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Iterative weighted algorithm for 9-dof pose solution and its application

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Iterative weighted algorithm for 9-dof pose solution and its application

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Abstract: Nine-axis motion parameters need to be calculated according to the relative pose to be simulated when the precision calibration test of rendezvous and docking optical imaging sensor is carried out with nine-degree of freedom motion simulator. Based on the structural characteristics of the system and the principle of homogeneous coordinate transformation, the inverse kinematics equations are established in this paper, in order to improve the test efficiency and ensure the accuracy of pose simulation, the iterative algorithm with fixed degrees of freedom was adopted to approximate the solution results, at last, the nine-axis weighting algorithm was used to judge the end of iteration and obtain the solution results of relative pose optimization.

1. Introduction

With the gradual maturity of manned spaceflight technology and the development of space station, space rendezvous and docking technology is playing an increasingly important role. China has made rapid progress in the rendezvous and docking technology, especially in the autonomous rendezvous and docking technology. It has not only fully mastered the rendezvous and docking technology, but also completed the independent research and development and application of all the rendezvous and docking measurement equipment [1].

As the only sensor to measure the relative position and attitude of two aircraft in the final approach stage of the docking process, optical imaging sensor is the key to the success of rendezvous and docking mission [2-4]. The single machine precision calibration is an important step to verify its performance parameters, and in a strict sense, it is necessary to verify the measurement accuracy of all possible relative poses in the process of rendezvous and docking. At present, the precision calibration scheme of optical imaging sensor is to install it on a set of high-precision test equipment, which accurately simulates the relative pose of two aircraft and compares the measurement results with the optical imaging sensor to calibrate its measurement accuracy. The high-precision test equipment is mainly a motion simulation system with 9 or 12 degrees of freedom. A nine-degree-of-freedom motion simulation system was developed by the Fifth Academy of Aerospace Engineering, which sacrificed part of linear motion stroke to achieve higher pose simulation accuracy.

2. Introduction of 9 dof motion simulation system

The composition of the nine-degree-of-freedom motion simulation system developed by the Fifth Academy of Aerospace Engineering is shown in Figure 1, which consists of X, Y and Z straight-line motion systems which are perpendicular to each other, and target three-axis turntable and tracking three-axis turntable which are used to simulate the target aircraft and track the motion attitude of the aircraft respectively.

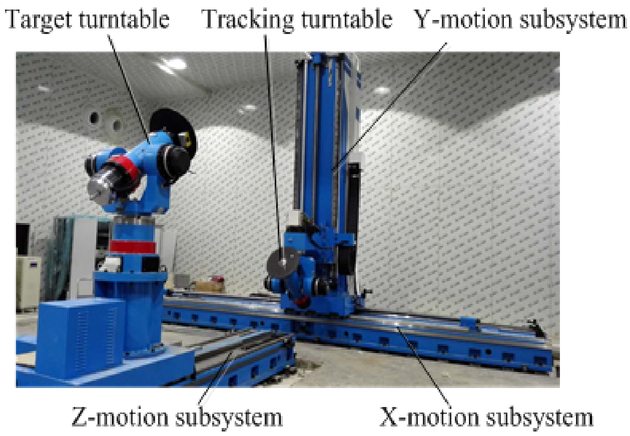

Fig. 1 Constitute of 9 degrees of freedom motion simulation system

According to the need to track vehicle simulation and relative position parameters of the target spacecraft, and the structure characteristics of nine degrees of freedom motion simulation system, choose the nine axis motion parameters optimization, make full use of system redundancy, on the premise of guarantee the posture simulation accuracy, reduce the axis exercise, application of high precision motion degrees of freedom as far as possible, In order to improve the test efficiency and motion simulation accuracy.

3. Mathematical Model

According to the composition characteristics of the nine-degree-of-freedom motion simulation system, a mathematical model of the nine-degree-of-freedom motion simulation system was established based on the homogeneous coordinate transformation theoretical system [7-10].

