A Robot-Camera Hand/Eye Self-Calibration System Using a Planar Target

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Abstract — **In many vision-based industrial robot applications, a camera is typically attached to a robot hand and the conversion relationship between the robot hand and the camera must be estimated accurately. Compared to the conventional complicated hand/eye calibration methods, in this paper, we propose a novel vision-based robotic hand/eye self-calibration method for industrial applications. Our method contains a fixed 2D calibration plane and a camera mounted on a moving robot hand. In our process, we compute the robot-camera relationship by pure translations and rotations of the robot hand. By doing this, we can eliminate the manual and tedious hand/eye calibration procedures performed by workers.**

Keywords: hand/eye, self-calibration, hand/eye calibration, camera calibration

I. INTRODUCTION

Our camera calibration process of the robot system can be divided into three steps:

[1] Calibration of the robot base and the robot hand
[2] Camera calibration
[3] Robot's base or the robot hand and camera calibration

We will cover the robot hand/eye calibration method based on the relationship between robot hand and camera. Generally, existed industrial robot and camera calibration methods teach pendant to use a separate actuator by moving the robot hand to a sequence of locations repeatedly. By doing this, they can estimate the conversion between camera and robot hand. Teaching Pendant of conventional methods is time consuming and complicated. Moreover, teaching robot to pick chess board corners for calibration could be a dangerous thing for worker, especially when they stands close to the robot hand. Any incorrect operation by worker or malfunction of robot could cause severe injury. Still, the accuracy of teaching robot relies on the precision of human, which includes many aspects of factors, like eye precision, concentration, and even personal responsibility, etc. In this paper, we propose a new method that overcomes the above problems. A variety of ways [1,2] have been proposed in order to overcome this, but procedures and formula is complex, requiring a practical way more simple.

Therefore, in this paper, in order to simplify the procedure to solve the above problems, related to the first provides a step-by-step instructions, as shown in Figure 1.

First, get the picture after moving the robot to the specified, and the second is based on the acquired image camera calibration and lens distortion correction is. Finally, the image information acquired by the robot's hand to find the relationship between the camera and converts hand / eye self-calibration method is performed.

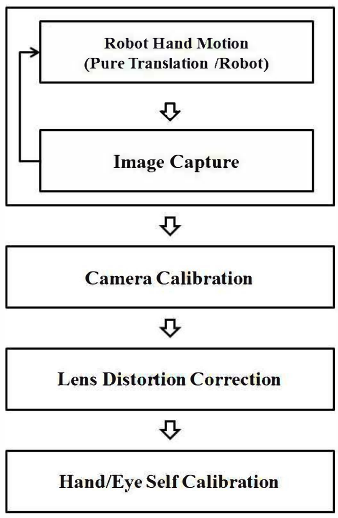

Fig 1. Hand / Eye self calibration process

The paper is organized as follows. In Section II, I will explain about the camera calibration of the process to find the parameters that describe and transform the relationship between the coordinates of the 2D image coordinates and 3D space, the relationship of this transformation. In Chapter III, describes a method of correcting the distortion of the lens of the camera, in Chapter IV, a description will be given of the hand / eye self calibration method of providing. In addition, in Chapter V, I will describe the results and experiments for hand / eye self calibration. Finally, in chapter VI, I describe the conclusion of this paper.

II. CAMERA CALIBRATION

Camera Calibration is a process as shown in Fig 2, find the parameters that describe and convert the relationship between

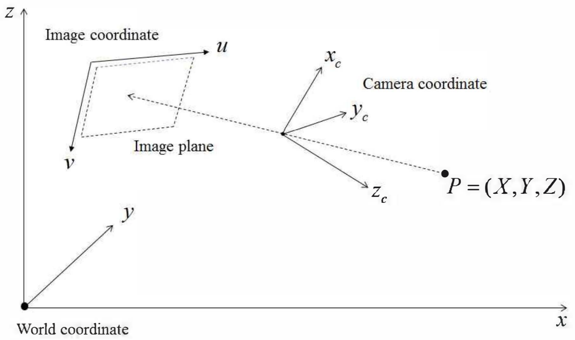

Fig 2. 3D space coordinates to 2D image coordinates and the transformation of the relationship between

the coordinates of the 2D image and the coordinates of the 3D space, the relationship of this transformation.

