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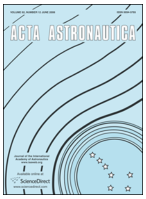

Magnetometer-only attitude and angular velocity filtering estimation for attitude changing spacecraft ☆

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ABSTRACT

This paper presents an improved real-time sequential filter (IRTSF) for magnetometer-only attitude and angular velocity estimation of spacecraft during its attitude changing (including fast and large angular attitude maneuver, rapidly spinning or uncontrolled tumble). In this new magnetometer-only attitude determination technique, both attitude dynamics equation and first time derivative of measured magnetic field vector are directly leaded into filtering equations based on the traditional single vector attitude determination method of gyroless and real-time sequential filter (RTSF) of magnetometer-only attitude estimation. The process noise model of IRTSF includes attitude kinematics and dynamics equations, and its measurement model consists of magnetic field vector and its first time derivative. The observability of IRTSF for small or large angular velocity changing spacecraft is evaluated by an improved Lie-Differentiation, and the degrees of observability of IRTSF for different initial estimation errors are analyzed by the condition number and a solved covariance matrix. Numerical simulation results indicate that: (1) the attitude and angular velocity of spacecraft can be estimated with sufficient accuracy using IRTSF from magnetometer-only data; (2) compared with that of RTSF, the estimation accuracies and observability degrees of attitude and angular velocity using IRTSF from magnetometer-only data are both improved; and (3) universality: the IRTSF of magnetometer-only attitude and angular velocity estimation is observable for any different initial state estimation error vector.

1. Introduction

Miniaturization is a popular concept in the design of low-earth orbiting (LEO) spacecraft so that the attitude determination and control system with one or two kinds of sensors (such as star sensor, sun sensor, earth horizon sensor and magnetometers) become one of hot spacecraft technologies [1–5]. Among these sensors, three-axis magnetometer (TAM) is an important and essential sensor for LEO spacecraft to determine attitude and angular velocity, and implement attitude control, because of its small volume and mass, reliable performance, low power consumption and firm installation [6]. Therefore, using only TAM (TAM-only) as attitude determination sensor will be helpful for the spacecraft miniaturization development, e.g. the EduSAT microsatellite [7]. However, an all-sided TAM-only attitude determination technology requires that TAM to be a solely reliable sensor to determine the attitude of spacecraft not only in the period of steady-state (attitude) control but also in the period of attitude changing (fast and large angular attitude maneuver, rapidly spinning or uncontrolled tumble).

As for the TAM-only attitude determination method in the period of steady-state control of spacecraft, in the

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early, the attitude, attitude rate, and constant disturbance torque estimation filter based on attitude kinematics and dynamics equations was proposed by Psiaki et al. [8]. Then, to process initial condition uncertainties and estimate three-axis attitude and attitude rate from magnetometer data, through an attitude representation of minimum quaternion, they developed a globally self-initializing attitude determination filter for steady-state control spacecraft with wire booms [9]. Also, via using a square-root unscented Kalman filter algorithm, a magnetic-only orbital and attitude estimation scheme is proposed by Cote and Lafontaine, and applied to a sun-synchronous LEO steady-state control spacecraft [10]. Hart presented a method to estimate attitude and attitude angular velocity by extended Kalman filtering and an additional single-axis Kalman filtering of state initialization for a gravity-gradient stabilized spacecraft [11]. Summarized these TAM-only attitude determination methods in the period of steady-state control of spacecraft, they can be regarded as an attitude determination method of spacecraft with only one single observation vector (TAM-only measurement vector) without angular rate measurements from gyros [12]. However, these methods for spacecraft to effectively estimate attitude and angular velocity in the period of attitude changing (fast and large angular attitude maneuver, rapidly spinning or uncontrolled tumble) have not been verified, because the measurement equation of a single observation vector only involves attitude information and is not related with attitude changing.

