A fast calibration method of the robot's 3D vision system

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Abstract: Calibration accuracy and convenience are very important for the rapid production of vision-based robots. Although there are many calibration methods for the 3D vision system, the convenience of calibration cannot meet the needs of industrial sites. In this paper, we propose a fast calibration method based on a 3D calibration block. Its key point is to complete the calibration process through multiple space point constraints, and the space points used are jointly solved by multiple planes obtained by local point cloud fitting. The experimental results show that the proposed method can quickly complete the calibration of the robot's 3D vision system, and the calibration accuracy can meet low precision occasions.

1. Introduction

Compared with traditional contact measurement methods, non-contact measurement techniques have been extensively focused on efficiency and dimensional flexibility, and the devices developed are increasingly integrated into automatic measurement systems [1]. At present, a large amount of work has been carried out on non-contact measurement [2], calibration and scanning precision [3], 3D laser measurement methods [4] and reverse engineering [5] etc. to study on-line measurement and compensation techniques in robotic machining.

It is necessary to calibrate the robot vision measurement system. Yin S et al. [6] proposed a robotic scanning system and expanded the scanning range, but the hand-entry eye calibration method used has limited calibration accuracy. Based on the summary of the above methods, this paper proposes a fast calibration method based on a 3D calibration block based on an invented 3D calibration block.

2. Problem description and calibration method

2.1. Problem description

The role of the robot vision system is to detect the operating points, which are used to guide the operation of the robot end. The calibration task of the robot vision system is to fit the transformation matrix between the robot vision system coordinate system and the robot's sixth joint coordinate system. Figure 1 shows the coordinate systems involved in the calibration process, including the world coordinate system (W), the robot base coordinate system (B), the robot's sixth joint coordinate system (J6), and the 3D vision sensor coordinate system (S).
As can be seen from Figure 1, the 3D vision sensor is fixed on the robot’s sixth joint. Assume that the coordinate value of a certain point in space in the visual system is $S \mathbb{X}$, then the coordinate value $B \mathbb{X}$ of the target point detected by the 3D vision sensor in the robot base coordinate system is:

$$B \mathbb{X} = \mathbb{T} \cdot S \mathbb{X}$$  \hspace{1cm} (1)

Here, the matrix $\mathbb{T}$ is the parameter to be solved during the calibration.

2.2. calibration method

The calibration method used in this paper is based on multi-point constraints to fit the transformation matrix between the sixth joint coordinate system of the robot and the coordinate system of the vision system. The multi-point here refers to the corner points of the 3D calibration block, and the corner points are the intersection points of the three planes, and the coordinates of the intersection points can be obtained by jointly solving the relevant planes. The fitting plane in this paper is based on the Random Sample Consensus (RANSAC) [7] algorithm.

After fitting the relevant planes, the coordinate value of the 3D calibration block in the robot vision coordinate system $S$ can be obtained by solving the intersection points of the three planes. At the same time, the coordinate value of the corner point of the calibration block in the robot base coordinate system $B$ can be obtained through the calculation of the kinematics of the robot and the probe length compensation in the Z-axis direction of the sixth joint.

In order to calibrate the 3D vision system of the robot, a workpiece coordinate system $P_B$ relative to the robot base coordinate system and a workpiece coordinate system $P_S$ relative to the robot vision coordinate system need to be constructed.

First, we construct the workpiece coordinate system $P_S$. We can obtain the unit vector $A_{3x}$ of the X-axis with $P_{S1}$ as the origin of the coordinate system $P_S$:

$$A_{3x} = \frac{P_{S1} - P_{S2}}{\left\|P_{S1} - P_{S2}\right\|_p}$$ \hspace{1cm} (2)

Similarly, we can also get another unit vector $B_{32}$ in the XY plane:

$$B_{32} = \frac{P_{S3} - P_{S2}}{\left\|P_{S3} - P_{S2}\right\|_p}$$ \hspace{1cm} (3)

The unit vector $C_{5z}$ of the Z-axis of the coordinate system $P_S$ is:

$$C_{5z} = A_{3x} \times B_{32}$$ \hspace{1cm} (4)

