Оптический журнал

Иконика — наука об изображении

An efficient vision-based pose determination method of five coplanar points

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Submitted 27.01.2016

The existing approaches to a solution of object pose fall into two distinct categories: analytical solutions and iterative solutions. In this paper, a two-step pose estimation method based on five coplanar points by combining the advantages of the above two methods is studied. In the first step, after the image coordinates of points are extracted through image processing the pose of object is determined with two affine invariants formed by the five points. In the second step, an iterative method is introduced, and the results of the first step are passed to the current step being used as initial values of the iterative process to ensure the accuracy and convergence rate of non-linear algorithm. The proposed method is then compared with other two existing methods. Experimental results demonstrate that the proposed method has the advantage of lower computational cost. The accuracy, which is the main concerns during the real-time applications, is also improved.

Keywords: *pose estimation, affine invariants, coplanarity, non-linear.*

OCIS codes: *330.4060; 330.5000; 330.0100.*

Эффективный способ визуального определения ориентации объекта с помощью пяти компланарных точек

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Существующие методы определения ориентации объекта распадаются на две отдельные категории: аналитические и итерационные. В работе исследуется двухступенчатый метод определения ориентации, использующий пять компланарных точек, сочетающий достоинства этих подходов. На первом этапе, после определения координат точек изображения в результате цифровой обработки, ориентация объекта определяется двумя аффинными инвариантами, формируемыми пятью точками. На втором этапе, вводится итеративный метод, причем результаты первого этапа используются как начальные данные для итерационного процесса, обеспечивая точность и быстроту сходимости нелинейного алгоритма. Приведены результаты сравнения предложенного метода с двумя другими существующими. Результаты экспериментов показывают, что предложенный метод имеет преимущества меньшей стоимости вычислений. Точность определения ориентации, являющаяся главным критерием в практических применениях, также повышается.

Ключевые слова: *определение ориентации, аффинные инварианты, компланарность, нелинейность.*

INTRODUCTION

With the development of modern industrial technology, quickly and accurately determine the position and orientation between objects is becoming more and more important. It can be widely applied in the fields of robot navigation [1], coordinate vision measurement system using a light pen [2], electro-optic aiming system [3, 4], wheel alignment system [5], aerospace [6, 7, 8], so the research in this area is more active in recent years.

Pose estimation based on points is also known as PnP (Perspective n-Points Problem), in 1981 first proposed by Fischler and Bolles [9]. Given the relative positions

of n control points, the angles between connecting lines of control point and optical center, solve the distance from each control point to the optical center. The problem has been further studied by other researchers [10, 11]. The existing approaches to a solution of object pose based on points fall into two distinct categories: analytical solutions and iterative solutions.

Analytical solutions: [12] proved that four points can achieve a linear solution, but may have more than one solution. [13] presented a linear algorithm in the condition of five points. In [14] a non-linear pose estimation model is established on the basis of distance factor. With algebraic transformation method, the nonlinear mathematic mode is transformed into a linear non-homogeneous equation system. Ansar and Daniilidis [15] presented a general framework to directly recover the rotation and translation. Duan [16] introduced a new affine invariant of trapezium. Given the lengths of two parallel sides of a trapezium, pose estimation and plane measurement can be realized in a very simple way from the projection of trapezium.

Iterative solutions: DeMenthon et al. [17, 18] proposed POSIT algorithm which gets the initial value of solution using the scaled orthographic model to approximate the perspective projection model. [19] solved the rotation and translation matrix using least squares method according to the orthonormal constraints. [20] achieved the object pose non-linearly on basis of five points using least squares approach. [21] proposed a positioning method based on three points, but this approach had a smaller measurement range (0°–5°). [22] proposed a positioning method according to the corresponding geometrical constraints of four points. [23] proposed an efficient solution for vision-based pose determination of a parallel manipulator.

Both analytical solutions and iterative solutions have their advantages and disadvantages. Compared with iterative solutions, analytical solutions generally take less computation time for the same accuracy. But on the other hand, the analytical solutions are extremely susceptible to noise because of the orthonormal constraints associated with the rotation matrix that are not taken into account. Whenever the number of points is larger than 4, the analytical solutions are not efficient. Iterative solutions are normally solved with some variation on gradient descent or Gauss–Newton methods and they have drawbacks: (1) non-linear optimization needs a good initial estimate of the true solution (2) they are more time consuming than analytical solutions. Therefore, such approaches cannot be used in tasks that require high speed performance.