In general, to perform a camera calibration method is divided into two. The first way to know in advance the form of a pattern in the form of place in front of the camera, camera calibration by observing it is to perform. Conversely, the second way to know the type of the object and the environment by observing camera calibration methods exist to perform. The former method is a method of using the exact camera calibration objects very dimensions are known in advance, estimates the extrinsic parameter and intrinsic parameter of the camera. Is a technology that is generally used camera calibration for three-dimensional measurement, the method is possible to obtain the coefficients of the exact camera. Objects for camera calibration using planar pattern [3], and if that is not parallel to each other with the pattern [4] There is a way to use. Figure 3 shows the one obtained for camera calibration image shows an example of a chess board. The latter method, without the compensation object using the various constraints of the camera intrinsic parameter / extrinsic parameter estimation method to automatically [5] or, the accuracy of the method compared to the electronic meters are rarely used in industrial applications.

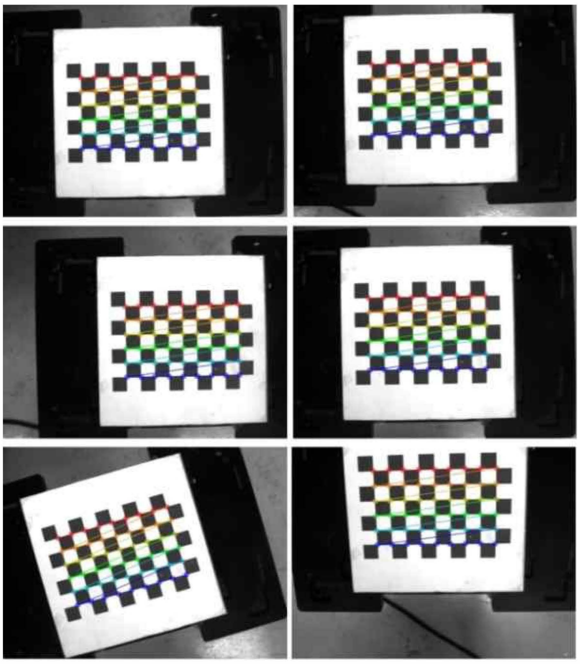
Fig 3. Camera calibration using multiple images

III. Distortion Correction of Camera Lens

Lens distortion of the shape of the object is not represented as it is, transforms the original shape. lens distortion can be divided into tangential distortion and radial distortion. generally, radial distortion to ignore.

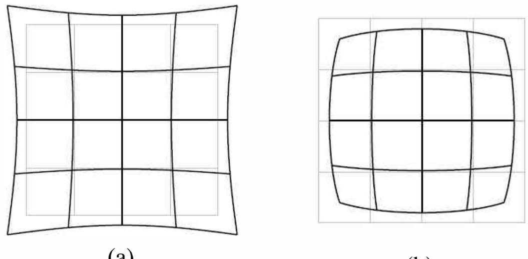

Fig4. Distortion: (a) pincushion distortion. (b) barrel distortion)

Figure 4 shows the image of the boundary line was originally going into parts, carefully bending curve represents the radial distortion created by the image. The radial distortion can be expressed as the following polynomial.

$$r_d = r + \delta_r = r(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 + \ldots) \qquad (2)$$

The subscript r, CCD sensor surface in the center position of the measured radius is the size. The subscript d indicates the distortion.

Using, $r_d{}^2 = x_d{}^2 + y_d{}^2$

$$\begin{aligned} x_d &= x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 + \ldots) \\ y_d &= y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 + \ldots) \end{aligned} \qquad (3)$$

As shown, equation (2) can be rewritten

Only two distortion factor k_1 and k_2, considering equation (3) can be written briefly as follows.

$$\begin{aligned} x_d &= x(1 + k_1 r^2 + k_2 r^4) = x + x(k_1 r^2 + k_2 r^4) \\ y_d &= y(1 + k_1 r^2 + k_2 r^4) = y + y(k_1 r^2 + k_2 r^4) \end{aligned} \qquad (4)$$

That we observe is the pixel coordinates of the image plane coordinates. First, if the CCD sensor of the image plane coordinates are converted to pixel coordinates. Coordinate and non-coordinate assignment distortion, the following equation is obtained.

$$\begin{aligned} u_d &= u + (u - u_0)(k_1 r^2 + k_2 r^4) \\ &= u + (u - u_0)(k_1(x^2 + y^2) + k_2(x^2 + y^2)^2) \\ v_d &= v + (v - v_0)(k_1 r^2 + k_2 r^4) \\ &= v + (v - v_0)(k_1(x^2 + y^2) + k_2(x^2 + y^2)^2) \end{aligned} \qquad (5)$$

