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Magnetic attitude control for Earth-pointing satellites in the presence of gravity gradient

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ABSTRACT

A sliding mode control law is applicable to a variety of nonlinear problems and can adapt itself to disturbance torques and parameter uncertainties in real time. In this work, an adaptive sliding mode control law for purely magnetic actuated Earth-pointing satellite with a gravity gradient boom is presented. This control law has been developed for the BUAA-SAT microsatellite, which is designed and manufactured by Beihang University, Beijing. The new control law is a modification of the general sliding mode strategy that enables the satellite to achieve an Earth-pointing attitude and deal with the uncertainty of the principal moment of inertia, which is caused by the incomplete deployment of the gravity gradient boom. In addition, a B-dot algorithm is employed for the detumbling before the boom is deployed. The performance and applicability of the proposed methods have been analyzed and demonstrated by implementing the control law in the BUAA-SAT mission simulator and compared with the proportional derivative-like controller. Presented results show good performance in terms of acquisition and stability of the satellite rotation rate and Earth-pointing attitude.

1. Introduction

Since the successful implementation of magnetic attitude control in the early space missions [1], the magnetic actuator has turned into an attractive alternative for the attitude control of spacecrafts operating in low Earth orbits (LEO). The magnetic actuator generally operates on the basis of the interaction between a set of three orthogonal current-driven coils with the geomagnetic field [2], and the implications make it significantly saves cost, power, weight, and complexity of the system compared to other attitude actuators. Thanks to not having any propellant or moving parts, the risk of failure of the control strategy based on the magnetic actuators is effectively reduced, for which the reliability of system is obviously improved. However, despite its advantages, a magnetic actuated spacecraft would always be an underactuated system due to the magnetic torques which can be applied to the spacecraft for attitude control purposes are constrained to the plane perpendicular to the local geomagnetic field vector [3], this means it is not possible to provide three independent control torques at each time instant. In addition, the magnetic control system is intrinsically time-varying, as the controllability of the attitude motion by purely magnetic actuation relies on the variation of the local geomagnetic field along the orbit of satellite [4]. This fact makes the magnetic attitude control especially suitable in practice for those small (micro-, nano-, and pico-) satellites with not-too-demanding orientation requirements.

A number of control methods have been developed for attitude acquisition, maneuver, and stabilization of magnetic actuated satellites during the last decades [5–10]. The well-known B-dot control law was proposed early in 1972 [11], which is a nonlinear strategy widely used for attitude detumbling of magnetic actuated satellites. Thereafter, the relevant research work mainly focus on the stability analysis of magnetic control law. Besides the local asymptotic stability of attitude equilibrium is addressed by using either periodic optimal control in the linear case [12–14] or suitable time-varying controllers [15], the problem of global asymptotic stability has also been extensively studied. To the best knowledge of the authors, an ultimate solution of the global attitude stabilization problem by purely magnetic actuation is still to be provided. While it is encouraged by recent authors [16–18] that the global stabilization is possible when the magnetic field variation is sufficient along the complete orbit, their effort are important in this respect even just for an "almost" global stabilization achievement. Particularly, the case of purely magnetic actuated Earth-pointing satellites in the presence of gravity gradient has been proved to be globally convergent [17]. In consideration of this fact and takes the brisk demand into account, the Earth-pointing case in the presence

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of gravity gradient concerns more practical interests, especially for the purely magnetic actuated microsatellites.

As previously mentioned, the local and global stability problem of the magnetic control system have been widely studied, while the consideration about external disturbances and uncertainties problem is relatively scarce in those conventional magnetic control laws, which means that the controllers are not adapted depending on the disturbance level or some drastic change in plant parameters in real time [19]. The dynamics of the satellite is subject to multiple disturbance torques and various sources of uncertainty, including the uncertainty of the moment of inertia and the quasi-periodic behavior of the geomagnetic field [3] along the orbit. Therefore, it is imperative to design a robust controller that adapts itself in real time, depending on the nature of the disturbances and uncertainties, to provide a better control for magnetic actuated satellites. The sliding mode control is known as a nonlinear technique which can reject the external disturbances and bring robustness to the system parameter uncertainty and variations [20], it has been successfully applied to address the satellite attitude maneuver problem [21–23] and the attitude tracking problem [24]. Considering the external disturbances and uncertainties problem, it does make sense to apply sliding mode control to the purely magnetic actuated satellites.