Based on the discussion above, in this paper an efficient two-step method for pose estimation based on five coplanar points is proposed : In the first step, the pose of object is estimated by a simple analytical solving process. The image coordinates of points are extracted through image processing. Then by utilizing the affine invariants formed by points, the coordinates of points in the camera coordinate system are solved. In the second step, the results obtained in the first step are set as the initial values of an iterative solving process to ensure the accuracy and convergence rate of non-linear algorithm. An unconstrained nonlinear optimization objective function is established through the objective functions produced by the depth estimation and the coplanarity of five points. The Levenberg-Marquardt optimization method is utilized to refine the initial values. The coordinates of points in the camera coordinates system are finally obtained.

THE ANALYTICAL SOLVING MODEL OF OBJECT POSE

The target pattern with five points is designed for pose estimation as shown in fig. 1. P_1, P_2, P_3 and P_4 form a trapezium. P_1P_4 is parallel to P_2P_3. P_0, P_1 and P_2 are on the same straight line. P_0 is set as the origin of coordinate system. The connecting line of P_0 and P_1 is x axis. The line which is parallel to the connecting line of P_3, P_4 and passes through P_0 is y axis. Z axis is determined according to the principle of right hand. In this way, the world coordinate system (target coordinate system) is constructed.

To achieve the solution of target pose, the coordinates of points in the camera coordinate system need to be solved firstly. The perspective projection model of five points is shown in fig. 2. o_c-$x_cy_cz_c$ is the camera coordinate system, which denotes the camera frame. uv is the CCD image plane with the original point at the image center. o_w-$x_wy_wz_w$ is the world coordinate system.

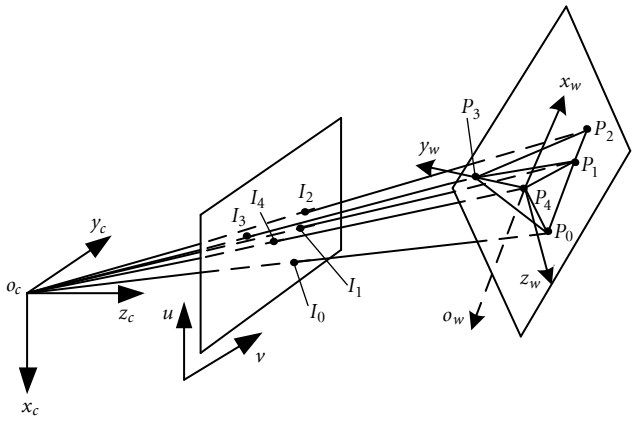

Fig. 2. Five points perspective projection model.

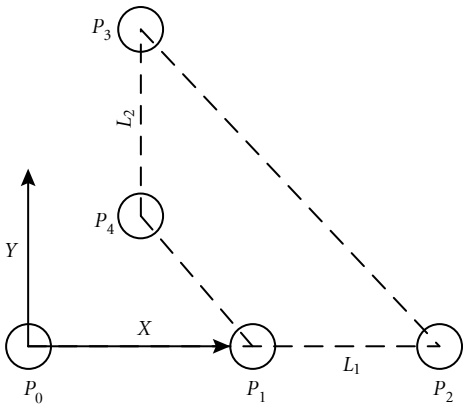

Fig. 1. The measurement target with five points.

The coordinates of each point in the camera coordinate system is $P_{ci} = (x_{ci}, y_{ci}, z_{ci})^T$ and that in the world coordinate system is $P_{wi} = (x_{wi}, y_{wi}, z_{wi})^T$. P_{wi} is known before solving the pose. The corresponding ideal image coordinates is $I_{ui} = (x_{ui}, y_{ui}, 1)^T$. The relationship of P_{ci} and I_{ui} could be described as:

$$\begin{cases} z_{ci} I_{ui} = \begin{bmatrix} s_x f / d_x & 0 & u_0 \\ 0 & f / d_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} P_{ci} = \begin{bmatrix} f_x & 0 & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} P_{ci} = K P_{ci} \\ P_{ci} = \lambda_i K^{-1} I_{ui} (\lambda_i = z_{ci}) \end{cases}, \tag{1}$$

where (u_0, v_0) is the center pixel of the computer image, s_x is the uncertainty image factor, d_x and d_y are center to center distances between pixels in the row and column directions respectively, f is the focal length, and λ_i is the scale factor (the projection depth of point).

