Acta Astronautica 133 (2017) 269–281

Contents lists available at ScienceDirect

Acta Astronautica

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

Online attitude determination of a passively magnetically stabilized spacecraft

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ARTICLE INFO

Keywords:
Attitude determination
Nano satellites
Passive magnetic stabilization
Kalman Filter
MEKF
Online estimation

ABSTRACT

An online attitude determination filter is developed for a nano satellite that has no onboard attitude sensors or gyros. Specifically, the attitude of NASA Ames Research Center's O/OREOS, a passively magnetically stabilized 3U CubeSat, is determined using only an estimate of the solar vector obtained from solar panel currents. The filter is based upon the existing multiplicative extended Kalman filter (MEKF) but instead of relying on gyros to drive the motion model, the filter instead incorporates a model of the spacecraft's attitude dynamics in the motion model. An attitude determination accuracy of five degrees is demonstrated, a performance verified using flight data from the University of Michigan's RAX-1. Although the filter was designed for the specific problem of a satellite without gyros or attitude determination it could also be used to provide smoothing of noisy gyro signals or to provide a backup in the event of gyro failures.

1. Introduction

In this paper the problem of providing an online attitude determination capability to satellites that have no dedicated attitude or attitude rate sensing hardware is studied. The specific problem studied originated from work relating to NASA Ames Research Center's O/OREOS [1] nano satellite, a 3U CubeSat illustrated in Fig. 1(a). The primary science mission on O/OREOS required neither an attitude pointing nor an attitude knowledge capability. To minimize mission cost, complexity and risk, a passive magnetic attitude stabilization system was used and no attitude or attitude rate sensing hardware was installed. After launch and completion of the primary science mission, however, there was a subsequent desire to estimate the attitude of the spacecraft to help with the design of a future mission. The only data available to perform this task were the electrical currents from the body mounted solar panels from which an estimate of the body frame sun vector, the unit vector pointing from the spacecraft to the sun, can be made.

A single isolated measurement of a known inertial vector, such as the sun vector, is insufficient to determine attitude due to a rotational ambiguity around the vector itself. Taking sequential measurements of the vector can help, although if the spacecraft is undergoing torque free motion then the ambiguity will still remain. To resolve the ambiguity, the spacecraft's attitude motion either needs to be forced with a known external torque that is aperiodic with the rotation in the body frame, or the known inertial vector being measured needs to be moving in the inertial frame. For O/OREOS, the passive magnetic stabilization system provides the external torques necessary to resolve the ambiguity.

Attitude estimators that use sequential measurements incorporate a motion model whose purpose is to propagate the estimate between each measurement. Existing attitude determination algorithms that incorporate a motion model [2,3], have relied on gyro readings to drive the motion model and so are not suitable for use in this case, where the spacecraft does not have gyros. The online attitude filter presented in this paper instead uses a model of the spacecraft's attitude dynamics as the motion model, allowing attitude determination to be performed using only sequential sun vector measurements and no onboard gyros.

The new filter is based upon the popular multiplicative extended Kalman filter [4] (MEKF), a recursive estimator that in its original formulation uses a gyro driven motion model. In an MEKF, spacecraft attitude is represented by the unit quaternion. In this work, the gyro-driven kinematic motion model in the original MEKF is replaced with a model of the spacecraft attitude dynamics, a two step process requiring the formulation of an attitude dynamics model and the reformulation of the original filter equations to account for the different motion model.

Formulating an accurate attitude dynamics model is non-trivial due

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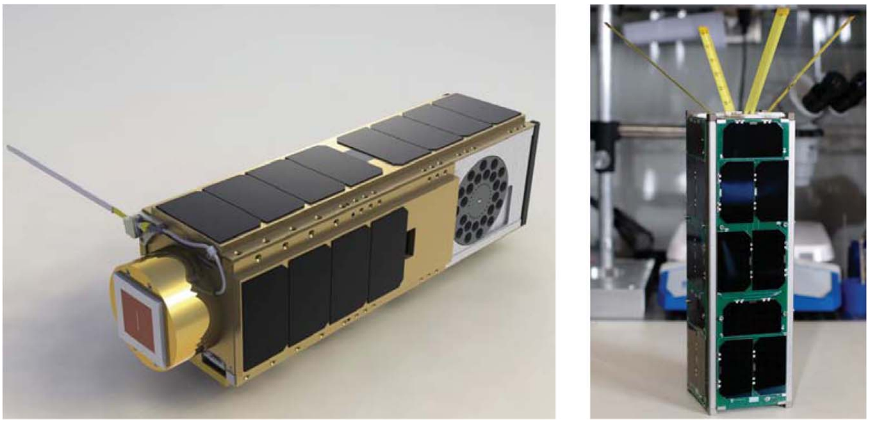
http://dx.doi.org/10.1016/j.actaastro.2017.01.024
Received 8 October 2015; Accepted 19 January 2017

