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Gyro-free attitude and rate estimation for a small satellite using SVD and EKF

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ABSTRACT

This paper describes the development of a gyroless attitude determination system that can rely on magnetometer and sun sensor measurements and achieve good accuracy. Vectors coming from the selected sensor data and developed models can be placed in Wahba's problem. The system uses Singular Value Decomposition (SVD) method to minimize the Wahba's loss function and determine the attitude of the satellite. In order to obtain the attitude of the satellite with desired accuracy an extended Kalman filter (EKF) for satellite's angular motion parameter estimation is designed. The EKF uses this attitude information as the measurements for providing more accurate attitude estimates even when the satellite is in eclipse. The "attitude angle error covariance matrix" calculated for the estimations of the SVD method is regarded as the measurement noise covariance for the EKF.

The SVD and EKF algorithms are combined to estimate the attitude angles and angular velocities, respectively. Besides, the proposed algorithm and traditional approach using nonlinear measurements are compared and concluded that SVD/EKF gives more accurate results for most of the time intervals. The algorithm can be used for low-cost small satellites where using high power consuming, expensive, and fragile gyroscopes for determining spacecraft attitude are not reasonable.

1. Introduction

Sun sensors and magnetometers are common attitude sensors for small satellites missions; they are cheap, simple, light and available as commercial of-the-shelf equipment. However the overall achievable attitude determination accuracy is limited with these sensors mainly as a result of their inherent limitations and unavailability of the sun sensor data when the satellite is in eclipse. Vectors coming from the selected sensor data and developed models can be placed in Wahba's problem [20,21]. Coordinate systems used as reference frame and body frame can be transformed to each other with necessary input parameters. The system uses Singular Value Decomposition (SVD) method to minimize the Wahba's loss function and determine the attitude of the satellite. As a reference direction, the unit vectors toward the Sun, and the Earth's magnetic field are used. Thus, magnetometers and Sun sensors are used as measuring devices.

Additionally, an attitude determination system is the subsystem of the spacecraft avoiding from high power consuming, expensive, and fragile gyroscopes. Developed micro electrical–mechanical systems (MEMS) are low power consuming and cheap sensors but they have inaccurate and with inadequate resolution for providing the desired performance. Besides gyroscopes have a tendency to degrade or fail in orbit with time because of their nature. Three types of rate gyros are used in today's Inertial Measurement Unit (IMU) systems which are ring laser gyro (RLG), fiber optic gyro (FOG) and MEMS. RLGs can have got "locked-in" condition at very slow rotation rates. FOGs in comparison to RLGs require no mechanical burden for their operation and thus eliminate a troubled noise source. The drawback is that the sensed angular velocity is limited with respect to the phase difference due to the Sagnac effect. Solid-state inertial sensors, such as MEMS devices, have potentially significant cost, size, and weight advantages on the contrary they have a disadvantage which their accuracy and resolution are lower than expected mission requirements mostly. If a satellite does not have any back up mode for gyro failure the whole mission may fail in the mentioned case. A couple of examples for the gyroscope failures can be given. International Ultraviolet Explorer (IUE) launched in 1978 had six gyroscopes for the designed inertial system. In 1985, fourth gyro failed and IUE used only two gyros for the mission. To continue operations and achieve all scientific goals of the spacecraft, innovative redesign of specific systems was

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developed on the ground [3]. Hubble Space Telescope had six gyros including redundant three gyros, also its components have a chance to be replaced with the new equipment by the astronauts. In 1999, third gyro of the telescope failed so telescope started to use redundant, spare gyroscopes [14]. Failures of the gyroscopes can be caused by chemical, mechanical and electrical effects. Information about satellite operations of European Space Agency (ESA) can be obtained in which one of them, ESA Remote Sensing Satellites (ERS)-2, had an orbital rescue by reason of the gyro failure. In 2000, one gyro design for attitude and orbit control system is improved to minimize the necessity of the number of gyros without affecting from gyroscope failures [6]. In 2001, after the last gyroscope failed, a method of operating the ERS-2 sensors and actuators in a new way was developed for gyroless ERS-2.

Gyroless attitude estimation with magnetometer and sun sensor measurements has been addressed in many researches [1,4,5,7,11,13] and various algorithms that intend improving the estimation accuracy have been proposed. A basic solution for the problem is to use a Kalman filtering algorithm for integrating the measurements under the propagation model of the satellite dynamics and estimate the attitude of the satellite possibly along with the sensor biases. The main drawback of the existing algorithms is the degradation in the estimation results when the satellite is in eclipse and sun sensor data is not available.

The aim of the study is to design an attitude determination system that gives attitude knowledge with desired accuracy within the whole orbit. In order to obtain the attitude of the satellite with desired accuracy an extended Kalman filter (EKF) for satellite's angular motion parameter estimation can be used.

The traditional approaches to design of Kalman filter for satellite attitude and rate estimation use the nonlinear measurements of reference directions (Earth magnetic field, Sun, etc.) [15–17,20].

