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1

0.53 mm 0.19 mm

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: A : 1674–5124(2018)06–0001–05

A hand-eye calibration method based on robot with stationary viewpoint

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Abstract: Aiming at the problem of hand-eye calibration of robot with stationary viewpoint, a new hand-eye calibration method is proposed according to the characteristics of robot with stationary viewpoint and visual system. Based on the binocular vision measurement, the end of the manipulator is controlled to achieve three translational movements, and the rotation matrix is calibrated by the translation amount of the end and the binocular visual measurement value. Then the end of the manipulator is controlled to perform one rotation movement, and the translation matrix in hand-eye relationship is calibrated by the rotation amount of end and the binocular visual measurement value. The visual-robot positioning accuracy test shows that, after calibrating the hand-eye relationship, the average spatial distance deviation of positioning accuracy is 0.53mm and the standard deviation is 0.19mm. This method can achieve high accuracy without solving complex solutions and the calibration process is simple, which means the method has certain application value.

Keywords: robot; stationary viewpoint; hand-eye calibration; binocular vision

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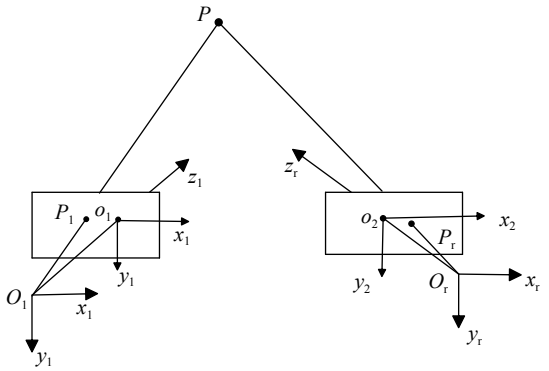
[1-3]

eye-in-hand

eye-to-hand [4]



1

[5-6]

P_l P_r

P_l P_r

P_l P_r

d

Tsai [7-8] P

3

Ma[9] 3

[10]

[11]

Wu [12] RANSAC

3 1

$$\begin{cases} Z = \dfrac{T_x f}{d - c_1 + c_2} \\ X = \dfrac{x - c_1}{f} Z = \dfrac{(x - c_1) T_x}{d - c_1 + c_2} \\ Y = \dfrac{y - c_y}{f} Z = \dfrac{(y - c_y) T_x}{d - c_1 + c_2} \end{cases} \quad (1)$$

T_x—— mm

c_1 c_2—— mm

c_y—— mm

f—— mm

d—— mm

x y——

X Y Z——

1.2

2

$\{R\}$

$\{E\}$ $\{C\}$

$\{B\}$

$\{R\}$

$\{C\}$ ${}^{C}_{R}\boldsymbol{T}$

$\{B\}$

$\{E\}$ ${}^{E}_{B}\boldsymbol{T}$

1

1.1

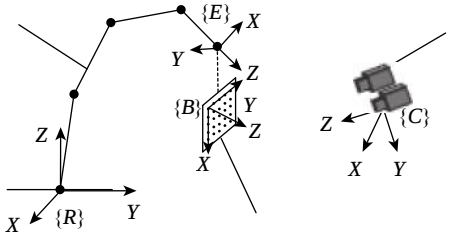
[13] 1

$O_l - x_l y_l z_l$

$O_r - x_r y_r z_r$

P

P



2

$\{R\}$ ${}^{R}\boldsymbol{P}$ $\{C\}$ ${}^{C}\boldsymbol{P}$

$$\begin{cases} {}^{R}\boldsymbol{P} = {}^{R}_{E}\boldsymbol{T}\,{}^{E}\boldsymbol{P} \\ {}^{C}\boldsymbol{P} = {}^{C}_{R}\boldsymbol{T}\,{}^{R}\boldsymbol{P} \end{cases} \tag{2}$$

${}^{R}_{E}\boldsymbol{T}$—— $\{E\}$ $\{R\}$

${}^{C}_{R}\boldsymbol{T}$—— $\{R\}$ $\{C\}$

2 3× 3 $\boldsymbol{R}$ 3×1 $\boldsymbol{t}$

$$\begin{cases} {}^{R}\boldsymbol{P} = {}^{R}_{E}\boldsymbol{R}\,{}^{E}\boldsymbol{P} + {}^{R}_{E}\boldsymbol{t} \\ {}^{C}\boldsymbol{P} = {}^{C}_{R}\boldsymbol{R}\,{}^{R}\boldsymbol{P} + {}^{C}_{R}\boldsymbol{t} \end{cases} \tag{3}$$

