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A Method of Self-localization of Robot Based on Infrared Landmark*

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Abstract – **Aiming at the problem of robot self-localization based on vision, this paper proposed a method for robot's localization based on infrared landmark. First select the suitable infrared source. Second calculate the camera extrinsic parameters using the algorithm based on P3P. Third give the calculation method of robot's pose to the landmark based on the camera extrinsic. Experiment results validate the feasibility and effectiveness of the proposed method.**

Index Terms – P3P, Infrared landmark, Self-localization.

I. INTRODUCTION

Landmark is an identifiable feature that can be identified by the sensors installed on the robot. Using its own sensor to detect the fixed landmark in the environment, robot can calculate its pose to the landmark. Design, detection, location are the core of self-localization based on landmark for robot.

Landmark can be divided into natural landmark and artificial landmark. Natural landmark is a class of objects that already exit in the natural world and can be used for robot's localization. Artificial landmark is the special designed object placed in the environment for robot's localization. Landmark can be detected by laser sensor, infrared sensor, sonar and camera. The visible artificial landmarks can be detected by camera and provide rich information for robot's localization. But visible landmarks need a good lighting environment., can't be used in the complex environment. So this paper proposed a new method for robot's self-localization based on infrared landmark. Experiment results validate the feasibility and effectiveness of the proposed method.

II. INFRARED LANDMARK

Infrared light emitting diode is a common infrared light source. It can transform electrical energy directly to near-infrared light (not visible) and eradiate. The structure, principle of infrared light-emitting diode is similar to ordinary light emitting diode, just uses different semiconductor materials. Infrared light emitting diode typically used gallium arsenide (GaAs), aluminum gallium arsenic (GaAlAs) and other materials, used transparent or light blue, black resin encapsulation. Pipe pressure drop is about 1.4 V, working current is generally less than 20 mA. In order to adapt to different working voltage, limited flow resistance is often used[1].

Commonly used infrared light-emitting diode's wavelength is 850 nm, 870 nm, 880 nm, 840 nm, 980 nm, etc. The lower the wavelength is, the more the power is. The emission intensity of infrared light-emitting diode owes to the different directions. The direction of maximum emission intensity is along to the optical axis and the emission intensity decreases with the increase of angle with the optical axis direction. The angle whose emission intensity is half of the maximum is called half Angle of radiation intensity. The half angle of different models of infrared light-emitting diodes is different.

For the same camera, the sensitivity of infrared diodes of 850nm wavelength is 10 times better than the diodes of 950nm. So the 850nm wavelength is selected. The half angle of infrared diodes is usually from 8 degrees to 90 degrees. The visual range of the infrared diodes increases with the increase of half angle, and in the same process, the emission intensity decreases and the difficulty for the camera detection increases. So this paper choosed the eclectic, more commonly used infrared diodes whose half angle is 30 degrees.

In order to avoid the effect of visible light, a filter whose wavelength is 850nm is set on the camera lens. So the image of camera has only the target and the black background. Using method of image segmentation and connected component analysis, the landmark can be easily identified[2]. Figure 1 shows the results of identify.

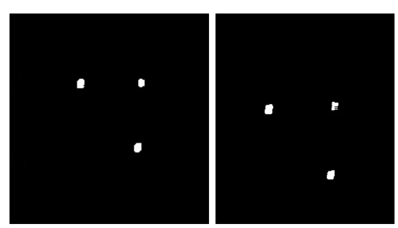

Fig.1 Identify of the landmark

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III. METHOD OF SELF-LOCALIZATION

This paper proposed a method of self-localization using infrared landmark based on PnP problem.

PnP problem is first proposed by Fischler in 1981[3]. It is defined as: The relative position of n points and the angles from these points to the centre of camera are given. Based on these information, calculate the distance from these points to the centre of camera. PnP problem is also known as pose estimation problem of given points. Horaud[4] gives the definition of pose estimation problem in 1989:In the target coordinate system, given the coordinates and projection in the image plane of some points and assume that the camera intrinsic parameters are known, calculate the camera extrinsic matrix between the target coordinate system and the camera coordinate system, which contains three rotation parameters and three translation parameters[5].

