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In-Flight Identification of Magnetometer and Attitude Determination System for Land-survey Mini-satellite ⋆

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Abstract: We present discrete algorithms for in-flight identification, calibration and alignment of a low cost strap-down inertial navigation system with correction by signals from the Sun and magnetic sensors. Proposed algorithms are simulated through attitude dynamics of a small land-survey satellite.

Keywords: mini-satellite, attitude determination, identification, calibration

1. INTRODUCTION

Magnetometers provide the direction of magnetic field and its magnitude, therefore they are useful for small satellites attitude determination and control system. Moreover, their low mass and power consumption make them attractive for small satellites. For these reasons, most low Earth orbit (LEO) small satellites have magnetometers as part of their basic sensor package. In order to estimate the components of the geomagnetic field vector for attitude determination and attitude control accurately, effects of measurement bias should be canceled. In last decade, popularity of small satellites with low cost and weight has increased significantly. That brought about a search for lighter but more accurate sensors. Under these circumstances, three-axis magnetometer (TAM) has become so attractive because of its advantages such as providing a continuously available two-axis attitude measurements, relative low cost and almost insignificant power demand.

Operating magnetometers as primary sensor in small satellite missions is a common method for achieving attitude information in small satellite missions (Psiaki et al., 1990). However, these sensors are not error free because of the biases, scaling errors and misalignments (nonorthogonality). These terms inhibit the filter efficiency and so attitude data accuracy and even they may bring about the filter divergence in long terms. The attitude accuracy requirements demand compensation for the magnetometer errors such as misalignments and biases (Wertz, 1988). Estimating magnetometer biases and scale factors as well as the attitude of the satellite is a proposed technique to solve such problems and increase onboard accuracy. One method to calibrate magnetometer measurements is to follow up an attitude free scheme. In usual cases, magnetometers may be the only operating sensors at the orbit injection phase where attitude data is not available since the spacecraft is spinning rapidly. Besides, magnetometer measurements are not bias free at that stage because of the large magnetic disturbances on the spacecraft such as charging during the launch and the electrical currents within the spacecraft. Hence, magnetometers must be calibrated without the knowledge of attitude in such cases. In literature there are several methods for estimating the magnetometer bias in case of lack of attitude knowledge. Bias vector can be basically solved by minimizing the weighted sum of the squares of residuals which are the differences in the squares of the magnitudes of the measured and modeled magnetic fields (Wertz, 1988). Shuster and Alonso proposed a relatively new algorithm called two-step, which combines the convergence in a single step of a heuristic algorithm with the correct treatment of the statistics of the measurement (Shuster and Alonso, 1996; Alonso and Shuster, 2002a,b,c). In Alonso and Shuster (2003) they presented a modified two-step algorithm that estimates

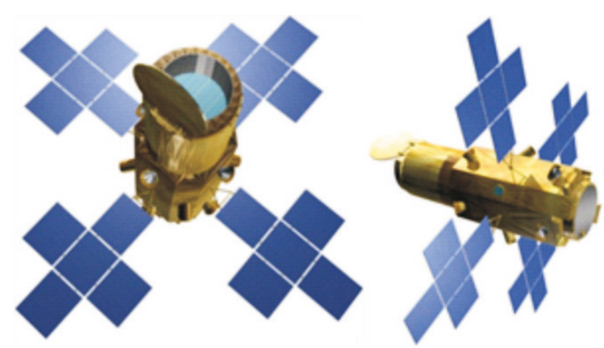

Fig. 1. The land-survey mini-satellite, two views

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all three components of the magnetometer bias vector in case where the centered portion of the negative-log-likelihood function provides incomplete observability of the magnetometer bias vector. Besides, in Alonso and Shuster (2002b) it is shown that two-step algorithm can be also used to estimate scale factors and nonorthogonality corrections as well as magnetometer biases by an attitude-independent procedure.

As another implication example of two-step algorithm, Kim and Bang (2007) integrate it with the genetic algorithm and uses the genetic algorithm for providing the initial estimates of the magnetometer bias estimation . Two-step algorithm like methods can be used for guessing an initial estimate for Kalman filter type stochastic attitude determination methods. Those a priori estimates for the estimator may be then corrected on an expanded state vector including attitude parameters and biases. It is possible to also meet with other attitude-free magnetometer bias estimation methodologies in literature. In Crassidis et al. (2005), it is proved that a full magnetometer calibration can be performed on-orbit during typical spacecraft (SC) mission-mode operations by the use of real-time algorithms based on both Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF). Although these studies (Soken and Hajiyev, 2011a,b) can estimate the magnetometer characteristics such as biases, scale factors and non-orthogonality corrections, they all disregard the SC attitude dynamics and if this information is possible at any instant, their accuracies can be exceeded. Hence they may be considered as a part of the SC modes where attitude data is absent. In Ma and Jiang (2005) and Sekhavat et al. (2007) magnetometer bias and scale factor are estimated as a part of attitude estimation process. The magnetometer calibration process is fulfilled together with the estimation of attitude parameters. Ma and Jiang (2005) solve magnetometer calibration and attitude estimation problem via two UKFs working synchronously. As a disadvantage, this approach requires a high computational effort because of two distinct UKFs and it may be not suitable for small satellites where the processing capacity of the attitude computer is limited. A normalization of the magnetic field vectors are performed, since the values are very big, respectively, leading to numerical problems in matrix computations. Normalizing of vector information is suggested, since it is only the direction of the vectors and not the magnitude that is important for attitude estimation. In order to obtain accurate geomagnetic field measurements (direction cosines), the sensor should be calibrated precisely. In this study a Linear Kalman Filter (LKF) based algorithm is proposed for the TAM bias calibration. The computation burden of the proposed calibration algorithm is not significant.

