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Surface registration algorithm for rapid detection of surface thermal deformation of paraboloid antennas①

Ma Kaifeng(马开锋)②***, Huang Guiping*, Hu Qingfeng***, He Peipei*
(* School of Resources and Environment, North China University of Water Resources and Electric Power, Zhengzhou 450045, P. R. China)
(** Henan Engineering Laboratory of Pollution Control and Coal Chemical Resources Comprehensive Utilization, Zhengzhou 451191, P. R. China)

Abstract

In order to obtain and master the surface thermal deformation of paraboloid antennas, a fast iterative closest point (FICP) algorithm based on design coordinate guidance is proposed, which can satisfy the demands of rapid detection for surface thermal deformation. Firstly, the basic principle of the ICP algorithm for registration of a free surface is given, and the shortcomings of the ICP algorithm in the registration of surface are analysed, such as its complex computation, long calculation time, low efficiency, and relatively strict initial registration position. Then an improved FICP algorithm based on design coordinate guidance is proposed. Finally, the FICP algorithm is applied to the fast registration test for the surface thermal deformation of a paraboloid antenna. Results indicate that the approach offers better performance with regard to fast surface registration and the algorithm is more simple, efficient, and easily realized in practical engineering application.

Key words: paraboloid antenna, surface thermal deformation, ICP algorithm, fast iterative closest point (FICP) algorithm, surface registration

0 Introduction

Based on the performance and practical requirements of space satellite missions, larger paraboloid antennas are used in satellite antennas. The paraboloid antenna has the advantages of high relative gain, low side-lobes, and high reliability, so it is one of the most widely used antenna shapes for all kinds of satellites. Due to the long signal transmission distances involved, which result in weak signal intensities, it is often required that the satellite antenna should have higher surface precision and larger aperture, so that relatively weak satellite signals can be received and transmitted. Therefore, the surface precision of a satellite antenna can be used to indicate the quality of antenna and its performance when the aperture of the satellite antenna is fixed. When in orbit, the antenna surface will produce certain surface deformation in vacuum environment with alternating action of hot and cold, which may affect the reliability and accuracy of satellite antenna when sending and receiving signals and even the reliability and safety of the whole satellite system. Therefore, before a satellite is launched into orbit, it must be tested on the ground in a simulated space environment according to the relevant test standards for thermal deformation measurement and calculation to verify design and manufacturing quality of aerospace products[1], and to master the quality and surface deformation of antenna, thus providing a reliable basis for ensuring the normal working of the satellite antenna, while making it easy to optimise and improve antenna structures, materials, etc. The surface deformation of satellite antennas is usually evaluated by surface precision. Therefore, surface precision index is used and it is usually obtained through surface registration of point-cloud data.

Many researchers have investigated the point-cloud data registration technology since 1980s. Besl and Chen,[2,3] et al. proposed a high-level registration method based on free-form surfaces in 1992, known as iterative closest point (ICP). ICP method is widely used in various registrations because of its strong adaptability and high registration precision. The least squares matching principle is used and iteratively calculated until a certain convergence limit is reached;

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② To whom correspondence should be addressed. E-mail: makf@163.com
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but, it also has four obvious disadvantages: complex calculation, long calculation time, low efficiency, and a relatively strict initial position of registration requirement. In view of the shortcomings of ICP method, scholars have improved and optimised it to some extent. Therefore, an improved accurate registration algorithm[4] based on ICP has been developed. For example, an ICP improved algorithm[5] based on curvature feature points, and an accurate registration method based on various methods for searching for nearest point are available[6-9]. Other methods[10] are introduced from simplex perspectives, and 3-d Delaunay sub-division is used to find the nearest point, but the efficiency of dealing with massive datasets remains relatively low.

In view of the strict requirements on the initial position in ICP method, researchers have proposed the idea of using coarse registration to find the initial position before precise registration. In the coarse registration algorithm, the most important methods are the central coincidence method[11], the label method[12], the feature extraction method[13], the algebraic surface model method[14], the principal curvature method[15], the principal component analysis method[16], the traversal search method based on random sampling consistency[17], the genetic algorithm[18], and so on. In short, each method has its own characteristics and advantages, according to point-cloud data characteristics and registration requirements, and the most appropriate method should be chosen.

At present, there has been a great deal of work done on point-cloud data registration, especially using the ICP algorithm and its improvement, with encouraging results, however, most of the aforementioned methods are aimed to the optimisation for the application. Therefore, known information should be combined with the ICP algorithm to realise rapid, high-precision, surface registration with large datasets.