The coordinates of points in the camera coordinate system could be obtained by solving λ_i. Since P_1P_2 is equal to P_3P_4 and P_1P_4 is parallel to P_2P_3, two affine invariants are introduced. The first affine invariant is shown in formula (2).

$$\begin{cases} k = \|P_{w4} - P_{w1}\| / \|P_{w3} - P_{w2}\| \\ P_{w4} = k(P_{w3} - P_{w2}) + P_{w1} = [P_{w1}, P_{w2}, P_{w3}][1, -k, k]^{\mathrm{T}} \end{cases}. \tag{2}$$

The transformation matrix from the world coordinates system to the camera coordinates system is **R** and **T**. P_{ci} could be expressed as $P_{ci} = \mathrm{R}P_{wi} + \mathrm{T}$, and then P_{c4} could be represented with P_{c1}, P_{c2}, P_{c3}.

$$\begin{aligned} P_{c4} = \mathrm{R}P_{w4} + \mathrm{T} = \mathrm{R}\big(k(P_{w3} - P_{w2}) + P_{w1}\big) + \mathrm{T} = \mathrm{R}\big(k(P_{w3} - P_{w2} + \mathrm{T} - \mathrm{T}) + P_{w1}\big) + \mathrm{T} = \\ = k(\mathrm{R}P_{w3} - \mathrm{R}P_{w2} + \mathrm{T} - \mathrm{T}) + \mathrm{R}P_{w1} + \mathrm{T} = k(P_{c3} - P_{c2}) + P_{c1}. \end{aligned}$$

Finally formula (3) is obtained.

$$P_{c4} = k(P_{c3} - P_{c2}) + P_{c1} = [P_{c1}, P_{c2}, P_{c3}][1, -k, k]^{\mathrm{T}}. \tag{3}$$

Given $P_c = [P_{c1}, P_{c2}, P_{c3}]$, according to formula (1) and formula (3), formula (4) is deduced

$$P_c = [P_{c1}, P_{c2}, P_{c3}] = \mathrm{K}^{-1}[I_{u1}, I_{u2}, I_{u3}]diag(\lambda_1, \lambda_2, \lambda_3). \tag{4}$$

The both sides of equation (4) are multiplied with P_{c4}

$$P_c^{-1} P_{c4} = diag(1/\lambda_1, 1/\lambda_2, 1/\lambda_3)[I_{u1}, I_{u2}, I_{u3}]^{-1} \mathrm{K}(\lambda_4 \mathrm{K}^{-1} I_{u4}) = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3)[I_{u1}, I_{u2}, I_{u3}]^{-1} I_{u4}.$$

Given $[\eta_1, \eta_2, \eta_3] = [I_{u1}, -I_{u2}, I_{u3}]^{-1} I_{u4}$

$$\begin{aligned} P_c^{-1} P_{c4} = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3)[I_{u1}, I_{u2}, I_{u3}]^{-1} I_{u4} = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3)\big(diag(1,-1,1)[I_{u1}, I_{u2}, I_{u3}]diag(1,-1,1)\big)^{-1} I_{u4} = \\ = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3)\big([I_{u1}, -I_{u2}, I_{u3}]diag(1,-1,1)\big)^{-1} I_{u4} = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3) \times diag(1,-1,1)\big([I_{u1}, -I_{u2}, I_{u3}]\big)^{-1} I_{u4}. \end{aligned}$$

Finally formula (5) is obtained which represent the second affine invariant

$$P_c^{-1} P_{c4} = diag(\lambda_4/\lambda_1, \lambda_4/\lambda_2, \lambda_4/\lambda_3)[\eta_1, -\eta_2, \eta_3]^{\mathrm{T}}. \tag{5}$$