In the period of spacecraft attitude changing, to determine the attitude and angular velocity from TAM-only measurement data, two approaches of deterministic magnetometer-only attitude and rate determination (DADMOD) [13,14] and real-time sequential filter (RTSF) [14,15] were used successfully to obtain the attitude and angular velocity by Natanson, et al., during the earth radiation budget satellite (ERBS) experienced an on-orbit uncontrolled tumble. Then, based on TAM-only measurement data, these two methods are also used to estimate the three-axis attitude and rates of rapidly spinning gyroless spacecraft [16]. However, according to their related numerical calculation results, although the DADMOD algorithm is alike with TRIAD algorithm [17] including two dependent measurement vectors to sufficiently determine attitude, that is a magnetic field vector and its first time derivative, the TAM measurement noises in DADMOD algorithm are not processed during the attitude calculation, and because the second time derivative of magnetic field vector used in the DADMOD algorithm is in a small enough magnitude, the calculation result of angular velocity determination involves large uncertainties. Therefore, the accuracies of attitude and angular velocity determination using DADMOD algorithm are not sufficient. Compared with DADMOD algorithm, RTSF can process the measurement noises of TAM via attitude determination filtering and acquire a corrected angular velocity vector, but the attitude estimation accuracy of RTSF is also insufficient, because the angular velocity is not directly estimated via the process noise model including attitude dynamics equation and only corrected via a first-order Markov rate correction model of filter, indirectly.

Taking into account the defects of two previous TAM-only attitude determination methods for attitude changing spacecraft, an improved real-time sequential filter (IRTSF) based on RTSF, including attitude dynamics equation as a part of process noise model, is proposed to enhance the accuracies of attitude and angular velocity estimation of attitude changing spacecraft in this paper. Moreover, in order to evaluate the presented attitude determination filter, the observabilities of IRTSF for the attitude changing spacecraft with small or large initial angular velocity are evaluated by the Lie-Differentiation [18], and the degrees of observability of IRTSF for different initial estimation errors are analyzed by the condition number [19] and a solved covariance matrix [20].

The organization of this paper proceeds as follows. First, an improved attitude filter IRTSF based on TAM-only sensor, RTSF and attitude dynamics equation will be designed to estimate the attitude and angular velocity of spacecraft in the period of attitude changing. Next, observability analysis is used to evaluate the feasibility of the new TAM-only attitude determination filtering method (IRTSF). Finally, numerical simulations are implemented to verify the presented TAM-only attitude filtering method (IRTSF).

2. Mathematic modeling for improved real-time sequential filter (IRTSF)

In this section, to obtain the mathematic model of IRTSF, the process noise model and the measurement model of TAM-only attitude filtering system are, respectively, established by attitude motion equations and TAM-only measurements corresponding to the attitude changing spacecraft.

2.1. Coordinate systems

To depict the attitude changing of an on-orbit spacecraft, two coordinate frames, including the inertial reference frame $\boldsymbol{S}_i$ and the spacecraft body frame $\boldsymbol{S}_b$, are established for IRTSF. The origin of the inertial frame $\boldsymbol{S}_i$ locates at the center of mass of spacecraft, and its three axes $\boldsymbol{x}_i, \boldsymbol{y}_i$ and $\boldsymbol{z}_i$ point to the inertial space. The body frame $\boldsymbol{S}_b$ also has its origin at the center of mass of spacecraft, and its three axes $\boldsymbol{x}_b, \boldsymbol{y}_b$ and $\boldsymbol{z}_b$ point to three principle axes of spacecraft body.

If the axes order of rotation from the inertial frame $\boldsymbol{S}_i$ to the body frame $\boldsymbol{S}_b$ is chosen $3-1-2$, a set of rotation Euler angles denoted by $\begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^T$ respectively represents the roll, pitch and yaw angle of spacecraft relative to the inertial reference frame $\boldsymbol{S}_i$. Also, the attitude transformation matrix from the inertial frame $\boldsymbol{S}_i$ to the body frame $\boldsymbol{S}_b$ is given by

$$\boldsymbol{A}_{bi} = \boldsymbol{L}_y(\theta)\boldsymbol{L}_x(\phi)\boldsymbol{L}_z(\psi) \tag{1}$$

where the subscript *bi* represents two transformed coordinate frames and their transformation order, and $\boldsymbol{L}_x(\cdot)$, $\boldsymbol{L}_y(\cdot)$ and $\boldsymbol{L}_z(\cdot)$ are the principle rotation matrices about $\boldsymbol{x}$-, $\boldsymbol{y}$- and $\boldsymbol{z}$-axis. The transition relationship of these two frames is shown in Fig. 1. Also, in this paper, to simplify the related