# Fast Calibration for Robot Welding System with Laser Vision

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***Abstract*—Camera calibration and robot hand-eye calibration are important parts in applications of robots with visions. A way to simultaneously carry out camera calibration and robot hand-eye calibration is presented in robot welding system with laser vision. It is based on a certain relation between hand-eye matrix and matrix of robot hand frame to robot base frame. Calibration experiments are performed in this way using specifically designed calibration objects. And all parameters to be calibrated are solved out in nonlinear least square optimization method. 3D world coordinates of 20 sample points selected from a v-groove seam are reconstructed with the calibration results. By contrasting their real coordinates, average error is 0.12mm, which is sufficient to the requirement of robot seam tracking.**

***Keywords*—robot welding, camera calibration, hand-eye calibration, laser vision**

## I. Introduction

So far, robots are widely used in research as well as in industrial production. When robots are fixed with visual sensors, they can catch environment information through their visions to perform specific tasks such as finding, positioning and grasping objects. By the use of vision system, in order to realize the transformation from 2D image information to 3D information, the first step is to determine the relation between image coordinates and world coordinates. This problem is the process of coordinates calibration and it includes camera calibration and robot hand-eye calibration.

Camera calibration and hand-eye calibration are both traditional problems in robot applications, and versatile calibration techniques are presented for the moment[1-5]. Camera calibration is mostly based on pin-hole model, and it not only includes determining geometric and optical camera features (intrinsic parameters), but also the 3D position and orientation of the camera relative to the world frame (extrinsic parameters). Many literatures have introduced methods to calibrate camera parameters[6-10]. These methods can be basically sorted into linear solution and nonlinear solution. Linear solution is brief and quick, but distortion parameter is ignored and precision is not enough. So, nonlinear solution is often used when precision is emphasized[ 11].

Robot hand-eye calibration is to determine the relative positions and orientations of camera frame to hand frames. The general solution for hand-eye calibration is to solve a homogeneous transformation equation as follows:

$$AX = XB \tag{1}$$

Where $X$ represents the relative position and orientation matrix of camera frame to robot hand frame, and $A$ is transformation matrix of camera movement and $B$ is that of robot hand movement. $A$ is determined by two locations in the camera frame and $B$ is determined by two robot hand positions[ 3].

In the applications of vision robots the camera parameters and the position and orientation of robot hand-eye both need to be calibrated. Reference [12] make extensions to the standard plane-based calibration method and introduce how to use pure translational motions for camera intrinsic calibration as well as hand-eye calibration. But there are two respective calibration experiments, so much calculation and time are needed, and calibration error is cumulated from one experiment to the next experiment. Practically, in some specific applications of vision robot, camera calibration and robot hand-eye calibration can be performed simultaneously and calculation is also greatly reduced.

In this paper simultaneous calibration of camera and robot hand-eye is introduced for the application of robot welding with laser sensor.

## II. Calibration

### A. *Configuration for Laser Vision Robot Welding System*

In the area of robot welding, vision system is often used to determine the welding position on workpiece. Fig.1 shows the configuration. Welding torch and laser vision are rigidly mounted on robot hand. Laser light from the vision system is projected on welding workpiece and the information of V-groove is reflected on a laser line. Then V-groove center (welding position) can be recognized from the image captured by the vision system. After the coordinates transformation of welding position from image frame to world frame, the displacement of robot hand is controlled according to the world coordinates of welding position. Then the torch is moved from current position to the next and welding task is automatically performed by robot.

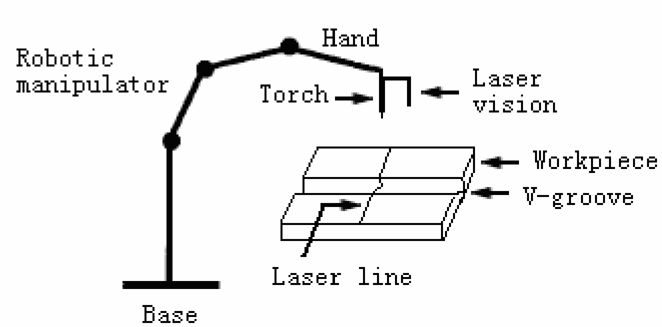


Fig.1 Configuration for robot welding with laser vision

*B. Camera Model*

Pinhole (perspective) camera model is used in this paper. Fig.2. illustrates the basic geometry of the camera model. $o-xyz$ is the camera coordinate system. The origin point $o$ is defined on the optical center and $z$ axis is the same as the optical axis. Point $o'$ is the intersection of optical axis $z$ and image plane and the distance between $o$ and the image plane is the focal length $f$ of the camera. $P$ is a point in space, and $p$ is its image point.