3.1 Pose transformation matrix

According to the coupling characteristics of the three axes of the three-axis turntable, the rotation sequence is rotation around Y axis (outer frame axis), rotation around X axis (middle frame axis) and rotation around Z axis (inner frame axis), and the translation sequence is not sequential. Using the principle of homogeneous coordinate transformation, the position and pose transformation matrix of the target or tracker after rotation and translation is:

$$T_0 = \begin{bmatrix} \cos(\alpha)\cos(\gamma)+\sin(\beta)\sin(\alpha)\sin(\gamma) & -\cos(\alpha)\sin(\gamma)+\sin(\beta)\sin(\alpha)\cos(\gamma) & \cos(\beta)\sin(\alpha) & x \\ \cos(\beta)\sin(\gamma) & \cos(\beta)\cos(\gamma) & -\sin(\beta) & y \\ -\sin(\alpha)\cos(\gamma)+\sin(\beta)\cos(\alpha)\sin(\gamma) & \sin(\alpha)\sin(\gamma)+\sin(\beta)\cos(\alpha)\cos(\gamma) & \cos(\beta)\cos(\alpha) & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Among them,

α -- The Angle of the outer frame of the three-axis turntable (yaw Angle);

β -- Angle of frame axis in three-axis turntable (pitch Angle);

γ -- Rotation Angle of inner frame of three-axis turntable (rolling Angle);

x -- Translational X-axis parameters;

y -- Translational Y-axis parameters;

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z -- Translational z-axis parameters.

4. Mathematical analysis and simulation

4.1 Input Conditions

According to the test requirements, definitely need simulation of target and tracking the relative pose (based on tracking coordinate system, the target coordinate system of the three Angle transformation parameters and translation transformation parameters), and then get the target and tracking position transformation matrix, and combined with nine degrees of freedom motion simulation system, the mathematical model to solve the inverse kinematic solution, for nine axis motion parameters, namely Six to nine for short.

4.2 Optimization Strategy

The nine degrees of freedom motion simulation system ensures the relative pose relationship between target and tracker by controlling their absolute pose. Through analysis and research, it is very important to reduce the translational position change of the simulator as much as possible to improve the overall accuracy and stability of the system while ensuring the relative posture of the simulator. Subsequently, the optimization strategy of six to nine in static test cases can be found by optimizing the incremental weighted algorithm of nine axes.

4.3 Iterative Algorithm

In order to realize the optimization strategy and make full use of the redundancy of the system, the motion parameters are controlled by fixing different motion degrees of freedom in one iteration cycle, and the kinematic solution accuracy is ensured.

In order to ensure that the motion positions of X and Y axes in the current nine-axis motion parameters are close to those of X and Y axes in the previous set, the iterative method adopted in this paper is shown in Table 1 below.

Table 1 Iterative calculation procedure

The number of iterations	Number of calculations	Target organα_1 β_1 γ_1	trackerα_2 β_2 γ_2	Translation parameters X, Y, Z
0	1	α_{101} β_{101} γ_{101}	**0 0 0** (Fixed degree of freedom)	X_{01}, Y_{01}, Z_{01}
1	2	$\boldsymbol{\alpha_{112}}$ $\boldsymbol{\beta_{112}}$ $\boldsymbol{\gamma_{112}}$ (Fixed degree of freedom)	α_{212} β_{212} γ_{212}	$\boldsymbol{X_{12}, Y_{12}}$ (Fixed degree of freedom) Z_{12}
	3	α_{113} β_{113} γ_{113}	$\boldsymbol{\alpha_{213}}$ $\boldsymbol{\beta_{213}}$ $\boldsymbol{\gamma_{213}}$ (Fixed degree of freedom)	X_{13}, Y_{13}, Z_{13}
Determine if the iteration is over				
2	4	$\boldsymbol{\alpha_{124}}$ $\boldsymbol{\beta_{124}}$ $\boldsymbol{\gamma_{124}}$ (Fixed degree of freedom)	α_{224} β_{224} γ_{224}	$\boldsymbol{X_{24}, Y_{24}}$ (Fixed degree of freedom) Z_{24}
	5	α_{125} β_{125} γ_{125}	$\boldsymbol{\alpha_{224}}$ $\boldsymbol{\beta_{224}}$ $\boldsymbol{\gamma_{224}}$ (Fixed degree of freedom)	X_{25}, Y_{25}, Z_{25}
Determine if the iteration is over……				

X0 and Y0 are the calculation results of motion parameters of X and Y axes in the upper group of nine-axis data. The optimization strategy of this solution is that motion parameters of X and Y axes are as close to X0 and Y0 as possible.

The first calculation: the tracker's three-axis rotation Angle is fixed at 0°, and the three-axis rotation and motion parameters of the target are solved.

