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Performance evaluation of star sensor low frequency error calibration

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ABSTRACT

This paper studies the star sensor low frequency error (LFE) in-flight calibration problem. The star sensor low frequency error, which is caused primarily by the periodic thermal distortion, has a great impact on the satellite attitude determination accuracy. It is formulated as a Fourier series in this paper. The low frequency error calibration is fulfilled by estimating the Fourier coefficients, which are assumed time-constant. The performance of the calibration method is evaluated through the derivation of the estimation error covariance. It is specified that the attitude determination accuracy can be improved by using the calibration method in the case that the calibration error is less than the true low frequency error parameters. The low frequency error model for numerical simulation are established based on the telemetry data from real star sensors operating under in-orbit conditions. The simulation results illustrate the efficiency of the proposed methods.

1. Introduction

Many spacecraft missions require precise pointing of their payload boresight and precise knowledge of the payload boresight attitude from the attitude determination system. Among the spaceborne attitude determination systems, the stellar inertial attitude determination (SIAD) system that combines the persistent attitude knowledge from gyroscopes with the absolute knowledge from star sensors is the most accurate. Attitude determination involves estimating both the satellite attitude and the gyroscope bias. In the past three decades, many filtering methods have been proposed for the problem of attitude determination [1–9]. Nevertheless, the extended Kalman filter (EKF), especially in the form known as the multiplicative extended Kalman filter (MEKF), remains the method of choice for the great majority of spacecraft missions due to its simplicity and flexibility [10].

The performance of the SIAD system relates to the accuracy of the star sensor, which usually contains unknown low frequency error (LFE). A primary cause for the periodic error is the thermal distortion of the optical head and the bracket of the star sensor, which yields pointing change of the optical axis. The thermal distortion is related to the line of sight (LOS) direction of the Sun relative to the spacecraft, which is shown in Fig. 1.

As the variation of the LOS direction of the Sun relative to the spacecraft repeats from orbit to orbit, the star sensor LFE varies regularly with a period similar to the orbital period. The periodic LFE is found in many spacecrafts, such as the Aqua spacecraft [11], the PROBA (Project for OnBoard Autonomy) satellite [12], the CHAMP (Camera, Hand Lens, and Microscope Probe) satellite [13] and the Advanced Land Observing Satellite (ALOS) [14]. The star sensor LFE is not taken into consideration in the traditional attitude determination Kalman filter (KF). It is difficult to cancel the LFE by using the KF directly. The attitude determination performance may be degraded in the presence of the LFE. Thus, more advanced attitude determination algorithm, which is able to cope with the LFE, needs to be investigated.

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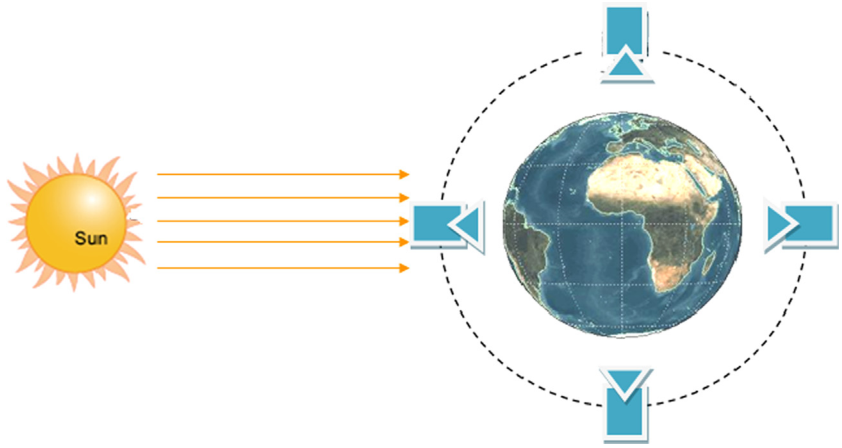

Fig. 1. LOS direction of Sun relative to spacecraft.

One method of calibrating the star sensor LFE is presented in [15]. In this method, the LFE is modeled as a 1 order Gauss–Markov process, and estimated together with the attitude error and the gyroscope bias. The drawback of the method is that the required gyroscope accuracy is rather high. Another method is to estimate the star sensor LFE by using the payload data as absolute attitude measurement [16]. However, the payload attitude measurement is often unavailable for attitude control system (ACS) engineers. In our prior work [17], the multiple model adaptive estimation (MMAE) algorithm is adopted to estimate the LFE parameters according to the frequency spectrum of the gyroscope bias estimate. The limitation of the method is the heavy computational burden of the multiple model (MM) algorithm [18–20]. From an engineering viewpoint, it is not appropriate for in-flight calibration. See [21–24] for other relevant works.

In this paper, we propose a practical method, where the attitude determination KF based on an attitude kinematics model augmented with the calibration error model is used to estimate the LFE parameters recursively. Our work differs from the method in [15] in that we model the star sensor LFE as a Fourier series, and the augmented Kalman filter (A-KF) is used to estimate the Fourier coefficients instead of the LFE itself. In comparison with the method based on the MMAE [17], the advantage of the proposed LFE calibration method is its simplicity and ease of application. It is appropriate for in-flight calibration. The performance of the proposed method is evaluated through the derivation of the estimation error covariance. It is specified that the effect of the LFE calibration to the attitude determination is related to the magnitude of the LFE. The attitude determination performance can be improved by using the LFE calibration method in the case that the true LFE is larger than the calibration error. To the authors' knowledge, the relation between the efficiency of the calibration method and the magnitude of the LFE has not been revealed in prior works.

The rest of the paper is organized as follows. Section 2 formulates the attitude determination problem with unknown measurement error as a state estimation problem. The star sensor LFE calibration method based on the A-KF is given. The performance evaluation of the LFE calibration method is presented in Section 3. Section 4 analyzes the feasibility of the LFE calibration method by using the Cramer–Rao lower bound (CRLB). Section 5 shows the simulation results, which consist of the comparisons between the KF and the A-KF in different scenarios. Finally, our conclusion is drawn in Section 6.

2. Method

In this section, the traditional attitude determination KF is briefly described. Then the star sensor LFE calibration method based on the A-KF is given. We assume that the reader is familiar with the basics of attitude determination, which are given in [25]. Several parameterizations of the satellite attitude are possible. For modern-day applications, the quaternion, which forms a singularity-free attitude parameterization of the lowest dimension, has been the most widely used attitude parameterization [26]. The quaternion algebra is briefly reviewed in [10,4]. The quaternion kinematics equation is nonlinear. The traditional attitude determination KF is based on the linearization of the quaternion differential equation around each attitude estimate. Strictly speaking, it should be called as the attitude determination extended Kalman filter (EKF).

The KF is designed based on the system model. A dynamic system has the following components: the state, the measurement, the state propagation equation and the measurement equation. For the attitude determination KF, the state consists of the error quaternion and the gyroscope bias error. It is

$$\mathbf{x}_k = \begin{bmatrix} \delta\rho_k^T & \delta\mathbf{b}_k^T \end{bmatrix}^T \tag{1}$$

where $\delta\rho_k \in R^3$ is the vector part of the error quaternion that represents the rotation from the estimated quaternion $\hat{\mathbf{q}}_k$ to the true attitude quaternion $\mathbf{q}_k$, and $\delta\mathbf{b}_k \in R^3$ is the gyroscope bias error, k is the time index. The error quaternion $\delta\rho_k$ can be composed with the estimated quaternion $\hat{\mathbf{q}}_k$ to obtain the true quaternion $\mathbf{q}_k$. The scalar part of the error quaternion is omitted here for technical reason discussed in [9] (in summary, because the error