The survey results concluded that a relatively small number of publications are available in terms of applying the sliding mode control to the purely magnetic actuated satellites [25–30]. These publications carried out some useful attempts to deal with the underactuated problem of magnetic system, either by designing a special sliding manifold or a better reaching control law, while the disturbance torques and parameter uncertainties are out of their consideration. With regard to the Earth-pointing case in the presence of gravity gradient previously mentioned, the uncertainty of the moment of inertia is a critical problem due to the long gravity gradient boom. Therefore, it's necessary to improve the existing sliding mode strategy for this special and very attractive case. In the light of this, a new quaternion-based adaptive sliding mode control law is developed in the present work to deal with the uncertainty of the moment of inertia and achieve an Earth-pointing attitude for a purely magnetic actuated satellite in the presence of gravity gradient. The proposed control law is based on a modification of the general sliding mode strategy. The main advantage of this modification is that it enables an "estimation" of the principal moment of inertia for the satellite, which is not possible using the conventional sliding mode control law.

This paper is organized as follows: in Section 2, a description of the BUAA-SAT microsatellite missions and the attitude control system requirements is included, whereas in Section 3, the general mathematical models of a magnetically controlled satellite are introduced. In Section 4, the development and implementation of the proposed control law is presented, the controllability problem is discussed whereafter. Section 5 presents the simulation results of the different cases from the BUAA-SAT attitude control simulator. The conclusions of this work are summarized in Section 6.

2. BUAA-SAT microsatellite

The attitude control proposed in this paper was designed for the BUAA-SAT satellite, which is a 35 kg microsatellite developed at the School of Astronautics, Beihang University (SA/BUAA). The satellite is purely magnetic actuated and scheduled to be launched into a Sun-synchronous dawn/dusk orbit, at 600 km altitude and 97.8° inclination, for a two years' LEO mission. Three main flight missions will be implemented on the BUAA-SAT platform: (1) the coilable mast deployment demonstration, (2) the space-based automatic dependent surveillance-broadcast (ADS-B) verification, (3) the space debris identification based on a space camera (SpaceCam). The mission characteristics greatly impacted and determined the attitude control approach and design. These characteristics are summarized in the following.

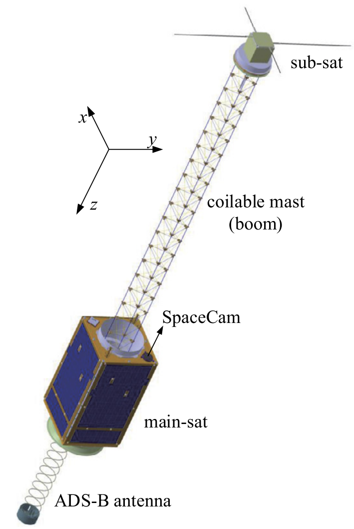

Fig. 1. The gravity gradient configuration of the considered microsatellite after the coilable mast is deployed. The body frame is also shown in this figure.

The coilable mast will be stowed in a cylinder during the launch phase. After the SC/LV separation, a detumbling phase is required to decrease the angular rotation rate of satellite. When the desired rotation rate is approached, the coilable mast will be deployed and the deployment process will be observed and recorded by the SpaceCam. After the successful deployment, a gravity gradient configuration including three parts (the main-sat, the sub-sat, and the boom) would form, as shown in Fig. 1. Then the satellite will enter the Earth-pointing phase, so as to sustain the target orientation of ADS-B antenna, which is installed at the bottom of the main-sat. The broadcast signals from the aircraft will be received (by the ADS-B antenna and receiver) and forwarded (by the tracking, telemetry, and command subsystem) to the ground station to verify the space-based ADS-B technology. The SpaceCam, which is installed on the top of the main-sat and its lens is facing the zenith, will be mainly used for the space debris identification in this phase. If the experiment is successful, this type of camera will be applied to a space debris removal mission based on another satellite. The plant parameters of BUAA-SAT are listed in Table 1.

Fig. 2 indicates the nominal attitude and motion of the satellite in the selected orbit. The main-sat points to the Earth, and meanwhile, the satellite slowly rotates about the principal axis of the minimum moment of inertia. Taking into account the aforementioned orbit, the satellite will experience a maximum duration of

Table 1
The plant parameters of the BUAA-SAT microsatellite.

Dimensions (before deployment)	$0.30 \times 0.30 \times 0.55$ m^3
Moment of inertia before deployment	diag([1.1470, 1.1360, 0.5330]) kg m^2
Moment of inertia after fully deployment	diag([7.6590, 7.6490, 0.5330]) kg m^2
Maximum length of the coilable mast	2 m
The maximum magnetic dipole moment	12 A m^2