmatrix} 0.8278 & 0.5607 & 0.0204 & -73.09 \\ -0.5599 & 0.8279 & -0.0349 & -161.1 \\ -0.0363 & 0.0176 & 0.9993 & 124.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9} $$

Hereto, the whole hand-eye calibration process is completed, and the industrial robot is not moved. Considering there is always error when measuring, in order to enhance the hand-eye calibration accuracy and later the traditional calibration method will be used to verify the result, the industrial robot is moved to three different configurations, another two hand-eye matrices are obtained as (10) and (11), and the final calibration result is the average of (9)-(11).

$$ {}^{f}\boldsymbol{T}_{c2} = \begin{bmatrix} 0.8336 & 0.5522 & 0.0111 & -71.11 \\ -0.5520 & 0.8336 & -0.0207 & -161.1 \\ -0.0207 & 0.0112 & 0.9997 & 124.1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10} $$

$$ {}^{f}\boldsymbol{T}_{c3} = \begin{bmatrix} 0.8308 & 0.5524 & 0.0676 & -72.25 \\ -0.5527 & 0.8332 & -0.0179 & -160.9 \\ -0.0662 & -0.0224 & 0.9976 & 122.2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11} $$

Defining a one-dimensional vector which has six elements. The first three elements represent the Rodrigues rotational vector transforming from the rotational part of hand-eye

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matrix using Rodrigues transform[3], and the last three elements represents the translation vector of hand-eye matrix, as is shown in (12). It shows that the calibration result using the proposed method has good robustness. Equation (13) is the average of all the Rodrigues rotational vectors in (12), and transform (13) into the form of homogeneous matrix, as is shown in (14).

$$\boldsymbol{V}_1 = \begin{bmatrix} 0.0278 \\ 0.0301 \\ -0.5949 \\ -73.09 \\ -161.1 \\ 124.0 \end{bmatrix}, \boldsymbol{V}_2 = \begin{bmatrix} 0.0169 \\ 0.0168 \\ -0.5850 \\ -71.11 \\ -161.1 \\ 124.1 \end{bmatrix}, \boldsymbol{V}_3 = \begin{bmatrix} -0.0024 \\ 0.0709 \\ -0.5861 \\ -72.25 \\ -160.9 \\ 122.2 \end{bmatrix} \quad (12)$$

$$\boldsymbol{V} = \begin{bmatrix} 0.0141 & 0.0393 & -0.5887 & -72.15 & -161.0 & 123.4 \end{bmatrix}^{\mathrm{T}} \quad (13)$$

$$^{\mathrm{f}}\boldsymbol{T}_{\mathrm{c}} = \begin{bmatrix} 0.8309 & 0.5554 & 0.0330 & -72.15 \\ -0.5548 & 0.8316 & -0.0245 & -161.0 \\ -0.0411 & 0.0021 & 0.9992 & 123.4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

D. Experimental Verification

As described above, the industrial robot is moved to three different configurations, and the hand-eye matrix is obtained by calculated $\boldsymbol{X}$ in the traditional equation $\boldsymbol{AX} = \boldsymbol{XB}$. Equation (15) is the form in detail. So that the calibration accuracy using the proposed method can be verified while compared with the calibration result using the traditional method.

$$({}^{\mathrm{b}}\boldsymbol{T}_{\mathrm{f2}})^{-1} \cdot {}^{\mathrm{b}}\boldsymbol{T}_{\mathrm{f1}} \cdot {}^{\mathrm{f}}\boldsymbol{T}_{c} = {}^{\mathrm{f}}\boldsymbol{T}_{\mathrm{c}} \cdot {}^{\mathrm{c}}\boldsymbol{T}_{\mathrm{calib2}} \cdot ({}^{\mathrm{c}}\boldsymbol{T}_{\mathrm{calib1}})^{-1} \quad (15)$$

${}^{\mathrm{f}}\boldsymbol{T}_{\mathrm{c}}$ represents $\boldsymbol{X}$; ${}^{\mathrm{b}}\boldsymbol{T}_{\mathrm{f}}$ represents the homogeneous matrix between the flange coordinate system and the base coordinate system of the industrial robot, and it is calculated by the forward kinematics according to the joint angles which are feedback of each encoder. The calibration results respectively using the traditional method and the proposed one are shown in Tab. II. It is obvious that there is little deviation in terms of orientation, and the position error is 1.5mm at most. Since the traditional calibration method is considered as a method with high accuracy, it proves that the proposed static calibration method is relatively reliable.

TABLE II. Hand-eye matrix calculated by two different calibration methods.

Traditional Calibration Method	Static Calibration Method
$\begin{bmatrix} 0.8308 & 0.5565 & 0.0131 & -71.67 \\ -0.5561 & 0.8308 & -0.0246 & -159.5 \\ -0.0246 & 0.0131 & 0.9996 & 124.3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0.8309 & 0.5554 & 0.0330 & -72.15 \\ -0.5548 & 0.8316 & -0.0245 & -161.0 \\ -0.0411 & 0.0021 & 0.9992 & 123.4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

V. CONCLUSION

Due to the drawbacks of three common methods for the hand-eye calibration of industrial robot, this paper proposed a hand-eye calibration method which can calculate the hand-eye matrix easy just by multiplying four matrices. There was no need to move the industrial robot during the whole calibration process, so the error caused by structure size of robot was avoided, and that was why the calibration method called static calibration method. Finally, the calibration result using the processed method was compared with that calculated by the traditional method. Experiments showed that the position error was at most 1.5mm. It proves that the proposed method is reliable, high-accuracy, and easy to calculate. In addition, this method can not only be used to deal with robot hand-eye calibration but also be used to get relation between the industrial camera and any base, so it performs good extensibility. This study, to some degree, has value that it can be used to verify the accuracy while using other hand-eye calibration method. The proposed method is totally different from other methods because it depends on measurement equipment which is usually very expensive. In the late-stage study, industrial cameras that are much cheap-er can be used to replace the measurement equipment or some of its functions, and it has great value to study further.

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