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Nonsingular terminal sliding mode control technique for attitude tracking problem of a small satellite with combined energy and attitude control system (CEACS)

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A B S T R A C T

Attitude control and power storage subsystems are two of the essential utilities provided on a spacecraft. As they comprise a significant fraction of a spacecraft mass, a synergism concept that integrates these two into one subsystem can reduce the mass and volume of a spacecraft. The reduction will decrease the total cost of development and deployment of a satellite. A combined energy and attitude control system (CEACS) utilizes flywheels as a means of power storage and simultaneously as actuators. A series of works on CEACS have proposed solutions for attitude control problem of pitch axis. However, their analyses disregarded the high non-linearity involved in the attitude control of a spacecraft. In addition, the proposed controllers' feasibility in the presence of unknown perturbations and uncertainties were not examined. This study proposes a Nonsingular Terminal Sliding Mode (NTSM) control scheme for the attitude tracking control of roll, pitch and yaw axes of a small satellite with CEACS. The nonlinear system is subjected to unknown but bounded disturbances and uncertainties. The Lyapunov stability theorem is used to prove finite-time convergence in both reaching and sliding phases. This proposed method avoids inherited singularity of conventional terminal sliding mode. The numerical analysis provides proof of the controller robustness in rejecting unknown disturbances and keeping the attitude errors within limits under the influence of uncertainties. Results provided by NTSM control method demonstrate the superiority of this sliding mode scheme compared to the previous proposed techniques for attitude control of the CEACS.

1. Introduction

The future of complex space missions especially those involved with scientific and commercial spacecraft depends on the cost of development and deployment. The cost of deployment can be decreased significantly by reducing the size and mass of a spacecraft. Therefore, a primary focus during spacecraft development is being placed on mass and volume optimization while fulfilling the challenging missions' requirements. Integration of two or more subsystems of a spacecraft could reduce the mass and size, decrease the cost of launch, and allow a greater fraction of the spacecraft mass to be devoted to payload.

Flywheels, as typical actuators used in spacecraft attitude control systems, can be simultaneously used as a power storage system [1]. This synergism concept can decrease a spacecraft utility mass fraction significantly. Combined Energy and Attitude Control System (CEACS) has adopted this synergism concept to minimize the mass and size of small satellites and yet provide additional advantages for an enhanced overall mission performance. CEACS also benefits from the favorable characteristics of flywheels such as high depth-of-discharge, long life cycle and temperature independence [2,3]. Many studies have investigated the feasibility of CEACS from a controlling point of view using several linear control techniques such as PD, PID, and PID-Active Force Control (AFC) [2,4–6]. The primary focus of the studies was to provide control strategies to reject disturbances effectively and be able to keep the pointing accuracy at less than 0.2° for pitch axis and 0.5° for roll and yaw axes. A better pointing accuracy was achieved through the implementation of a PID-Active Force Control (AFC) technique. The influence of internal errors on the performance of a small satellite featuring CEACS was examined to verify the robustness of the proposed linear controller [5]. However, the sensitivity of the linear controller to onboard errors (uncertainties) called for a more robust control method. In another study, the robustness and pointing accuracy of H_2 and H_∞ controllers for the attitude control of

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CEACS were inspected [7,8]. The optimal controllers are more robust to the induced onboard errors and the pointing accuracy is enhanced. The performance of H_2 and H_∞ controllers was also susceptible to onboard errors and the pointing accuracy of the non-ideal case degraded compared to the ideal scenario. In addition, the highly linearized mathematical models of satellite motion used in the aforementioned studies disregarded the nonlinearities involved in real-life behavior of a spacecraft in space environment. These simplifications burden the precision of the provided result with considerable errors. Therefore, it is of great interest to design a control law that addresses the nonlinearity of the system and is invariant to disturbances and uncertainties.

Sliding Mode Control (SMC) technique can provide the desirable robustness for the attitude control of CEACS. The well-known control method has proven capabilities in addressing uncertainties in highly nonlinear systems [9,10]. The application of sliding mode controllers in attitude control problem of spacecraft has been widely studied [11–17]. Some studies addressed the spacecraft attitude control problem using the conventional SMC method whose linear sliding surface is a function of tracking error and its derivatives. However, the conventional SMC only provides asymptotic stability and convergence; therefore, the control objective can be completed in infinite time and the convergence rate is at best exponential [15,16,18,19]. Consequently, fast maneuver and tracking, imperative in many space missions, is only possible by increasing the control gains significantly. This unrealistic and undesirable practice prompts action to develop a robust control solution with fast and finite-time stability and convergence [20].