In the paper, we consider a LEO land-survey mini-satellite (Fig. 1) and study the problem for in-flight identification and calibration of strap-down inertial navigation system (SINS) at a long-term forecasting of SC orbital motion, when its position is known with accuracy of up to 30 m along the orbit and up to 10 m both in the lateral direction and altitude.

Programmed angular motion of the maneuvering land-survey mini-satellite is presented by a sequence of time intervals for a target application – courses (CRs) and intervals of rotational maneuvers (RMs) with variable direction of SC angular rate vector $\boldsymbol{\omega}$, the module of which may be up to 1 deg/sec.

For agile land-survey mini-satellite an attitude determination system (ADS) is needed with the robust properties and small financial expenditures on practical implementation. In this situation, the SINS correction by signals from the sun-magnetic system (SMS) is most promising. The SINS considered contains an inertial measurement unit (IMU) based on the gyro sensors of the SC angular position quasi-coordinates, the SMS correction based on a Sun sensor (SS) with a set of optical heads (Rufino and Grassi, 2009) and TAM – a magnetic sensor (MS), all devices are fixed rigidly on the satellite body.

Best low cost ADS has the form of SMS and is based on cluster of MS and multi-head SS (Wertz, 1988), when the MS accuracy is $3\sigma^{\mathrm{m}} \approx 0.1$ deg and the SS has the accuracy $3\sigma^{\mathrm{s}} \approx 30$ arc sec.

2. MODELS AND THE PROBLEM STATEMENT

We have introduced inertial basis $\mathbf{I}$ and inertial reference frame (IRF); basis $\mathbf{B}$ and the body reference frame (BRF) connected with the SC body; standard orbital basis $\mathbf{O}$ and the orbit reference frame (ORF); the sensor basis $\mathbf{S}$ (by a telescope); virtual basis $\mathbf{A}$ which is calculated by processing an accessible measurement information from the ADS, and the IMU virtual basis $\mathbf{G}$, which is computed by processing the measurement information from the integrating gyros. The BRF attitude with respect to basis $\mathbf{I}$ is defined by quaternion $\boldsymbol{\Lambda} = (\lambda_0, \boldsymbol{\lambda}), \boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3)$, and with respect to the ORF – by column $\boldsymbol{\phi} \equiv \{\phi_1, \phi_2, \phi_3\}$ by angles of yaw $\phi_1 = \psi$, roll $\phi_2 = \gamma$ and pitch $\phi_3 = \theta$ in the sequence $31'2''$.

As mini-satellite moves along its orbit, magnetic field vector differs in a relevant way with the orbital parameters. If those parameters are known, then magnetic field can be presented as a function of a time analytically (Sekhavat et al., 2007) – by simplest model of the Earth magnetic induction vector $\mathbf{B}^{\mathrm{o}}(t) = \{B_i^{\mathrm{o}}(t)\}$ in the ORF. Normalizing of the vector information is suggested, since it is only direction of the vector and not the magnitude that is important for the SC attitude estimation. In the ORF unit $\mathbf{m}^{\mathrm{o}}(t)$ of the Earth magnetic induction vector can be written in the form $\mathbf{m}^{\mathrm{o}}(t) = \mathbf{B}^{\mathrm{o}}(t)/ \parallel \mathbf{B}^{\mathrm{o}}(t) \parallel$. Satellite onboard TAM measures the geomagnetic field vector components in the BRF, therefore magnetic field terms $B_i^{\mathrm{o}}(t)$ must be transformed by the use of direction cosine matrix $\mathbf{A}(\boldsymbol{\phi}(t)) \equiv \mathbf{A}(t)$. Overall measurement model is presented as follows

$$\mathbf{m}^{\mathrm{m}}(t) = \mathbf{A}(t)\,\mathbf{m}^{\mathrm{o}}(t) + \mathbf{b}^{\mathrm{m}} + \mathbf{v}(t), \qquad (1)$$

where $\mathbf{m}^{\mathrm{m}}(t) = \{m_i^{\mathrm{m}}(t)\}$ is the measured and computed Earth magnetic field unit in the BRF, $\mathbf{b}^{\mathrm{m}} = \{b_i^{\mathrm{m}}\}$ is the TAM bias vector and $\mathbf{v}(t) = \{v_i(t)\}$ is the zero mean Gaussian white noise vector with characteristic $E[\mathbf{v}_k\mathbf{v}_j^{\mathrm{t}}] = \mathbf{I}_3(\sigma^{\mathrm{m}})^2\,\delta_{k\,j} = \mathbf{R}_v$. Here $\mathbf{v}_k \equiv \mathbf{v}(t_k)$, $t_k = k\,T_o$, $t_{k+1} = t_k + T_o$, $k, j \in \mathbb{N}_0 \equiv [0, 1, 2, ...)$; $\mathbf{I}_3$ is the identity matrix, σ^{m} is the standard deviation of each direction cosine measurement error and δ_{kj} is the Kronecker symbol. In order to obtain high accurate magnetometer measurements, the sensor should be calibrated before mission on the ground