0094-5765/

Nomenclature

Notation

μ_0	permeability of free space $= 4\pi \times 10^{-7}$, $\mathrm{H\,m^{-1}}$
c	solar unit vector in body frame
c_{ECI}	solar unit vector in inertial frame
H	external magnetic field, body frame, $\mathrm{Am^{-1}}$
H_{ECI}	Earth's magnetic field, ECI frame, $\mathrm{Am^{-1}}$
B	induced magnetic flux density in permeable material, T
V	volume of permeable rod material, $\mathrm{m^3}$
M	total dipole of magnetic material, $\mathrm{Am^2}$
M_{P}	permanent dipole in a permanent magnet, $\mathrm{Am^2}$
I	moment of inertia, body frame, $\mathrm{kgm^2}$
T_{dist}	external disturbance torque, body frame, N m
q	unit quaternion, inertial to body frame
a	attitude error vector
ω	angular velocity, body frame, $\mathrm{rads^{-1}}$
t	time, s
Σ	state covariance matrix
ν	measurement noise
η	system noise
Σ_ν	measurement noise covariance matrix
Σ_η	system noise covariance matrix
σ_{a0}	Standard deviation of uncertainty in initial attitude error
$\sigma_{\omega 0}$	Standard deviation of uncertainty in initial attitude rate, $\mathrm{rads^{-1}}$
$\sigma_{\boldsymbol{c}}$	Standard deviation of errors in solar vector
$\sigma_{\boldsymbol{H}}$	Standard deviation of errors in the external magnetic field, $\mathrm{Am^{-1}}$
$\sigma_{\boldsymbol{T}}$	Standard deviation of external disturbance torques, $\mathrm{Am^{-1}}$



(a) O/OREOS (NASA)

(b) RAX-1 (University of Michigan)

Fig. 1. 3U CubeSat nano satellites, (a) O/OREOS (NASA), (b)RAX-1 (University of Michigan).

to the large uncertainties in inertia properties and external torques [3]. Recent work [5], however, has shown that an attitude dynamics model can be reconstructed using a batch parameter estimation process. Reformulating the MEKF to incorporate an attitude dynamics model is presented in this paper.

While in this paper the new filter is only applied to the specific case of a passively magnetically stabilized nano satellite, the filter is applicable to any spacecraft for which there exists (1) an accurate dynamics model (2) the ability to measure an inertial vector and (3) either known external torques or movement of that inertial vector to resolve the rotational ambiguity.

Although the motivating problem concerns a satellite without any attitude sensors, the new filter does also have utility in modern spacecraft designs that do include dedicated attitude sensors. Firstly, the algorithm can provide a backup attitude determination capability in the event that some or all of the dedicated attitude or attitude rate sensors fail or for use when the spacecraft is in safe-mode and not all systems are operational. Secondly, the gyro-free MEKF can be trivially modified to include both gyro measurements and the attitude dynamics model. This has the potential to provide an improved attitude determination capability over just using gyros when the gyros are noisy, as is often the case with the MEMS gyros now commonly used on nano satellites.

The new filter is tested and shown to converge using actual flight data from O/OREOS. Unfortunately, as O/OREOS contained no attitude hardware, no independent estimate of attitude is available and filter performance cannot be verified. In order to verify filter performance, the filter is also applied to flight data from the University of Michigan's RAX-1 [6], illustrated in Fig. 1(b). Like O/OREOS, RAX-1 was a passively magnetically stabilized 3U CubeSat. Unlike O/OREOS, however, RAX-1 also carried attitude sensors, including a gyro, magnetometers and photodiode sun sensors. An independent attitude estimate is made using traditional methods from these sensors and compared to the estimate generated using only measurements of the sun vector and a model of the satellite's attitude dynamics. Attitude determination performance of 5° with the new filter is observed.

This paper is organized as follows: Section 2 describes the nano satellites studied in this paper and details the flight data available from each. A gyro free MEKF, where the motion model has been changed from the customary one utilizing gyros to one based on an attitude dynamics model is presented in Section 3. In Section 4 the new gyro-free filter is implemented for a passively magnetically stabilized nano satellite and that section includes the derivation of the required attitude dynamics model. Results from testing the filter in simulation are presented in Section 5 and results from application to actual flight data are presented in Section 6.

2. The spacecraft

Passive magnetic stabilization is commonly employed in nano satellites where a precision pointing capability is not required. The spin axis of a passively magnetically stabilized spacecraft stays nominally aligned with the local magnetic field vector, providing rudimentary nadir pointing. The low mass and zero power require-