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A New Method of Self-calibration of Hand-Eye Systems Based on Active Vision

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Abstract: This paper presents a new approach to self-calibration of the robotics hand-eye relations based on active vision systems. At the same time, the calibration of the line structured light sensor can be accomplished. According to the special designed motion of the camera, the whole calibration process can be divided into two steps, including two groups of four linearly independent translations and one pure rotation. This method requires no reference object and only needs two characteristic points in the scene. Besides, it can accomplish the self-calibration of the camera intrinsic parameters and the rotational matrix as a whole, which reduce the computation errors and cost. After verification by our experiments, the method is proved to be convenient and rapid with the precision required by the industrial fields with much fewer steps of calibration.

1. INTRODUCTION

The line structured light sensor has been utilized in many industrial fields (Jason *et al*., 2011). It mainly consists of an imaging sensor and a structured-light projector. The imaging sensor can catch the distorted pattern of the projected structured-light. Then, according to the relative positions between the camera and the projector, we can extract the three-dimensional information of the surface (Chen *et al*., 2012). The calibration of the line structured-light sensor includes the calibration of camera intrinsic parameters and the light plane. Several methods of calibrating the camera intrinsic parameters and the light plane have been already presented by (Wang *et al*., 2007) and (Chen *et al*., 2012).

Calibration of the robotics hand-eye system plays a significant role in the computer vision. One purpose of calibration is to identify the unknown position and orientation of the camera with respect to the end of the manipulator. However, the motion of the robot's end effector is considered under the robot base coordinate system, while the image data are in the camera frame. So, the basic constraints of the calibration of the hand-eye vision system has originally been discussed by (Shiu and Ahmad, 1989), (Tsai and Lenz, 1989) and (Chen, 1991). They have presented ingenious methods to solve the transformation between different coordinate systems, on which our new method is based. Later the solution is optimized by the research work of (Zhuang *et al*., 1994), (Dornaika and Horaud, 1998) and (Strobl and Hirzinger , 2006). However, because of involving many nonlinear equations, the computation of above methods costs too much. Then, (Henrik *et al*., 2006) utilized calibration reference to determine the rotation matrix of hand-eye relation. However, there are some occasions when the reference objects cannot be placed in the scene easily (Ma *et al*., 1996). So, the technique of self-calibration is significant. Research work concerned with the active vision systems in which the motion of the camera can be controlled, has been considered (Hu and Wu, 2002).

Fig.1 shows that the camera motion can be controlled with the motion of the manipulator. That is, the manipulator can be controlled to do translational and rotational motions along the designed path. In the new method proposed in this paper, the calibration of the line structured-light sensor and hand-eye relations can be achieved in two steps. In this way, our method improves the efficiency of the whole process of calibration with much fewer steps. Additionally, the self-calibration of the camera intrinsic parameters and the rotational matrix can be accomplished as a whole to reduce the computation effort and errors. Furthermore, characteristic points, instead of reference object, are easy to be found in any common scene. With the continuity of the designed process, the method can be utilized in certain industrial fields, where the accuracy requirement could be met.

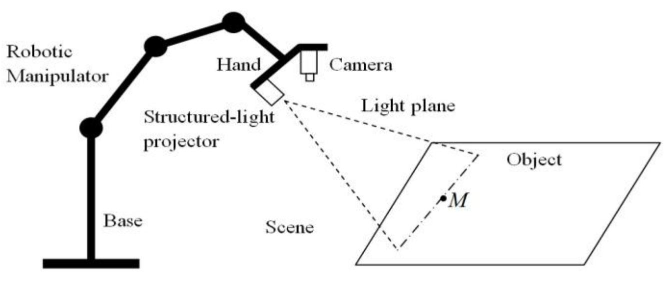

Fig. 1. Schematic diagram of hand-eye vision system

2. PRELIMINARIES

2.1 Coordinate Relations of Hand-eye Vision Systems

In robotics hand-eye systems, the coordinate relations of hand-eye vision systems can be expressed as follows (Wang *et al.*, 2007)

$$X_W = \partial\, {}^B R_H\, {}^H R_C A^{-1} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} + {}^B R_H\, {}^H t_C + {}^B t_H \tag{1}$$

