Multi-view coordinate system transformation based on robot*

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The registration of point cloud is important for large object measurement. A measurement method for coordinate system transformation based on robot is proposed in this paper. Firstly, for obtaining extrinsic parameters, the robot moves to three different positions to capture the images of three targets. Then the transformation matrix $\boldsymbol{X}$ between camera and tool center point (TCP) coordinate systems can be calculated by using the known parameters of robot and the extrinsic parameters, and finally the multi-view coordinate system can be transformed into robot coordinate system by the transformation matrix $\boldsymbol{X}$. With the help of robot, the multi-view point cloud can be easily transformed into a unified coordinate system. By using robot, the measurement doesn't need any mark. Experimental results show that the method is effective.

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With the development of three-dimensional (3D) measurement techniques, it's easy to measure one side of an object. But the data of complete object can't be measured only one time. In order to obtain a complete object, several measurements are needed. Then multi-view point cloud can be transformed into a unified coordinate system.

There have been many data registration methods based on target[1-4]. In those methods, the target should be captured by each measurement, and then the transformation matrix can be calculated. But for large object, such as a car door and the frame of motorcycle, the position of target should be chosen carefully. Because of the target, some parts of the object can't be captured by cameras. In order to obtain the complete object, many targets are needed for measurements. Zhou Langming et al[5] proposed a flexible easy-implemented and low-cost alignment method for multi-view point clouds of small-size objects based on the idea of rotating measurement. Lin Hongbin et al[6] proposed a single image based on 3D reconstruction method of an axisymmetric forge piece. Feng Hang et al[7] designed a measurement system of binocular stereo vision that used the two-axis numerical control turntable and discussed the multi-view measurement data registration principle and implementation. Li Huaize et al[8] proposed an effective registration approach for multiple-view images, which captured the target on a turntable and a complete system for 3D reconstruction in combination with binocular stereo. But the methods based on turntable can't be used for large object measurement. After the turntable calibration, the camera's position is fixed and can't be moved, so it's not suitable for industrial application. Long Changyu et al[9,10] proposed an un-coding point matching method based on spatial intersection and a novel indirect fundamental matrix solving method based on coding network geometry, but the marks have to be pasted on the object. For large object, it would need many marks, and some objects can't be marked.

In order to measure large object efficiently, the measurement method using robot is proposed based on previous work in our lab[11-13]. Compared with other methods, the proposed method only needs once calibration. By using robot, the multi-view point cloud can easily be transformed into a unified coordinate system. It's easy to program, and the calculation is relatively simple.

The eye-in-hand calibration is to calculate the transformation matrix $\boldsymbol{X}$ between the camera and the tool

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center point (TCP) coordinate systems.

The method proposed by Tsai[14] is used in this paper for eye-in-hand calibration. The transformation relationships among all coordinate systems are shown in Fig.1. Suppose that the camera coordinate system in position 1 is C_{c1} and that in position 2 is C_{c2}, and the TCP coordinate system in position 1 is C_{T1} and that in position 2 is C_{T2}. The matrix $\boldsymbol{A}$ between C_{T1} and C_{T2} can be calculated by the parameters which are given by the robot. After camera calibration, the transformation matrices $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ between the camera and target can be calculated.

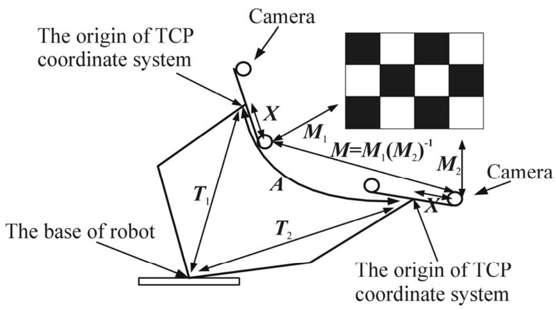


Fig.1 The transformation relationships among all coordinate systems

Assuming the coordinates of point P in the above four coordinate systems of C_{c1}, C_{c2}, C_{T1} and C_{T2} are $\boldsymbol{P}_{c1}$, $\boldsymbol{P}_{c2}$, $\boldsymbol{P}_{T1}$ and $\boldsymbol{P}_{T2}$, respectively, it can be obtained that

$$\begin{cases} \boldsymbol{P}_{c1} = \boldsymbol{M}\boldsymbol{P}_{c2} \\ \boldsymbol{P}_{c1} = \boldsymbol{X}\boldsymbol{P}_{T1} \\ \boldsymbol{P}_{T1} = \boldsymbol{A}\boldsymbol{P}_{T2} \\ \boldsymbol{P}_{c2} = \boldsymbol{X}\boldsymbol{P}_{T2} \end{cases}, \tag{1}$$