In an approach based on the linear measurements the attitude angles are first found by using the vector measurements and applying a suitable single-frame (point-by-point) attitude determination method [22] at each step. Then these attitude angles are directly used as measurement input for the Kalman filter. Hence measurement model is linear in this case, since the states are measured directly. Integrated satellite attitude determination system based on the linear measurements is presented by [9,10], in which the algebraic method and EKF algorithms are combined to estimate the attitude angles and angular velocities respectively. Attitude determination system uses the algebraic method (two-vector algorithm). This method is based on computing any two analytical vectors in the reference frame and measuring the same vectors in the body coordinate system. The magnetometers, Sun sensors, and horizon scanners/sensors are used as measurement devices and three different two-vector algorithms based on the Earth's magnetic field, Sun vector, and nadir vector are proposed. In order to obtain the satellite's angular motion parameters with the desired accuracy, an EKF is designed, the measurement inputs for which are the attitude estimates obtained using two-vector algorithms.

In Ref. [23] an EKF is proposed for real-time estimation of the orientation of human limb segments. The filter processes data from small inertial/magnetic sensor modules containing tri-axial angular rate sensors, accelerometers, and magnetometers. Quaternion representation is used for representing the rotation in the filter instead of the Euler angles. QUEST algorithm that solves the attitude based on the acceleration and magnetometer measurements gives the input for the EKF. Thus, dimension of the state vector reduces and measurement equations become linear.

In Ref. [2] the q-method for quaternion estimation has been integrated into an EKF to produce the novel qEKF filter for attitude estimation, which is capable of treating both attitude and non-attitude states without additional numerical iterations. Within the filter, attitude vector measurements are first processed using the q-method, which solves the nonlinear Wahba problem directly without any linearizing assumptions. Remaining measurements are processed to update the non-attitude states using the standard multiplicative EKF algorithm.

In general, the papers that are using untraditional approach techniques did not consider possibility of attitude determination in eclipse and the investigation of the accuracy in eclipse. Furthermore, those considered integrated algorithms did not investigate a comparative study with traditional methods. In this study, attitude determination algorithm is developed for whole orbital period including eclipse. A two-phased estimation algorithm is proposed for a small satellite which has magnetometers and sun sensors as the attitude sensors onboard. In the first phase, Wahba's problem, a well-known approach for single frame attitude estimation with vector sun sensor and magnetometer measurements, is solved by the Singular Value Decomposition (SVD) method and Euler angle-estimations are obtained for the satellite's attitude. Obtained Euler angle-estimations are used as measurement inputs for an Extended Kalman Filter (EKF), which forms the second phase of the algorithm. The covariance estimation of the SVD is used as the measurement noise covariance matrix of the EKF; this is how the filter is tuned specifically in the eclipse period. The results of the proposed algorithm are compared with traditional approach using nonlinear measurements.

2. SVD method

In this section, SVD method which is the pre-step for non-traditional approach and the models used in SVD method are explained briefly. Magnetic field and sun direction model with their sensor definitions are expressed in the subsections. After Wahba's optimization problem definition, two or more vectors can be used in statistical methods to minimize the loss [21]. In the equation (1), the loss can be seen as the difference between the models and the measurements which are found in unit vectors.

$$L(A) = \frac{1}{2}\sum_i a_i |b_i - Ar_i|^2 \tag{1}$$

$$B = \sum a_i b_i r_i^T \tag{2}$$

$$L(A) = \lambda_0 - tr\left(AB^T\right) \tag{3}$$

where b_i (set of unit vectors in body frame) and r_i (set of unit vectors in reference frame) with their a_i (non-negative weight) are the loss function variables obtained for instant time intervals and λ_0 is the sum of non-negative weights. Also, 'B' matrix is defined to reduce the loss function into the equation (3). Here, maximizing the trace ($tr(AB^T)$) means minimizing the loss function (L). In this study, Singular Value Decomposition (SVD) Method is chosen to minimize the loss function [12].

$$B = \mathrm{USVT} = U\, diag\, |\mathbf{S_{11}S_{22}S_{33}}|\mathrm{VT} \tag{4}$$

$$A_{opt} = U\, diag\begin{bmatrix} 1 & 1 & \det(U)\det(V) \end{bmatrix} V^T \tag{5}$$

The matrices U and V are orthogonal left and right matrices respectively and the primary singular values ($\mathbf{S_{11}}, \mathbf{S_{22}}, \mathbf{S_{33}}$) can be calculated in the algorithm. To find the rotation angles of the satellite, transformation matrix should be found in the equation (5) first with the determinant of one. "*diag*" operator returns a square diagonal matrix with elements of the vector on the main diagonal.

Rotation angle error covariance matrix (P) is necessary for determining the instant times which gives higher error results than desired.

$$P_{SVD} = U\, diag\begin{bmatrix} (s_2+s_3)^{-1} & (s_3+s_1)^{-1} & (s_1+s_2)^{-1} \end{bmatrix} U^T \tag{6}$$

where $s_1 = \mathbf{S_{11}}$, $s_2 = \mathbf{S_{22}}$, $s_3 = \det(U)\det(V)\mathbf{S_{33}}$.