The first calculation of the first iteration cycle: Target fixed calculation result for the last three axis Angle, X, Y axis fixed values X12, Y12 translational parameters, based on a set of nine axis X, Y axis parameters in the data (X0, Y0) and the last results X01, Y01 jointly set (see 2, 3), calculating tracker three axis Angle and the Z axis translation parameters (regardless of the X, Y axis decoding error);

$$X_{12} = a_0 \bullet X_0 + a_1 \bullet X_{01} \tag{2}$$

$$Y_{12} = b_0 \bullet Y_0 + b_1 \bullet Y_{01} \tag{3}$$

According to the specific values of parameters A0, A1, b0 and b1, the convergence rate and convergence rate of the iteration should be determined $a_0 + a_1 = 1$, $b_0 + b_1 = 1$. The second calculation of the first iteration cycle: the fixed trackers' three-axis rotation is the last calculation result, and the three-axis rotation and motion parameters of the target are solved.

Judge whether the iteration is over: Set the weight of each axis, and judge whether the iteration is over after each iteration cycle according to the nine-axis weighting algorithm and the end condition of iteration. The nine - axis weighting algorithm is as follows.

$$\begin{aligned} A = {} & \Delta_{\alpha_1} \bullet |\alpha_{11} - \alpha_{10}| + \Delta_{\beta_1} \bullet |\beta_{11} - \beta_{10}| + \Delta_{\gamma_1} \bullet |\gamma_{11} - \gamma_{10}| + \Delta_{\alpha_2} \bullet |\alpha_{21} - \alpha_{20}| + \Delta_{\beta_2} \bullet |\beta_{21} - \beta_{20}| + \\ & \Delta_{\gamma_2} \bullet |\gamma_{21} - \gamma_{20}| + \Delta_{\mathrm{X}} \bullet |\mathrm{X}_1 - \mathrm{X}_0| + \Delta_{\mathrm{Y}} \bullet |\mathrm{Y}_1 - \mathrm{Y}_0| + \Delta_{\mathrm{Z}} \bullet |\mathrm{Z}_1 - \mathrm{Z}_0| \end{aligned} \tag{4}$$

Where A -- nine-axis weighted value;

Δ -- The total weight of each axis is 1, which is determined according to the optimization strategy. In this case, the rest are 0;

$|\alpha_{11} - \alpha_{10}|$ -- Absolute value of target yaw Angle increment, and the same for others;

5. Result

Aiming at the static calibration test condition, the above optimization strategy and iterative algorithm were adopted to solve the nine-axis parameters. After each axis moved to the corresponding position according to the nine-axis parameters, the laser tracker was used to detect the actual relative pose. The test process is shown in the figure.

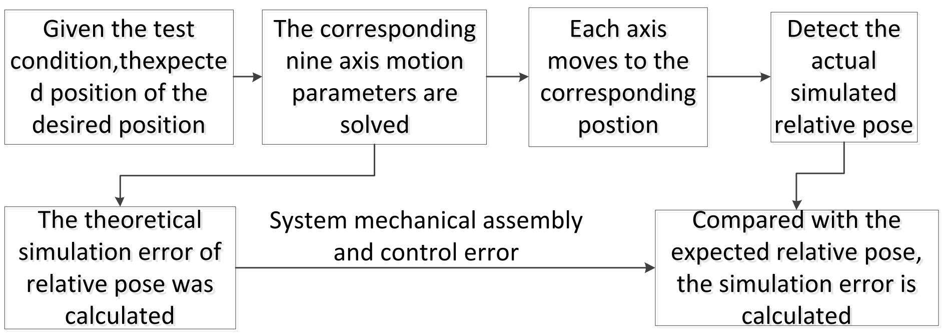

Fig.2 Test flow

5.1 Results of theoretical solution

Such a solution method can effectively limit the motion increment of X and Y axes, carry out kinematic forward calculation on the parameters of nine axes, and compare them with the expected value of relative pose. It is concluded that the error of Angle solution is 10-6°, and the error of position solution is 10-4mm, as shown in FIG. 3 and FIG. 4. The corresponding angular motion parameters become larger, the maximum input Angle is 8°, and the calculated rotational momentum is 16°.