$P_c^{-1} P_{c4}$ could be expressed as formula (6) according to formula (3)

$$P_c^{-1} P_{c4} = [1, -k, k]^{\mathrm{T}}. \tag{6}$$

According to both formula (5) and formula (6), λ_i is solved

$$\begin{cases} \lambda_1 = \eta_1 \lambda_4, \lambda_2 = \eta_2 \lambda_4 / k, \lambda_3 = \eta_3 \lambda_4 / k, \lambda_4 = \eta_4 \lambda_4 (\eta_4 = 1) \\ k = \|P_{w4} - P_{w1}\| / \|P_{w3} - P_{w2}\| \\ \|P_{w3} - P_{w2}\| = \|P_{c3} - P_{c2}\| = \lambda_4 \left\| \eta_3 \mathrm{K}^{-1} I_{u3} / k - \eta_2 \mathrm{K}^{-1} I_{u2} / k \right\| \\ \lambda_4 = \|P_{w4} - P_{w1}\| / \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| \end{cases}, \tag{7}$$

according to formula (1). With knowing P_{c1}, P_{c2}, P_{c3}, P_{c4}, P_{c0} could also be calculated. So the vector from the optical center O_c to each point could be calculated through formula (8)

$$\begin{cases} \overrightarrow{O_cP_{ci}} = \eta_i \mathrm{K}^{-1} I_{ui} \left\| P_{w4} - P_{w1} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| (i = 1,4) \\ \overrightarrow{O_cP_{ci}} = \eta_i \mathrm{K}^{-1} I_{ui} \left\| P_{w3} - P_{w2} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| (i = 2,3). \\ \overrightarrow{O_cP_{ci}} = \lambda_i \mathrm{K}^{-1} I_{ui} \end{cases} \quad (8)$$

$\pi X_{ci} = 1$, ($\pi = [\pi_1, \pi_2, \pi_3]$) is the equation that express the plane π composed of the five points in the camera coordinate system. X_{ci} is the coordinates of points on the plane π in the camera coordinate system. The both sides of equation are multiplied with X_{ci}^T

$$\pi X_{ci} X_{ci}^T = X_{ci}^T, \qquad \pi \sum_{i=0}^{4} X_{ci} X_{ci}^T = \sum_{i=0}^{4} X_{ci}^T.$$

Finally, formula (9) is obtained

$$\pi = \sum_{i=0}^{4} X_{ci}^T \left(\sum_{i=0}^{4} X_{ci} X_{ci}^T \right)^{-1}. \quad (9)$$

Substitute P_{ci} for X_{ci}. The equation of π is represented with formula (10)

$$\begin{cases} \pi = \alpha_\pi (H_\pi)^{-1} \\ H_\pi = \sum\limits_{i=1,4} \left(\eta_i \left\| P_{w4} - P_{w1} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| \right)^2 (\mathrm{K}^{-1} I_{ui} I_{ui}^T \mathrm{K}^{-T}) + \\ + \sum\limits_{i=2,3} \left(\eta_i \left\| P_{w3} - P_{w2} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| \right)^2 (\mathrm{K}^{-1} I_{ui} I_{ui}^T \mathrm{K}^{-T}) + P_{c0} P_{c0}^T \\ \alpha_\pi = \sum\limits_{i=1,4} \eta_i I_{ui}^T \mathrm{K}^{-T} \left\| P_{w4} - P_{w1} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| + \\ + \sum\limits_{i=2,3} \eta_i I_{ui}^T \mathrm{K}^{-T} \left\| P_{w3} - P_{w2} \right\| \Big/ \left\| \eta_3 \mathrm{K}^{-1} I_{u3} - \eta_2 \mathrm{K}^{-1} I_{u2} \right\| + P_{c0}^T \end{cases} \quad (10)$$

THE ITERATIVE SOLVING MODEL OF OBJECT POSE

The distance from the optical center O_c to the plane π composed of five points D could be represented with formula (11)

$$D = \pi P_{c0} / \|\pi\|. \quad (11)$$

The length from the optical center O_c to each point L_i could be calculated through formula (12)

$$L_i = D \left[\left\| \lambda_i K^{-1} \overrightarrow{O_c I_{ui}} \right\| \|\pi\| \Big/ \left(\pi (\lambda_i K^{-1} \overrightarrow{O_c I_{ui}}) \right) \right]. \quad (12)$$

