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High spin rate magnetic controller for nanosatellites ☆

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ABSTRACT

This paper presents a study of a high rate closed-loop spin controller that uses only electromagnetic coils as actuators. The controller is able to perform spin rate control and simultaneously align the spin axis with the Earth's inertial reference frame. It is implemented, optimised and simulated for a 1-unit CubeSat ESTCube-1 to fulfil its mission requirements: spin the satellite up to 360 deg s^{-1} around the z-axis and align its spin axis with the Earth's polar axis with a pointing error of less than 3°. The attitude of the satellite is determined using a magnetic field vector, a Sun vector and angular velocity. It is estimated using an Unscented Kalman Filter and controlled using three electromagnetic coils. The algorithm is tested in a simulation environment that includes models of space environment and environmental disturbances, sensor and actuator emulation, attitude estimation, and a model to simulate the time delay caused by on-board calculations. In addition to the normal operation mode, analyses of reduced satellite functionality are performed: significant errors of attitude estimation due to non-operational Sun sensors; and limited actuator functionality due to two non-operational coils. A hardware-in-the-loop test is also performed to verify on-board software.

1. Introduction

The development of nanosatellites has opened up new opportunities for space exploitation by decreasing average development times and mission costs [1]. Widespread use of the CubeSat standard [2] has enabled further reductions in average launch costs as standardised deployment systems have been developed for many different launchers. A wide range of general subsystems designed specifically for Cube Satellites is commercially available. Also, CubeSat developers often rely on the commercial off-the-shelf (COTS) components [3]. At the same time, strict limitations on mass and volume are challenging because of limited power production, limited computational performance as well as limited means of attitude measurements and control [4–6].

Despite these limitations, nanosatellites can accommodate more and more ambitious scientific payloads and technology for in-orbit demonstrations. Some experiments require active Attitude Determination and Control Systems (ADCS) using only electromagnetic actuation and on-board software of reduced computational complexity. [7–11].

Multiple nanosatellites have performed, or plan to perform, spin control using electromagnetic actuation. HAMSAT [12,13], Solar sail Cubesat [14], UOSAT [15] and TSUBAME [16] use B-dot [17] based spin controllers. Balaraman et al. [18] and Grahn [19] also discuss the B-dot based approach. FAST [20] and CINEMA [21] satellites use a two-stage controller (spin rate and precession) based on an analysis by Shigehara [22] and Grubin [23].

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Ovchinnikov et al. [24] have developed a controller that can also be implemented as a two-stage controller. The magnetic fault-tolerant spin stabilising controller for the JC2Sat-FF mission [25] stands out with its efficient simultaneous control of spin rate and alignment of the spin axis with the Earth's inertial reference frame. However, the use of this controller for high spin rate control (magnitudes of hundreds of deg s^{-1}) has not previously been examined.

This study presents a spin control algorithm, which has been implemented, optimised and simulated for a 1-unit CubeSat [2] ESTCube-1 [26,27]. Monte Carlo simulation results of a fully operational satellite are presented. Two analyses of the satellite of reduced functionality are carried out, in the first instance by simulating non-operational Sun sensors and in the second instance by simulating two non-operational coils. Hardware-in-the-loop (HIL) test results are presented.

The spin control algorithm is implemented and tested in a MATLAB® Simulink® space simulation environment [28,29] that includes models of space environment and environmental disturbance, sensor and actuator emulation, an Unscented Kalman Filter (UKF) [30] for attitude estimation, and a model to simulate the time delay caused by on-board calculations.

