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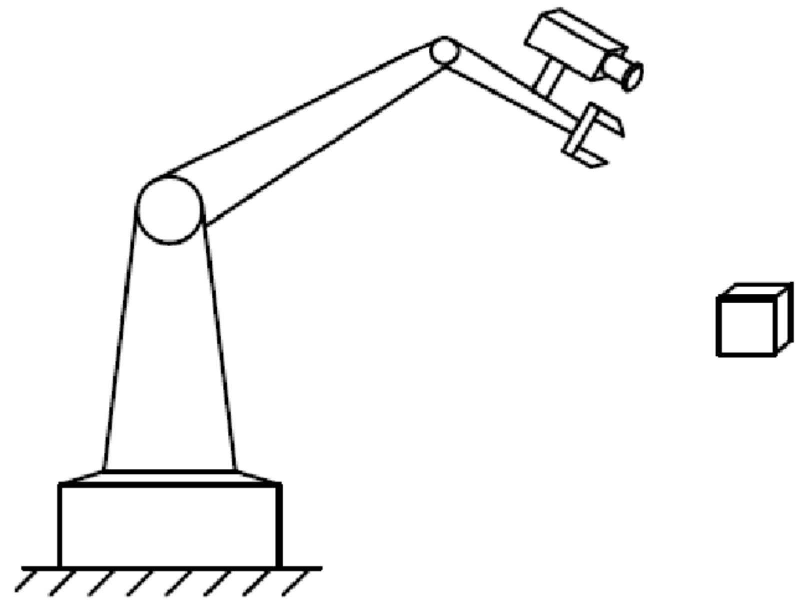
Hand-Eye Calibration

Friday 16 Mar 2018, 12:00PM

Outlines

- Introduction
- Algorithm
- Experiment and evaluation



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Introduction

Hand-eye calibration

With Camera installed, robot may perform some specific tasks with visual access to environmental information:

Measurement, tracking, Navigation, etc.

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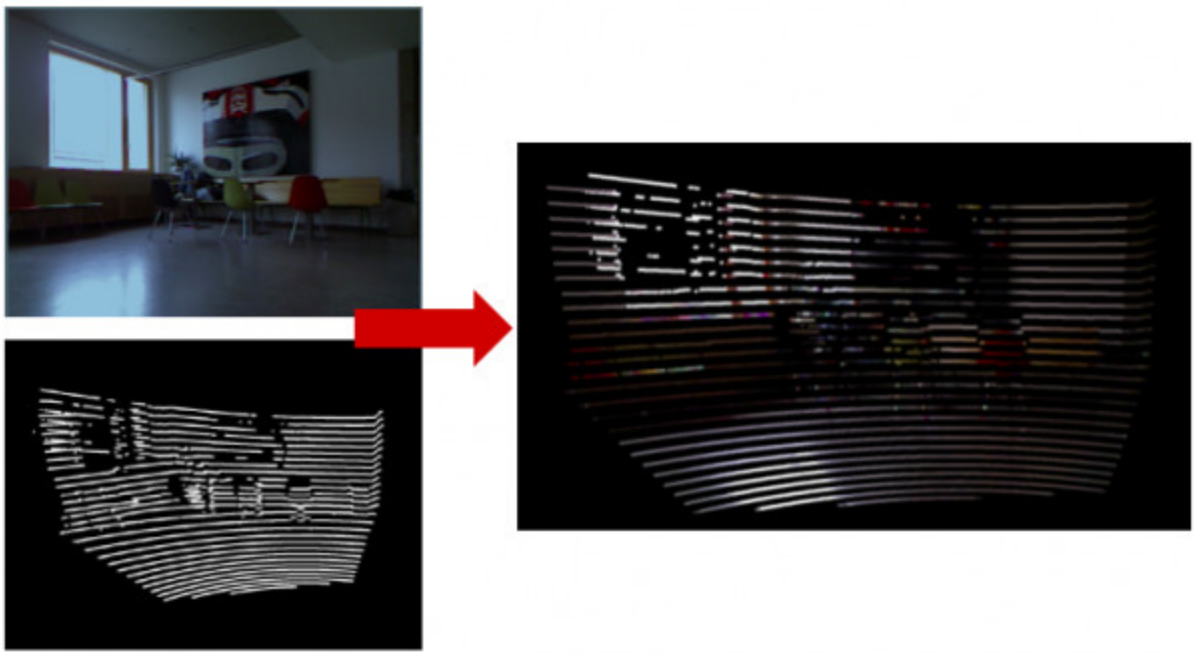
Introduction

