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Development and experimental validation of a multi-algorithmic hybrid attitude determination and control system for a small satellite

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ABSTRACT

Advanced missions of satellites are increasingly demanding more accurate and robust attitude maneuvering capabilities. However, it is difficult to achieve especially for small satellites due to limited hardware resources of sensors, actuators, and processors. In this paper, to achieve the desired performance, a multi-algorithmic hybrid attitude determination and control system (ADCS) that utilizes a family of control and estimation algorithms is developed and implemented in numerical simulations and experiments for a small satellite. The hybrid automaton framework of the ADCS is designed to accomplish the desired performance with the limited hardware capability by switching the control and estimation algorithms effectively for given situations in space. The performance of the hybrid ADCS is evaluated through numerical and hardware-in-the-loop simulations that are based on a three-dimensional air-bearing testbed, CubeSat Three-Axis Simulator (CubeTAS). Simulation and experimental results demonstrate the effectiveness of the multi-algorithmic hybrid ADCS. The significance of this paper is in demonstrating that the hybrid automaton framework can be an effective approach to handle operational situations in space. It also provides a design reference for a small satellite ADCS.

1. Introduction

With the increasing application of small satellites, there exist massive and concurrent requests for extensive functions and capabilities such as higher pointing accuracy or maximum power generation [1]. One representative of these requests is an extension in attitude maneuvering capability from passive stabilization to active attitude control. The passive magnetic stabilization methods with a permanent magnet and hysteresis strips only guarantee nadir pointing in a specific orbit region [2]. This method is simple to design and easy to build, and does not even require on-orbit calculation or management. However, this is not precise enough to conduct reconnaissance on a specific area, environmental monitoring, and communication with a specific ground station. These popular and advanced missions can only be achieved with an active ADCS for agile maneuvering in orbit, which is a challenging task not only for a small satellite but also for a large satellite.

In the early stage of small satellite development, rough nadir pointing with magnetic devices was used for missions, but recent missions often require less than a few degrees of pointing accuracy with the use of a reaction wheel assembly (RWA), magnetorquer, and even paired thrusters. This trend is found in the project history of several universities and research institutes that have conducted multiple satellite missions successfully. For example, all the missions from the Michigan eXploration Laboratory (MXL) at the University of Michigan [3–6], the Delfi series from the Delft University of Technology (TU Delft) [7,8] and the CAN-X series of the University of Toronto [9] present similar ADCS development trends. Each of them has started only with passive stabilization, then they have transferred to more complex active ADCS development as their experiences and know-how of spacecraft attitude managing have been accumulated from the early stage missions. A survey of the attitude control method for each individual launched CubeSat mission is provided in [10].

The limited resources, such as small actuators, low-cost sensors, and low-powered processors, and operational capability make active ADCS of a small satellite difficult. For example, small-sized reaction wheels that are popular in a small satellite design experience an easy saturation of angular momentum due to disturbance torques in Low Earth Orbits (LEO). In such a case, stability or

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pointing accuracy of the spacecraft could be lost. To prevent this, a magnetic control device and algorithm is required as a complement for an RWA. The implementation of the magnetic control, however, degrades the pointing accuracy of a satellite due to the objective conflict between the required algorithms. Another challenge in the active ADCS takes place when an Extended Kalman Filter (EKF) [11] is used for on-orbit attitude determination. A large error in the initial estimation may cause divergence in the attitude estimation due to the linearization-based characteristics of the EKF [12]. Consequently, in practice, simpler estimation algorithms, such as QUaternion ESTimation (QUEST) [13,14] and TRIAD [15,16], are implemented prior to activating the EKF to reduce the initial estimation error. A condition to switch from QUEST to EKF, therefore, should be selected carefully [3], similarly with the switching of the control algorithms. These challenges demonstrate that the development and implementation of multi-algorithmic control and estimation are essential in an active ADCS.

Active ADCS approaches for small satellites have been studied and developed by several research groups. The Space Flight Laboratory (SFL) at the University of Toronto developed an active ADCS algorithm for CanX-2 that performed successful attitude estimation and pointing with sensors and miniature wheels in space [17]. CanX-4 and CanX-5 of SFL achieved in-orbit demonstrations of formation flight by ADCS with three reaction wheels mounted orthogonally [18]. Through the Delfi nanosatellite program of the TU Delft, the Delfi-n3Xt satellite has been developed and tested in space with a highly integrated ADCS that performs three-axis active control using reaction wheels [19]. The Institute of Space Research of the Russian Academy of Sciences has developed the Chibis-M microsatellite ADCS using six reaction wheels and three magnetoquers as a demonstration with redundant actuators [20]. The ADCS was validated through the laboratory tests and in-orbit flight. A one-unit small satellite, ESTCube-1, was developed by the University of Tartu. It utilized the spin rate control algorithm to simultaneously align the spin axis with the Earth's inertial reference frame using only electro-magnetic coils [21]. Its algorithm was verified to achieve a pointing error less than 3 deg by implementing numerical simulations.