2. Requirements

While there could be many applications of magnetic satellite spin control for nanosatellites (e.g., spin-stabilisation), this paper studies the use of controller for the ESTCube-1 satellite to fulfil the following mission requirement: spin the satellite up to 360 deg s^{-1} around the z-axis (major axis of inertia) and align its spin axis with the Earth's polar axis with a pointing error of less than 3°. This mission is the first in-space Electric Solar Wind Sail (E-sail) [31] experiment carried out on the ESTCube-1 satellite, a 1-unit, 1.1 kg CubeSat that will be in Sun-synchronous polar orbit at an altitude of $\approx$680 km. The satellite will use the centrifugal force provided by spin-up manoeuvre to deploy a 10 m long tether. A rather high value of angular rate of 360 deg s^{-1} was selected to ensure a high enough tether tension to pull the tether out from the reel reliably. The angular rate of 360 deg s^{-1} will decrease to $\approx$20 deg s^{-1} during tether deployment due to angular momentum conservation. After tether deployment, the E-sail experiment will be run by charging the tether synchronously with the satellite spin to increase and decrease the satellite angular rate by employing the Coulomb drag force. In a polar orbit, the Coulomb drag force changes the spin rate of the tether maximally when the orbital velocity vector lies in the spin plane. Tilting of the spin plane caused by the magnetic Lorentz force should be avoided. Having the spin plane aligned with the equatorial plane and running the experiment near the Earth's geographical poles provides a set-up with a maximal influence of the Coulomb drag force and a minimal spin plane tilt caused by the magnetic Lorentz force because the magnetic field is perpendicular to the spin plane. An alignment error of less than 3° is a safe selection for the influence of the Coulomb drag force to be big enough and of the magnetic Lorentz force to be small enough. The ESTCube-1 ground station is located at an approximate latitude of 58° North. ESTCube-1 has monopole antennas perpendicular to the z-axis. This set-up provides a communication link without blind spots even if the satellite has a high spin rate around the satellite z-axis that is aligned with the Earth's polar axis. [27]

The attitude determination system uses three-axis magnetometers, three-axis gyroscopic sensors and two-axis Sun sensors, one on each side of the satellite. Attitude estimation is performed using an UKF and attitude control is performed by three electromagnetic coils.

The electrical power system is able to provide constantly 150 mW from batteries for coils for more than 30 orbits in the worst-case scenario assuming that no power is generated by solar panels. Since each side of the satellite is covered with two solar panels, power generation of a spinning satellite should not drop below the estimated worst-case scenario of 2.2 W assuming that one side of the satellite is directed towards the Sun. [26]

To mitigate the risk of mission failure due to hardware malfunction, analyses of reduced satellite functionality are carried out. While magnetometer and gyroscope failure would lead to failure of the mission, this risk is mitigated by the use of two magnetometers and four gyroscopes. Sun sensor failure would increase errors in estimated attitude. Worst-case scenario analysis is carried out by simulating spin control when all Sun sensors fail. The implications of failed magnetic actuators are described by de Ruiter [25]. Analysis shows that the spin controller is able to reach the desired state even when up to two coils fail, providing that the working coil is perpendicular to the spin plane. In this paper, this worst-case scenario analysis is carried out by simulating spin control when two coils fail (x–z and y–z).

To mitigate the risk of software failure, a HIL test is carried out on a MCU prototype with the same processor and memory capacity as on the flight hardware.

3. Space simulation environment

The space simulation environment is a set of adjustable and expandable models and signal processing tools that interact with each other to provide a realistic basis for modelling attitude determination and control.

In this analysis, the following reference frames are used. First, the Earth Centred Inertial reference Frame (ECIF): the origin of the frame is at the centre of the Earth, the x-axis passes through the point where the vernal equinox and equatorial plane intersect, and the z-axis passes through the Geographic North Pole. Second, the Earth Centred Earth Fixed reference frame (ECEF): the origin of the frame is at the centre of the Earth, the x-axis passes through the point where the Greenwich Meridian intersects the equatorial plane, and the z-axis passes through the Geographic North Pole. Third, the Satellite Body Reference Frame (SBRF): the origin of the frame is at the geometrical centre of the satellite and all axes are aligned with the satellite frame. According to Vinther et al. [30], the rotation between the SBRF and the principal reference frame is not required since 1-unit CubeSats are close to symmetric in terms of mass distribution.