where ∂ stands for the depth information of target objects under the camera coordinate system. The rotation matrix ${}^B R_H$ and the translation vector ${}^B t_H$ stand for the transformation between the robot base coordinate system and the hand coordinate system. ${}^H R_C$, ${}^H t_C$ stand for the transformation between the hand coordinate system and the camera coordinate system. X_W stands for the three-dimensional coordinate of the target point under the world coordinate system. (u,v) stands for the image pixel coordinates of the target point. All the coordinate systems are shown in Fig.1. ${}^B R_H$, ${}^B t_H$, (u,v) can be obtained from the controller.

A is the matrix of the camera intrinsic parameters. When taking the lens distortion into consideration (Weng *et al.*, 1992)

$$A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where α , β stands for the scale factor of the image plane in the direction of u,v respectively. γ is the distortion parameter of the two axes of the image plane. (u_0,v_0) is the image centre.

2.2 Proposition of Focus of Expansion

Proposition (Ma et al., 1996)**:** If the camera motion is a pure translation, the displacement vectors (the lines in the image plane obtained by connecting matched points) in the image intersect at a point e, known as the focus of expansion (FOE) (Jain et al., 1983), and the vector $\overrightarrow{O_1 e}$ connecting O_1 (the optical center of the camera before the translation) and the point e is parallel to the translation. And we have

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = z_c A^{-1} \begin{bmatrix} u_e \\ v_e \\ 1 \end{bmatrix} = \overrightarrow{O_1 e} = k_1 \vec{c} \tag{3}$$

and

$$\overrightarrow{O_1 O_2} = k\vec{c} \tag{4}$$

where $k > k_1 > 0$. (x_c, y_c, z_c) are the coordinates of the point e under the camera coordinate system. (u_e, v_e) is the projection of the point e represented by the image pixel coordinates. O_2 represents the optical centre of the camera after the translation. $\vec{c}$ is the unit vector of the orientation of the camera motion. So, $k = \left|\overrightarrow{O_1 O_2}\right|$ and $k_1 = \left|\overrightarrow{O_1 e}\right|$. The geometrical relation is shown in Fig.2.

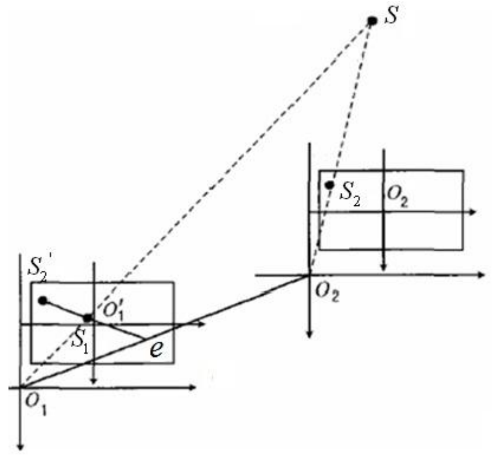

Fig.2. Geometrical relations before and after the camera translation.

Suppose S is a point in the scene, then S_1 and S_2 are the projections of S in the two images before and after the translation.

3. CALIBRATION OF ROTATIONAL MATRIX

Suppose X_{H1} , X_{H2} are the coordinates of a point S in the scene before and after the translational motion of the manipulator, respectively, using the hand coordinate system. Similarly, X_{C1} , X_{C2} are the coordinates of S in the camera coordinate system. Then, according to (1), we have

$$X_{H1} = {}^H R_C X_{C1} + {}^H t_C , \tag{5}$$

$$X_{H2} = {}^H R_C X_{C2} + {}^H t_C . \tag{6}$$

Suppose $k\vec{b}$ is the translational vector of the motion, then we have

$$k\vec{b} = X_{H1} - X_{H2} . \tag{7}$$

Substituting (5) and (6) into (7) yields

$$k\vec{b} = {}^H R_C (X_{C1} - X_{C2}) . \tag{8}$$

Then, according to (4), it equates with the equation

$$k\vec{b} = {}^H R_C k\vec{c} . \tag{9}$$

It is then further equivalent to

$$\vec{b} = {}^H R_C \vec{c} \tag{10}$$

where $\vec{b} = (b_x, b_y, b_z)^T$ and $\vec{c} = (c_x, c_y, c_z)^T$.