${}^{R}_{E}\boldsymbol{R}$——${}^{R}_{E}\boldsymbol{T}$

${}^{R}_{E}\boldsymbol{t}$——${}^{R}_{E}\boldsymbol{T}$

${}^{C}_{R}\boldsymbol{R}$——${}^{C}_{R}\boldsymbol{T}$

${}^{C}_{R}\boldsymbol{t}$——${}^{C}_{R}\boldsymbol{T}$

1.3

3

3 P

$$\begin{cases} {}^{R}\boldsymbol{P}_0 = {}^{R}_{E}\boldsymbol{R}_0\,{}^{E}\boldsymbol{P}_0 + {}^{R}_{E}\boldsymbol{t}_0 \\ {}^{C}\boldsymbol{P}_0 = {}^{C}_{R}\boldsymbol{R}_0\,{}^{R}\boldsymbol{P}_0 + {}^{C}_{R}\boldsymbol{t}_0 \end{cases} \tag{4}$$

1

3 P

$$\begin{cases} {}^{R}\boldsymbol{P}_1 = {}^{R}_{E}\boldsymbol{R}_1\,{}^{E}\boldsymbol{P}_1 + {}^{R}_{E}\boldsymbol{t}_1 \\ {}^{C}\boldsymbol{P}_1 = {}^{C}_{R}\boldsymbol{R}_1\,{}^{R}\boldsymbol{P}_1 + {}^{C}_{R}\boldsymbol{t}_1 \end{cases} \tag{5}$$

5 1 4 1

5 2 4 2

$$\begin{cases} {}^{R}\boldsymbol{P}_1 - {}^{R}\boldsymbol{P}_0 = {}^{R}_{E}\boldsymbol{R}_1\,{}^{E}\boldsymbol{P}_1 + {}^{R}_{E}\boldsymbol{t}_1 - {}^{R}_{E}\boldsymbol{R}_0\,{}^{E}\boldsymbol{P}_0 - {}^{R}_{E}\boldsymbol{t}_0 \\ {}^{C}\boldsymbol{P}_1 - {}^{C}\boldsymbol{P}_0 = {}^{C}_{R}\boldsymbol{R}_1\,{}^{R}\boldsymbol{P}_1 + {}^{C}_{R}\boldsymbol{t}_1 - {}^{C}_{R}\boldsymbol{R}_0\,{}^{R}\boldsymbol{P}_0 - {}^{C}_{R}\boldsymbol{t}_0 \end{cases} \tag{6}$$

$\{B\}$

$\{E\}$ ${}^{E}\boldsymbol{P}_0 = {}^{E}\boldsymbol{P}_1$

$\{E\}$ $\{R\}$

${}^{R}_{E}\boldsymbol{R}_0 = {}^{R}_{E}\boldsymbol{R}_1$

$\{C\}$ $\{R\}$

${}^{C}_{R}\boldsymbol{R}_0 = {}^{C}_{R}\boldsymbol{R}_1 = {}^{C}_{R}\boldsymbol{R}$ ${}^{C}_{R}\boldsymbol{t}_0 = {}^{C}_{R}\boldsymbol{t}_1 = {}^{C}_{R}\boldsymbol{t}$ 6

$$\begin{cases} {}^{R}\boldsymbol{P}_1 - {}^{R}\boldsymbol{P}_0 = {}^{R}_{E}\boldsymbol{t}_1 - {}^{R}_{E}\boldsymbol{t}_0 \\ {}^{C}\boldsymbol{P}_1 - {}^{C}\boldsymbol{P}_0 = {}^{C}_{R}\boldsymbol{R}({}^{R}\boldsymbol{P}_1 - {}^{R}\boldsymbol{P}_0) \end{cases} \tag{7}$$

7

$$({}^{C}\boldsymbol{P}_1 - {}^{C}\boldsymbol{P}_0) = {}^{C}_{R}\boldsymbol{R}({}^{R}_{E}\boldsymbol{t}_1 - {}^{R}_{E}\boldsymbol{t}_0) \tag{8}$$