where $\boldsymbol{M}=\boldsymbol{M}_1\boldsymbol{M}_2^{-1}$. Then it can be derived from Eq.(1) that

$$\boldsymbol{MX} = \boldsymbol{XA}, \tag{2}$$

where $\boldsymbol{X}$ is the eye-in-hand transformation matrix. The transformation matrices $\boldsymbol{A}$, $\boldsymbol{M}$ and $\boldsymbol{X}$ consist of rotation and translation, for example, $\boldsymbol{A}=\begin{bmatrix} \boldsymbol{R}_A & \boldsymbol{t}_A \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}$. So we can rewrite Eq.(2) as

$$\begin{bmatrix} \boldsymbol{R}_M & \boldsymbol{t}_M \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}\begin{bmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}=\begin{bmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}\begin{bmatrix} \boldsymbol{R}_A & \boldsymbol{t}_A \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}. \tag{3}$$

Then it can be obtained by Eq.(3) that

$$\begin{cases} \boldsymbol{R}_M\boldsymbol{R} = \boldsymbol{R}\boldsymbol{R}_A \\ \boldsymbol{R}_M\boldsymbol{t}+\boldsymbol{t}_M = \boldsymbol{R}\boldsymbol{t}_A+\boldsymbol{t} \end{cases}. \tag{4}$$

$\boldsymbol{R}$ and $\boldsymbol{t}$ will be calculated respectively. To calculate $\boldsymbol{R}$ and $\boldsymbol{t}$, the robot has to move to three different positions. Then we can get two equation groups as

$$\begin{cases} \boldsymbol{R}_{Ma}\boldsymbol{R} = \boldsymbol{R}\boldsymbol{R}_{Aa} \\ \boldsymbol{R}_{Ma}\boldsymbol{t}+\boldsymbol{t}_{Ma} = \boldsymbol{R}\boldsymbol{t}_{Aa}+\boldsymbol{t} \end{cases}, \tag{5}$$

$$\begin{cases} \boldsymbol{R}_{Mb}\boldsymbol{R} = \boldsymbol{R}\boldsymbol{R}_{Ab} \\ \boldsymbol{R}_{Mb}\boldsymbol{t}+\boldsymbol{t}_{Mb} = \boldsymbol{R}\boldsymbol{t}_{Ab}+\boldsymbol{t} \end{cases}. \tag{6}$$

$\boldsymbol{R}$ can be calculated by

$$\boldsymbol{R} = (\boldsymbol{k}_{Ma} \quad \boldsymbol{k}_{Mb} \quad \boldsymbol{k}_{Ma}\times\boldsymbol{k}_{Mb})(\boldsymbol{k}_{Aa} \quad \boldsymbol{k}_{Ab} \quad \boldsymbol{k}_{Aa}\times\boldsymbol{k}_{Ab})^{-1}, \tag{7}$$

where $\boldsymbol{k}_{Ma}$ and $\boldsymbol{k}_{Mb}$ note the rotating vectors, which can be obtained by Rodrigues' rotation formula. From Eqs.(5) and (6), we can get

$$(\boldsymbol{R}_{Ma}-\boldsymbol{I})\boldsymbol{t} = \boldsymbol{R}\boldsymbol{t}_{Aa}-\boldsymbol{t}_{Ma}, \tag{8}$$

$$(\boldsymbol{R}_{Mb}-\boldsymbol{I})\boldsymbol{t} = \boldsymbol{R}\boldsymbol{t}_{Ab}-\boldsymbol{t}_{Mb}, \tag{9}$$

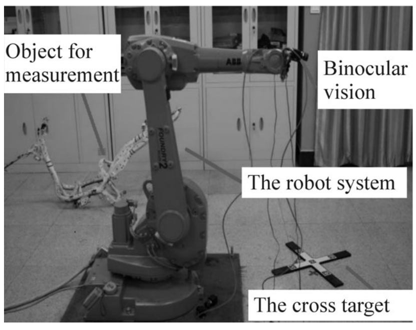
where $\boldsymbol{R}$ is calculated by Eq.(7). By using linear least squares solutions, $\boldsymbol{t}$ can be computed from Eqs.(8) and (9).