1 Basic principles of ICP algorithm for free surface registration

ICP algorithm can solve the transformation matrix $\boldsymbol{R}$ and translation vector $\boldsymbol{T}$ between the measured data and the CAD model data, so that the two sets of point-cloud data meet the optimal fitting registration under certain criteria. Let V represent the CAD model data and P the object data: both can be either spatial point-cloud data, or some surface model.

Let p_i ($i = 1, 2, 3, \cdots, n$) denote the coordinates of any point on the object, v_i ($i = 1, 2, 3, \cdots, n$) denote the model coordinate point corresponding to the object point. To fit them, the initial value of the registration transformation between the object $P = \{p_1, p_2, \cdots, p_n\} \subset \boldsymbol{R}^3$ and model $V = \{v_1, v_2, \cdots, v_n\}$ should be given first, that is, the rotation transformation matrix $\boldsymbol{R}$ and the translation vector $\boldsymbol{T}$ should be defined based on existing information. Assuming that the corresponding set of points obtained in the kth iteration calculation is expressed as $V^k = \{v_1^k, v_2^k, \cdots, v_n^k\} \subset \boldsymbol{R}^3$, the conversion matrix between calculated object data P and V^k is updated again until the objective function of Eq. (1) is minimised.

$$e(k) = \sum_{i=1}^{n} \{[\boldsymbol{R}^k p_i + \boldsymbol{T}^k] - v_i\}^2 = \min \tag{1}$$

The specific solving steps are as follows.

1) Rotation matrix $\boldsymbol{R}^0$ and translation matrix $\boldsymbol{T}^0$ are respectively initialised as the unit matrix and the zero matrix.

2) Theoretical point v_i^0 ($i = 1, 2, \cdots, n$) on the free surface corresponding to measured data point p_i^0 ($i = 1, 2, \cdots, n$) is initialized, and the number of iterations is $k = 0$.

3) Calculate deviation $e(k = 0)$ between the measured point p_i and the theoretical free surface:

$$e(k = 0) = \sum_{i=1}^{n} \{[\boldsymbol{R}^0 p_i + \boldsymbol{T}^0] - v_i^0\}^2 \quad k = k + 1 \tag{2}$$

4) Calculate the theoretical point v_i^k ($i = 1, 2, \cdots, n$) on a free surface.

5) Translation matrix $\boldsymbol{T}$ and transformation matrix $\boldsymbol{R}$ are updated using the calculated $\boldsymbol{T}^{k-1}$, $\boldsymbol{R}^{k-1}$, and v_i^k, respectively, and $\boldsymbol{T}^k$ and $\boldsymbol{R}^k$ are obtained.

6) Calculate and update measured point $p_i^k = \boldsymbol{R}^k p_i^0 + \boldsymbol{T}^k$.

7) Again calculate deviation $e(k)$ between p_i^k and the theoretical free surface:

$$e(k) = \sum_{i=1}^{n} \{[\boldsymbol{R}^k p_i + \boldsymbol{T}^k] - v_i^k\}^2 \tag{3}$$

8) Compare the results of the iteration. If $|e(k-1) - e(k)| \geqslant \varepsilon$ (ε is the convergence threshold), then return to Step 7). If $|e(k-1) - e(k)| < \varepsilon$, the iteration calculation is ended. $R(k)$ and $T(k)$ are stored. In the iterative computation process, $k < M$ ($M > 50$) is generally required, in which M is the limitation of the number of iteration, preventing the number of iteration from being excessive or diverging.

The essence of the registration is to calculate the transformation parameters between p and v^k by the optimal analytic calculation, and the optimal registration parameters are obtained by iterative calculation. In each iteration step, the corresponding process in the matching spatial data model is as follows:

Let the two spatial data sets corresponding to the matching points be $P = \{p_1, p_2, \cdots, p_n\}$, $v^k = \{x_1^k, x_2^k, \cdots, x_n^k\}$, only consider the rigid transformation relationship between them, that is, $v_i^k = \boldsymbol{R}p_i + \boldsymbol{T}$. The objective function of the calculation is to seek the optimal rotation matrix $\boldsymbol{R}$ and translation matrix $\boldsymbol{T}$, so that the function

$$f(\boldsymbol{R},\boldsymbol{T}) = \sum_{i=1}^{n} \{v_i^k - (Rp_i + \boldsymbol{T})\}^2 = \min \quad (4)$$

After each iteration, the transformation matrix is obtained and the new data sets are calculated, which are used as the input parameters for the next iteration. The iteration is repeated until the error convergence is less than the given threshold. Among them, rotation matrix $\boldsymbol{R}$ and translation matrix $\boldsymbol{T}$ can be solved by the unit quaternion method[19-22].