The distance of any two points could be calculated by L_i and the distance constraints of points $E(i, j)$ could be expressed as formula (13).

$$\begin{cases} E(i,j) = L_i^2 + L_j^2 - 2L_iL_j \left[\overrightarrow{O_cI_i} \cdot \overrightarrow{O_cI_j} \Big/ \left(\left\| \overrightarrow{O_cI_i} \right\| \cdot \left\| \overrightarrow{O_cI_j} \right\| \right) \right] - \left\| \overrightarrow{P_{wj}P_{wi}} \right\|^2 \\ \overrightarrow{O_cI_i} = K^{-1} \overrightarrow{O_cI_{ui}} \Big/ \left\| K^{-1} \overrightarrow{O_cI_{ui}} \right\| \\ \overrightarrow{O_cI_j} = K^{-1} \overrightarrow{O_cd_{uj}} \Big/ \left\| K^{-1} \overrightarrow{O_cd_{uj}} \right\| \end{cases} \quad (13)$$

Only the distance constraints are not enough to get the exact pose of target. In order to maintain the rigidity of target, the coplanar constraint $C(i, j)$ which is expressed as formula (14) should also be considered

$$\begin{aligned} CO(i,j,l,n) = & \left(\left(L_j \overrightarrow{O_cI_j} \Big/ \left\| \overrightarrow{O_cI_j} \right\| - L_i \overrightarrow{O_cI_i} \Big/ \left\| \overrightarrow{O_cI_i} \right\| \right) \times \right. \\ & \times \left(\left(L_l \overrightarrow{O_cI_l} \Big/ \left\| \overrightarrow{O_cI_l} \right\| - L_i \overrightarrow{O_cI_i} \Big/ \left\| \overrightarrow{O_cI_i} \right\| \right) \right) \times \\ & \left. \times \left(L_n \overrightarrow{O_cI_n} \Big/ \left\| \overrightarrow{O_cI_n} \right\| - L_i \overrightarrow{O_cI_i} \Big/ \left\| \overrightarrow{O_cI_i} \right\| \right). \right. \end{aligned} \quad (14)$$

According to formula (13) and formula (14), the objective function of constraints is obtained as shown in formula (15)

$$\begin{cases} \min F = \sum\limits_{i=0}^{4} \sum\limits_{j=i+1}^{4} E(i,j) \\ \sum\limits_{i=0}^{4} \sum\limits_{\substack{j=i+1 \\ l \neq i,j \\ n \neq i,j,l}}^{4} CO(i,j,l,n) = 0 \end{cases}. \quad (15)$$

The penalty function method is used to translate the objective function of constraints into an unconstrained objective function as shown in formula (16)

$$F=\sum_{i=0}^{4}\sum_{j=i+1}^{4}E(i,j)+M\sum_{i=0}^{4}\sum_{\substack{j=i+1\\ l\neq i,j\\ n\neq i,j,l}}^{4}CO(i,j,l,n), \quad \textbf{(16)}$$

where M is the penalty factor. The Levenberg — Marquardt optimization method is used to solve λ_i through the objective function. The values of points depth information λ_i obtained in section 2 is used as the initial values to ensure the accuracy and convergence speed of the non-linear algorithm in this section.

Finally on the basis of the results of λ_i ($i = 0, 1, 2, 3, 4$), the rotation and translation matrix between the target coordinate system and the camera coordinate system could be obtained by formula (17)

$$\begin{cases} R_1=\overrightarrow{O_cP_{c2}}-\overrightarrow{O_cP_{c1}}\Big/\left\|\overrightarrow{O_cP_{c2}}-\overrightarrow{O_cP_{c1}}\right\| \\ R_2=\overrightarrow{O_cP_{c3}}-\overrightarrow{O_cP_{c4}}\Big/\left\|\overrightarrow{O_cP_{c3}}-\overrightarrow{O_cP_{c4}}\right\| \\ R_3=R_1\times R_2 \\ \mathrm{R}=\begin{bmatrix} R_1^T & 0 \\ R_2^T & 0 \\ R_3^T & 0 \\ 0\ \ 0\ \ 0 & 1 \end{bmatrix} \quad \mathrm{T}=\begin{bmatrix} 1 & 0 & 0 & -P_{c0x} \\ 0 & 1 & 0 & -P_{c0y} \\ 0 & 0 & 1 & -P_{c0z} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \end{cases} \quad \textbf{(17)}$$