Since the camera is rigidly mounted on the end of the manipulator, ${}^H R_C$ is constant during the translations. So, after three linearly independent translations, we can get

$$\begin{cases} \vec{b}_1 = {}^H R_C \vec{c}_1 \\ \vec{b}_2 = {}^H R_C \vec{c}_2 \\ \vec{b}_3 = {}^H R_C \vec{c}_3 \end{cases} . \tag{11}$$

It can be written in the form of multiplication of matrices:

$$B = {}^H R_C C \tag{12}$$

where $B = \left(\vec{b}_1, \vec{b}_2, \vec{b}_3\right)$ and $C = \left(\vec{c}_1, \vec{c}_2, \vec{c}_3\right)$, respectively.

Since the parameters of B and C can be obtained, we have

$$ {}^H R_C = BC^{-1} . \tag{13}$$

4. CALIBRATION OF CONSTANT MATRIX

After multiplying (10) with the coefficient k_1 and substituting (3) into (10), we have

$$k_1\vec{b} = k_1\,{}^{H}R_C\vec{a} = {}^{H}R_C k_1\vec{c} = {}^{H}R_C\overrightarrow{O_1 e} = {}^{H}R_C z_c A^{-1}\begin{bmatrix} u_e \\ v_e \\ 1 \end{bmatrix}. \quad (14)$$

It equates with

$$k_1 A\,{}^{C}R_H\,\vec{b} = z_c\begin{bmatrix} u_e \\ v_e \\ 1 \end{bmatrix}. \quad (15)$$

Let a constant matrix $P = A\,{}^{C}R_H$, then we have

$$k_1 P\vec{b} = z_c\begin{bmatrix} u_e \\ v_e \\ 1 \end{bmatrix}. \quad (16)$$

Suppose $P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix}$, considering the matrix P and combining equations 14, 15 and 16, we get

$$\begin{cases} b_{i1}p_{11} + b_{i2}p_{12} + b_{i3}p_{13} - b_{i1}u_i p_{31} - b_{i2}u_i p_{32} - b_{i3}u_i p_{33} = 0 \\ b_{i1}p_{21} + b_{i2}p_{22} + b_{i3}p_{23} - b_{i1}v_i p_{31} - b_{i2}v_i p_{32} - b_{i3}v_i p_{33} = 0 \end{cases}. \quad (17)$$

Equation (17) proves that we can get eight linear equations of the elements belonging to P after four translational motions. Then, we can change the form of P as

$$P = p_{33}P' = p_{33}\begin{bmatrix} \overrightarrow{p_1'} \\ \overrightarrow{p_2'} \\ \overrightarrow{p_3'} \end{bmatrix} = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \vec{r_1} \\ \vec{r_2} \\ \vec{r_3} \end{bmatrix} \quad (18)$$

where $\vec{r_i}, i = 1,2,3$ is the row vector of the ${}^{C}R_H$. Since ${}^{C}R_H$ is $({}^{H}R_C)^{-1}$, $\|\vec{r_3}\|$ can be obtained.

According to (18), $p_{33}\overrightarrow{p_3'} = \vec{r_3}$. Then, we can get that $p_{33} = \|\vec{r_3}\| / \|\overrightarrow{p_3'}\|$. The only solution of the eight linear equations can be solved using least square method. In other words, all parameters of P can be obtained. Then, the entity of camera intrinsic and rotational matrix has been figured out. To complete the calibration of the robotics hand-eye system, we only need the solution of the translational vector of the system.

5. CALIBRATION OF NORMAL VECTOR

Suppose there is a point M on the intersecting line of the light plane and the object surface. $(x_c, y_c, z_c, 1)^T$ stands for the homogeneous coordinate of M in the camera coordinate system. $(u_m, v_m, 1)^T$ is the homogeneous image pixel coordinate of M . $(x_m, y_m, 1)^T$ is the homogeneous coordinate of M in the image plane. The position of M in the space is shown in Fig.1. And the relations between its coordinates are shown in Fig.3.