This again represents an expression of matrix multiplication as follows.

$$\begin{bmatrix} (u-u_0)(x^2+y^2)(u-u_0)(x^2+y^2)^2 \\ (v-v_0)(x^2+y^2)(v-v_0)(x^2+y^2)^2 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} u_d - u \\ v_d - v \end{bmatrix} \quad (6)$$

In equation (6), K is the actual measured pixel coordinates, G is a distortion-free ideal pixel coordinates, H is the coordinate of the CCD sensor surface is measured. Thus, equation (6) using the radial distortion coefficient k_1 and k_2 values can be obtained. Equation can be expressed as follows.

$$\mathbf{Dk} = \mathbf{d} \quad (7)$$

Equation (7), $\mathbf{k}$ is a $[k_1\ k_2]^{\mathrm{T}}$. n-image, each point m if there is one correction, $\mathbf{D}$ is the size of the $2mn \times 2$. $\mathbf{k}$ is the Pseudo-Inverse, using the following equation is given by.

$$\mathbf{k} = (\mathbf{D}^{\mathrm{T}}\mathbf{D})^{-1}\mathbf{D}^{\mathrm{T}}\mathbf{d} \quad (8)$$

The distortion of the lens may be calculated as described above. But ignoring lens distortion methods Iterative Least-Squares Method distortion of the lens can be solved.

IV. Hand / Eye Self-Calibration

As shown in Figure 5, we denote ${}^h\mathbf{T}_c$ as the transformation matrix between the robot hand coordinate frame and the camera coordinate frame. We use a fixed chess board plane as hand / eye self-calibration object. The superscript *h* refers to the coordinate system of the robot hand, and the subscript *c* refers to the camera coordinate system. We denote ${}^{h_0}\mathbf{T}_{h_j}$ as the initial position (j-th) of the robot hand in the robot hand coordinate frame, as shown in Figure 6. The coordinate frame of h_0 and h_j represent the different position of a robot hands. Similarly, we denote ${}^{c_0}\mathbf{T}_{c_j}$ as the initial position (j-th) of a camera, attached to the robot hand, in the camera coordinate frame. Therefor c_0 and c_j represent the different position of a camera.

When we move the camera from its initial position to the j-th position, matrix ${}^{c_0}\mathbf{T}_{c_j}$ shows the transformation between coordinate frames c_0 and c_j. Similarly, when we move the robot hand from its initial position to the j-th position, matrix ${}^{h_0}\mathbf{T}_{h_j}$ shows the transformation between coordinate frames h_0 and h_j. In addition, matrix ${}^h\mathbf{T}_c$ shows the transformation between robot hand coordinate frames and camera coordinate frame.

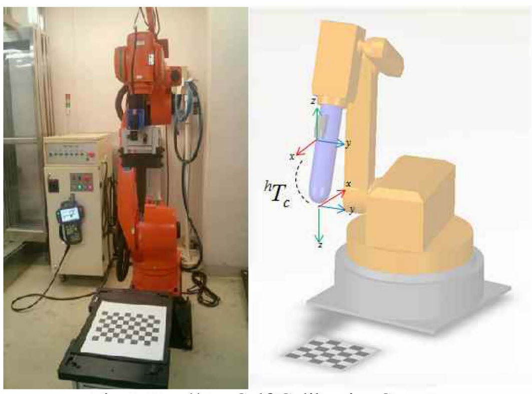

Fig 5. Hand/Eye Self-Calibration System

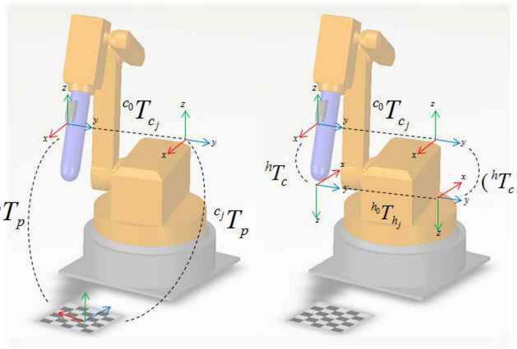

Fig 6. Hand/Eye Self-Calibration Transformation Relations

$$\begin{aligned} {}^{c_0}\mathbf{T}_{c_j} &= \left({}^h\mathbf{T}_c\right)^{-1} {}^{h_0}\mathbf{T}_{h_j}\, {}^h\mathbf{T}_c \\ &= \begin{bmatrix} {}^{c_0}\mathbf{R}_{c_j} & {}^{c_0}\mathbf{t}_{c_j} \\ \mathbf{0} & 1 \end{bmatrix} \end{aligned} \quad (9)$$