PnP problem has an important application prospect in many fields, such as robotics and automation, computer vision, computer animation, automatic drawing, photogrammetry, and other fields[6]. In the field of computer vision, PnP problem draws the attention of researchers. When n>5, using Faugeras camera calibration method, we can calculate camera intrinsic and extrinsic parameters. When n<3, it’s impossible to calculate the camera parameters under the above definition. Therefore, PnP problem research is mainly for P3P, P4P and P5P. Because the less the number of points are, the higher the application flexibility is, many researchers dedicated to the P3P and P4P problem.

The image coordinates of infrared landmarks can be calculated by the landmark recognition algorithm[2]. Landmarks’ position in the environment is fixed., so their world coordinates can be measured. The intrinsic parameters of camera can be calibrated. Using generic PnP problem solutions, the extrinsic parameters can easily be calculated, then we can gain the world coordinates of robot.

A. Solution of P3P problem

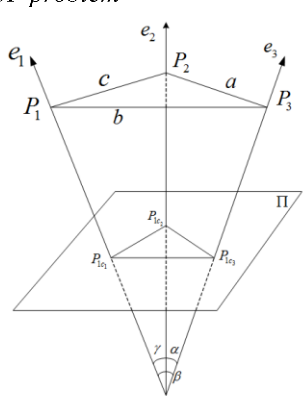

Fig.2 Sketch map of P3P

Establish the camera coordinate system on optical axis center, whose Z axis is parallel to the direction of camera optical axis and the positive direction is from the camera to the scene. The X axis of the camera coordinate system is along the horizontal direction. The camera intrinsic parameters have been calibrated using four parameters model. We can calculate the coordinates of the point P_{1c_i} in the imaging focal length normalized image plane of the camera by the image coordinate (u_i, v_i) of point P_i, such as in (1):

$$\begin{bmatrix} x_{1c_i} \\ y_{1c_i} \\ 1 \end{bmatrix} = \begin{bmatrix} k_x & 0 & u_0 \\ 0 & k_y & v_0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} \tag{1}$$

For the three known spatial points P_1, P_2 and P_3, the three sides of triangle composed by these three points are recorded as a, b and c (Fig. 2[7]). a is the length from P_2 to P_3, b is the length from P_1 to P_3, c is the length from P_1 to P_2. The unit vector from point P_i to the centre point O of optical axis is denoted as e_i. $\begin{bmatrix} x_{1c_i} & y_{1c_i} & 1 \end{bmatrix}^T$ in (1) represented the direction of e_i. So e_i can be calculated as in (2):

$$e_i = \frac{1}{\sqrt{x_{1c_i}^2 + y_{1c_i}^2 + 1}} \begin{bmatrix} x_{1c_i} \\ y_{1c_i} \\ 1 \end{bmatrix} \tag{2}$$

α is the angle between e_2 and e_3, β is the angle between e_1 and e_3, γ is the angle between e_1 and e_2. The cosine of angles between two vectors e_i and e_j can be calculated as shown in (3):

$$\begin{cases} \cos\alpha = e_2^T e_3 \\ \cos\beta = e_1^T e_3 \\ \cos\gamma = e_1^T e_2 \end{cases} \tag{3}$$

d_1 is the length from P_1 to O, d_2 is the length from P_2 to O, d_3 is the length from P_3 to O. According to the geometry principle, the equations below can be gained:

$$d_2^2 + d_3^2 - 2d_2d_3\cos\alpha = a^2 \tag{4}$$

$$d_1^2 + d_3^2 - 2d_1d_3\cos\beta = b^2 \tag{5}$$

$$d_1^2 + d_2^2 - 2d_1d_2\cos\gamma = c^2 \tag{6}$$

Let $d_2 = xd_1$, $d_3 = yd_1$ and we can gain the equations below:

$$d_1^2 = \frac{a^2}{x^2 + y^2 - 2xy\cos\alpha} \tag{7}$$

$$d_1^2 = \frac{b^2}{1 + y^2 - 2y\cos\beta} \tag{8}$$

$$d_1^2 = \frac{c^2}{1 + x^2 - 2x\cos\gamma} \tag{9}$$

Based on (7) and (8), cancel d_1^2:

$$x^2 = 2xy\cos\alpha - \frac{2a^2}{b^2} y\cos\beta + \frac{a^2-b^2}{b^2} y^2 + \frac{a^2}{b^2} \tag{10}$$