${}^{C}\boldsymbol{P}_0$ ${}^{C}\boldsymbol{P}_1$——

$\{C\}$

${}^{R}_{E}\boldsymbol{t}_0$ ${}^{R}_{E}\boldsymbol{t}_1$—— $\{E\}$

$\{R\}$

8 3

$$\begin{aligned} {}^{C}_{R}\boldsymbol{R} = [\ {}^{C}\boldsymbol{P}_1 - {}^{C}\boldsymbol{P}_0 \quad {}^{C}\boldsymbol{P}_2 - {}^{C}\boldsymbol{P}_0 \quad {}^{C}\boldsymbol{P}_3 - {}^{C}\boldsymbol{P}_0\ ] \times \\ [\ {}^{R}_{E}\boldsymbol{t}_1 - {}^{R}_{E}\boldsymbol{t}_0 \quad {}^{R}_{E}\boldsymbol{t}_2 - {}^{R}_{E}\boldsymbol{t}_0 \quad {}^{R}_{E}\boldsymbol{t}_3 - {}^{R}_{E}\boldsymbol{t}_0\ ]^{-1} \end{aligned} \tag{9}$$

P

4

P 5

${}^{E}\boldsymbol{P}_0 = {}^{E}\boldsymbol{P}_1 = {}^{E}\boldsymbol{P}$

$\{E\}$

$\{R\}$

${}^{R}_{E}\boldsymbol{t}_0 = {}^{R}_{E}\boldsymbol{t}_1$ $\{C\}$

$\{R\}$ ${}^{C}_{R}\boldsymbol{R}_0 = {}^{C}_{R}\boldsymbol{R}_1 = {}^{C}_{R}\boldsymbol{R}$

${}^{C}_{R}\boldsymbol{t}_0 = {}^{C}_{R}\boldsymbol{t}_1 = {}^{C}_{R}\boldsymbol{t}$

5 1 4 1

$${}^{R}_{E}\boldsymbol{R}_0^{-1}({}^{R}\boldsymbol{P}_0 - {}^{R}_{E}\boldsymbol{t}) = {}^{R}_{E}\boldsymbol{R}_1^{-1}({}^{R}\boldsymbol{P}_1 - {}^{R}_{E}\boldsymbol{t}) \tag{10}$$

4 2 5 2 10

11

$$\begin{aligned} {}^{C}_{R}\boldsymbol{t} = ({}^{R}_{E}\boldsymbol{R}_1^{-1}\,{}^{C}_{R}\boldsymbol{R}^{-1} - {}^{R}_{E}\boldsymbol{R}_0^{-1}\,{}^{C}_{R}\boldsymbol{R}^{-1}) \times \{ {}^{R}_{E}\boldsymbol{R}_1^{-1}\,{}^{C}_{R}\boldsymbol{R}^{-1}\,{}^{C}\boldsymbol{P}_1 - {}^{R}_{E}\boldsymbol{R}_0^{-1}\,{}^{C}_{R}\boldsymbol{R}^{-1}\,{}^{C}\boldsymbol{P}_0 + \\ ({}^{R}_{E}\boldsymbol{R}_0^{-1} - {}^{R}_{E}\boldsymbol{R}_1^{-1})\,{}^{R}_{E}\boldsymbol{t} \} \end{aligned} \tag{11}$$

$^{C}\boldsymbol{P}_0$ $^{C}\boldsymbol{P}_1$——

$\{C\}$

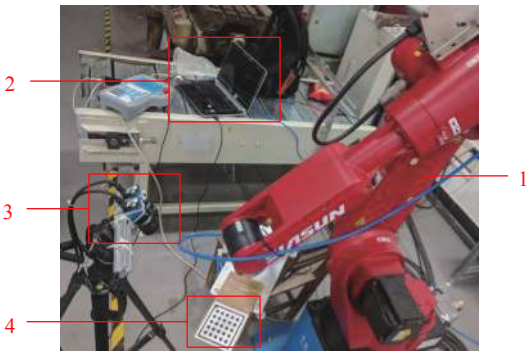
$^{R}_{E}\boldsymbol{R}_0$ $^{R}_{E}\boldsymbol{R}_1$——

