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A residual based adaptive unscented Kalman filter for fault recovery in attitude determination system of microsatellites ☆

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ABSTRACT

This paper presents an adaptive unscented Kalman filter (AUKF) to recover the satellite attitude in a fault detection and diagnosis (FDD) subsystem of microsatellites. The FDD subsystem includes a filter and an estimator with residual generators, hypothesis tests for fault detections and a reference logic table for fault isolations and fault recovery. The recovery process is based on the monitoring of mean and variance values of each attitude sensor behaviors from residual vectors. In the case of normal work, the residual vectors should be in the form of Gaussian white noise with zero mean and fixed variance. When the hypothesis tests for the residual vectors detect something unusual by comparing the mean and variance values with dynamic thresholds, the AUKF with real-time updated measurement noise covariance matrix will be used to recover the sensor faults. The scheme developed in this paper resolves the problem of the heavy and complex calculations during residual generations and therefore the delay in the isolation process is reduced. The numerical simulations for TSUBAME, a demonstration microsatellite of Tokyo Institute of Technology, are conducted and analyzed to demonstrate the working of the AUKF and FDD subsystem.

1. Introduction

The main objective of spacecraft attitude estimation is to determine the orientation of a spacecraft body-fixed coordinate frame with respect to a reference coordinate frame. After almost five decades of research work in the attitude determination (AD) field, one can distinguish between two broad classes of attitude estimation algorithms: these are the single frame and the filtering based methods. The filtering based methods are usually more accurate and possess the advantage of being capable of yielding estimates at times when there are insufficient observation data for single frame methods to work. Due to the nonlinearity imposed by the attitude determination problem, most of the present-day attitude filtering algorithms rely upon the Kalman filter (KF) extension for nonlinear systems, namely the extended Kalman filter (EKF) or unscented Kalman filter (UKF) [1]. The EKF and UKF are both well-known and flight-confirmed algorithms for satellite attitude estimation [2,3]. However, the EKF has a well-known drawback that is the first-order linearization of the nonlinear system which can introduce large errors in mean and covariance of the state vector [4].

In microsatellites, due to the limitation in power generation, spacecraft size, onboard computer performance

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and memory, there are usually no hardware redundancy devices. Therefore, to increase the robustness and reliability of the AD system, a model-based FDD working as a redundant function is compactly implemented. The study on model-based FDD began in the early 1970s [5]. The natural idea of the model-based fault diagnosis technique is to replace the hardware redundancy by a process model which is implemented in the software form in a computer. In this way, we are able to reconstruct the process behavior on-line, which is associated with the concept of hardware redundancy, and is called software redundancy concept.

The processes of model-based FDD techniques can be divided into three steps. The first step is to generate a set of variables known as residuals by using one or more residual generation filters. Normally, in the absence of failure/fault, the residuals are zero-mean and white noise, thereby demonstrating the agreement between the estimates and the observed measurements. In contrast, a biased residual is indicative of abnormal behavior or failures. For practical applications, they should be insensitive to noise, disturbances, and model uncertainties while maximally sensitive to faults. Some FDD schemes use two or more residual generation filters in parallel for fault isolation. In such schemes, each of the residual generation filters is designed to be sensitive only to the corresponding selective set of faults. The second step is to make decisions on whether a fault has occurred (fault detection) and on where it has occurred (fault isolation) on the basis of the residuals. This step is usually done using statistical tools to test if the residuals have significantly deviated from zero. Finally, the controller is recovered online in response to the detected faults.

The general and most basic model-based FDD techniques are reviewed and discussed by Ding [5] and Hwang et al. [6]. Regarding the FDD for AD system, Williamson et al. present the fault detection and isolation methods for satellites which use a set of star tracker and a fiber optic gyroscope (FOG) as the main AD sensors [7]. Pirmoradi and Sassani present a FDD subsystem for the satellites which use a rate gyro and vector sensors [8]. Both proposals take into account the satellite dynamics model to detect and isolate the faults of gyroscope. To solve dynamics function, the observers need an iterative numerical method for the approximation of solutions of ordinary differential equations. Moreover, these FDD subsystems require the knowledge about internal and external torques acting on the satellites.

Together with the adaptive filter, this paper also introduces a new FDD subsystem for the satellites which use one rate gyro and two vector sensors, a Three-axis-magnetometer (TAM) and a sun acquisition sensor (SAS). This FDD subsystem includes two filters for residual generations, hypothesis tests for fault detections and a logic table for fault isolations and fault recovery. Only a satellite attitude rotation kinematics model is needed in the first filter which is based on the UKF to estimate the satellite attitude, gyro bias value and to generate a residual vector for the fault detection process. Another estimator is based on a quaternion estimator (QUEST) [9] method which uses TAM and SAS for only attitude estimation. The scheme developed in this paper resolves the problem of the heavy and complex calculations during residual generation parts and therefore also the delay in isolation process is reduced.

Adaptive filters have the property to adapt to a permanently changing environment by which their behavior is kept optimal. There exist many adaptive methods that either update the noise covariance matrices in a filter design, or update filter parameters through least-squares techniques or by using nonlinear techniques [3]. In this proposed AUKF, the measurement noise covariance matrix is updated by using a statistical estimator for attitude sensors. This statistical estimator and AUKF are activated right after the fault is detected in ADS. The main purpose of proposed method is to resist the sensor faults with a fast and easy to implement method. Therefore the calculation cost will not increase too much.

The organization of the paper is as follows. In Section 2, the spacecraft rotation kinematics using quaternion representation and sensor models is briefly reviewed. In Section 3, the UKF algorithm and the application of the UKF to satellite attitude estimation using attitude local error representation are presented. In Section 4, all of FDD subsystems including filter designs, residual generations, statistical tests, diagnosis, and recovery processes are shown. In Section 5, the details of the residual-based AUKF algorithm are presented and discussed. In Section 6, some simulation scenarios and their results are given to discuss about the robustness and convergence speed of filter. Finally, in Section 7, the conclusions are given.

2. Attitude kinematics and sensor models

In this section, a brief review of the attitude kinematics equation of motion using quaternions is shown. Then, the models of gyro and attitude sensor are briefly reviewed.

2.1. Attitude kinematics

The quaternion is defined by $q=[\rho^T \quad q_4]^T$, where $\rho^T=[q_1 \quad q_2 \quad q_3]^T$ is the vector part and q_4 is the scalar part. The quaternion representation is desirable because of its singularity free property. However, the norm constraint must be maintained. Since a four-dimension vector is used to represent three dimensions, the quaternion has a single constraint given by $q^Tq=1$. The attitude matrix is calculated as a quadratic function of q, that is

$$A(q)=(q_4^2-||\rho||^2)I_{3\times3}+2\rho\rho^T-2q_4[\rho\times] \tag{1}$$

where $I_{3\times3}$ is the 3×3 identity matrix and $[\rho\times]$ is the cross matrix defined as

$$[\rho\times]=\begin{bmatrix}0 & -q_3 & q_2\\ q_3 & 0 & -q_1\\ -q_2 & q_1 & 0\end{bmatrix} \tag{2}$$

The quaternion kinematics differential equation is given by

$$\dot{q}=\frac{1}{2}\Xi(q)\omega=\frac{1}{2}\Omega(\omega)q \tag{3}$$