2 Fast iterative closest point (FICP) algorithm

To obtain the surface deformation of paraboloid antenna in a high-low temperature environment, it is necessary to fit the free surface of the satellite antenna to evaluate the surface quality and performance of the satellite antenna. Due to some of the design coordinate values of satellite antenna surface CAD model have been given, considering the high-low temperature surface deformation caused by the design coordinate scaling characteristics. To determine the initial value of accurate registration, some known design coordinates information is used to calculate the registration results between the measured data and the CAD model by seven-parameter conversion method. The improved ICP algorithm is used to accelerate its registration calculation convergence rate which is defined as the FICP free surface registration algorithm based on the design coordinate guidance.

2.1 Seven-parameter coordinate transformation method for initial value

The existing rough registration algorithm is used in the process of seeking the initial value of the registration, but there are some shortcomings or deficiencies, such as registration overlap, rotation dislocation, low computational efficiency, etc. In view of the characteristics of the object, the known information, and the particularity of the high-low temperature environment, a seven-parameter coordinate transformation method with a scale factor is used to solve the initial value of the fitting registration which is faster, more efficient, more accurate and more reliable.

Three-dimensional coordinate transformation is usually undertaken by using the Bursa seven-parameter model:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \lambda \boldsymbol{R} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \quad (5)$$

where (X, Y, Z) are the surface coordinates of the satellite antenna in the close-range photogrammetric coordinate system, (x, y, z) are the model coordinates in the design coordinate system, $\boldsymbol{R}$ is the orthogonal rotation matrix (consisting of three rotation angles), λ is the ratio (or scale) factor coefficient, $(\Delta X, \Delta Y, \Delta Z)$ is the amount of translation between the two coordinate systems. The seven parameters of coordinate transformation can be solved according to Eq. (5) by the known part of the design coordinates and the measured point coordinates; however, in view of the characteristics of the object and the particularity of the known design coordinates (the position distribution is not good on the antenna feed), the unit quaternion method can be used to solve the rotation and translation vector, so as to obtain stable and reliable results. The relevant solution given by the unit quaternion method is described in detail in the literature[19-22].

2.2 Fast iterative closest point (FICP) algorithm[22,23]

The common ICP algorithm can meet the precision requirements in the application of fitting registration, but it is quite difficult to get it such as requiring more iterations and offering slow convergence, especially when the data volume is large. It is difficult to meet actual imposed computational demands. Therefore, it is necessary to improve the conventional ICP algorithm to speed up the calculation convergence.

A unit quaternion method is used to optimise the calculation of the registration parameters. The FICP algorithm is formed by modifying the search and registration strategy of the multivariate unconstrained minimisation problem of the objective function in the iterative calculation. In the process of fitting registration, a series of registration state vectors are generated: $\bar{v}_1, \bar{v}_2, \bar{v}_3, \cdots$, these vectors form a trajectory in the optimised registration state space.

If the number of iteration is k, the results of the last two iterations produce a trend vector sequence in the registration state space: $\Delta\bar{v}_k = \bar{v}_k - \bar{v}_{k-1}$, $\Delta\bar{v}_{k-1} = \bar{v}_{k-1} - \bar{v}_{k-2}$, the angle between the last two trend vectors is

$$\beta_k = \cos^{-1}\left(\frac{\Delta\bar{v}_k \Delta\bar{v}_{k-1}}{\| \Delta\bar{v}_k \| \times \| \Delta\bar{v}_{k-1} \|}\right) \quad (6)$$

If the calculated angles β_k and β_{k-1} are both smaller than a sufficiently small angle limit, it is considered that the direction of the three registered state vectors $\bar{v}_k, \bar{v}_{k-1}, \bar{v}_{k-2}$ is more consistent. Let d_k, d_{k-1}, d_{k-2} denote the root mean square error (RMSE) of the measured point to the free surface distance (objective function) from the last three iterations respectively, and w_k, w_{k-1}, w_{k-2} are the approximate arc lengths of the iterative computational vector space respectively, which can be obtained:

$$w_k = 0, \quad w_{k-1} = \| \Delta \bar{v}_k \|, \quad w_{k-2} = - \| \Delta \bar{v}_{k-1} \| + w_{k-1} \tag{7}$$

