Measurement xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A survey of calibration algorithms for small satellite magnetometers

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ARTICLE INFO

Keywords:
Magnetometer calibration
Attitude estimation
Small satellite

ABSTRACT

Magnetometers are an integral part of attitude determination system for the low-Earth orbiting small satellites as they are lightweight, inexpensive and reliable. Yet using magnetometers for attitude determination is not straightforward because of the sensor errors. These errors limit the overall achievable attitude determination accuracy. Thus far different methods to cope with magnetometer errors and calibrate the magnetometers have been proposed. A new research field is the specific errors for magnetometers onboard the small satellites and their time-variation characteristics. In accordance, algorithms which consider also the time-varying error terms are proposed. This paper reviews the recent calibration algorithms for small satellite magnetometers. The survey mainly covers batch and recursive estimation algorithms which are capable of estimating the time-varying magnetometer error terms. It presents the foundation of each algorithm and covers issues about the algorithm design, application and performance. In the end possible directions in this research field are briefly discussed.

1. Introduction

Three-axis magnetometers (TAMs) are part of the attitude sensor package for almost all of the low-Earth orbiting small satellites [1,2]. Being lightweight, small, reliable, and having low-power requirements make them ideal for small satellite applications. In fact, in addition to their well-known implementation for attitude determination, TAMs can be used also for orbit determination [3].

The main challenge for using the TAM for attitude estimation is sensor errors. These errors limit the overall achievable attitude estimation accuracy, unless they are taken care of. Until now researchers suggested various solutions for dealing with the magnetometer errors. These include straightforward satellite design issues such as keeping the TAMs far from the electromagnetic interference. Best example is locating the sensors on platforms separated from the satellite main body, such as the tip of a boom [4]. However, for especially nanosatellite missions, this is not an option as the size of the satellite should be kept to a minimum. In this case, the magnetometers must be in-flight calibrated.

A new research area is the time-varying errors for small satellite magnetometers [5–7]. Onboard the small satellites the magnetometers are located close to the other subsystems because of size limitations. Thus, nearby electronics and satellite magnetic torquers (MTQs) cause time-varying magnetometer errors. Various algorithms exist to estimate both time-invariant and time-varying errors, which are covered by three general error types: bias, scale factors, and nonorthogonality [8]. Researchers usually address both time-invariant and time-varying parameter estimation together and propose an overall calibration algorithm for magnetometers. This algorithm must be in-flight applicable.

In this paper, we review recent calibration algorithms for small satellite magnetometers. We emphasize the algorithms that consider time-varying magnetometer errors or algorithms that are responsive to the time-variation in the errors. In this sense, we first review the batch methods which are capable of calibrating the magnetometers in different circumstances against the time-varying errors. In particular, we discuss the optimization algorithms for batch magnetometer calibration methods. New optimization algorithms are investigated recently as a part of the search for ensuring algorithm's convergence to the global minima. Then we review the recursive estimation algorithms which are capable of sensing the time-variation in the estimated error terms. We categorize the recursive magnetometer calibration algorithms in two: attitude-dependent and attitude-independent algorithms. Although they are referred if necessary, magnetometer calibration methods for other applications, e.g. navigation systems, are not directly a subject of this survey.

This survey discusses the underlying ideas and assumptions of the magnetometer calibration methods rather than their specific implementations. The reader should note that, although the algorithms in some of the surveyed papers are implemented on platforms different than satellites, we present these algorithms considering their applicability for calibration of small satellite magnetometers against time-varying errors. The aim of the survey is to present the algorithms in a broad perspective such that the reader easily understands how they

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http://dx.doi.org/10.1016/j.measurement.2017.10.017
Received 27 September 2017; Accepted 9 October 2017
0263-2241/

work and what their pros and cons are. The relationship between different algorithms is examined to show the reader how the algorithms can be integrated to improve the accuracy of the calibration. Lastly, further research directions for the small satellite magnetometer calibration are discussed.

A preliminary version of this survey is presented in [9]. In this extended version, errors for a small satellite magnetometer are presented along with discussion for their characteristics and effects on the measurements. Advantages and drawbacks of each magnetometer calibration method are discussed in detail. Furthermore new references are included specifically for magnetometer calibration using gyro measurements.

This paper is organized as follow. Section 2 presents the magnetometer errors and measurement model for the magnetometers. A discussion showing how this model is modified to include the effects of time-varying errors is also included. In Section 3 the batch estimation algorithms for magnetometer calibration are presented. Section 4 gives recursive estimation algorithms for the magnetometer calibration. Both attitude-dependent and attitude-independent approaches are presented. Section 5 concludes the survey with a brief discussion on the future directions for small satellite magnetometer calibration.

2. Magnetometer measurement model

2.1. Errors for a small satellite magnetometer

Errors for a small satellite magnetometer are summarized in Fig. 1. In Fig. 1 errors that are originated from the internal/external disturbances are given in white boxes whereas the inherent sensors errors are given in dark gray boxes. Errors that may be either inherent to sensor or originated from the disturbances are given with light gray boxes.

In following subsections we briefly present different error types [8] and discuss how they affect the magnetometer measurements.