Hand-eye calibration may help in sensor fusion



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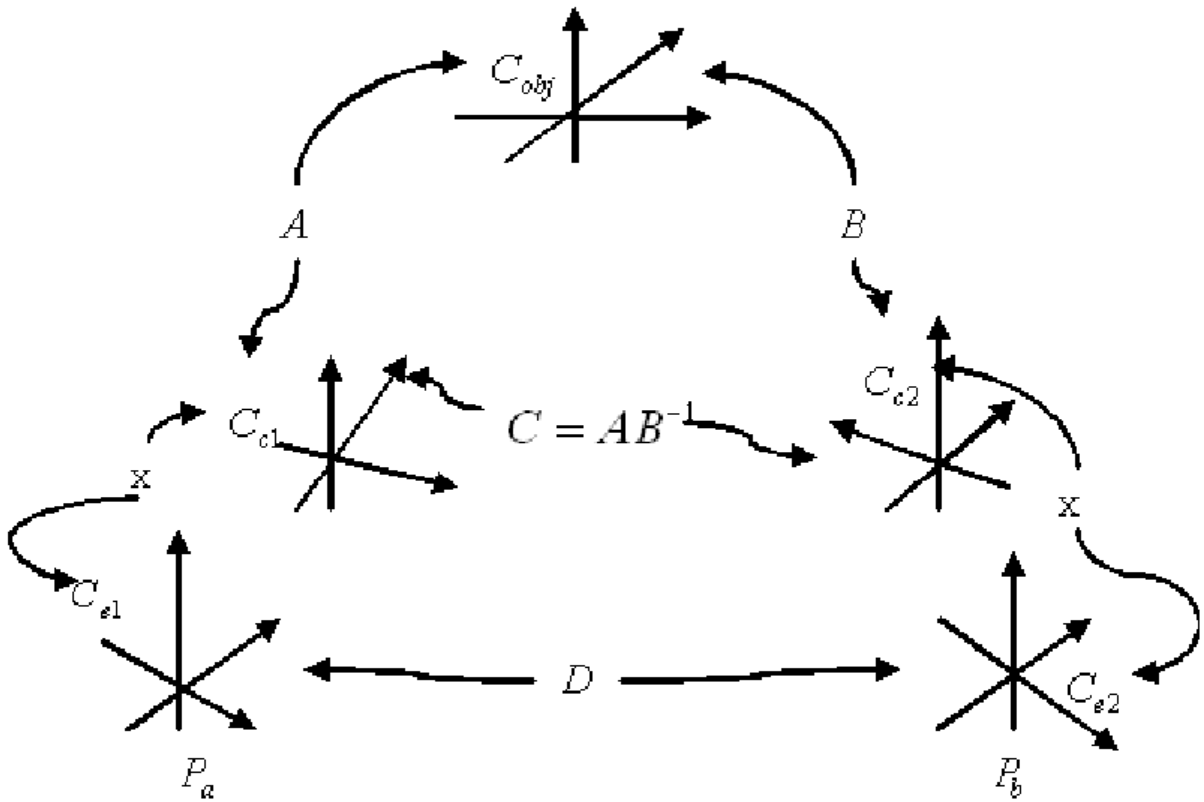
Introduction