According to (3), we have

$$z_c\begin{bmatrix} x_m \\ y_m \\ 1 \end{bmatrix} = \begin{bmatrix} E & 0 \end{bmatrix}\begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix} \quad (19)$$

and

$$\begin{bmatrix} u_m \\ v_m \\ 1 \end{bmatrix} = A\begin{bmatrix} x_m \\ y_m \\ 1 \end{bmatrix} \quad (20)$$

where E is a 3×3 identity matrix.

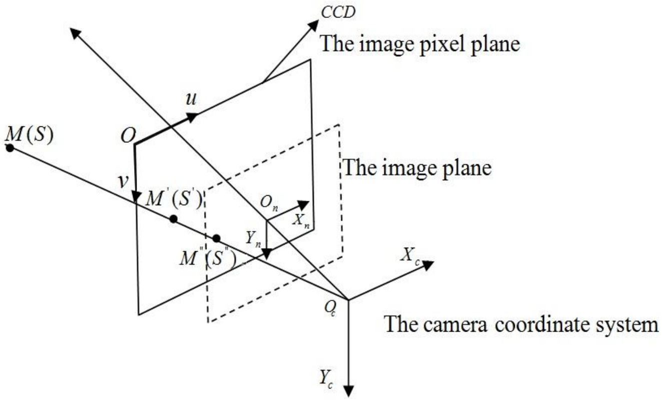

Fig.3. Model of relations between different coordinate systems

After one group of translations, the projections of intersecting lines of the light plane and the object surface are caught by the camera. Since the lines are parallel during the translations, their projections intersect at the vanishing point. The point is the intersection of these parallel lines and the plane at infinity, which can stand for the orientation of the lines (Yang *et al.*, 2006).

Suppose the equation of the projection is

$$a_i x + b_i y + c_i = 0 \quad (21)$$

where $i = 1, 2, \cdots, n$

Then, the coordinate (u_m, v_m) of the vanishing point is the optimal solution of the equation

$$f(u_m, v_m) = \min\sum_{i=1}^{n}\left|\frac{a_i x + b_i y + c_i}{\sqrt{a_i^2 + b_i^2}}\right|^2. \quad (22)$$

Equation (22) can be solved using least squares method. Then, according to (19) and (20), $(x_m, y_m, 1)^T$ can be obtained, which also represents the orientation of the intersecting lines in the camera coordinate system. Similarly, we can get the orientation vector of the other group of parallel lines in the same way after the second group of translations.

Suppose the equation of the light plane in the camera coordinate system is

$$d_1 X + d_2 Y + d_3 Z + d_4 = 0. \quad (23)$$

Since M is on the plane, then we have

$$d_1 x_c + d_2 y_c + d_3 z_c + d_4 = 0. \quad (24)$$

Suppose the orientation vectors of the two groups of parallel lines obtained above are $\vec{\gamma_1}, \vec{\gamma_2}$ respectively. The normal vector of the light plane is $\vec{n}$. Then, we have

$$\vec{n} = \vec{\gamma_1} \times \vec{\gamma_2} = (d_1, d_2, d_3). \quad (25)$$

6. CALIBRATION OF TRANSLATIONAL VECTOR

6.1 Computation of Depth Information

$(u_{s1}, v_{s1}, 1)^T$, $(u_{s2}, v_{s2}, 1)^T$ are the homogeneous image pixel coordinates of S before and after a translational motion. $(x_s, y_s, 1)^T$ is the homogeneous coordinate of S in the image plane. $X_{C1} = (x_{c1}, y_{c1}, z_{c1})^T$ and $X_{C2} = (x_{c2}, y_{c2}, z_{c2})^T$ stand for the coordinate of S before and after the motion in the camera coordinate system. The position of S in the space is shown in Fig.2. And the relations between its coordinates are also shown in Fig.3.