2.1.1. Soft iron error

Soft irons are materials that generate magnetic fields in response to an externally applied field. The field generated by these materials can vary over a wide range depending on both the magnitude and direction of the applied external magnetic field. In result, soft irons impose error on the magnetometer measurements depending on the specifications of the generated magnetic field. In this study we represent the soft iron error with a 3×3 matrix, D_{si}.In most applications, D_{si} is assumed to be a

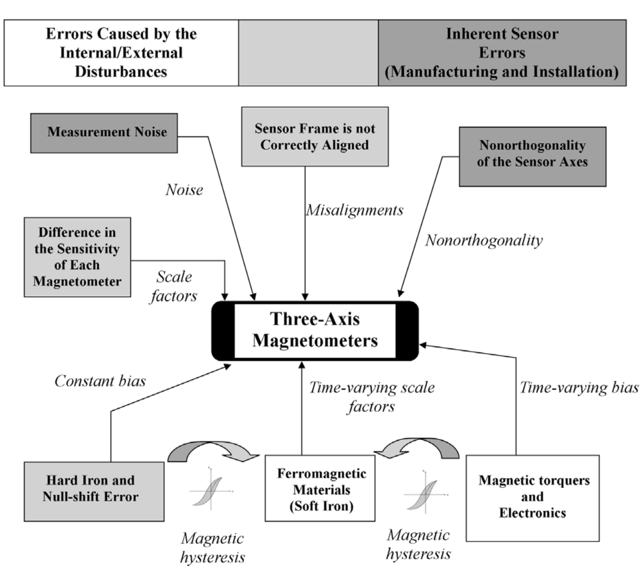

Fig. 1. Magnetometer errors.

matrix with constant terms [10]. In this case, D_{si} is given as

$$D_{si} = \begin{bmatrix} \alpha_{xx} & \alpha_{xy} & \alpha_{xz} \\ \alpha_{yx} & \alpha_{yy} & \alpha_{yz} \\ \alpha_{zx} & \alpha_{zy} & \alpha_{zz} \end{bmatrix}, \tag{1}$$

where α_{ij} are the effective soft iron coefficients that show the proportionality between the magnetic field applied to a soft iron and resulting induced magnetic field.

Assumption of constant soft iron coefficients is valid as long as the objects that generate large magnetic field (e.g. MTQs, current carrying wires) are not located close to the magnetometers. For small satellites, where all the subsystems are closely located, an accurate soft iron error model that considers the error's time-variation is needed.

2.1.2. Hard iron and null-shift error

Any unwanted magnetic field, generated by materials with permanent magnetic field (hard irons), impose bias on the magnetometer measurements. This constant bias term, $\boldsymbol{b}_{hi}$ must be in-flight estimated for small satellite applications since it may vary after the launch [6]. It is assumed that the hard iron bias remains constant once the satellite is in orbit and fully functional.Null-shift error, $\boldsymbol{b}_{ns}$, which is inherent to the sensor, has also constant bias effect on the magnetometer measurements.

2.1.3. Time-varying bias

Items inside the satellite such as MTQs may generate unwanted magnetic fields that are time-varying [5]. Depending on the satellite configuration, the strength of the time-varying bias, $\boldsymbol{b}_{tv}$, may be either small or large compared to the permanent hard iron bias. All bias terms - hard iron, null-shift and time-varying biases - may be treated together and in-orbit estimated as a single time-varying bias vector $\boldsymbol{b} = \boldsymbol{b}_{hi} + \boldsymbol{b}_{ns} + \boldsymbol{b}_{tv}$.

2.1.4. Scaling

Ideally, three sensors of a magnetometer triad are identical so their output will be the same when they are subjected to an identical magnetic field. However, in practice sensitivity of each magnetometer is different and to represent this difference the output of each sensor must be multiplied with a scale factor. Scaling error is represented with a 3×3 matrix, D_{sf} built of scale factors,

$$D_{sf} = \begin{bmatrix} 1+\xi_x & 0 & 0 \\ 0 & 1+\xi_y & 0 \\ 0 & 0 & 1+\xi_z \end{bmatrix}. \tag{2}$$

Here, ξ_x, ξ_y and ξ_z are scale factors representing the input-to-output sensitivity of each magnetometer.

Scale factor terms may vary over time due to the environmental influences, e.g., temperature [11].

2.1.5. Nonorthogonality

In case the sensors are not orthogonal to each other, this error should be reflected to the measurements as a transformation of vector space basis. Nonorthogonality is parameterized by D_{no} matrix:

$$D_{no} = \begin{bmatrix} 1 & 0 & 0 \\ \sin(\rho) & \cos(\rho) & 0 \\ \sin(\phi)\cos(\lambda) & \sin(\lambda) & \cos(\phi)\cos(\lambda) \end{bmatrix}, \tag{3}$$

where ρ, ϕ and λ are respectively the angles between the y-sensor and y-axis, the z-sensor and y-z plane, and the z-sensor and y-z plane (Fig. 2) [12].

2.1.6. Misalignment

In ideal case the alignment of the TAM frame with respect to the spacecraft body frame would be known accurately. However, in practice a perfect alignment cannot be achieved. As a result of different