where ${}^{c_0}\mathbf{R}_{c_j}$ and ${}^{c_0}\mathbf{t}_{c_j}$ are as follows:

$${}^{c_0}\mathbf{R}_{c_j} = {}^h\mathbf{R}_c^{\mathrm{T}}\, {}^{h_0}\mathbf{R}_{h_j}\, {}^h\mathbf{R}_c \quad (10)$$

$$\begin{aligned} {}^{c_0}\mathbf{t}_{c_j} &= {}^h\mathbf{R}_c^{\mathrm{T}}\, {}^{h_0}\mathbf{R}_{h_j}\, {}^h\mathbf{t}_c + {}^h\mathbf{R}_c^{\mathrm{T}}\, {}^{h_0}\mathbf{t}_{h_j} - {}^h\mathbf{R}_c^{\mathrm{T}}\, {}^h\mathbf{t}_c \\ &= {}^h\mathbf{R}_c^{\mathrm{T}} \left({}^{h_0}\mathbf{R}_{h_j}\, {}^h\mathbf{t}_c + {}^{h_0}\mathbf{t}_{h_j} - {}^h\mathbf{t}_c \right) \end{aligned} \quad (11)$$

The movement of the gripper is linear, so the rotation matrix ${}^{h_0}\mathbf{R}_{h_j} = \mathbf{I}$. Then we have

$${}^{c_0}\mathbf{t}_{c_j} = {}^h\mathbf{R}_c^{\mathrm{T}}\, {}^{h_0}\mathbf{t}_{h_j} \quad (12)$$

In equation (9), we donate ${}^{h_0}\mathbf{T}_{h_j}$ as the transformation matrix of the movement of robot hand from h_0 to h_j. Similarly, we denote ${}^{c_0}\mathbf{T}_{c_j}$ as the conversion between the camera planes. Also, we can obtain ${}^{c_0}\mathbf{T}_p$ and ${}^{c_j}\mathbf{T}_p$ by using the conversion relationship. The relationship between them is shown as follow:

$${}^{c_0}\mathbf{T}_{c_j} = {}^{c_0}\mathbf{T}_p \left({}^{c_j}\mathbf{T}_p\right)^{-1} \quad (13)$$

We can obtain ${}^{h_0}\mathbf{T}_h$ and ${}^{c_0}\mathbf{T}_{c_j}$ from the images we captured in each position. That is, with the corner point coordinates, we can solve the ${}^{h_0}\mathbf{T}_h$ and ${}^{c_0}\mathbf{T}_{c_j}$ by mathematic method, like the least square solution. Rotation matrix ${}^h\mathbf{R}_c$ in equation (12) can be obtained by computing the transformation between robot hand and camera. As shown in the following equation, the rotation is in fact a multiplication of two, each translates three times. One is the translation from initial robot hand position to h_1, h_2, h_3 robot hand position respectively, the other is from initial camera position to c_1, c_2, c_3 camera positions.

$${}^h\mathbf{R}_c = \left[{}^{h_0}\mathbf{t}_{h_1}\ {}^{h_0}\mathbf{t}_{h_2}\ {}^{h_0}\mathbf{t}_{h_3} \right] \left[{}^{c_0}\mathbf{t}_{c_1}\ {}^{c_0}\mathbf{t}_{c_2}\ {}^{c_0}\mathbf{t}_{c_3} \right]^{-1} \quad (14)$$

Equation (14) can be affected by the noise, and ${}^h\mathbf{R}_c$ we obtained may not be a orthogonal matrix. Thus, we have to restore the orthogonality of ${}^h\mathbf{R}_c$. We use the SVD (Singular Value Decomposition) to maintain orthogonalization of ${}^h\mathbf{R}_c$. In equation (15), the SVD decomposition of ${}^h\mathbf{R}_c$ is $\mathbf{UDV}^{\mathrm{T}}$, where $\mathbf{D}$ should be orthogonal. However, in case of noise, matrix **D** may not be orthogonal. We need to manually change **D** to an orthogonal matrix, and make a new ${}^{h}\mathbf{R}_{c}$ by the multiplication.