After getting $\boldsymbol{X}$, the camera coordinate system can be easily transformed into the robot coordinate system by

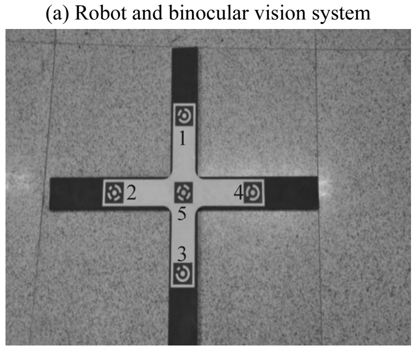
$$\boldsymbol{P}_{W} = \boldsymbol{TXP}_{C}, \tag{10}$$

where $\boldsymbol{P}_W$ and $\boldsymbol{P}_C$ are the coordinates of point P in robot coordinate system and camera coordinate system, respectively, and $\boldsymbol{T}$ is the transformation matrix from TCP coordinate system to robot coordinate system. Then the two measurement data can be transformed into a unified coordinate system.

The robot used in this experiment is ABB1600, and the robot system is shown in Fig.2(a).



(a) Robot and binocular vision system



(b) Cross target

Fig.2 The pictures of measurement system and cross target

The quaternion q_1, q_2, q_3 and q_4 of the rotation $\boldsymbol{R}$ of T_1 in Fig.1 can be obtained from the demonstrator, and then the rotation can be derived as

$$\boldsymbol{R}=\begin{bmatrix} q_1^2+q_2^2-q_3^2-q_4^2 & 2(q_2q_3-q_1q_4) & 2(q_2q_4+q_1q_3) \\ 2(q_2q_3+q_1q_4) & q_1^2-q_2^2+q_3^2-q_4^2 & 2(q_3q_4-q_1q_2) \\ 2(q_2q_4-q_1q_3) & 2(q_3q_4+q_1q_2) & q_1^2-q_2^2-q_3^2+q_4^2 \end{bmatrix}. \tag{11}$$

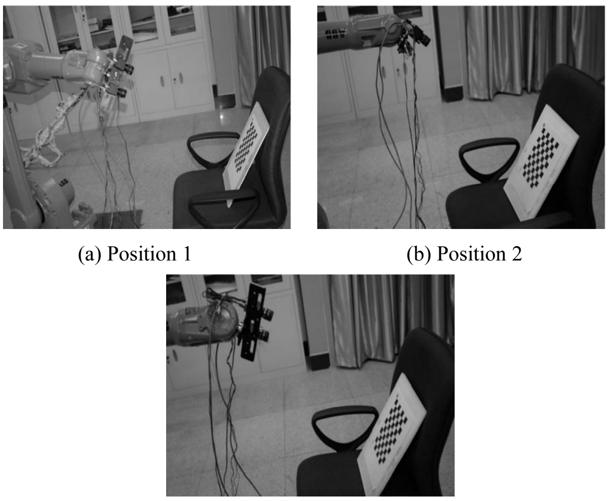
The translation $\boldsymbol{t}$ of T_1 is the position of origin of TCP coordinate system in robot coordinate system.

In order to get the transformation matrix $\boldsymbol{X}$ between camera and TCP coordinate systems, the planar target can be taken from three different positions by controlling the robot, and the quaternion and origin of the TCP coordinate system from the demonstrator are recorded, respectively. Then Eqs.(5) and (6) can be obtained.

In position 1, as shown in Fig.3(a), the quaternion is $\boldsymbol{Q}_1$=[0.169 248 0.338 681 0.630 323 −0.677 749], and then the rotation $\boldsymbol{R}_1$ can be calculated as

$$\boldsymbol{R}_1=\begin{bmatrix} -0.7133 & 0.6564 & -0.2457 \\ 0.1975 & -0.1481 & -0.9690 \\ -0.6724 & -0.7398 & -0.0240 \end{bmatrix}, \tag{12}$$

and the translation is $\boldsymbol{t}_1$=[128.36 −394.44 1 051.65].



(a) Position 1 (b) Position 2

(c) Position 3

Fig.3 Eye-in-hand calibration positions

In position 2, as shown in Fig.3(b), the quaternion is $\boldsymbol{Q}_2$=[0.316 172 0.159 88 0.408 206 −0.841 333], and then the rotation $\boldsymbol{R}_2$ can be calculated by

$$\boldsymbol{R}_2=\begin{bmatrix} -0.7489 & 0.6625 & -0.0109 \\ -0.4015 & -0.4668 & -0.7880 \\ -0.5272 & -0.5858 & -0.6156 \end{bmatrix}, \tag{13}$$

and the translation is $\boldsymbol{t}_2$=[155.78 −204.38 979.51].

