An Estimation Method of Accurate Adjustment of Spacecraft Instruments

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Abstract. Spacecraft instruments require to be assembled and adjustment precisely. In this essay, an estimation algorithm of precise assembly adjustment of Spacecraft instruments in the manufacturing field of satellite assembly. This algorithm, based on measurement data and measuring technology, transforms the estimation of unidirectional spacer adjustment into the form of coordinate system changing so as to realize precise adjustment of orientation of satellite instruments. The implementation method is as follows: According to the value of the actual measurement matrix and the design measurement matrix, the measured global coordinates and the designed global coordinates of each spacer are obtained to establish the spacer adjustment equation. Then, according to the number of the spacers, constraint equation of spacer plane is established to form over-determined set. Spacer adjustment value could be obtained by solving the over-determined set. In case it does not satisfy the standard, repeat the above procedure. This method is more applicable by transforming the adjustment process of the targeted spacer of satellite instrument into three-dimensional coordinate transformation. A three-dimensional coordinate transformation model of precise adjustment of Spacecraft instruments in complex state is established, which overcomes the problem of insufficient practicality of vector algorithm and improves the adjustment efficiency.

1. Introduction
To guarantee that the satellite can work normally during the flight, some instruments on the satellite (such as solar sensors, earth sensors, inertial devices, thrust components, etc.) have strict requirements for installation accuracy, so the final assembly of the Spacecraft equipment is an essential part of satellite assembly. Accurate measurement and adjustment of Spacecraft instrumentation includes mainly precision measurement and fine-tuning, among which precision measurement is the front-loading part of fine-tuning. Satellite design department has put forward strict requirements for installation position and accuracy of the instruments on the satellite. However, in actual assembly process, affected by factors such as machining error and deformation by force, the actual position after installation may exceed the requirements of the overall design department, therefore, it is necessary to take certain adjustment measures and processes to enable the Spacecraft instrument so that the actual installation position could be adjusted within the specified range.
2. Definition of the coordinate system
The star coordinate system of the spacecraft shown in Fig. 1 takes the docking plane A of the satellite and the launch vehicle as the datum plane. For convenience of analysis and measurement, two docking holes that are precisely positioned are distributed on the OZ axis deliberately. The origin point O is at the center of the positioning holes, axis OX is perpendicular to the docking surface, and axis OY in plane A is perpendicular to axis OZ. I, II, III, and IV in Fig. 1 are four quadrant lines (or datum lines) formed by the intersection of the OY and OZ axes on the star and the outside surface of the lower end frame, and on the upper and lower end frames of each compartment of the shell structure, there are engraved four lines on the top as a structural reference for accuracy measurement.

A reference cubic mirror of the star is installed on the docking frame which is mounted to the star body, which has three mutually perpendicular mirror surfaces, and the normal lines are defined as the X-axis, the Y-axis and the Z-axis, respectively, whose coordinate system origin is the geometric center point of the cubic mirror. Once the satellite is installed and fixed, the relationship between the start coordinate and the star reference cubic mirror coordinate.

3. Accurate measurement of the satellite
The satellite accuracy measurement is to determine the target position deviation of the tested instrument based on the direction of the normal line of the target mounting surface of the instrument to be tested. At present, the measuring system adopted by fine-tuning satellite assembly department is non-contact large scale measurement system, which could be used to measure the angle and the coordinate value of the target.

Accurate measurement of satellite instruments: The measurement angle can be divided into one-way measurement and two-way measurement. The measured coordinate values can be divided into non-position measurement and position measurement.

One-way measurement measures only the angle of the normal of one reflecting surface of the cubic mirror, while the two-way measurement can measure the angle of the normal of all reflecting surfaces of the cubic mirror. The non-position measurement does not require to obtain the characteristic coordinate values of the satellite device, while the position measurement requires to obtain the characteristic coordinate values of the satellite device. All of the above could interact with one another, which could be summarized into four types, that is, one-way non-position measurement, one-way position measurement, two-way non-position measurement and two-way position measurement, among which one-way non-position measurement is the simplest and two-way position measurement is the most complicated.