Unifying coordinate system could be a problem



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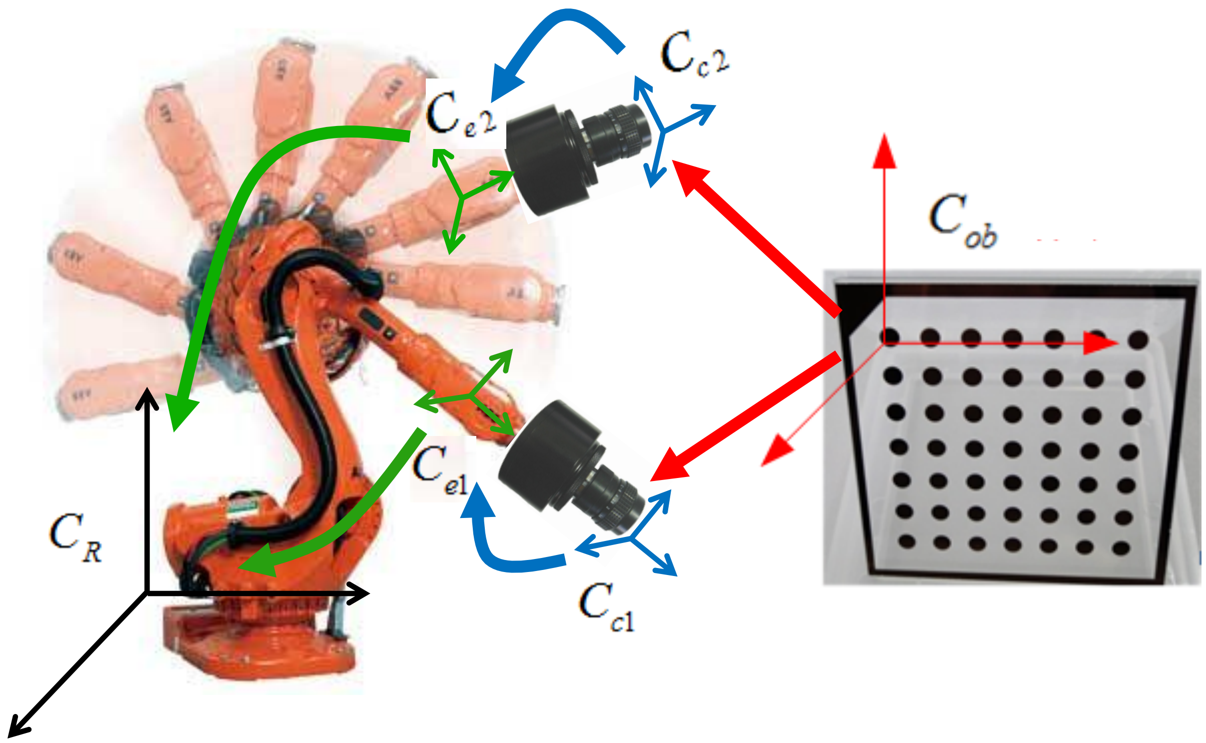
Introduction

Eye-in-hand: the camera is either grasped by the gripper, or just fastened to it.



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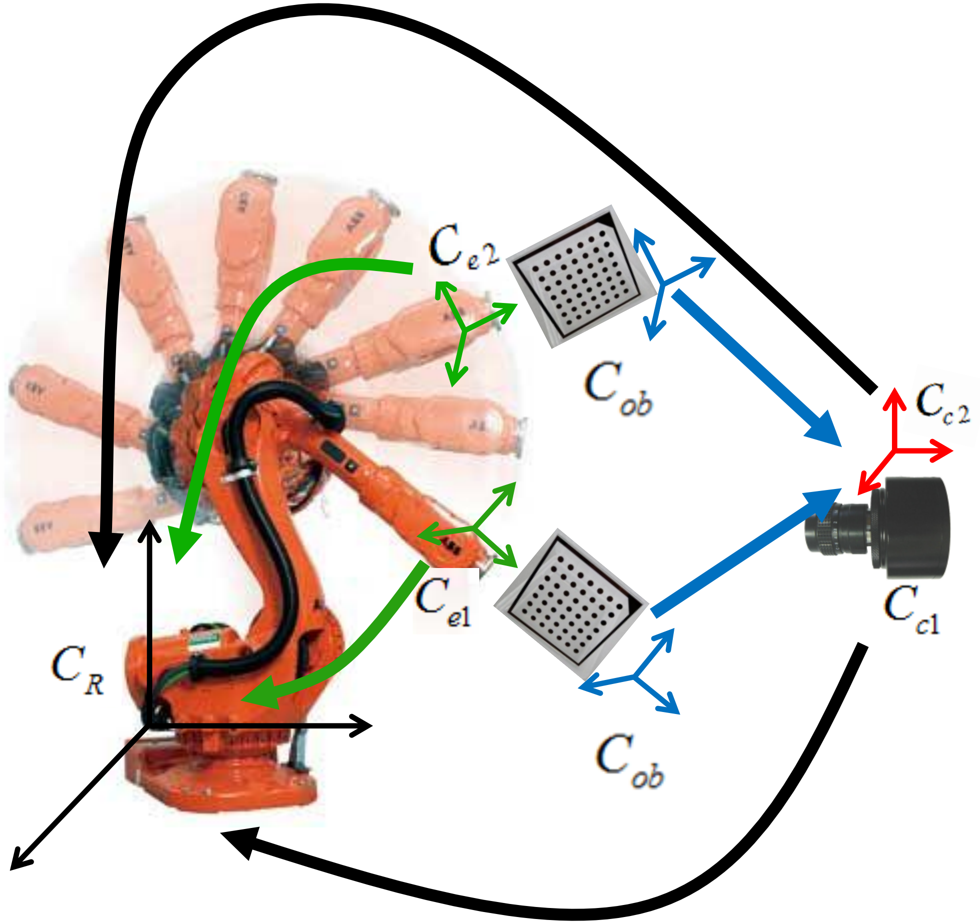
Introduction

Eye-to-hand: the camera is fixed in a position.