$\{E\}$ $\{R\}$

9 $^{C}_{R}\boldsymbol{R}$

11 $^{C}_{R}\boldsymbol{t}$

11 1



1.SR6C 机器人；2.计算机； 3.双目相机；4.平面标定板。

1.4

3

1 $\{C\}$ $^{C}\boldsymbol{P}$ $\{C\}$

$\{R\}$ $^{C}_{R}\boldsymbol{R}$ $^{C}_{R}\boldsymbol{t}$

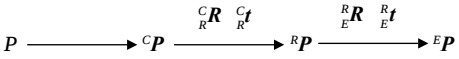
P $\{R\}$ $^{R}\boldsymbol{P}$

$\{R\}$ $\{E\}$

$^{R}_{E}\boldsymbol{R}$ $^{R}_{E}\boldsymbol{t}$ P $\{E\}$ $^{E}\boldsymbol{P}$

2 3 4

9



4

3 1

2

11

4 $^{C}_{R}\boldsymbol{t}$ 3

$^{R}_{E}\boldsymbol{R}$ $^{R}_{E}\boldsymbol{t}$ $\{C\}$

2 $\{R\}$ $\{E\}$

2.1

3

USB2.0 MicroVision

1280×960 15 f/s

LH070

3.5 mm ±0.01 mm

SIASUN SR6C 6 kg

±0.05 mm

Visual Studio C++

Windows7

Intel(R) Core i3 3210M CPU @ 2.5 GHz 4 GB

2.2

P

$^{R}_{E}\boldsymbol{R}$ $^{R}_{E}\boldsymbol{t}$

3

N

$\{C\}$

$\{R\}$ $\{A_i, i=1,2,3,\ldots,N\}$

$\{E\}$

$\{R\}$ $\{B_i, i=1,2,3,\ldots,N\}$ A_i B_i

12

$\{S_i, i=1,2,3,\ldots,N\}$

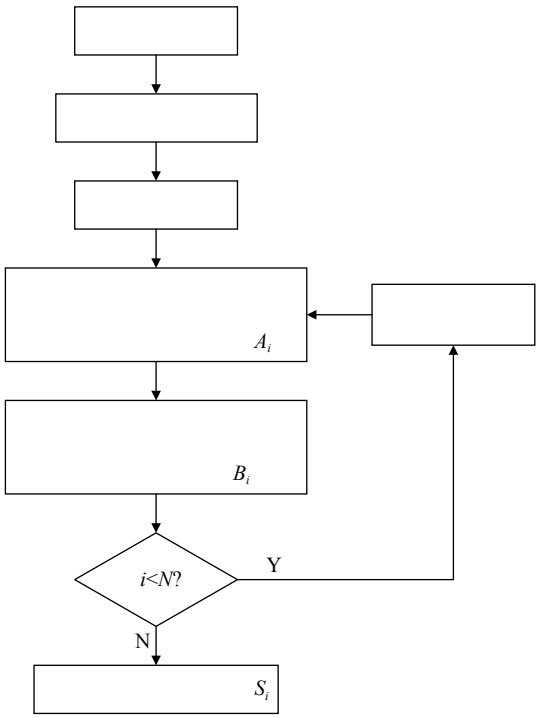
$$d=\sqrt{(x_A-x_B)^2+(y_A-y_B)^2+(z_A-z_B)^2} \quad (12)$$

d——

x_A y_A z_A—— A_i

x_B y_B z_B—— B_i

5



5

2.3

AFT-MCT-OV

30 mm×30 mm

±0.01 mm 400 mm×300 mm×5 mm

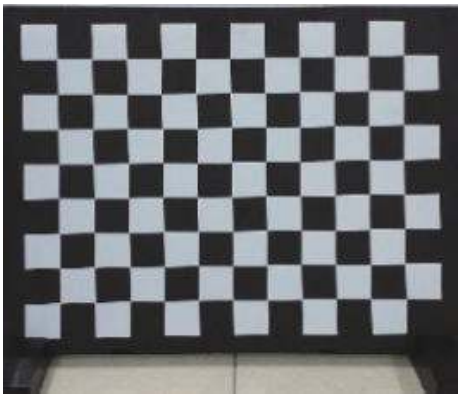
6

5

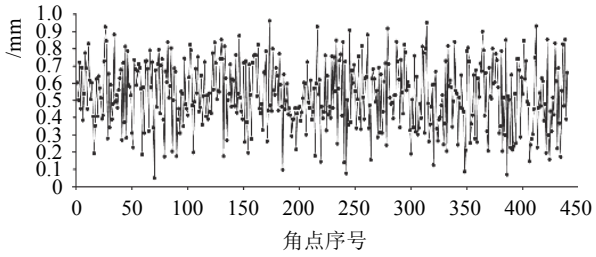
N=5 88

440 S_i

7



6



7

S_i 1

1

		/mm	/mm	/mm	/mm
1	88	0.05	0.93	0.56	0.19
2	88	0.18	0.96	0.55	0.18
3	88	0.08	0.93	0.51	0.18
4	88	0.09	0.95	0.52	0.20
5	88	0.07	0.93	0.51	0.20
	440	0.05	0.96	0.53	0.19

7 1

1 mm

0.53 mm 0.19 mm

3

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auto ïfocus algorithm with adaptive step size searching technique for digital camera[J]. Consumer Electronics IEEE Transactions on, 2003, 49(2):257ï262.

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SIASUN

SR6C

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