As shown in Fig. 2, T1, T2, T3, and T4 are the theodolites required by the test. T1 is collimated with a reflection surface of the star reference cubic mirror, and then T2 is aligned with another reflection surface of the star reference cubic mirror. After the data of the angle is collected, align T1 and T2 to...
determine the reference plane. Keep T1 unmoved, align T3 with a reflection surface of the cubic mirror of the measured target. After the data of the angle is collected, align again it with T1. T4 is aligned with another reflection surface of the cubic mirror of the measured object. Collect the angle data and then align it with T1 again. Keep T1 unmoved, move T2 to appropriate location. T1 and T2 are aligned respectively with the right and left target points of the gauge so as to orient the system and establish the coordinate. Then, T1 and T2 are aligned respectively with the cross-shaped line in the center of the reflection surface of the reference cubic mirror and the target cubic mirror to obtain the space coordinate. After the above operation, the obtained data is processed by the computer to obtain the spatial relationship (position and angle) of the measured target cubic coordinate system and the star reference coordinate system. The spatial relationship between the star reference coordinate system and the star coordinate system can be calibrated.

Adjustment of the satellite instrument is conducted in relative to the star cubic coordinate. The obtained data require several times of coordinate transformation to transmit to the data of the star coordinate system, that is, coordinate system of the target cubic mirror of the measured instrument → coordinate system of star reference cubic mirror → coordinate system of the star. All the data used in the accurate measurement are data of the transformed star coordinate system.

4. Adjustment process of the satellite components
In Fig. 3, ABCD is used for the four reference pins of the target instrument which are installed on the star. The plane formed by these four points is the installation surface of the instrument (the plane to be adjusted). The direction of the normal line of the plane nearly accord with the normal of the reflection surface of the cubic mirror pasted to the instrument surface. It can be seen that by comparing the direction of the reflecting surface of the target cubic mirror with the design value, the offset angle of the measured plane can be obtained. In actual operation, the adjustment direction and the adjustment amount are manually estimated based on the offset angle, which is adjusted by adding corresponding spacers under each reference pin. Since the accurate adjustment amount of each positioning point is undetermined and that it is affected by the difference of the gasket specifications and the force of the parts, the adjustment process becomes a repetitive process of test-adjustment-retest-re-readjustment. To reduce the number of repetitions and to improve the efficiency, the adjustment process should be modeled.
The adjustment can be divided into three types, cross adjustment, vertical adjustment and tilt adjustment. Cross adjustment and vertical adjustment are special types of tilt adjustment.

Vertical adjustment: Vertical adjustment is designed aiming at one-way measurement in accurate measurement of satellite. As shown in Fig. 3, the direction of electronic theodolite aligning the cubic mirror is the adjustment direction of the spacer thickness.

Cross adjustment: Cross adjustment is designed aiming at two-way measurement in accurate measurement of satellite. As shown in Fig. 4, the electronic theodolite aligns two axles of the cubic mirror and the adjustment direction of the spacer thickness is the direction of the third axle, which could be calculated by vector product.

Tilt adjustment: Tilt adjustment is rather complicate, with small proportion in current adjustment. The adjustment direction of the spacer thickness is unparallel to any axial direction.

5. General computation model for adjustment amount

5.1. Model algorithm

Suppose the coordinates of the spacers are coordinates in some local coordinate system (generally the star reference cubic coordinate system). The origin of the cubic mirror coordinate system is located at the geometric center of the cubic mirror, whose three axial directions are perpendicular to three mirrors. Due to the manufacturing error of the mirror surface, it is impossible to achieve absolute verticality, so, orthogonalization processing is required when the cubic mirror coordinate system is constructed.

In the star coordinate system, the theoretical design coordinate matrix of each spacer (represented by homogeneous matrix) is:
Superscript \( W \) in \( \mathbf{P}_{TH}^W \) is the coordinate system of the star, and subscript \( TH \) is the theoretical design value. There are altogether \( i \) spacers, \( i = 1,2,\cdots,N \).