According to (3) and (4), we have

$$\begin{cases} \begin{bmatrix} x_{c1} \\ y_{c1} \\ z_{c1} \end{bmatrix} = z_{c1} A^{-1} \begin{bmatrix} u_{s1} \\ v_{s1} \\ 1 \end{bmatrix} \\ \begin{bmatrix} x_{c2} \\ y_{c2} \\ z_{c2} \end{bmatrix} = z_{c2} A^{-1} \begin{bmatrix} u_{s2} \\ v_{s2} \\ 1 \end{bmatrix} \end{cases} \tag{26}$$

and

$$\overrightarrow{X_{C1} X_{C2}} = k\vec{c} \tag{27}$$

where A can be obtained by computing $A = P^H R_C$

Substituting (2) and (26) into (27), we can obtain

$$\begin{cases} z_{c2} u_{s2} - z_{c1} u_{s1} = k(\alpha c_1 + \gamma c_2 + u_0 c_3) \\ z_{c2} v_{s2} - z_{c1} v_{s1} = k(\beta c_2 + v_0 c_3) \\ z_{c2} - z_{c1} = k c_3 \end{cases} . \tag{28}$$

Equations (28) can be induced to

$$\begin{cases} z_{c1}(u_{s2} - u_{s1}) = k(\alpha c_1 + \gamma c_2 + u_0 c_3 - c_3 u_2) \\ z_{c1}(v_{s2} - v_{s1}) = k(\beta c_2 + v_0 c_3 - c_3 v_2) \end{cases} . \tag{29}$$

Then, when $u_{s2} - u_{s1} \neq 0$, we have

$$z_{c1} = \frac{k(\alpha c_1 + \gamma c_2 + u_0 c_3 - c_3 u_2)}{u_{s2} - u_{s1}} . \tag{30}$$

Or $v_{s2} - v_{s1} \neq 0$, we have

$$z_{c1} = \frac{k(\beta c_2 + v_0 c_3 - c_3 v_2)}{v_{s2} - v_{s1}} . \tag{31}$$

From (30) and (31), we can see that there is corresponding relationship between the distance of the translation of the camera frame k and the depth information z_{c1}. Similarly, z_{c2} can be solved in the same way.

6.2 Calibration from Pure Rotation

Let the end of the manipulator do one pure rotation, as is shown in Fig.4. O_5 is the position of optical centre of the camera after the last translation of the manipulator. It is also the position of the optical centre before the rotation of the manipulator. O_6 stands for that of camera after the rotation.

Then, according to the (5) and (6), we have

$$\begin{cases} X_{C5} = {}^C R_H X_{H5} + {}^C t_H \\ X_{C6} = {}^C R_H X_{H6} + {}^C t_H \end{cases} . \tag{32}$$

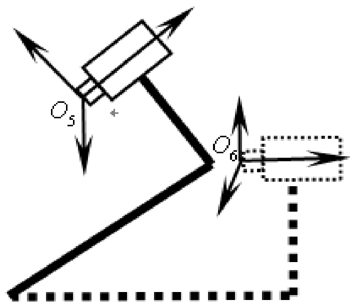

Fig.4. Schematic diagram before and after the rotation

Since the end of the manipulator do a pure rotation, the relationship between X_{H5} and X_{H6} is

$$X_{H6} = R_H X_{H5} . \tag{33}$$

According to (32) and (33), we can get

$$X_{c6} = {}^C R_H \, R_H \, {}^H R_C X_{c5} + \left(E - {}^C R_H \, R_H \, {}^H R_C\right) {}^C t_H \tag{34}$$

where ${}^C R_H$ has already been figured out and R_H can be read from the controller. Equation (34) shows that the motion of the camera coordinate system can be divided into two parts comprised of translation and rotation.

Then, let the camera coordinate system do an imaginary rotation around O_6, which is shown in Fig.5. O_7 is the optical centre of the camera after the imaginary rotation, which is actually on the same position of O_6.