The three sets of data obtained above can constitute their linear approximation and parabolic interpolation model:

$$\begin{cases} d_1(w) = a_1 w + b_1 \\ d_2(w) = a_2 w^2 + b_2 w + c_2 \end{cases} \tag{8}$$

The zero-intercept linear correction coefficient and the parabolic correction coefficient near the extremum can be obtained respectively:

$$\begin{cases} w_1 = b_1 / a_1 \quad (>0) \\ w_2 = - b_2 / (2a_2) \end{cases} \tag{9}$$

Then, the maximum allowable correction factor $w_{\max} = N \| \Delta \bar{v}_k \|$ is set, N is generally 20 – 40, which is selected according to actual conditions. For registration, the state vectors are updated as follows:

1) If the relationship $0 < w_2 < w_1 < w_{\max}$ or $0 < w_2 < w_{\max} < w_1$ is used, the registration state vector is modified by parabola correction:

$$P_{k+1} = \bar{v}_k (P_0) \tag{10}$$

where,

$$\bar{v}_k = \bar{v}_k + w_2 \times \Delta \bar{v}_k / \| \Delta \bar{v}_k \| \tag{11}$$

2) If there is relationship $0 < w_1 < w_2 < w_{\max}$ or $0 < w_1 < w_{\max} < w_2$, or $w_2 < 0$ and there is $0 < w_1 < w_{\max}$, the registration state vector is updated by linear correction:

$$\bar{v}_k = \bar{v}_k + w_1 \times \Delta \bar{v}_k / \| \Delta \bar{v}_k \| \tag{12}$$

3) If the two relationships $w_1 > w_{\max}$ and $w_2 > w_{\max}$ are simultaneously established, the registration state vector is updated with the maximum allowable correction method:

$$\bar{v}_k = \bar{v}_k + w_{\max} \times \Delta \bar{v}_k / \| \Delta \bar{v}_k \| \tag{13}$$

The FICP algorithm is based on the trend of the last few attempted fits to the registration vector space, and is constantly updated to change the direction of the space vector fitting registration, so as to improve the iterative speed of the ICP algorithm, and this acceleration effect is attained for the benefit of the fit registration process.

3 Experiments and analysis

The Chenway MPS/S36 industrial photogrammetry system is adopted for the experimental data acquisition. The system is mainly composed of the high-resolution photographic camera with the CCD pixels of 7360 × 4912 and 24.5mm fixed-focus lens, length calibration scale-bar, Retro-reflective Target (RRT), system software, and so on, which has spatial measuring precision with 0.020mm@3m. The system uses the camera to capture the antenna surface two pieces or pieces of digital images in different positions and orientations: through image pre-treatment, symbol recognition, image matching, spatial triangle intersection, and bundle adjustment, produces the 3-d coordinates (X, Y, Z) of the measured point.

To verify the effect of the proposed algorithm, the experimental data of antenna surface photogrammetry at a high temperature mode (such as 60°C) in high-low temperature test of satellite antenna are chosen as an example. As the satellite antenna surface parameters are designed at normal temperature, the given design coordinates will produce a certain displacement at 60°C with the deformation of the antenna surface. In this case, the results obtained directly using the coordinate transformation method are not accurate, but they can be used as the initial value of the fine registration, which can ensure the reliability of the registration results and accelerate the calculation of the fine registration. To test the computational efficiency and registration precision of FICP algorithm, the computation speed and registration precision of the ICP algorithm are compared and analysed.

3.1 Coarse registration

The initial relative position of the measured data and the CAD model are shown in Fig. 1. According to the actual situation, the eight design coordinates are not-well distributed on the antenna feed, and the seven-parameter coordinate transformation based on the unit quaternion is used to obtain the initial results of the free surface fitting registration. The obtained results are shown in Table 1. Then, the coarse registration results of the measured data and the CAD model can be obtained as shown in Fig. 2. After calculation, the fitting

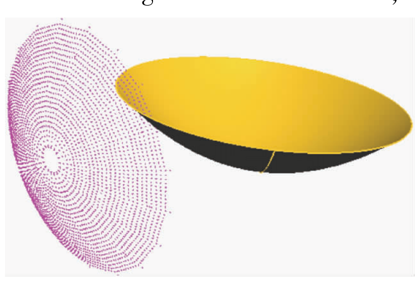

Fig. 1 The relationship diagram for initial position

Table 1 The coordinate conversion parameters

Conversion precision RMS(mm)			Translation parameters (mm)			Rotation parameters(°)			Scale factor
0.021	0.018	0.010	-3181.030	719.817	-551.786	-1.216	0.947	-2.703	0.999876

alignment normal deviation surface precision RMS is 0.48mm, and the fitting registration normal error distribution is shown in Fig. 3.