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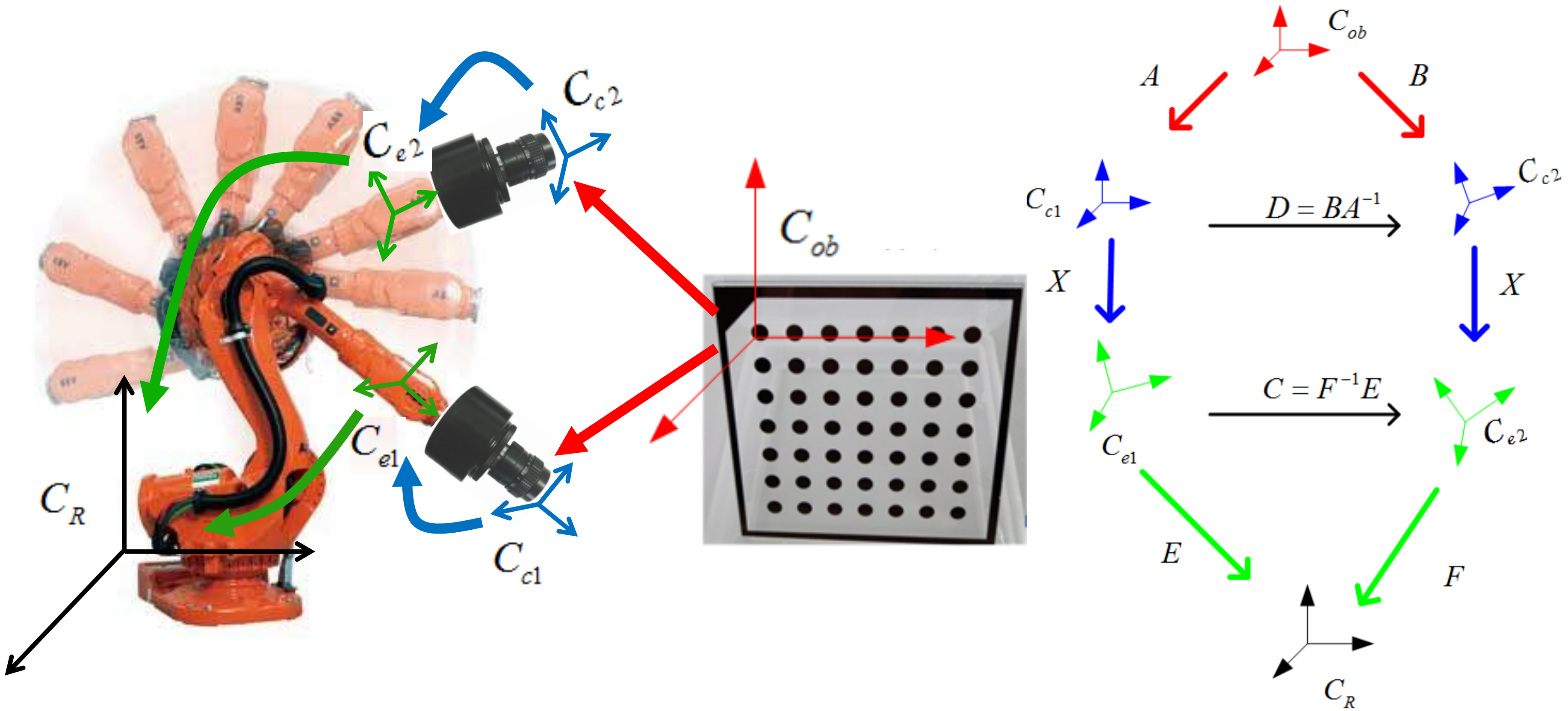
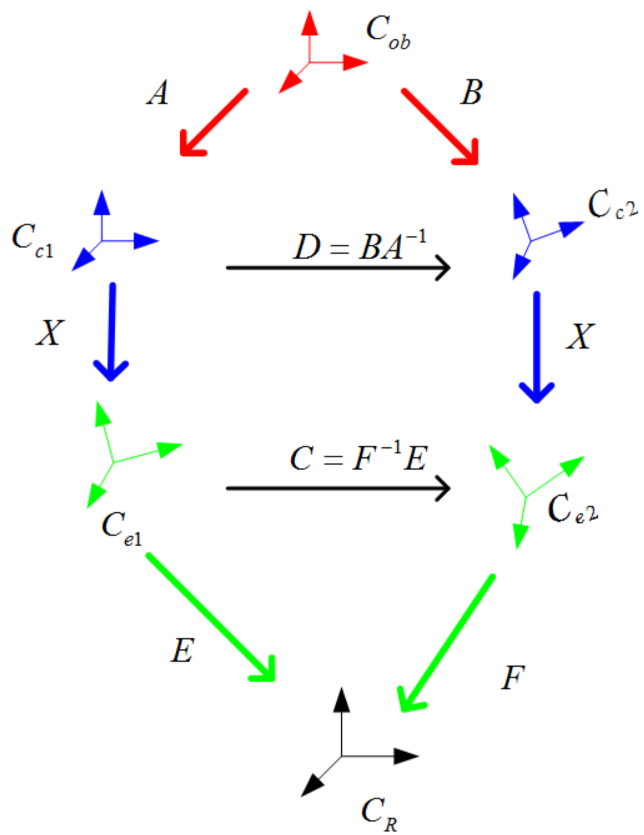
Algorithm