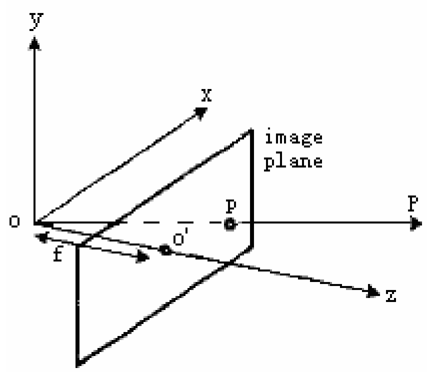


Fig.2 Pinhole camera model

Suppose, a point in image plane is denoted by $m=[x,y]^T$, and a point in world frame is denoted by $M=[x_w,y_w,z_w]^T$. Then their homogeneous coordinates are $\tilde{m}=[x,y,1]^T$ and $\tilde{M}=[x_w,y_w,z_w,1]^T$. Then the relation from $\tilde{M}$ to $\tilde{m}$ is given by :

$$s\tilde{m}=KT\tilde{M} \quad \text{with} \quad K=\begin{bmatrix}\alpha & c & u_0\\ 0 & \beta & v_0\\ 0 & 0 & 1\end{bmatrix},$$

$$T=\begin{bmatrix}r_1 & r_2 & r_3 & t_x\\ r_4 & r_5 & r_6 & t_y\\ r_7 & r_8 & r_9 & t_z\end{bmatrix} \tag{2}$$

Where $s$ is an arbitrary scale factor, $K$ is the camera intrinsic parameter matrix in which $(u_0,v_0)$ is the coordinates of camera principal point, $\alpha$ and $\beta$ are the scale factors in $x$ and $y$ axes, and $c$ denotes the skewness of two image axes, and $T$ is the camera extrinsic parameter matrix in which $r_1 \sim r_9$ are the rotation part of the camera frame to the world frame and $t_x,t_y,t_z$ the translation part.

*C. Hand-eye Model*

Suppose $H$ is the transformation matrix of robot hand frame to the camera frame, $T_6$ the robot hand frame to robot base frame, and $R$ the camera frame to robot base frame. It is obvious that the relation of these three matrix can be expressed as follows:

$$R=T_6H \tag{3}$$

Here $H$ is called hand-eye transformation matrix which consists of rotation part and translation part with the same form as matrix $T$. Since laser vision is rigidly mounted on robot hand in Fig.1, hand-eye matrix $H$ is a constant.

*D. Simultaneous Calibration for Camera and Hand-eye*

In the configuration of robot welding system shown in Fig.1, the base frame of robot is fixed on the ground. So for convenience, the world frame is defined as the same to the robot base frame. From equation (2), the following equation (4) is obtained:

$$s\begin{bmatrix}x\\ y\\ 1\end{bmatrix}=\begin{bmatrix}\alpha r_1+cr_4+u_0r_7 & \alpha r_2+cr_5+u_0r_8 & \alpha r_3+cr_6+u_0r_9 & \alpha t_x+ct_y+u_0t_z\\ \beta r_4+v_0r_7 & \beta r_5+v_0r_8 & \beta r_6+v_0r_9 & \beta t_y+v_0t_z\\ r_7 & r_8 & r_9 & t_z\end{bmatrix}\begin{bmatrix}x_w\\ y_w\\ z_w\\ 1\end{bmatrix}$$

$$\begin{cases}(\alpha r_1+cr_4+u_0r_7)x_w+(\alpha r_2+cr_5+u_0r_8)y_w+(\alpha r_3+cr_6+u_0r_9)z_w+(\alpha t_x+ct_y+u_0t_z)\\ -(r_7x_w+r_8y_w+r_9z_w+t_z)x=0\\ (\beta r_4+v_0r_7)x_w+(\beta r_5+v_0r_8)y_w+(\beta r_6+v_0r_9)z_w+(\beta t_y+v_0t_z)\\ -(r_7x_w+r_8y_w+r_9z_w+t_z)y=0\end{cases} \tag{4}$$

Here $\alpha,\beta,c,u_0,v_0$, $r_1 \sim r_9$, $t_x,t_y,t_z$ are unknown parameters, and $x,y,x_w,y_w,z_w$ are known from specific calibration control points.