In this paper, we propose an autonomous active ADCS that exploits multiple control and attitude determination algorithms based on a hybrid automaton framework to achieve high pointing accuracy. Pre-developed control and estimation methods are modified and merged into the proposed hybrid automaton framework. Realistic operation scenarios in orbit are assumed and simulated on a numerical simulator. The hybrid automaton framework is also experimentally validated on an air-bearing testbed. Motivated by the importance of ground testing and verification of ADCS algorithms, an experimental air-bearing testbed, CubeSat Three-Axis Simulator (CubeTAS) [22–24], has been developed to simulate a frictionless and torque-free environment. The CubeTAS hardware-in-the-loop (HIL) simulator consists of a hemispherical air bearing in which contains the sensors, actuators, computers, and power storage. The developed hybrid ADCS using multiple algorithms is implemented in the embedded system of CubeTAS to verify the maneuvering performance with real sensors, actuators, and computing resources.

While there are not many references about active ADCS for CubeSat from the design stage to the final ground validation stage, this paper provides the design and validation process including design requirements and the related considerations, a theoretical approach to the hybrid control, system implementation, and experimental validation methods and procedures on the ground. An important contribution of this paper is experimentally validating the hybrid system's framework for multi-algorithms using the three-axis air-bearing test bed. To the best of our knowledge, there are no research papers on the validation of multi-algorithms for a small satellite in the three-axis air-bearing test facilities. In this research, we validate the attitude determination and control algorithm through the hardware-in-the-loop-simulations. Secondly, we provide the definition of modes and jump conditions in the hybrid system theory. This has not been reported in the research community related to CubeSat although this is crucial for designing a multi-mode algorithm to avoid mission failures and early, successful completion of CubeSat missions. What's especially crucial is the hybrid system framework targets CubeSat with the reaction wheel assembly that has an angular momentum desaturation problem.

The paper is organized as follows. The mission requirement analysis and selection of actuators and sensors are presented in Section 2. Next, main estimation and control algorithms are designed and analyzed in Section 3. To complement the expected limitations in various situations, auxiliary control algorithms are also developed and added. In Section 4, the developed control and estimation algorithms are integrated with a hybrid automaton framework. The hybrid automaton strategy enables various control modes of the satellite to autonomously handle the situations instead of sending commands from a ground station. The hybrid automaton framework is a key enabler for autonomous and precise pointing control of an active ADCS in this research. As the last stage of the design process, numerical simulations and HIL simulations (HILS) are implemented to validate the multi-algorithmic hybrid ADCS in Section 5.

2. ADCS design process

Fig. 1 provides an overview of this ADCS design process. First, the satellite coordinate frames with the desired attitude and the pointing error range are defined based on the requirements of the mission. Next, actuators and sensors are selected by considering the required pointing accuracy. Notice that reaction wheels need to be combined with other devices such as magnetoquers for the angular momentum desaturation. Main estimation and control algorithms are then designed and analyzed. However, a smaller satellite with fast initial rotating speed and low-cost hardware requires intermediate and complementary algorithms that can reduce the uncertainty caused by the operational characteristics and hardware performance limitation. Therefore, these complimentary algorithms are also developed and implemented. One important contribution of this research is integrating the multiple algorithms using a hybrid automaton framework. Normally, various situations of a satellite have been handled with commands given from a ground station. However, using the hybrid automaton framework, an autonomous ADCS can be designed. Operation strategies and commanding sequences after the deployment in space are investigated to design the hybrid automaton. As the last stage, numerical simulations and experiments are conducted to validate the design. For the numerical simulations, a MATLAB/Simulink simulator base on the Lie Group Variational Integrator (LGVI) is implemented. The 3D air-bearing testbed, CubeTAS, is used for experiments.

2.1. Mission requirement analysis

The first step of an ADCS design is to analyze mission requirements. During the analysis procedure, satellite body and orbit coordinates must be defined for measuring the pointing accuracy of the satellite. The coordinates that the mission requirements are subjective must be defined clearly. For example, in the small satellite mission of CADRE [6], capturing ions and neutral winds with a device is the main goal of the mission. To capture ions, the satellite with the field-of-view requires to point within 15 deg of the velocity vector to accomplish measurements. Moreover, in order to maximize captured ions, the pointing direction of the satellite should be within one degree angle from its orbital velocity vector