EXPERIMENT RESULTS

The algorithm proposed above has been tested experimentally by utilizing a target as shown in fig. 1. The experimental system that consists of a target, a three-axis motorized stage, two CCD cameras is shown in fig. 3. Target pose measurement experiment includes two parts: the measurement experiments for accuracy, and comparative experiments with other methods.

With the spacing 5°, the 3-axis turntable takes the target to rotate at the two degrees of freedom (yaw and pitch) respectively. The left camera or the right camera (only one camera) is chosen to capture an image at each location. The angle between the current position and the initial position (zero position) is calculated according to section 2, 3. The measuring range of yaw angle is set to 0°–90°, the measuring range of pitch angle is set to 0°–60°. The calculated angles are shown in tab. 1, and tab. 2.

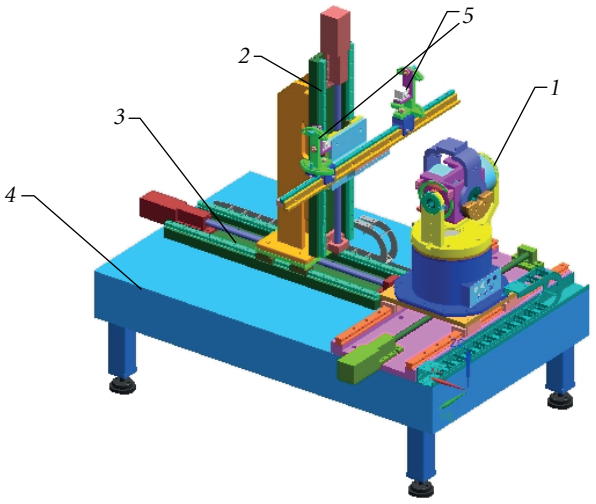

Fig. 3. The experiment system. *1* — three-axis motorized stage, *2* — lifting gear of CCD camera, *3* — translation stage, *4* — working platform, *5* — CCD cameras.

Table 1. Measurement results of yaw angle

Serial No.	Position of Target (°)	The angle between location *i* and location 0 (°)	
		actual value (°)	error (°)
0	0		
1	5	5.052	0.052
2	10	10.109	0.109
3	15	15.082	0.082
4	20	19.982	–0.018
5	25	24.977	–0.023
6	30	30.001	0.001
7	35	35.062	0.062
8	40	40.061	0.061
9	45	45.084	0.084
10	50	50.072	0.072
11	55	55.045	0.045
12	60	59.992	–0.008
13	65	64.919	–0.081
14	70	69.879	–0.121
15	75	74.932	–0.068
16	80	79.892	–0.108
17	85	84.919	–0.081
18	90	89.895	–0.105

Table 2. Measurement results of pitch angle

Serial No.	Position of Target (°)	The angle between location *i* and location 0 (°)	
		actual value (°)	error(°)
0	0		
1	5	4.994	–0.006
2	10	10.006	0.006
3	15	14.953	–0.047
4	20	19.932	–0.068
5	25	24.946	–0.054
6	30	29.964	–0.036
7	35	34.999	–0.001
8	40	39.967	–0.033
9	45	44.930	–0.070
10	50	49.922	–0.078
11	55	54.959	–0.041
12	60	60.035	0.035

In the yaw degree of freedom, the algorithm proposed in this paper, duan algorithm and least squares algorithm are used to calculate target pose, the comparative experimental results are shown in tab. 3.

We can see from tab. 3 that the values estimated by our algorithm are very close to the real values. The least squares algorithm has several errors that exceed 0.2° for it does not provide a well initial value at the beginning of iteration. The duan algorithm does not have iterative process so the results are far from the real value when the measurement range is greater. The results prove that the proposed algorithm is more accurate compared with the other two algorithms. With the condition of same measurement range, the proposed algorithm has an advantage to identify the pose of object.