In the target cubic coordinate system of the tested instrument, the theoretical coordinate matrix of each spacer is:

\[
\mathbf{P}_{TH}^L = \begin{pmatrix}
    x_1^L & x_2^L & \cdots & x_i^L & \cdots & x_N^L \\
    y_1^L & y_2^L & \cdots & y_i^L & \cdots & y_N^L \\
    z_1^L & z_2^L & \cdots & z_i^L & \cdots & z_N^L \\
    1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}_{TH} \tag{2}
\]

This value is fixed and known, which is determined by the geometric dimension of the support structure of the cubic mirror. The superscript \( L \) in \( \mathbf{P}_{TH}^L \) is the target cubic coordinate system (local coordinate system) of the tested instrument, and the subscript \( TH \) is the theoretical value.

The theoretical value of the spatial relationship between the star coordinate system and the target cubic coordinate system of the tested instrument is represented by \( \mathbf{M}_{TH} \).

\[
\mathbf{P}_{TH}^W = \mathbf{M}_{TH} \mathbf{P}_{TH}^L \tag{3}
\]

In which, \( \mathbf{M}_{TH} \) is 4-order homogeneous matrix, which could be obtained by calculation.

\[
\mathbf{M}_{TH} = \begin{pmatrix}
    l_1 & l_2 & l_3 & t_1 \\
    m_1 & m_2 & m_3 & t_2 \\
    n_1 & n_2 & n_3 & t_3 \\
    0 & 0 & 0 & 1
\end{pmatrix} \tag{4}
\]

\( OX, OY, OZ \) are three coordinate axes of the start coordinate system, \( O'X', O'Y', O'Z' \) are three axes of the target cubic coordinate system of the tested instrument. Table 1 represents the spatial relationship between two coordinate systems.
Table 1. Spatial relationship between the star coordinate system and the target cubic coordinate system of the tested instrument

|    | OX | OY | OZ |
|----|----|----|----|
| O'X' | $l_1$ | $m_1$ | $n_1$ |
| O'Y' | $l_2$ | $m_2$ | $n_2$ |
| O'Z' | $l_3$ | $m_3$ | $n_3$ |
| Centre | $t_x$ | $t_y$ | $t_z$ |

$M_{ME}$ Could be obtained in accurate measurement of the satellite, which represents the spatial relationship between the star coordinate system and the actually measured state of the measured cubic coordinate system. The actually measured coordinate value of the spacers in the star coordinate system is:

$$L_{THME}^W = ME^W ME P_{MP}^W$$

Where, $ME^W$ is the adjustment matrix of the spacer.

$$P_{ME}^W = M_{ME} P_{TH}^L$$

Where, $P_{ME}^W$ =

$$\begin{pmatrix}
X_1^W & X_2^W & \cdots & X_i^W & \cdots & X_N^W \\
Y_1^W & Y_2^W & \cdots & Y_i^W & \cdots & Y_N^W \\
Z_1^W & Z_2^W & \cdots & Z_i^W & \cdots & Z_N^W \\
1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}_{ME}$$

In case it could be guaranteed the Spacecraft instrument is installed to place, it should be guaranteed $P_{ME}^W \rightarrow P_{TH}^W$, it could be obtained that:

$$P_{ME}^W + AD = P_{TH}^W$$

Where, AD is the adjustment matrix of the spacer.

$$AD = \begin{pmatrix}
D_1 \cos \alpha & D_2 \cos \alpha & \cdots & D_i \cos \alpha & \cdots & D_N \cos \alpha \\
D_1 \cos \beta & D_2 \cos \beta & \cdots & D_i \cos \beta & \cdots & D_N \cos \beta \\
D_1 \cos \gamma & D_2 \cos \gamma & \cdots & D_i \cos \gamma & \cdots & D_N \cos \gamma \\
0 & 0 & \cdots & 0 & \cdots & 0
\end{pmatrix}$$

Set the adjustment height of the spacer is $D_i, D_2, \cdots D_i (i = 1, 2, \cdots, N)$.