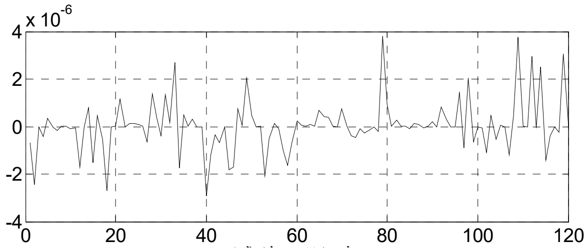

Fig. 3 Angle calculation error

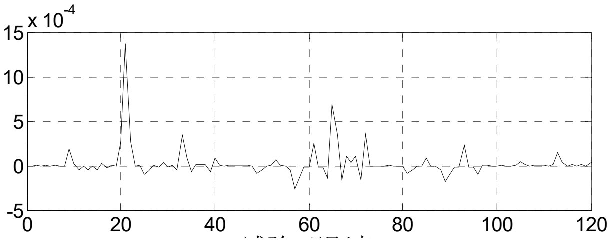

Fig. 4 Translation calculation error

5.2 Actual test results

Calculated in accordance with the nine shaft parameters, control of nine degrees of freedom movement simulation system, the actual measurement by laser tracker simulate relative position compared with expectations, on the one hand, further verify the nine calculating precision of the axis decoding algorithm, on the other hand the system level verification the posture of the nine degrees of freedom motion simulation system simulation accuracy. FIG. 5 shows the field measured photos of the relative position and pose of the two turntables, FIG. 6 shows the measured error of the relative Angle, and FIG. 7 shows the measured error of the relative position.

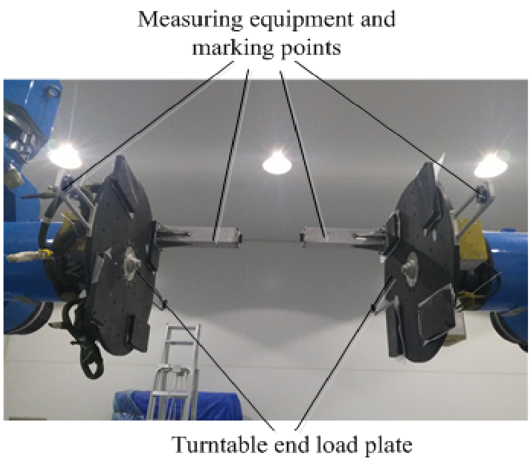

Fig. 5 Field measurement

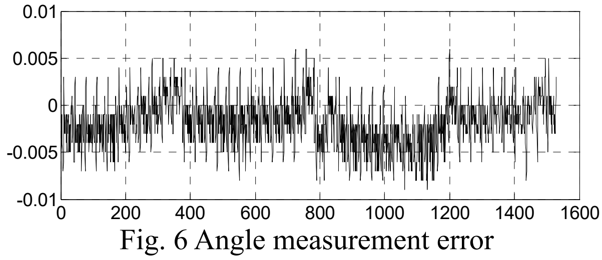

Fig. 6 Angle measurement error

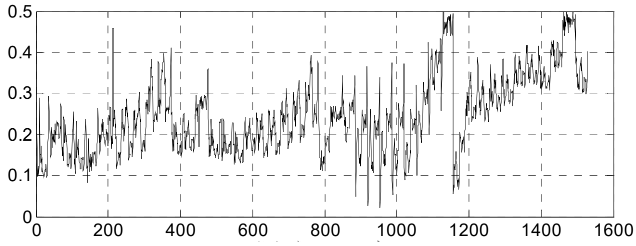

Fig.7 Translation measurement error

The errors in the system physical model mainly come from the mechanical adjustment error, control error and detection error, etc. The measurement shows that the relative position simulation accuracy of the nine-dOF motion simulation system is better than 0.5mm, and the relative attitude simulation accuracy is better than 0.01°.

6. Conclusion

In this paper, a nine-degree-of-freedom pose solution algorithm is derived. In the analysis of static working conditions, the method of fixing different degrees of freedom is adopted to realize the control of corresponding degrees of freedom, mainly for the purpose of reducing the movement increment of the translational system. By iterative optimization and selecting the initial value of iteration, the optimization results of pose solution are gradually approximated. Finally, the weighted algorithm was used to judge the end of iteration, which not only realized the optimization strategy but also ensured the computational accuracy. The iterative weighting algorithm is described as below:

(1) In the last solution of each iteration cycle, the freedom degree must be greater than or equal to 6 to ensure the solution accuracy;

(2) When the translational motion is reduced, the rotation Angle of the turntable is increased, and the optimization strategy can be changed according to different system precision characteristics;

(3) Subsequently, the nine-axis weighting algorithm can be further optimized to achieve accurate control of iteration results.

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