The unit vector $D_{3y}$ of the Y-axis of the coordinate system $P_S$ is:
\[ D_{xy} = A_{sx} \times C_{sx} \]  
(5)

Therefore, the workpiece coordinate system \( P_3 \) is:

\[
P_3 = \begin{bmatrix} A_{sx} & D_{sy} & C_{sz} & P_{s2} \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]  
(6)

Using a similar method as above, \( P_B \) can be calculated as:

\[
P_B = \begin{bmatrix} A_{bx} & D_{by} & C_{bz} & P_{b2} \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]  
(7)

And because the transformation matrix between the coordinate system of the sixth joint of the robot and the base coordinate system of the robot is

\[
^{B}_T = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 6 & 1 & 2 & 3 & 4 & 5 & 6 \end{bmatrix}
\]  
(8)

The coordinate value of the corner points of the calibration block satisfies Equation (9) in the robot base coordinate system and the 3D vision system coordinate system.

\[
P_B = ^{B}_T \begin{bmatrix} x \end{bmatrix} P_S
\]  
(9)

Therefore, we can determine the transformation matrix \( ^{S}_T \) as

\[
^{S}_T = ^{B}_T P_B P_S^{-1}
\]  
(10)

In this way, we can calibrate the robot’s vision system and obtain the required transformation matrix \( ^{S}_T \).

3. Experimental verification

3.1. Experimental scene

In order to verify the calibration method proposed in this paper, a calibration platform was built, as shown in Figure 2. From Figure 2, we can see that this calibration platform includes a robot, a probe, a 3D vision sensor and a 3D calibration block. The robot used here is manufactured by Universal Robots, the product model is UR3, the load is 3Kg, the working range is 500mm, and the repeat positioning accuracy is ±0.1mm. The 3D vision sensor used here is manufactured by Microsoft, the product model is Kinect2, the theoretical error of measurement accuracy is 2.0-4.0mm, the measuring distance is 0.5-4.50m, and the vision sensor is fixed on the robot’s sixth joint and does not interfere with the normal rotation of all robot joints. The total length of the probe and the flange for fixing the probe is 64.02mm, which is fixed at the end of the robot, and the centre line of the probe coincides with the Z-axis of the sixth joint coordinate system of the robot. The coordinate value of the corner points of the calibration block in the robot base coordinate system can be calculated by the probe and robot parameters.

3.2. Fast Calibration Experiment of Robot’s 3D vision system

According to the calibration method described above, a rapid calibration experiment of the robot vision system is carried out. First, design the calibration block, and then adjust the robot to a proper attitude to obtain the point cloud of the calibration block, and fit the relevant point cloud to four planes based on the RANSAC algorithm (that is, Plane1, Plane2, Plane3 in Figure 3 (c), Plane4). Finally, combining any three of the related planes to calculate the plane intersection point, then the three corner points of the calibration block can be calculated (as shown in Point 3, Point 2 and Point 3 in Figure 3 (c)). And the coordinates of these corner points are described in the visual system coordinate system.
Through the above process, we can get $P_{S1}$, $P_{S2}$, $P_{S3}$, and $P_S$ can be calculated according to Equations (2)-(6). In addition, when the end of the probe fixed on the sixth joint coincides with the corner point of the calibration block, the angle value of each joint can be read from the robot controller. After recompensating the length of the probe, we can calculate $P_{B1}$, $P_{B2}$, and $P_{B3}$ through the robot’s forward kinematics calculations, and $P_B$ can be obtained according to Equation (7).