$$ {}^{h}\mathbf{R}_{c} = \mathbf{UDV}^{\mathrm{T}} \tag{15} $$

In detail, since matrix **D** is not orthogonal due to noise, we can replace it with a identical matrix **I**. Then do the multiplication in equation (16) from right to left, and we will receive a orthogonal matrix ${}^{h}\mathbf{R}_{c}$.

$$ {}^{h}\mathbf{R}_{c} = \mathbf{UIV}^{\mathrm{T}} \tag{16} $$

As soon as we have ${}^{h}\mathbf{R}_{c}$, equation (11) can be determined by translation matrix ${}^{h}\mathbf{t}^{c}$. As the motion of robot is pure rotational, which means there is actually no translation between each position, thus every element in ${}^{h_0}\mathbf{t}_{h_j}$ equals zero. The only translation vector remains in equation (11) is ${}^{h}\mathbf{t}^{c}$. Then equation (11) can be written as follows:

$$ {}^{c_0}\mathbf{t}_{c_j} = \left({}^{h}\mathbf{R}_{c}^{\mathrm{T}}\, {}^{h_0}\mathbf{R}_{h_j} - {}^{h}\mathbf{R}_{c}^{\mathrm{T}} \right) {}^{h}\mathbf{t}_{c} \tag{17} $$

When we rewrite the ${}^{h}\mathbf{t}^{c}$ by elements, equation (17) can be expressed as the following equation (18), where ${}^{h}\mathbf{t}^{c}$ has two rotations. The first is from the initial position to the j-th position, while the other is from robot hand coordinate frame to camera coordinate, and the rest part can be solved by Pseudo-Inverse.

$$ \begin{bmatrix} {}^{c_0}\mathbf{t}_{c_1} \\ {}^{c_0}\mathbf{t}_{c_2} \end{bmatrix} = \begin{bmatrix} {}^{h}\mathbf{R}_{c}^{\mathrm{T}}\, {}^{h_0}\mathbf{R}_{h_1} - {}^{h}\mathbf{R}_{c}^{\mathrm{T}} \\ {}^{h}\mathbf{R}_{c}^{\mathrm{T}}\, {}^{h_0}\mathbf{R}_{h_2} - {}^{h}\mathbf{R}_{c}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} {}^{h}\mathbf{t}_{c} \\ {}^{h}\mathbf{t}_{c} \end{bmatrix} \tag{18} $$

V. Experimental Results

The estimated rotation and translation results of hand/eye self-calibration are shown in Table 1. We take the first image when the robot and the camera are at the initial position, and take the second at the next arranged position. As only the linear motion of robot hand matters, we ignore any random rotation motion.

Table 1. The Estimated Results of Hand/Eye Self-Calibration

Axis	Rx (°)	Ry (°)	Rz (°)	Tx (mm)	Ty (mm)	Tz (mm)
Value	-179.726	0.221	170.400	-74.023	2.818	-363.561

To verify the above results, we perform the following procedures.

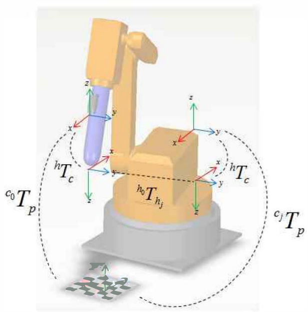

Fig 7. Verification Procedures

By moving the robot hand to a sequence of positions for image capturing, we can estimate the corresponding camera positions. On the other hand, we also can estimate the camera positions through hand/eye self-calibration. After comparing their results, we found the average distance error is 1.2mm, and the average rotation error is 0.042 °. These errors are suitable for industrial sites. Also we find that the more images we use, the smaller the errors will be. Table 2 shows the errors when we take six images in all.

Table 2. Rotation and Distance Error Result

Axis	Rx (°)	Ry (°)	Rz (°)	Tx (mm)	Ty (mm)	Tz (mm)
Value	-0.001	0.041	-0.009	-1.171	-1.128	0.980

VI. Conclusions

In our paper, we skip the knowledge of camera, as well as the methods of camera calibration and hand/eye calibration. Instead, we focus on two particular things. First, the movement of the robot itself is enough for camera calibration. Second, we can shorten the time of hand/eye calibration. Furthermore, the risk of worker injury during manual calibration is eliminated.

VII. Acknowledge

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