Based on (8) and (9), cancel $d_1^{\,2}$:

$$x^2 = 2x\cos\gamma - \frac{2c^2}{b^2} y\cos\beta + \frac{c^2}{b^2} y^2 + \frac{c^2-b^2}{b^2} \tag{11}$$

Based on (10) and (11), cancel x^2:

$$x = \frac{\frac{a^2-b^2-c^2}{b^2} y^2 + 2\cos\beta \frac{a^2-c^2}{b^2} y + \frac{a^2+b^2-c^2}{b^2}}{2(\cos\gamma - \mathrm{y}\cos\alpha)} \tag{12}$$

Based on (12) and (11), a quartic equation with one unknown can be gained as in (13):

$$a_4 y^4 + a_3 y^3 + a_2 y^2 + a_1 y + a_0 = 0 \tag{13}$$

In (13),

$$a_0 = \left(\frac{a^2+b^2-c^2}{b^2}\right)^2 - \frac{4a^2}{b^2}\cos^2\gamma$$

$$a_1 = 4\left[-\left(\frac{a^2+b^2-c^2}{b^2}\right)\left(\frac{a^2-c^2}{b^2}\right)\cos\beta + \frac{2a^2}{b^2}\cos^2\gamma\cos\beta + \left(\frac{a^2-b^2+c^2}{b^2}\right)\cos\alpha\cos\gamma\right]$$

$$a_2 = 2\left[\left(\frac{a^2-c^2}{b^2}\right)^2 - 1 - 4\left(\frac{a^2+c^2}{b^2}\right)\cos\alpha\cos\beta\cos\gamma + 2\left(\frac{b^2-c^2}{b^2}\right)\cos^2\alpha + 2\left(\frac{a^2-c^2}{b^2}\right)^2\cos^2\beta + 2\left(\frac{b^2-a^2}{b^2}\right)\cos^2\gamma\right]$$

$$a_3 = 4\left[-\left(\frac{a^2-b^2-c^2}{b^2}\right)\left(\frac{a^2-c^2}{b^2}\right)\cos\beta + \frac{2c^2}{b^2}\cos^2\alpha\cos\beta + \left(\frac{a^2-b^2+c^2}{b^2}\right)\cos\alpha\cos\gamma\right]$$

$$a_4 = \left(\frac{a^2-b^2-c^2}{b^2}\right)^2 - \frac{4c^2}{b^2}\cos^2\alpha$$

Using (13), we calculated y and putting y into (12), x can be calculated. Then based on (7), (8), (9), d_1, d_2, d_3 are calculated. The coordinates of P_1, P_2 and P_3 in the camera coordinate system can be calculated using (14):

$$P_{ci} = d_i e_i, i = 1,2,3 \tag{14}$$

B. *Calculation algorithm of camera extrinsic parameters*

The transformation of two different space coordinate systems usually includes rotation, translation and scaling, which can be abstracted into rotation matrix, transfer matrix and the scale factor.

1) Three coordinate translation component ΔX , ΔY and ΔZ , which represent the coordinate difference between the origins of two coordinate systems.

2) Three rotation angle $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$ around axis of X, Y, Z.

3) The scale factor k which is the ratio of the two lengths of a same line in two space coordinate systems. Usually k is equal to 1.

$P_{wi} = \begin{pmatrix} x_{wi} & y_{wi} & z_{wi} \end{pmatrix}^T$ is the coordinate in the world coordinate system of P_i . $P_{ci} = \begin{pmatrix} x_{ci} & y_{ci} & z_{ci} \end{pmatrix}^T$ is the coordinate in the camera coordinate system. The transformation from world coordinate system to camera coordinate system is shown as in (15):

$$\begin{pmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{pmatrix} = kR_1(\alpha)R_2(\beta)R_3(\gamma)\begin{pmatrix} x_{wi} \\ y_{wi} \\ z_{wi} \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \tag{15}$$

In (15),

$$R_1(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix} \tag{16}$$

$$R_2(\beta) = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix} \tag{17}$$

$$R_3(\gamma) = \begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{18}$$

Let $R = R_1(\alpha)R_2(\beta)R_3(\gamma)$, R can be transformed as shown in (19):

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix}\begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{19}$$

According to the principle of Rodrigo matrix, rotation orthogonal matrix R with 3 degrees of freedom can be transformed into the Rodrigo matrix composed by the antisymmetric matrix S [8]:

$$R = (I+S)(I-S)^{-1} \tag{20}$$

$$S = \begin{bmatrix} 0 & -r & -q \\ r & 0 & -p \\ q & p & 0 \end{bmatrix} \tag{21}$$

p , q , r are three independent unknown parameters. So based on Rodrigo matrix, the transformation model of coordinate system has 7 unknown parameters, including 3 parameters of transfer matrix, 3 parameters of antisymmetric matrix and scale factor. This idea established the transformation model of space coordinate system by replacing α, β, γ with p, q, r. Solutions for parameters need to step by step. First, calculate the scale factor. Second, calculate the rotate parameters and last the transfer parameters.

