Star Sensor Calibration Using Fine Guidance Sensor Information for Installation Errors

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Abstract: To correct installation errors of star sensors, we propose an error calibration method based on the measurement information from fine guidance sensors (FGS). This work established an extended Kalman filter model by using the measurement information of FGS as the observation to estimate position errors. Simulation experiments are presented to assess the effectiveness of the proposed star sensor calibration technique, and the results demonstrate the improved error estimation accuracy.

1. Introduction

Star sensor as a high precision astronomical sensor, the measurement accuracy can reach arc-second level[1-2]. However, due to some uncontrollable factors, the installation error of the star sensor can reach angular grading level[3-4]. Therefore, it is necessary to calibrate the installation error of the star sensor.

At present, there are two types of installation errors calibration methods of star sensor[5]. One is to rely on the external reference attitude information, compared with the star-sensitive attitude information to obtain the installation error angle[6-7]. The other type of method is to rely on the measurement information of the star sensor by establish the Kalman filter model to estimate installation error angle[8].

The FGS as a kind of ultra-high precision astronomical sensor, It has two main functions: (1) A a measurement device provide pointing information for spacecraft or space equipment. (2) As an ultra-high-precision measuring device for the position of celestial bodies[9-10]. Based on the feature that the FGS can provide higher accuracy measurement information than the star sensor at any position in any sky area, it is of practical significance to calibrate and correct the installation error of star sensor by the measurement information of FGS. At present, it is relatively rare to calibrate and correct the installation error of the star sensor by using the measurement information of the FGS at home and abroad.

Therefore, we propose a method that established an extended Kalman filter model by using the measurement information of the FGS as the observation to estimate the installation error of the star sensor.
2. Materials and Methods

2.1. Measurement model
The measurement model of the FGS is similar to the measurement model of the star sensor. We make that the measured values of both the star sensor and the FGS output in the form of quaternion. Supposed the measurement models are as follows:

\[
\begin{align*}
q_{sm} &= q_s + \eta_{ss} \\
q_{fm} &= q_f + \eta_{sf}
\end{align*}
\]  

(1)

Where \( q_{sm} \) is the measured value of the star sensor, \( q_s \) is real attitude quaternion, \( \eta_{ss} \) is Gaussian white noise with mean value of zero and a variance of \( \sigma_{ss}^2 \).

Where \( q_{fm} \) is the measured value of the FGS, \( q_f \) is real attitude quaternion, \( \eta_{sf} \) is Gaussian white noise with mean value of zero and a variance of \( \sigma_{sf}^2 \).

2.2. Installation error calibration model
This model uses the method of state expansion dimension and introduce the attitude information output by the FGS as the observation. The installation error coefficient matrix of the star sensor is extended to the state matrix.

The state variable after dimension expansion matrix is as follow:

\[
x_A = \left[ \Delta \bar{q} \quad \Delta b \quad \Delta q_e \right]^T
\]  

(2)

where \( \Delta q_e = [x_e \ y_e \ z_e]^T \) is the installation error coefficient matrix.

The equation of state is as follow:

\[
\dot{x}_A = F_a x_A + \Gamma_a w_A
\]  

(3)

where \( F_a = \begin{bmatrix}
-\frac{1}{2} I_{3 \times 3} & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3}
\end{bmatrix} \) is the system state transition matrix.

\[
\Gamma_a = \begin{bmatrix}
\frac{1}{2} I_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \\
0_{3 \times 3} & I_{3 \times 3} & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & I_{3 \times 3}
\end{bmatrix}
\]

is the system noise driver array.

where \( w_A = \begin{bmatrix}
w_{g} \\
w_{p} \\
w_{q}
\end{bmatrix} \) is the extended noise matrix, \( w_{g}, w_{p}, w_{q} \) is Gaussian white noise with mean value of zero and a variance of \( \sigma_{q_g}^2, \sigma_{q_p}^2, \sigma_{q_q}^2 \).

It is generally believed that the coefficient of installation error remains unchanged during the calibration process. i.e. \( \Delta q_e \approx 0_{3 \times 1} \).

From this, the observation equation after the expanded dimension can be obtained as follow:

\[
y = H_a x_A + \nu
\]  

(4)

Where \( y \) is the corresponding observation information.
Where \( H_A = \begin{bmatrix} I_{3 \times 3} & 0_{3 \times 3} & I_{3 \times 3} \end{bmatrix} \) is extended dimension observation matrix.

2.3. Installation error calibration process

The specific process is as follows:

Step 1: When FGS enabled, star sensor and the FGS output corresponding measurement values \( q_{sm} \) and \( q_{sf} \) in the same field of view in the same sky area at the same time.

Step 2: Use the measurement information of the FGS to identify the three-axis installation error parameters \( x_c \), \( y_c \) and \( z_c \) of the star sensor.

Step 3: Use EKF method to estimate three-axis installation error parameters.

Step 4: Obtain three-axis estimates \( \hat{x}_c \), \( \hat{y}_c \), \( \hat{z}_c \).

Step 5: Use estimated value \( \hat{x}_c \), \( \hat{y}_c \), \( \hat{z}_c \) to correct the installation error of star sensor.

Step 6: Get the revised star sensor information \( q_{after} \).

The specific process chart is shown in Figure 1.

3. Results & Discussion

We take the three-axis stable earth observation satellite as an example for simulation. The simulation parameters are shown in Table 1 below.

| Table 1. Simulation parameters |
|--------------------------------|
| The sample time of gyro        | 1s                      |
| The constant drift of gyro     | \[[1.0 \quad 1.2 \quad -0.8]\] (°/h) |
| The angular velocity wandering of gyro | 1.5×10^{-4} (°/h^{1/2}) |
| The angular rate random walk coefficient of gyro | 1.5×10^{-4} (°/h^{3/2}) |
The sample time of star sensor 30s
The measures noise of star sensor 3"
The sample time of FGS 120s
The measures noise of FGS 0.005"
The total simulation run time 5400s

The installation error data profile of the star sensor is established based on the on-orbit telemetry data which can be fitted with typical error parameters. The installation error fitting data is shown in Table 2 below.

| Installation error fitting data |
|---------------------------------|
| Roll $x_c$                      |
| Pitch $y_c$                     |
| Yaw $z_c$                       |
| 3"                             |
| 5"                             |
| 4"                             |

Table 2 shows the results of the installation error estimation.

Figure 2 shows the results of the installation error estimation.

Table 3 shows the installation error estimated results of star sensor.

| Installation error estimated results of star sensor |
|-----------------------------------------------|
| Installation error estimation item | Theoretical value (") | estimated value (") | Estimation error (") |
| Roll angle                          | 3 | 3.0039 | -0.0039 |
| Pitch angle                         | 5 | 4.9930 | 0.0065  |
| Yaw angle                           | 4 | 3.9938 | 0.0062  |
The figure 3 shows the comparison before and after the installation error corrected of the star sensor.

Figure 3. Comparison result map before and after installation error correction

In figure 3, the blue line represents the installation error of the star sensor before correction, and the red line represents the position after correction. It can be seen from the figure 3 that the installation error of the star sensor is effectively weakened.

4. Conclusions
The method proposed in this paper can effectively calibrate the installation error of the star sensor through the measurement information of the FGS. It can effectively weaken the influence of the installation error of the star sensor on the measurement accuracy.

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