In addition, according to the orthonormality of the rotation part $r_1 \sim r_9$ in matrix $T$, the following 6 equations are given:

$r_1^2+r_4^2+r_7^2=1$, $r_2^2+r_5^2+r_8^2=1$, $r_3^2+r_6^2+r_9^2=1$, $r_1r_2+r_4r_5+r_7r_8=0$, $r_1r_3+r_4r_6+r_7r_9=0$, $r_2r_3+r_5r_6+r_8r_9=0$

Thus, there are 17 unknown parameters in all to be solved. As 2 nonlinear equations can be obtained from each calibration control point by equation (4), 6 or more calibration control points, which set up 18 or more nonlinear equations, are needed to solve out these 17 unknown parameters.

As 18 or more nonlinear equations are used to solve 17 unknown parameters, then the problem becomes a common nonlinear least-squares estimation problem that can be solved with standard nonlinear optimization methods. Gauss-Newton, Levenberg-Marquardt and quasi-Newton are popular algorithms for nonlinear least-squares optimization problem[13]. Although the convergence of quasi-Newton algorithm is more effective than the other two, calculation is big and it is difficult to modify Hesse matrix. Gauss-Newton depends greatly on the precision of initial values to converge. Accordingly Levenberg-Marquardt is adopted in this paper.

As the world frame is the same with robot base frame, it is obvious that equation (5) is concluded:

$$T = R = T_6 H \tag{5}$$

where matrix $T$ is solved out by nonlinear least-squares optimization method, and matrix $T_6$ can be transformed from the current orientation quaternion or robot hand, which can be read out from the robot controller. Therefore, the robot hand-eye matrix $H$ is calibrated simultaneously when camera parameters are calibrated as expressed by equation (6):

$$H = T_6^{-1} T \tag{6}$$

## III. EXPERIMENT TEST

The robot used to experiment in this paper is a small ABB arc welding robot and the vision system is Meta Laser Probe. The configuration is shown as Fig.1. Fig.3 shows calibration objects which are two little cubes with a hole in each. When laser light is projected to the two cubes along the dashed line in Fig.3, a laser image shown as Fig.4 is obtained, which is $256 \times 192$ pixels. Point 1 to 6 in Fig.3 are calibration control points, and their corresponding image points are shown in Fig.4.

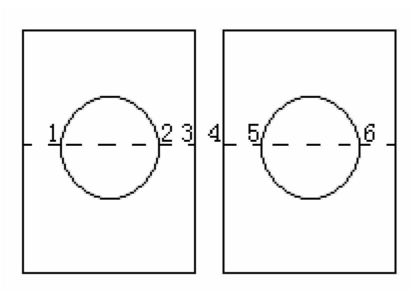

Fig.3 Calibration objects

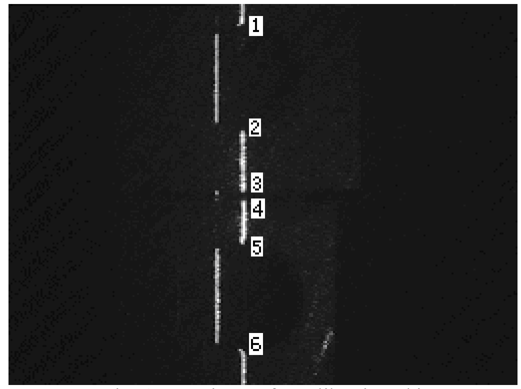

Fig. 4 Laser image for calibration objects

Image coordinates of control points 1 to 6 in Fig.4 are extracted according to the following flowchart in Fig.5. First binarizing Fig.4 at a threshold of grey value 150, and thinning the laser lines to keep one pixel wide. Then extracting end points coordinates of laser lines by structure elements $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 255^* & 0 \\ 0 & 255 & 0 \end{bmatrix}$ and $\begin{bmatrix} 0 & 255 & 0 \\ 0 & 255^* & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$. Finally seperating the control points 1 to 6 by their x coordinates which are different from those of non-control points.

World coordinates of control points are read in turn from robot controller when torch goes to point 1 to 6 on calibration objects, respectively. The experimental data are shown in Table 1.