1) Calculation of scale factor

Using the coordinate inverse calculation, we calculate the corresponding distance and then gain the scale factor by the distance ratio. Set two common points P_i, P_j and then calculate the ratio of the length according to their coordinates in two coordinate systems.

$$k_{ij} = \frac{\sqrt{\left(x_{ci}-x_{cj}\right)^2+\left(y_{ci}-y_{cj}\right)^2+\left(z_{ci}-z_{cj}\right)^2}}{\sqrt{\left(x_{wi}-x_{wj}\right)^2+\left(y_{wi}-y_{wj}\right)^2+\left(z_{wi}-z_{wj}\right)^2}} \tag{22}$$

So the scale factor can be calculated as shown below:

$$k = \frac{2}{n(n-1)}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} k_{ij} \tag{23}$$

In (23), n represents the number of common points.

2) Calculation of rotate parameters

Put the coordinates of P_i, P_j in the world coordinate system and camera coordinate system into (15),we can gain equation below:

$$\begin{pmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{pmatrix} = kR\begin{pmatrix} x_{wi} \\ y_{wi} \\ z_{wi} \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \tag{24}$$

$$\begin{pmatrix} x_{cj} \\ y_{cj} \\ z_{cj} \end{pmatrix} = kR\begin{pmatrix} x_{wj} \\ y_{wj} \\ z_{wj} \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \tag{25}$$

Equation (24) minus (25) and then put (20) into the result, we can get equation below:

$$\left(I-S\right)\begin{pmatrix} x_{ci}-x_{cj} \\ y_{ci}-y_{cj} \\ z_{ci}-z_{cj} \end{pmatrix} = k\left(I+S\right)\begin{pmatrix} x_{wi}-x_{wj} \\ y_{wi}-y_{wj} \\ z_{wi}-z_{wj} \end{pmatrix} \tag{26}$$

Put S and I into (25):

$$\begin{pmatrix} 0 & -k\cdot z_{wij}-z_{cij} & -k\cdot y_{wij}-y_{cij} \\ -k\cdot z_{wij}-z_{cij} & 0 & k\cdot x_{wij}+x_{cij} \\ -k\cdot y_{wij}-y_{cij} & k\cdot x_{wij}+x_{cij} & 0 \end{pmatrix}\begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{pmatrix} x_{cij}-k\cdot x_{wij} \\ y_{cij}-k\cdot y_{wij} \\ z_{cij}-k\cdot z_{wij} \end{pmatrix} \tag{27}$$

In (27), $x_{cij}=x_{ci}-x_{cj}$, $y_{cij}=y_{ci}-y_{cj}$, $z_{cij}=z_{ci}-z_{cj}$; $x_{wij}=x_{wi}-x_{wj}$, $y_{wij}=y_{wi}-y_{wj}$, $z_{wij}=z_{wi}-z_{wj}$.

Equation (27) has only two independent equation and calculation of 3 unknown parameters is impossible. So another common point P_k is needed. In the same principle as in (27), we can gain equation set:

$$\begin{pmatrix} 0 & -k\cdot z_{wij}-z_{cij} & -k\cdot y_{wij}-y_{cij} \\ -k\cdot z_{wij}-z_{cij} & 0 & k\cdot x_{wij}+x_{cij} \\ -k\cdot y_{wij}-y_{cij} & k\cdot x_{wij}+x_{cij} & 0 \\ 0 & -k\cdot z_{wik}-z_{cik} & -k\cdot y_{wik}-y_{cik} \\ -k\cdot z_{wik}-z_{cik} & 0 & k\cdot x_{wik}+x_{cik} \\ -k\cdot y_{wik}-y_{cik} & k\cdot x_{wik}+x_{cik} & 0 \end{pmatrix}\begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{pmatrix} x_{cij}-k\cdot x_{wij} \\ y_{cij}-k\cdot y_{wij} \\ z_{cij}-k\cdot z_{wij} \\ x_{cik}-k\cdot x_{wik} \\ y_{cik}-k\cdot y_{wik} \\ z_{cik}-k\cdot z_{wik} \end{pmatrix} \tag{28}$$

Calculate the parameters p, q, r of antisymmetric matrix S using adjustment of observation equations , and then based on (20) the rotation matrix R is gained.