In order to further show the advantage of the algorithm proposed in this paper, in the yaw degree of freedom, the distance between point *1*, point *2* is calculated with the algorithm proposed in this paper, duan algorithm and least squares algorithm. The results are shown in tab. 4.

Table 3. The comparative experiment of pose measurement with three algorithms

Serial No.	Position of Target (°)	The algorithm proposed in this paper (°)	Least squares algorithm (°)	Duan algorithm (°)
1	0			
2	5	0.052	0.261	−0.149
3	10	0.109	0.222	−0.254
4	15	0.082	0.105	0.282
5	20	−0.018	−0.265	0.210
6	25	−0.023	−0.279	0.208
7	30	0.001	0.280	0.300
8	35	0.062	0.144	−0.294
9	40	0.061	0.240	−0.290
10	45	0.084	0.141	−0.231

Table 4. The comparative experiment of distance measurement with three algorithms

Serial No.	Position of Target	Solving d_{12} by the algorithm proposed in this paper, mm	Solving d_{12} by the least squares algorithm, mm	Solving d_{12} by the duan algorithm, mm
1	0°	40.0144	40.1388	39.5452
2	5°	40.0515	40.0515	39.6702
3	10°	40.0878	40.1349	39.4327
4	15°	39.3281	40.1481	39.3281
5	20°	40.0628	40.1062	39.7874
6	25°	40.0553	40.1586	38.8929
7	30°	40.0559	40.1057	38.4446
8	35°	39.9752	40.1031	38.2640
9	40°	39.9707	40.0681	38.7469
10	45°	39.9660	40.0842	38.3411

Table 5. The time used by the three algorithms in pose measurement

Serial No.	Position of Target (°)	The algorithm proposed in this paper, ms	The algorithm proposed in this paper without initial value obtained, ms	Least squares algorithm, ms
1	0	0.526	0.700	0.654
2	5	0.189	0.687	0.540
3	10	0.194	0.573	0.528
4	15	0.193	0.464	0.557
5	20	0.181	0.518	0.568
6	25	0.193	0.486	0.533
7	30	0.180	0.364	0.577
8	35	0.184	0.599	0.602
9	40	0.173	0.463	0.637
10	45	0.179	0.573	0.469

The value of d_{12} is 40 mm according to P_{wi}. It can be seen that with the algorithm proposed in this paper the results of d_{12} are more close to the real value.

In order to show the advantage of this algorithm on computation efficiency, in the yaw degree of freedom, the algorithm proposed, least squares algorithm and the algorithm proposed without initial value obtained (without the step in section 2) are used to calculate target pose and the time used by the three algorithms are shown in tab. 5.

The experimental data from tab. 5 has shown that the pose estimation time with the proposed method is least. This indicates that taking the result obtained in the first step (section 2) as an initial value of the iterative process can reduce the number of iterative times to save computation time. Thus, it is reasonable to pass results of the first step to the second step. In addition, the least squares algorithm is more time-consuming, for it does not consider providing an initial value before iteration which slows down the speed of iteration process. This prove that the proposed algorithm is more efficient compared with the other two algorithms. With the condition of same measurement range, the proposed algorithm has a time advantage to identify the pose of object.

CONCLUSIONS

An efficient two-step solution that is able to accurately identify the pose of object with five coplanar points is presented in this paper. Compared with analytical methods the advantage of our algorithm is that the anti-noise ability is strengthened and the result is more stable. The analytical methods are sensitive to noise, because they are more dependent on the accuracy of the feature extraction. But in the method proposed, the feature extraction errors will be canceled or reduced during the iterative process of the second step. Compared with iterative methods, the

advantage of the proposed algorithm is that the calculation time is reduced for the iterative process is given a preferable initial value acquired independently by a direct solution, which enables the algorithm to have a large range of convergence and to be more stable.

This research was supported by the Tianjin application foundation and advanced technology research program (the youth fund project), No.14JCQNJC05500.

This research was supported by the Innovation Team Training Plan of Tianjin Universities and Colleges (grant no. TD12-5043).

This research was supported by the National Natural Science Foundation of China (No.11302149).

This research was supported by the Tianjin application foundation and advanced technology research program (the youth fund project), No. 15JCQNJC02400.

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