Table 1 shows the coordinate value of the corner points of the calibration block in different coordinate systems. In this experiment, the joint angles J1-J6 in the robot pose to obtain the point cloud of the calibration block are: (-46.58, -118.42, -16.47, -134.49, 95.64, 359.50), and the unit is degree. When the probe at the end of the robot contacts different corner points of the calibration block, the robot joint angles J1-J6 are: P1 (-32.76, -151.96, -98.30, -44.06, 98.16, 359.48), P2(-49.18, -162.77, -88.47, -44.30, 105.13, 359.51), P3(-45.24, -180.40, -57.14, -44.20, 106.52, 359.51).

| Parameters | Coordinate value (mm) |
|------------|-----------------------|
| $P_{S1}$   | -94.30, 139.60, 532.10 |
| $P_{S2}$   | -26.30, 144.80, 564.00 |
| $P_{S3}$   | -51.90, 41.50, 609.20  |
| $P_{B1}$   | 207.21, -242.30, -101.06 |
| $P_{B2}$   | 151.40, -288.88, -141.75 |
| $P_{B3}$   | 240.64, -343.29, -184.07 |

According to Equation (10), we can get the transformation matrix $^6S_T$ as:

$^6S_T = \begin{bmatrix} 0.9997 & 0.0026 & 0.0260 & 44.6792 \\ -0.0026 & 1.000 & 0.0024 & -101.3325 \\ -0.0260 & -0.0024 & 0.9997 & -54.6346 \\ 0 & 0 & 0 & 1.000 \end{bmatrix}$

### 3.3. Experiment on detection accuracy of the 3D robot vision system

In order to verify the effectiveness and accuracy of the fast calibration method proposed in this paper, this experiment randomly selects five positions from the measurement space to place calibration blocks, respectively. The horizontal height of the calibration block is different each time in the experiment. At each measurement position, the robot carries the vision system to detect from a suitable direction and records the Euclidean distance between the theoretical coordinate value of the
robot's basic coordinate system and the coordinate measurement value obtained by the vision system when the spatial position of these points is detected. The experimental results are shown in Table 2.

| Test points number | 1   | 2    | 3    | 4    | 5    |
|--------------------|-----|------|------|------|------|
| Measurement error (mm) | 11.86 | 6.33 | 5.09 | 10.32 | 12.61 |

It can be seen from Table 2 that the measurement accuracy of the vision measurement system after calibration is high, and the average absolute error is 9.242 mm. The point cloud error of the 3D vision sensor used is about 4 mm, so the calibration accuracy can meet the robot vision guidance of low precision occasions.

4. Conclusion
In this paper, a rapid calibration method for a robot's 3D vision system is proposed. The key point of this method is to realize the calibration process through multiple spatial point constraints, and these used spatial points are jointly solved by multiple planes obtained by local point cloud fitting.

The experimental results show that the calibration method proposed in this paper can quickly complete the calibration of the robot's 3D vision system, and the calibration accuracy can meet the robot vision guidance of low precision requirements. The method only needs to use a 3D calibration block and drag the end probe of the robotic arm to the three corner points of the calibration block to complete the calibration process. Therefore, this calibration method is simple to operate and suitable for industrial sites. Future research can focus on improving calibration accuracy by improving the accuracy of the point cloud.

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References
[1] Wang G, Wang Y and Xu Z 2009 Modeling and analysis of the material removal depth for stone polishing. *Journal of materials processing technology* 209 2453-2463.
[2] Fan K C, Lee M Z and Mou J I 2002 On-Line Non-Contact System for Grinding Wheel Wear Measurement. *International Journal of Advanced Manufacturing Technology* 19 14-22.
[3] Xie H, Pang C T, Li W L, et al. 2015 Hand-eye calibration and its accuracy analysis in robotic grinding. *IEEE International Conference on Automation Science and Engineering* 2015 862-867.
[4] Kosarevsky S 2010 Practical way to measure large-scale 2D parts using repositioning on coordinate-measuring machines. *Measurement* 43 837-841.
[5] Durupt A, Remy S and Ducellier G 2011 Reverse Engineering of a Piston Using Knowledge Based Reverse Engineering Approach. *Springer Berlin Heidelberg* 2011 683-690.
[6] Yin S B, Zhu J 2012 Calibration technology in application of robot-laser scanning system. *Optical Engineering* 51 4204.
[7] Chum O, Matas J 2008 Optimal randomized RANSAC. *IEEE Transactions on Pattern Analysis & Machine Intelligence* 30 1472-1482.