Eye-in-hand: sensor fusion



Algorithm



$$CX = XD$$

$$\begin{bmatrix} R_c & t_c \\ 0^T & 1 \end{bmatrix}\begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}\begin{bmatrix} R_d & t_d \\ 0^T & 1 \end{bmatrix}$$

$$R_c R = R R_d$$

$$R_c t + t_c = R t_d + t$$

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Let R_c be expressed as an angle of rotation ω_c around an arbitratry axis k_c, that is, R_c = Rot(k_c, ω_c). Similarly, R_d = Rot(k_d, ω_d).

$$\begin{cases} R_c = R R_d R^{-1} \\ (R_c - I)t = R t_d - t_c \end{cases}$$

According to above equations, we can get:

$$k_c = R k_d$$

When $R_c - I = 0$,

$$t_c = R t_d$$

$$[k_{c_1}, \ldots k_{c_N}, t_{c_1}, \ldots t_{c_M}] = R[k_{d_1}, \ldots k_{d_N}, t_{d_1}, \ldots t_{d_M}]$$

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$$[k_{c_1},\ldots,k_{c_N},t_{c_1},\ldots,t_{c_M}] = R[k_{d_1},\ldots,k_{d_N},t_{d_1},\ldots,t_{d_M}]$$

$$M_1 = R \cdot M_2$$

Theoretically, rank(M_1) = rank(M_2), but in fact, M_1 is more accuracy than M_2, and now we focus on rank(M_1).

When rank(M_1) ≠ 3:

$$\begin{cases} M_1^{**} = [n_{c_1}, n_{c_2}, n_c] \\ M_2^{**} = [n_{d_1}, n_{d_2}, n_d] \quad n_c = n_{c_1} \times n_{c_2}, \quad n_d = n_{d_1} \times n_{d_2} \\ M_1^{**} = R \cdot M_2^{**} \end{cases}$$