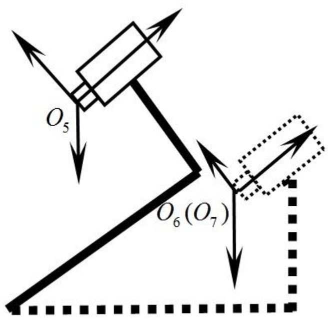

Fig.5. Schematic diagram before and after the imaginary rotation

After the imaginary rotation, the orientation of all the axes of the camera coordinate system should be parallel with that before the pure rotation of the manipulator. And if we let

$$X_{C7} = {}^C R_H \, R_H^{-1} \, {}^H R_C X_{C6} \tag{35}$$

where X_{C3} stands for the coordinates of S in the camera coordinate system after the imaginary rotation, we can substitute (34) into (35)

$$X_{C7} = X_{C5} + \left({}^C R_H \, R_H \, {}^H R_C - E\right) {}^C t_H . \tag{36}$$

This equation shows that X_{C1} and X_{C3} can be treated as the coordinates of S before and after a translational motion.

According to (3), we have

$$\begin{bmatrix} x_{c7} \\ y_{c7} \\ z_{c7} \end{bmatrix} = z_{c7} A^{-1} \begin{bmatrix} u_{s7} \\ v_{s7} \\ 1 \end{bmatrix} . \tag{37}$$

Substituting (37) and (26) into (35) yields

$$z_{c7}\begin{bmatrix}u_{s7}\\v_{s7}\\1\end{bmatrix}=z_{c6}A\ {}^{C}R_H\ R_H^{-1}\ {}^{H}R_C A^{-1}\begin{bmatrix}u_{s6}\\v_{s6}\\1\end{bmatrix}. \quad (38)$$

Let $g=z_{c7}/z_{c6}$, and matrix $G=\begin{bmatrix}g_{11}&g_{12}&g_{13}\\g_{21}&g_{22}&g_{23}\\g_{31}&g_{32}&g_{33}\end{bmatrix}=A\ {}^{C}R_H\ R_H^{-1}\ {}^{H}R_C A^{-1}$.

All the parameters of G can be solved according to the previous content in the paper. Then we have

$$\begin{cases}u_{s7}=(g_{11}u_{s6}+g_{12}v_{s6}+g_{13})/g\\ v_{s7}=(g_{21}u_{s6}+g_{22}v_{s6}+g_{23})/g\\ g=g_{31}+g_{32}+g_{33}\end{cases}. \quad (39)$$

(u_{s5},v_{s5}), (u_{s6},v_{s6}) are two projections of the same point S in the image pixel plane, whose values can be obtained from the controller. By substituting (u_{s6},v_{s6}) into (39), we can get the imaginary projection (u_{s7},v_{s7}). As is stated above, (u_{s5},v_{s5}) and (u_{s7},v_{s7}) can be treated as two coordinates before and after an imaginary translational motion. Suppose $\vec{d}$ is the unit orientation vector of the motion, which can be computed by the two coordinates.

Then, according to (4), we have

$$\overrightarrow{O_5O_7}=k_2\vec{d}. \quad (40)$$

Since this is an imaginary translation, we have

$$\overrightarrow{O_5O_7}=X_{C7}-X_{C5}. \quad (41)$$

Substituting (40) and (36) into (41) yields

$$k_2\vec{d}=\left({}^{C}R_H\ R_H\ {}^{H}R_C-E\right){}^{C}t_H, \quad (42)$$

from which we can get

$${}^{C}t_H=k_2\left({}^{C}R_H\ R_H\ {}^{H}R_C-E\right)^{-1}\vec{d}. \quad (43)$$

According to (40) and (41), k_2 can be solved as follows

When $\alpha d_1+\gamma d_2+u_0d_3-d_3u_2\neq 0$,

$$k_2=\frac{z_{c5}(u_{s7}-u_{s5})}{(\alpha d_1+\gamma d_2+u_0d_3-d_3u_7)}, \quad (44)$$

or

$$k_2=\frac{z_{c5}(v_{s7}-v_{s5})}{(\beta d_2+v_0d_3-d_3v_7)} \quad (45)$$

where z_{c5} can be obtained after the last translational motion using (30) and (31).

7. IMPLEMENTATION AND ANALYSIS

Our method has been verified by experiments with actual image data. We utilize the DENSO VP-6242E/GM six-axis robot. The positioning accuracy of this kind robot is 0.02 millimetres (mm). There is a camera (resolution 640×480) with the computer lens mounted on the end of the manipulator. Its focal length is 8mm. The manipulator has 6 degrees of freedom, which allows us to control its end to move along any direction. The motion parameters can be read from the controller.