From equation (4), it could be obtained that:
\[
\begin{pmatrix}
    x_1^w & x_2^w & \ldots & x_j^w & \ldots & x_N^w \\
    y_1^w & y_2^w & \ldots & y_j^w & \ldots & y_N^w \\
    z_1^w & z_2^w & \ldots & z_j^w & \ldots & z_N^w \\
\end{pmatrix}
\begin{pmatrix}
    1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}
\]

\[
\begin{pmatrix}
    D_1 \cos \alpha & D_2 \cos \alpha & \ldots & D_j \cos \alpha & \ldots & D_N \cos \alpha \\
    D_1 \cos \beta & D_2 \cos \beta & \ldots & D_j \cos \beta & \ldots & D_N \cos \beta \\
    D_1 \cos \gamma & D_2 \cos \gamma & \ldots & D_j \cos \gamma & \ldots & D_N \cos \gamma \\
    0 & 0 & \ldots & 0 & \ldots & 0 \\
\end{pmatrix}
\begin{pmatrix}
    1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}
\]

\[(8)\]

\[
\begin{pmatrix}
    D_1 \cos \alpha & D_2 \cos \alpha & \ldots & D_j \cos \alpha & \ldots & D_N \cos \alpha \\
    D_1 \cos \beta & D_2 \cos \beta & \ldots & D_j \cos \beta & \ldots & D_N \cos \beta \\
    D_1 \cos \gamma & D_2 \cos \gamma & \ldots & D_j \cos \gamma & \ldots & D_N \cos \gamma \\
    0 & 0 & \ldots & 0 & \ldots & 0 \\
\end{pmatrix}
\begin{pmatrix}
    1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}
\]

\[
\begin{pmatrix}
\cos \alpha \\
\cos \beta \\
\cos \gamma
\end{pmatrix}
= \begin{pmatrix}
l_1 & l_2 & l_3 \\
m_1 & m_2 & m_3 \\
n_1 & n_2 & n_3
\end{pmatrix}
\begin{pmatrix}
\cos \alpha' \\
\cos \beta' \\
\cos \gamma'
\end{pmatrix}
\]

\[(9)\]

\[
\begin{pmatrix}
    D_1 \cos \alpha & D_2 \cos \alpha & \ldots & D_j \cos \alpha & \ldots & D_N \cos \alpha \\
    D_1 \cos \beta & D_2 \cos \beta & \ldots & D_j \cos \beta & \ldots & D_N \cos \beta \\
    D_1 \cos \gamma & D_2 \cos \gamma & \ldots & D_j \cos \gamma & \ldots & D_N \cos \gamma \\
    0 & 0 & \ldots & 0 & \ldots & 0 \\
\end{pmatrix}
\begin{pmatrix}
    1 & 1 & 1 & 1 & 1 & 1
\end{pmatrix}
\]

\[
\begin{pmatrix}
\cos \alpha \\
\cos \beta \\
\cos \gamma
\end{pmatrix}
= (M_{TH} - M_{ME}) \mathbf{P}_{TH}^I
\]

\[(10)\]

Equation (10) is the adjustment equation, from which it could be seen that there are altogether \(N\) unknown numbers \(D_i (i = 1, 2, \ldots, N)\) and 3 equations.
It is required all spacers are on the same plane, which is guaranteed by the following equation:

\[
\begin{vmatrix}
  x_i - x_j & y_i - y_j & z_i - z_j \\
  x_j - x_k & y_j - y_k & z_j - z_k \\
  x_i - x_k & y_i - y_k & z_i - z_k 
\end{vmatrix} = 0
\]  

(11)

For any value, \( i \leq N \); \( j \leq N \) and \( j \neq i \); \( k \leq N \), \( k \neq i \) and \( k \neq j \); \( l \leq N \), \( l \neq i \), \( l \neq j \) and \( l \neq k \).

Formula (12) is constraint equation, from which it could be seen that if there are four spacer points, there is 1 equation in formula (12); if there are five spacer points, there are 4 equations in formula (12); if there are six spacer points, there are 10 equations in Formula (12). If there are \( \binom{i}{i} > 4 \) spacer points, there are \( \binom{C_{i-1}}{3} \) equations in formula (12).

Overdetermined equations is formed by formulas (10) and (12), and the least square solution \( \{ N_i D_1, \ldots, 2, 1 \} \) could be solved.