In position 3, as shown in Fig.3(c), the quaternion is $\boldsymbol{Q}_3$=[0.005 999 02 −0.481 792 −0.759 899 0.436 341], and then the rotation $\boldsymbol{R}_3$ can be calculated as

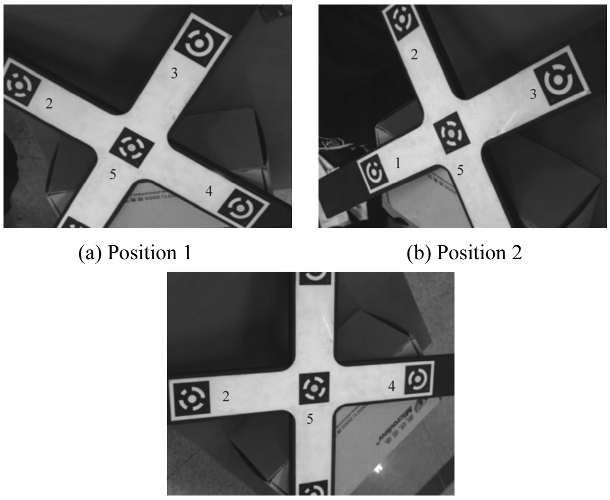
$$\boldsymbol{R}_3=\begin{bmatrix} -0.5357 & 0.7270 & -0.4296 \\ 0.7375 & 0.1550 & -0.6574 \\ -0.4113 & -0.6689 & -0.6191 \end{bmatrix}, \tag{14}$$

and the translation is $\boldsymbol{t}_3$=[77.6 −584.51 1 036.17].

Then the eye-in-hand transformation matrix $\boldsymbol{X}$ can be calculated by Eqs.(7)–(9) as

$$\boldsymbol{X}=\begin{bmatrix} 0.4610 & 0.2494 & -0.9623 & -101.2112 \\ -0.9766 & -0.0254 & -0.4631 & 285.4014 \\ -0.0684 & 0.9882 & 0.2537 & 538.4676 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{15}$$

Take the cross target pictures from the above three different positions, which are shown in Fig.4. Then use Eq.(10) to calculate the cross target's position in robot coordinate system, as shown in Tab.1.



(a) Position 1 (b) Position 2

(c) Position 3

Fig.4 Pictures of cross target taken from different positions for registration

Tab.1 3D coordinates from different positions

(a) Position 1

Coordinates	2	5	4	3
x	−63.903 6	7.877 3	79.212 0	−111.077 7
y	−515.966 5	−396.509 6	−277.044 8	−340.935 0
z	852.290 3	835.401 4	818.830 8	777.774 3

(b) Position 2

Coordinates	2	1	5	3
x	−63.840 4	124.659 9	6.285 8	−113.275 3
y	−515.998 3	−451.861 4	−396.383 3	−339.877 5
z	849.320 9	892.230 3	833.567 8	776.275 4

(c) Position 3

Coordinates	2	5	4
x	−61.583 1	13.200 0	86.100 8
y	−517.223 0	−395.670 9	−273.743 8
z	838.695 1	819.161 4	801.748 8

The result after registration is shown in Fig.5. The circles are the targets in position 1, the squares are the targets in position 2, and the stars are the targets in position 3. It can be calculated by $\sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i-\mu)^2}$ that the errors of the registration in x, y and z axes are 0.955 5 mm, 0.480 6 mm and 0.629 3 mm, respectively.

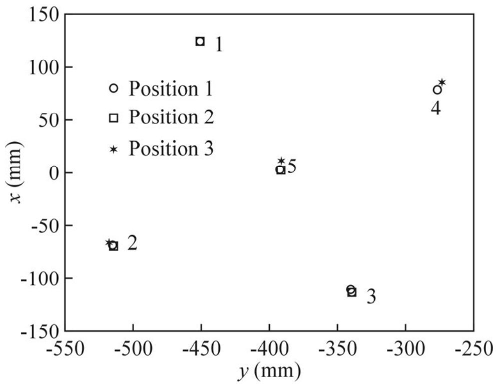


Fig.5 The measurement data after registration

A multi-view coordinate system transformation based on robot is proposed. The ABB1600 robot is used in this system. The parameters of the transformation matrix ***X*** between the camera and TCP coordinate systems can be obtained by eye-in-hand calibration. The multi-view point cloud of the object can be transformed into robot coordinate system by using the matrix ***X*** and the quaternion and translation of robot. Experimental results show that the algorithm is effective. It can be used for measuring the large object and can be used in manufactory. Compared with other methods, its operation is simple, and no mark is needed.

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