3) Calculation of transfer parameters

Put the scale factor, rotation matrix R and common points into (15):

$$\begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} = \frac{\left(\sum_{i=1}^{n}\left[\begin{pmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{pmatrix} - kR\begin{pmatrix} x_{wi} \\ y_{wi} \\ z_{wi} \end{pmatrix}\right]\right)}{n} \tag{29}$$

The key of the algorithm is to calculate the rotation matrix. The scale factor and transfer parameters are linear which is simple to calculate. The algorithm is feasible or not depends on (28) is solvable or not. As long as (28) has a solution, the rotation matrix R can be calculated using the Rodrigo matrix composed by antisymmetric matrix. When the three common points are on the same line, (28) is insoluble. When the three points are not on the same line, it’s feasible to calculate the rotation matrix based the model above.

Using the algorithm for P3P problem in the last section, the coordinates of three points P_1, P_2 and P_3 can be calculated whose coordinates in the world coordinate system are known. The model of the camera extrinsic parameters is shown as in (30):

$$\begin{pmatrix} x_c \\ y_c \\ z_c \\ 1 \end{pmatrix} = \begin{pmatrix} {}^cR_w & {}^cT_w \\ 0 & 1 \end{pmatrix}\begin{pmatrix} x_w \\ y_w \\ z_w \\ 1 \end{pmatrix} = {}^cM_w\begin{pmatrix} x_w \\ y_w \\ z_w \\ 1 \end{pmatrix} \tag{30}$$

Based on (15) and (30), the camera extrinsic parameters is shown as equation below:

$${}^cM_w = \begin{pmatrix} kR & T \\ 0 & 1 \end{pmatrix},\ T = \begin{pmatrix} \Delta X & \Delta Y & \Delta Z \end{pmatrix}^T \tag{31}$$

C. Solution for robot pose

Camera is set on the robot so the relative position between the camera and robot is constant. Establish the robot coordinate system $x_r - y_r$ on the robot. We can calibrate the homograph matrix ${}^cH_r$ between robot coordinate system and camera coordinate system:

$$\begin{pmatrix} x_c \\ y_c \\ z_c \\ 1 \end{pmatrix} = {}^cH_r \begin{pmatrix} x_r \\ y_r \\ z_r \\ 1 \end{pmatrix}, \; {}^cH_r = \begin{pmatrix} {}^cR_r & {}^cT_r \\ 0 & 1 \end{pmatrix} \tag{32}$$

Put it into (30):

$$\begin{pmatrix} x_w \\ y_w \\ z_w \\ 1 \end{pmatrix} = {}^cM_w^{-1} \cdot {}^cH_r \begin{pmatrix} x_r \\ y_r \\ z_r \\ 1 \end{pmatrix} \tag{33}$$

Assumed that ${}^wR_r$ and ${}^wT_r$ are the rotation matrix and transfer matrix from robot coordinate system to world coordinate system, α , β , γ are the rotate angle around axis X,Y,Z from robot coordinate system to world coordinate system, we can get the equation below according the (32):

$${}^wM_r = {}^cM_w^{-1} \cdot {}^cH_r = \begin{pmatrix} {}^wR_r & {}^wT_r \\ 0 & 1 \end{pmatrix} \tag{34}$$

$${}^wR_r = \begin{pmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{pmatrix}$$

$$= \begin{pmatrix} \cos\beta\cdot\cos\gamma & \sin\alpha\cdot\sin\beta\cdot\cos\gamma - \cos\alpha\cdot\sin\gamma & \cos\alpha\cdot\sin\beta\cdot\cos\gamma + \sin\alpha\cdot\sin\gamma \\ \cos\beta\cdot\sin\gamma & \sin\alpha\cdot\sin\beta\cdot\sin\gamma + \cos\alpha\cdot\cos\gamma & \cos\alpha\cdot\sin\beta\cdot\sin\gamma - \sin\alpha\cdot\cos\gamma \\ -\sin\beta & \sin\alpha\cdot\cos\beta & \cos\alpha\cdot\cos\beta \end{pmatrix} \tag{35}$$