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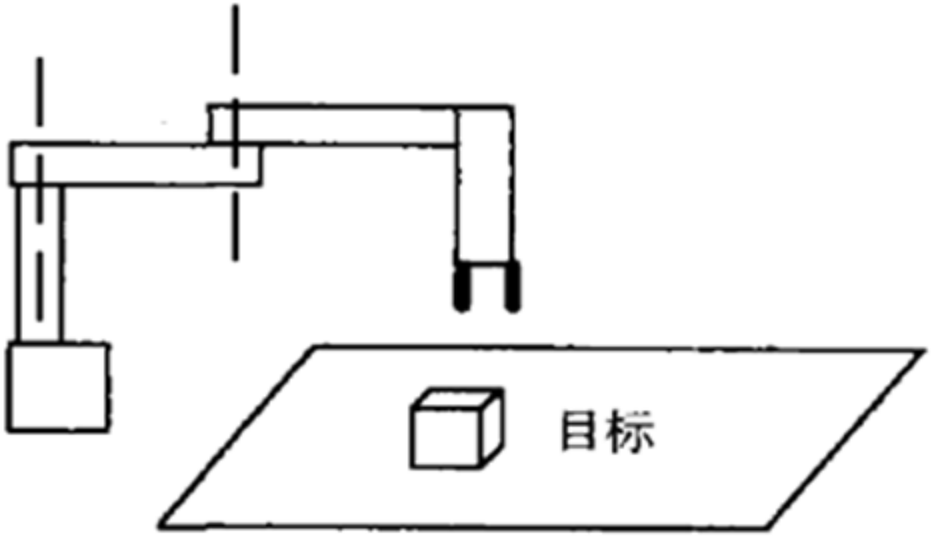
$$\begin{bmatrix} R_{c_{12}} - I \\ R_{c_{23}} - I \\ \cdots \\ R_{c_{N-1N}} - I \end{bmatrix} t = \begin{bmatrix} Rt_{d_{12}} - t_{c_{12}} \\ Rt_{d_{23}} - t_{c_{23}} \\ \cdots \\ Rt_{d_{N-1N}} - t_{c_{N-1N}} \end{bmatrix}$$

$$M_3 \cdot t = M_4$$



When rank(M_3) = 2 (4-DOF robot):

$$R_c = R \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} R^{-1}$$

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$$R_c - I = R\begin{bmatrix} \cos\theta - 1 & -\sin\theta & 0 \\ \sin\theta & \cos\theta - 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} R^{-1}$$

$$USV^T = R\begin{bmatrix} \cos\theta - 1 & -\sin\theta & 0 \\ \sin\theta & \cos\theta - 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} R^{-1} \qquad SV^T t = U^{-1}(Rt_d - t_c)$$

$$U^{-1}(Rt_d - t_c) = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \qquad S = \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} \lambda & 0 \\ 0 & \beta \end{bmatrix} V_{12}^T \cdot \begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} u_x \\ u_y \end{bmatrix}$$

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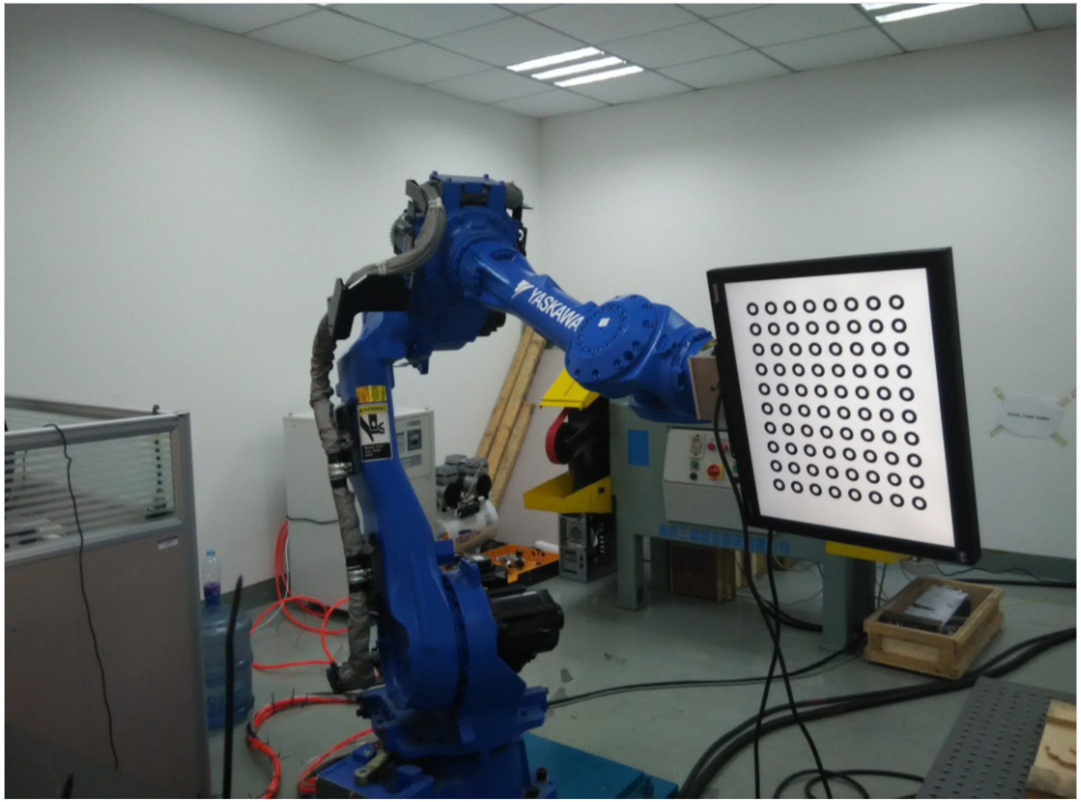
Experiment and evaluation