7.1 Experiments

After four translational motions, we can obtain the coordinates of four points as the focus of expansion (FOE). Then, we can compute the orientation vectors of the four translational motions respectively using the coordinates read from the controller before and after the translations.

After three translations, we can get the rotational matrix directly

$${}^{H}R_C=\begin{bmatrix}-0.9996&-0.0278&0.0142\\-0.0218&-0.9997&-0.0240\\0.0089&-0.0241&0.9997\end{bmatrix}.$$

After four translations, the constant matrix and camera intrinsic parameters matrix can be solved as

$$P=\begin{bmatrix}-1400.5&2.7&282.5\\39.2&-1399.5&205.9\\0&0&1\end{bmatrix}\text{ and }A=\begin{bmatrix}1413.46&-9.7941&285.565\\0&1425.20&236.27\\0&0&1\end{bmatrix}.$$

After the second group of translations, the camera can catch two groups of projections of parallel intersecting lines of the light plane and object surface. We can compute the coordinates of the two vanishing points in the image pixel plane and in the camera coordinate system respectively. Then, we can get the normal vector of the light plane is

$$\vec{n}=[0.1197\quad -8.8011\quad 1.8562]^T.$$

Therefore, we can get the depth information of the light plane $d_4=598.7141$. Finally, we can obtain the equation of the light plane is $10.0002X-0.0147Y+0.0031Z+1=0$.

According to our proposed method, the translational vector of the hand-eye vision system can be obtained after the rotation as

$${}^{H}t_C=[-4.9364\quad 103.3236\quad 103.1672]^T.$$

Table 1. Comparison of the actual and computed results

	The computed values			The actual values		
S	x axis	y axis	z axis	x axis	y axis	z axis
1	301.08	6.2873	-0.16	301.08	6.2873	-0.16
2	310.44	7.02	0.23	310.74	6.80	-0.16
3	325.99	7.33	0.22	325.91	7.18	-0.16
4	341.03	8.42	0.23	340.82	8.14	-0.16
5	341.44	-11.77	0.01	341.71	-11.95	-0.16
6	327.47	-12.52	0.23	327.08	-12.59	-0.16
7	312.06	-13.83	-0.51	311.68	-13.46	-0.16
8	313.04	-33.56	-0.54	312.72	-33.65	-0.16
9	328.11	-32.39	0.02	327.51	-32.62	-0.16
10	342.49	-32.27	0.07	342.87	-31.98	-0.16
11	332.34	-26.13	46.41	333.49	-25.94	46.57
12	328.88	-8.86	33.61	328.57	-8.50	33.26
13	324.13	7.52	23.47	324.53	7.91	23.07
14	320.79	23.63	12.24	320.90	24.03	11.84
15	312.46	40.24	1.94	312.82	40.63	1.76

Since the positioning accuracy of the robot is 0.02mm, the robot can get the standard values of the coordinates of these points by touching them. To verify our method, we fix a workpiece on the end of the manipulator. Then, we can get the standard coordinates by controlling the end of the workpiece to touch the points. The bias correction of the end of the workpiece is $t_s = [-6.1335 \quad 15.4984 \quad -286.7479]$. Then, we can get the actual values and the computed ones of the coordinates, which are shown in Table1. The unit is millimetre. $S_1 \sim S_{10}$ are the coordinates of two-dimensional text data of the characteristic points. $S_{11} \sim S_{15}$ are the three-dimensional ones.

7.2 Performance Evaluation and Comparison

Above all, our method enhances the efficiency of the whole process of the calibration and reduces its computation effort and errors.

a. We only need three linearly independent translational motions to get the rotation matrix, which requires one fewer translation than (Wang *et al*., 2007) did. Therefore, after we obtain the constant matrix, we can get the matrix of the camera intrinsic parameters more easily.
b. After the three translations stated above, we can also figure out the depth information without anther two translations along the direction of the normal vector of the light plane, which are required by (Chen *et al*., 2012).
c. Combining a and b, we can make the calibration of line structured light much faster.
d. The method is able to obtain the rotation matrix and the translational vector with two groups of translations and one pure rotation. However, the fastest process presented by (Wang *et al*., 2007), needs four groups of translations and two rotations. That is, we can accomplish the calibration of hand-eye relation with much fewer steps.