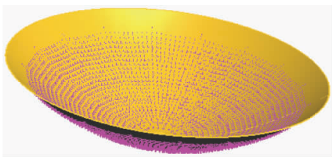

Fig. 2 Results of coarse registration

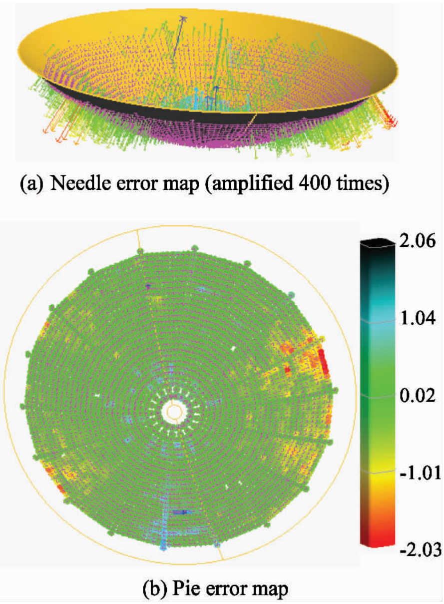

Fig. 3 Error distribution of coarse registration

3.2 Fine registration

The coordinate transformation parameters obtained by coarse registration processing are used as the initial values of fine registration. The ICP algorithm and the FICP algorithm are used for the fitting registration of the free surface respectively. The convergence limit for iterative computation is set to 0.00001. Since the initial values are more accurate, the free surface registration process can be completed after a relatively fast iterative calculation. The results of the translation parameters and the rotation parameters are −0.31mm, −0.24mm, 0.03mm and −0.0033°, 0.0017°, −0.0046° respectively. The specific results are shown in Table 2 and Fig. 4.

The results of coarse registration show that the precision of fitting registration is relatively high, and it

Table 2 Comparison of the results of ICP and FICP

Algorithm	ICP	FICP
No. of iterations	63	8
Registration precision RMS (mm)	0.4512	0.4511

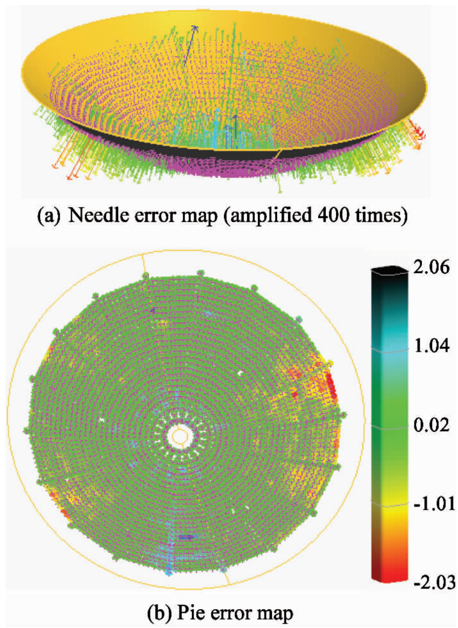

Fig. 4 Error distribution of fine registration

provides a better initial value for subsequent fine registration. Therefore, the computation speed of ICP algorithm and FICP algorithm are greatly improved, and the convergence calculation and registration process can be completed after fewer iterations. Moreover, from the number of iterations, it can be seen that the computating speed of the FICP algorithm is nearly eight times higher than that of the ICP algorithm in this case, thus verifying the performance of the FICP algorithm.

4 Conclusion

An improved fast iterative closest point (FICP) algorithm for rapid detection of surface thermal deformation of paraboloid antenna is presented. This approach combines the existing design coordinate information, simplifies the initial registration process and improves the precision of the initial registration and the initial iteration position of fine registration which enhances the algorithm efficiency. According to the test results, the improved algorithm offers greater efficiency when presented with a large amount of point-cloud coordinate data, which is much more adaptable to surface thermal deformation detection of paraboloid antenna surface of a satellite. At the same time, it lays a foundation for the quality and precision evaluation of the surface thermal deformation of paraboloid antenna surface of a satellite.

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Ma Kaifeng, born in 1978. He received his Ph. D degree from the China University of Mining and Technology in 2016. He received his M. Sc. from the Institute of Geodesy and Geophysics, Chinese Academy of Sciences in 2007. He also received his B. S. degree in engineering survey from the PLA Information Engineering University in 2002. His current research interests include precision engineering and industrial measurement, close-range photogrammetry.