Calculate the transformation matrix of the calibration plate relative to the camera using PnP algorithm;

Read the position and orientation of the end effector from the robot controller.



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Experiment and evaluation

$$err_i = ||(C_iX)^{-1} \cdot D_iX - I||$$

Table 1 Relative error of the hand-eye transformation matrix X in first experiment

	$\|\|(C_iX)^{-1} \cdot D_iX - I\|\|$
err_1	0.759559
err_2	0.940860
err_3	0.974952
均值	0.891790
标准差	0.115777

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Experiment and evaluation

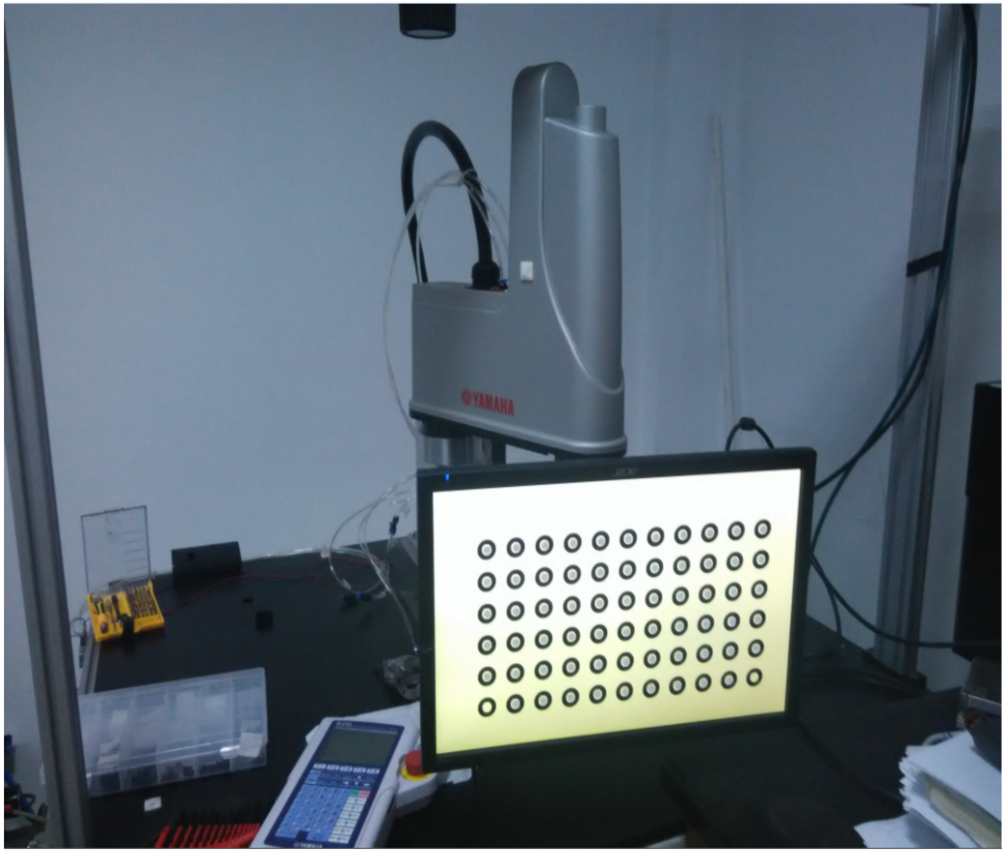

Table 2 Relative error of the hand-eye transformation matrix X in second experiment

	$\|\|(C_iX)^{-1} \bullet D_iX - I\|\|$
err_1	0.349424
err_2	1.788770
err_3	1.507480
err_4	0.213286
err_5	1.252840
err_6	1.113794
均值	1.037598
标准差	0.630913

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Next Friday, 23/03/2018 12:00PM GMT+8

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Website : **http://imorpheus.ai**
Email Address : **live@imorpheus.ai**