5.2. Explanation of the adjustment

After \( \{ N_i D_1, \ldots, 2, 1 \} \) is solved, the symbols of the solution may be different symbols, which could be analyzed as follows:

(a) In case \( \{ N_i D_1, \ldots, 2, 1 \} \) is positive, \( \{ N_i D_1, \ldots, 2, 1 \} \geq 0 \), \( i = 1, 2, \ldots, N \), the adjustment value of the spacer is \( D_i, i = 1, 2, \ldots, N \), when the theoretically value of the equipment direction and the position could be adjusted.

(b) In case \( \{ N_i D_1, \ldots, 2, 1 \} \) is different, \( \{ N_i D_1, \ldots, 2, 1 \} \leq 0 \), \( i = 1, 2, \ldots, N \), which could not guarantee the instrumentation direction and position could meet the requirements. Generally, in terms of actual use requirements, adjustment of the direction is in the first place, and the adjustment of the coordinate is in the second place. In case the direction is guaranteed, set \( D = \text{Abs} (\min (D_i, D_{i+1}, \ldots, D_N)) \), the adjustment value of each point is \( D_i = D_i + D, i = 1, 2, \ldots, N \).

(c) In case \( \{ N_i D_1, \ldots, 2, 1 \} \) is negative, that is, \( \{ N_i D_1, \ldots, 2, 1 \} \leq 0 \), \( i = 1, 2, \ldots, N \), which also could not guarantee that the target direction and position of the instrument could meet the requirement.

In the process of adjusting the target assembly of the spacecraft instrument, there are two criteria to be tested:

1. The normal direction of the plane consisting of N spacers is close to the theoretical plane (within certain error scope), and it is not required to check the target spatial position of the tested instrument.
2. The coordinate of the central point of the tested instrument is close to the theoretical design value (within certain error scope).

Cases (b) and (c) satisfy criterion (1) and case (a) satisfies the criterion (2).

5.3. Expected value of the adjusted direction

After the adjustment height \( D_i, i = 1, 2, \ldots, N \) of all spacers is determined, the coordinate matrix of the spacer could be renewed as:
After the coordinate of each spacer is updated, the normal direction will also change accordingly is updated to \((l'_i, m'_i, n'_i)\). Suppose the adjustment direction is the X direction.

Since the actual adjustment amount is not large, with the measurement device unmoved, the measuring personnel can quickly retest and obtain the latest measurement matrix \(M_{\text{ME}}\). If the allowable deviation scope is not reached, repeat the previous calculation process. Generally, all adjustments could meet the requirements after one calculation. The allowable deviation of the angle is generally within 1° and the allowable deviation of the position is within 0.2 mm.

5.4. General flow of adjustment calculation

(1) Obtain the theoretical coordinate \(P_{\text{TH}}^W\) of all spacers based on the star theoretical design value, obtain according to the geometrical structure of the support components \(P_{\text{TH}}^L\), and obtain the theoretical measurement matrix by calculation \(M_{\text{TH}}\).

(2) Obtain the measurement matrix \(M_{\text{ME}}\) based on the accurately measured value.

(3) List adjustment equation 6 based on the data of the accuracy measurement matrix.

(4) Get constraint equation 8 based on the characteristics and number of the spacers.

(5) Solve the adjustment height of all spacers \(D_i, i = 1, 2, \ldots, N\).

(6) Update the measurement coordinate \(P_{\text{ME}}^W\) of all spacers.

(7) Measure accurately again and renew the measurement matrix \(M_{\text{ME}}\).

(8) In case the allowable deviation of the design is not satisfied, repeat procedures 1-5.

6. Experimental data and analysis

Three electronic theodolites are adopted to measure a simulation instrument on some satellite model, on which a cubic mirror is mounted. The measurement is conducted in accordance with the flow of two-way measurement.