The attitude control laws with finite-time convergence provide faster convergence rate and higher control accuracies with better disturbance rejection properties, and better robustness against uncertainties. Terminal Sliding Mode (TSM) whose nonlinear sliding surface can provide finite-time convergence is an adequate alternative for more precise attitude control of a spacecraft [15,21,22]. However, the singularity of control input hinders its feasibility in many applications. Thus, a Nonsingular Terminal Sliding Mode (NTSM) control technique is utilized here to tackle the attitude control problem of a small satellite utilizing CEACS. The NTSM control of spacecraft system is of interest because systems with finite time stability usually demonstrate some superior properties such as faster response, better disturbances rejection and insensitivity to model uncertainties. A nonsingular terminal sliding mode control approach was adopted in [23] for attitude tracking of a rigid spacecraft. The controller is proven to be robust against disturbances and some uncertainties. However, the control solution proposed in [23] is only true for small rotation errors, hence the solution developed is not global and the conclusion derived is exclusive for a particular case.

The main contribution of this paper is the implementation of NTSM control concept to achieve an enhanced performance for attitude tracking problem of a small satellite with CEACS in the presence of disturbances and uncertainties. This study offers a global solution for highly nonlinear attitude tracking problems of all three axes of the CEACS, whereas the previous studies addressed linear control problems. The problem formulation adopted in this paper takes a global approach in which all typical rotations are included. It is important to explore different control solutions for this particular system to have a clear understanding of the combined system feasibility in different missions and conditions. The proposed implementation provides finite-time convergence in both the reaching and the sliding phases and assures robustness and precision for the duration of the mission. In contrast to the papers published in this specific area, this paper offers sufficient evidences in numerical analyses to prove the NTSM finite-time convergence. The numerical analyses herein show the performance of the controller for a complete orbital period. This is particularly important to verify the singularity avoidance properties of NTSMC. The study takes into account the unknown but bounded inertia property that usually arises due to the variation of the satellite mass distribution. This work offers not only a finite-time convergence solution guaranteed by the Lyapunov theory, but it also presents significant enhancement in attitude control accuracy.

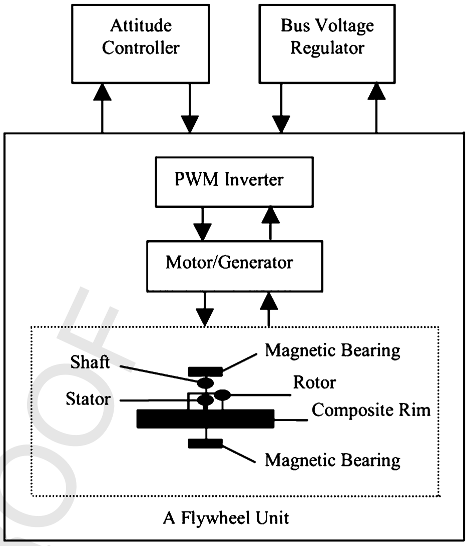

Fig. 1. Flywheel system setup in CEACS [4].

The paper is organized as follows: Section 2 is an introduction providing the essential facts about CEACS followed by the description of the spacecraft model in Section 3. The TSM technique and its limitations are described later to emphasize the importance of NTSM. Then, the control law derivation and stability proof are provided in Section 4. Numerical simulation of CEACS performance is provided in Section 5 to testify the claimed robustness of the proposed controller. Section 6 provides the conclusion to this paper.

2. CEACS architecture

CEACS generally consists of a set of counter-rotating composite rotors mounted along each rotation axis, a motor/generator unit, magnetic bearings and control electronics for energy/attitude control. A composite rim that is levitated with magnetic bearings rotates around a metallic shaft in a vacuum compartment. The flywheel unit is connected to the attitude and power control units via a motor/generator unit in order to execute the attitude and power control commands [6,24,25]. Fig. 1 illustrates the flywheel unit and its system setup in CEACS.

The system motion is considered friction free as the magnetic bearings provide a friction-less motion for the flywheel; and the vacuum compartment makes the system free of air drag/friction. The flywheel operates as an energy storage system and the bus voltage regulator carries out the energy storage tasks. During the sun phase, the solar panels produce enough electrical energy for the regular energy demands of the satellite as well as the storage demands. The regulator is responsible to issue a positive torque during this phase so that the motor/generator converts the excess electrical power to mechanical energy (kinetic) by speeding-up the flywheels. A discharging procedure is in action during the eclipse when a negative torque is generated by the regulator. Consequently, the counter-rotating flywheel spins-down and the generator converts the mechanical energy to electrical energy. The flywheels spin-up and spin-down constantly to meet the mission energy requirements [4,6,25]. The principles of this synergism concept are established based on the capacity and characteristics of wheels introduced in [26–28]. It should be pointed out that

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