According to (33) we can calculate the coordinate of robot in the world coordinate system. Based on the algorithm proposed in X, assumed that the rotate order of the transformation from robot system to world system is Z to Y to X, the rotate angle around every axis is shown as below:

$$\begin{aligned} \gamma &= \arctan\frac{r_4}{r_1} \\ \beta &= \arctan\frac{-r_7}{r_1\cdot\cos\gamma + r_4\cdot\sin\gamma} \\ \alpha &= \arctan\frac{r_3\cdot\sin\gamma - r_6\cdot\cos\gamma}{r_5\cdot\cos\gamma - r_2\cdot\sin\gamma} \end{aligned} \tag{36}$$

Based on the algorithm above, we can calculate the pose of robot $\begin{pmatrix} x_R & y_R & \gamma \end{pmatrix}^T$ in the world coordinate system.

IV. EXPERIMENTAL VERIFICATION

Set a landmark composed by three infrared diodes which are not on the same line in the environment and calculate robot's pose to the landmark in different position. The real pose of robot can be measured, so compare the real pose and the calculated values we can gain the accuracy of the algorithm. The result is shown in the table 1 , table 2 and table 3. Table 1 and Table 2 shows the real coordinate and calculated coordinate of robot. Data of Group 1 are all on the axis Y of world coordinate system and data of Group 2 and Group 3 are on some different positions. As the data show, the errors are all in centimeters. Table 3 shows the real orientation and calculated orientation angle and errors are below 4 degrees. So the algorithm proposed in this paper meet the need of robot's self-localization.

TABLE I
RESULT OF EXPERIMENT 1

Group 1	
Real value(cm)	Calculate value(cm)
(0,93)	(-2,94.5)
(0,100)	(-3,101)
(0,110)	(1,111)
(0,120)	(0,122)
(0,140)	(0,141)
(0,150)	(-3,151)
(0,170)	(-2,172)
(0,200)	(-2,200)

TABLE 2
RESULT OF EXPERIMENT 2

Group 2		Group 3	
Real value(cm)	Calculate value(cm)	Real value(cm)	Calculate value(cm)
(10,100)	(9,101)	(-10,100)	(-9,102)
(10,120)	(7.5,120)	(-10,120)	(-8,122)
(20,120)	(17,120)	(-20,120)	(-20,125)
(10,150)	(8,150)	(-10,150)	(-7,151)
(20,150)	(17,153)	(-20,150)	(-18,153)
(30,150)	(28,155)	(-30,150)	(-26,156)
(10,180)	(9,181)	(-10,180)	(-10,182)
(20,180)	(16,183)	(-20,180)	(-17,184)
(30,180)	(27,189)	(-30,180)	(-29,185)

TABLE 3
RESULT OF EXPERIMENT 3

Real value(degree)	Calculate value(degree)
0	1.21
10	10.32
20	21.08
30	32.23
40	41.14
50	53.25
60	62.78

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REFERENCES

[1] http://www.oneled.com/2068.html

[2] Wen Feng. “Research on Visual SLAM Method Based on a Novel Artificial landmark System for Mobile Robot:[D]”. Beijing: Institute of Automation, Chinese Academy of Sciences, 2010.

[3] Fischler M A, Bolles R C. Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography[J]. Communications of the ACM, 1981, 24(6): 381-395.

[4] Design and implementation of robot controller based PC platform[J]. Robot, 2000,22(7):738-740.

[5] Robot vision measurement and control[M]. National Defence Industry Press, 2011.

[6] Wang L K, Xu D,Han J Q. Research of visual servoing for industrial welding vehicles[J]. Chinese High Technology Letters, 2005, 18(3):23-29.

[7] Li Y, Xu D, Li T. On Visual Sensors for Welding Seam Tracking based on laser structured light[J]. Chinese Journal of Sensors and Actuators, 2005, 18(3):488-492.

[8] Yuan Y L, Jiang L X, Liu L J. Application of rodrigo matrix in coordinates transformation. Science of Surveying and Mapping, 2010, 35(2):178-179.