Additionally, the continuity of the whole process of the calibration enables the method to be applied in many industrial fields. For example, it can be utilized for the realization of trajectory tracking of robot manipulators guided by laser vision. From Table1, we can see that the maximal error between the actual and computed values from S_1 to S_{15} is 0.40mm. Since the accuracy requirement in this industrial field is that the maximal error should be no more than ± 0.4mm (Yu and He, 1996), our method can meet the requirement to help accomplish the whole process of positioning, tracking and welding of the weld seam automatically.

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REFERENCES

Chen, H.H.(1991). A screw motion approach to uniqueness analysis of hand-eye geometry. *Proc. CVPR'91*, pp. 145-151.

Chen, T.F., Ma, Z. and Wu, X. (2012). Calibration of light plane in line structured light sensor based on active vision [J]. *Optics and Precision Engineering*, **vol. 20, no. 2,** pp. 256-263.

Dornaika, F. and Horaud, R. (1998). Simultaneous robot-world and hand-eye calibration. *IEEE Trans. Robot. Automat.*, **vol. 14**, pp. 345-358.

Henrik, M. and Anders, H. (2006). Extensions of plane-Based Calibration to Case of Translation Motion in a robot vision setting, *IEEE Trans. on Robotics*, **vol. 22,** pp. 322-333

Hu, Z.Y. and Wu, F.C.(2002). Recent progress in active vision based camera calibration[J]. *Chinese Journal of Computers*, **vol. 25**, pp. 1149-1156.

Jain, R. (1983). Direct computation of focus of expansion, *IEEE Trans. Pattern Anal. Machine Intell.*, **vol. P M - 5** , pp. 5844

Jason, G. (2011). Structured-light 3D surface imaging: a turtorial [J]. *Advances in Optics and Photonics*, **vol. 3, no. 2**, pp.128-160.

Ma, S.D. (1996). A self-calibration technique for active vision system[J]. *IEEE Trans. Robotics and Automat.*, **vol.12, no. 1**, pp. 114-120..

Shiu, Y.C. and Ahmad, S. (1989). Calibration of wrist-mounted robotic sensors by solving homogeneous transform equations of the form *AX* = *XB* [J]. *ZEEE Trans. Robot. Automat.,* **vol. 5, no. 1,** pp. 16-29.

Strobl, H.K. and Hirzinger, G.(2006). Optimal Hand-Eye Calibration. *Proc. Int'l Conf. Intelligent Robots and Systems*, pp. 4647-4653.

Tsai, R.Y. and Lenz, R.K. (1989). A technique for fully autonomous and efficient 3D robotics handeye calibration[J]. *IEEE Trans. Robot. Automat.*, **vol. 5, no. 3**, pp. 345-358.

Wang, H.X., Wang, C.Y., and Lu, X. (2007). Self-Calibration Technique Based on Hand-Eye Vision Systems [C] *Proceedings of the 26th.Chinese Control Conference* July 26-31, Zhangjiajie, Hunan, China, pp. 212-215.

Weng, J., Cohen, P., and Herniou, M. (1992). Camera calibration with distortion model and accuracy evaluation[J]. *IEEE Transactionson Pattern Analysis and Machine Intelligence*. **vol. 14, no. 10**, pp. 965-980.

Yang, G.L., Kong, L.F., and Wang, J. (2006). A New Calibration Approach to Hand to Eye Relation of Manipulator. July, **vol. 28, no. 4**, pp. 400-405.

Yu, Y.D. and He, L.J. (1996). Present Situation of Foreign Arc Welding Sensors[J]. *Journal of Transducer Technology*, **vol.3**, pp. 5-7.

Zhuang, H., Roth, Z.S., and Sudhakar R (1994). Simultaneous robot/world and tool/flange calibration by solving homogeneous transformation equation of the form *ax* = *yb*. *IEEE Trans. Robot. Automat.,* **vol.10, no.4**, pp. 549-554.