TABLE 1 Coordinates of control points

| Control points | Image coordinates (pixel) | | World coordinates (mm) | | |
|---|---|---|---|---|---|
| | $x$ | $y$ | $x_w$ | $y_w$ | $z_w$ |
| 1 | 10 | 116 | 612.1 | 236.2 | 123.7 |
| 2 | 64 | 116 | 597.1 | 236.7 | 123.7 |
| 3 | 94 | 116 | 589.6 | 237.1 | 123.7 |
| 4 | 99 | 116 | 587.4 | 237.6 | 123.7 |
| 5 | 119 | 116 | 581.1 | 237.9 | 123.7 |
| 6 | 174 | 116 | 566.1 | 238.2 | 123.7 |

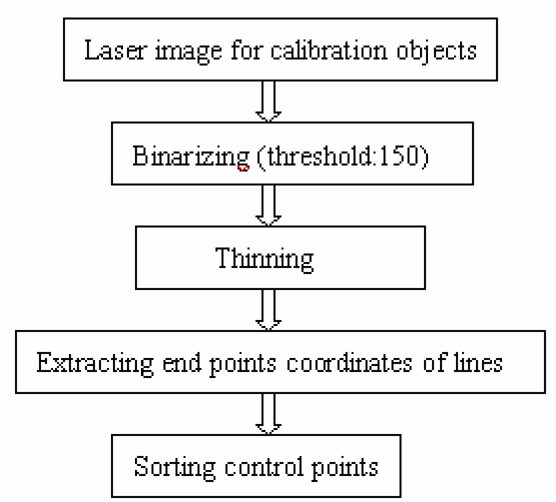


Fig.5 Flowchart of extracting image coordinates of control points

In nonlinear least-squares optimization, according to experience and parameter ranges, take optimization initial value as follows:

$$x_0 = [\alpha \quad \beta \quad c \quad u_0 \quad v_0 \quad r_1 \quad r_2 \quad r_3 \quad r_4 \quad r_5 \quad r_6 \quad r_7 \quad r_8 \quad r_9 \quad t_x \quad t_y \quad t_z] \\ = [1200 \quad 1200 \quad 10 \quad 128 \quad 96 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 100 \quad 100 \quad 150] \tag{7}$$

Then by Matlab software, calibration results are obtained following:

$$K = \begin{bmatrix} \alpha & c & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1207.5 & 12.375 & 127.99 \\ 0 & 1106.4 & 93.105 \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$R = \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \end{bmatrix} = \begin{bmatrix} -0.086562 & -0.1707 & -0.072956 & 99.935 \\ 0.0027366 & -0.0090344 & -0.79425 & 99.214 \\ 0.13266 & -0.42775 & -0.84273 & 148.52 \end{bmatrix} \tag{9}$$

$$H = \begin{bmatrix} -0.0716 & -0.3712 & -0.0665 & 143.6956 \\ -0.0359 & 0.0808 & -0.5276 & 62.9042 \\ 0.1489 & -0.1878 & -0.9223 & 85.1096 \end{bmatrix} \tag{10}$$

Here $K$ and $H$ are fixed and $R$ varies with different positions of camera.

## IV. CALIBRATION ACCURACY

20 frames of pictures were sampled from a v-groove seam. According to above calibration results, image coordinates of the v-groove center in the 20 frames of pictures were converted into 3D world coordinates denoted by $p_i'(x_{wi}', y_{wi}', z_{wi}')$ $(i = 1 \sim 20)$. At the same time, in each frame of pictures, the real world coordinates of v-groove center were measured by robot controller, which was denoted by $p_i(x_{wi}, y_{wi}, z_{wi})$ $(i = 1 \sim 20)$. Comparing $p_i'$ with $p_i$, and calculating average error with equation (11), $0.12mm$ was obtained from the 20 sampled pictures, which is sufficient for robot seam tracking.

$$e = \frac{1}{N}\left\{\sum_{i=1}^{20}\left[(x_{wi}' - x_{wi})^2 + (y_{wi}' - y_{wi})^2 + (z_{wi}' - z_{wi})^2\right]^{\frac{1}{2}}\right\} \tag{11}$$

## V. CONCLUSION

Camera calibration and hand-eye calibration are key problems in the applications of vision robots. In this paper, a method to simultaneously calibrate camera parameters and robot hand-eye matrix is presented. It is based on a special relation between hand-eye matrix and matrix of robot hand frame to base frame. Calculation results of camera parameters and hand-eye matrix are obtained at one time. Experiments are made to test the method, and the results show that the method is correct and feasible, and the calibration precision meets the need of robot seam tracking. Besides, calibration control points and optimization algorithm are two important factors to affect experiment results, so improving algorithm and selecting more control points with more precise coordinates can lead to better experiment results.

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