The theoretical design values and the measured values of the simulated star coordinate system and the cubic mirror coordinate system have been obtained as shown in Table 1 and Table 2. The geometric parameters of the simulated instrument support adjustment bracket are known as shown in Table 3, and the coordinates of all spacers in the cubic mirror coordinate system of the tested instrument are shown in Table 4. The theoretical coordinates of all spacers in the star coordinate system are shown in Table 5, the measured coordinates of all spacers in the star coordinate system are shown in Table 6, and the calculated adjustment amount of all spacers is as shown in Table 7. Retested, the obtained measurement matrix of star coordinate system and the cubic coordinate system of the tested instrument are shown in Table 8. After adjustment, the calculated angle of the adjustment surface of the instrument is shown in Table 9.

| Table 2. Designed value of the relationship matrix between the simulated star coordinate system and the cubic mirror coordinate system |
|-----------------|--------|--------|--------|
| \(X'(\degree)\) | 0.1500 | 90.0000 | 89.8500 |
| \(Y'(\degree)\) | 90.0000 | 0.0000  | 90.0000 |
| \(Z'(\degree)\) | 90.1500 | 90.0000 | 0.1500  |
| Centre          | -205.02| 209.20  | 118.35  |
Table 3. Measured value of the relationship matrix between the simulated star coordinate system and the cubic mirror coordinate system

|     | X    | Y    | Z    |
|-----|------|------|------|
| X'(^\circ) | 0.2545 | 89.7943 | 89.8501 |
| Y'(^\circ) | 90.2057 | 0.2057 | 89.9951 |
| Z'(^\circ) | 90.1499 | 90.0054 | 0.1500 |
| Center   | -205.24 | 209.236 | 118.30 |

Table 4. Angle between the spacer plane normal and the adjustment plane of the measured instrument

|     | \(\alpha'\) | \(\beta'\) | \(\gamma'\) |
|-----|-------------|------------|------------|
| Value (^\circ) | 0 | 90 | 90 |

Table 5. Coordinate of the spacer under the cubic coordinate of the measured instrument

|     | X(mm) | Y(mm) | Z(mm) |
|-----|-------|-------|-------|
| 1   | -80   | 60    | 100   |
| 2   | -80   | -60   | 100   |
| 3   | -80   | -60   | -100  |
| 4   | -80   | 60    | -100  |

Table 6. Theoretical coordinate of the spacer under star coordinate system

|     | X(mm) | Y(mm) | Z(mm) |
|-----|-------|-------|-------|
| 1   | -285.2815 | 269.2 | 218.1402 |
| 2   | -285.2815 | 149.2 | 218.1402 |
| 3   | -284.7579 | 149.2 | 18.1409  |
| 4   | -284.7579 | 269.2 | 18.1409  |

Table 7. The measured coordinate of the spacer under star coordinate system

|     | X(mm) | Y(mm) | Z(mm) |
|-----|-------|-------|-------|
| 1   | -285.7162 | 268.939 | 218.0955 |
| 2   | -285.2854 | 148.9398 | 218.0852 |
| 3   | -284.7622 | 148.9586 | 18.0859  |
| 4   | -285.193 | 268.9578 | 18.0962  |

Table 8. The solved adjustment amount of the spacer

|     | Adjustment amount |
|-----|------------------|
| \(D_1\)(mm) | 0.4358 |
| \(D_2\)(mm) | 0.005  |
| \(D_3\)(mm) | 0.0053 |
| \(D_4\)(mm) | 0.4360 |

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Table 9. The adjusted co values of each spacer ordinate

| X(mm) | Y(mm) | Z(mm) |
|-------|-------|-------|
| 1     | -285.2805 | 268.9405 | 218.0966 |
| 2     | -285.2804 | 148.9398 | 218.0852 |
| 3     | -284.7569 | 148.9586 | 18.0859  |
| 4     | -284.7569 | 268.9594 | 18.0973  |

Table 10. The expected angle of the normal after adjustment

| Direction angle | X' | Y' | Z' |
|-----------------|----|----|----|
|                 | 0.1500 | 90.0000 | 89.8500 |

Table 11. The measured value of the matrix after re-measurement

| X(°) | Y(°) | Z(°) |
|------|------|------|
| X'   | Y'   | Z'   |
|      |      |      |
| 0.1489 | 89.9990 | 89.8560 |
| 90.0003 | 0.0009 | 90.0009 |
| 90.1510 | 90.0012 | 0.1489 |
| Centre | -205.03 | 209.19 | 118.37 |

It could be seen from Table 8 that after simulation computation, the normal of the adjustment surface of the instrument conforms to the design value. From Table 9, it could be seen that after re-measurement, the measured value of the matrix is very close to the design value, with the angular deviation less than 0.001° and the position deviation less than 0.02mm.

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