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Singularity-free integral-augmented sliding mode control for combined energy and attitude control system

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Abstract

A combined energy and attitude control system (CEACS) is a synergized system in which flywheels are used as attitude control actuators and simultaneously as a power storage system. This paper, a subsequent to previous research on CEACS, addresses the attitude-tracking problem. Integral Augmented Sliding Mode Control with Boundary-Layer (IASMC-BL), a locally asymptotically stable controller, is developed to provide a robust and accurate solution for the CEACS's attitude-tracking problem. The controller alleviates the chattering phenomenon associated with the sliding mode using a boundary-layer technique. Simultaneously, it reduces the steady-state error using an integral action. This paper highlights the uncertainty of inertia matrix as a contributing factor to singularity problem. The inversion of the uncertain inertia matrix in simulation of a spacecraft dynamics is also identified as a leading factor to a singular situation. Therefore, an avoidance strategy is proposed in this paper to guarantee a singular-free dynamics behavior in faces of the uncertainties. This maiden work attempts to employ the singularity-free Integral Augmented Sliding Mode Control with Boundary-Layer (IASMC-BL) to provide a robust, accurate and nonsingular attitude-tracking solution for CEACS.

Keywords: Spacecraft guidance and control; CEACS; Flywheels; Low Earth orbit satellites; Sliding mode control; Synergism

1. Introduction

A very substantial fraction of the costs involved in a satellite mission is devoted to the deployment. The cost of launching a satellite depends on the volume and the mass. Therefore, mass and volume optimization is among the primary concerns of satellite engineers. Synergism of different subsystems of a satellite is an optimization approach to tackle the expanding demands and costs for space missions. The integration of the conventional subsystems provides a better overall performance, e.g., reliability and mass/cost savings.

Synergism for spacecraft attitude control system, as one of the most crucial and costly subsystems on-board, is very convenient. The idea of combining the power subsystem with the attitude control system was initially introduced as the integrated power and attitude control system (IPACS) during the 1960s. The concept received much more attention during the 1980s (Notti et al., 1975). Nickel cadmium, nickel hydrogen or lithium batteries are the typical storage systems used in satellites. The batteries store the excess energy collected during the sun phase to provide power to systems during the eclipse phase (Larson and Wertz, 1992). The recharge process occurs once the eclipse phase finishes. The short life cycle of batteries and the additional power system mass required to control the charge and discharge cycles are the disadvantages of the conventional storage systems. In addition, the increasing requirement for projected power has made the traditional storage

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media unattractive. The sophisticated payloads used in recent satellite systems call for grand batteries which in return is critical for the satellite mass/volume budgets.

The implementation of mechanical flywheels for controlling the orientation of a satellite and for simultaneous energy storage is, therefore, an attractive synergism concept. Possessing a great deal of rotational kinetic energy, flywheels can provide electrical energy in collaboration with a motor/generator unit integrated onboard. The promising characteristics of flywheels such as a high depth-of-discharge, long life cycle and temperature independence make these actuators and power storage devices highly competent (Ginter et al., 1998). This on-board combined subsystem decreases the mass/volume budgets of a platform allowing the payload mass increment. The concept of simultaneous application of flywheels for energy storage and attitude control was investigated for the International Space Station (Roithmayr, 1999). In addition, this concept was adopted for larger satellites in several studies (Richie et al., 2001; Tsiotras et al., 2001; Yoon and Tsiotras, 2002). Although the previous researches highlighted some enhanced performances and numerous advantages for this combined system, the implementations were limited to massive platforms.

Combined Energy and Attitude Control System (CEACS) (Varatharajoo et al., 2011), introduced by Varatharajoo in a series of works, provides synergism for small satellites (Ban and Varatharajoo, 2013; Ban et al., 2012; Varatharajoo, 2006a, 2006b; Varatharajoo and Abdullah, 2004; Varatharajoo and Fasoulas, 2002). The flywheels serve as a control actuator for the attitude control of the satellite. To establish a better understating of the CEACS qualification, a detailed study compared the integrated system with the conventional energy and attitude control system in terms of mass, system volume, power consumption and attitude performance (Varatharajoo et al., 2003). The linear control of CEACS has been examined in several studies addressing the attitude-pointing problem using classical control techniques such as PD, PID, and PID-Active Force Control (AFC).

The attitude control solutions provided for CEACS were linearized with extensive assumptions and simplifications in terms of uncertainties and disturbances. To provide a reliable solution for an attitude control task, the inherited nonlinearity in the attitude dynamics of the satellite and the uncertain model parameters should be considered. The failure to address these commonly overlooked aspects can lead to singularity problems. A very common imprecision included in the system's dynamics is the uncertainty of mass properties of the spacecraft during operation. The moment of inertia is not only a function of the rigid body's size and shape but also the distribution of the mass in relation to the local reference frame. A spacecraft's mass distribution is subjected to change due to the possible motion of the payloads onboard, rotation of the solar arrays and even fuel consumption. While the nature of these changes is well understood, the extent of their influence can only be estimated to a certain degree. Therefore, an uncertainty factor should be considered in the analysis of the system's dynamics to avoid degradation of the system's control performance or instability.

This uncertainty factor can also cause a spacecraft dynamics to encounter singularity. Often, the dynamic behavior of a spacecraft under the influence of a certain attitude control strategy is examined by numerical simulation of their dynamic equations. An important step in the dynamics simulation is the inversion of the inertia matrix. Commonly believed as a positive definite (or, nonsingular) factor, the inertia matrix can in fact encounter singularities due to the introduced mass-distribution uncertainty. This phenomenon is realistic to happen as the conventional system dynamics consider the satellite as a rigid-body. In other words, there is no redundancy plan considered for cases in which the inertia matrix changes due to the variation of the mass distribution.

Furthermore, the dynamics of the system is substantially affected by the external disturbances such as gravitational torque, aerodynamic torque and radiation torque. Therefore, robust control algorithms that can provide high control accuracy and fast maneuvers from large initial conditions in the presence of large external disturbances and internal uncertainties are of paramount importance for the attitude tracking control problem of the satellite. While the influence of small errors in inertia matrix and motor/generator gains on the attitude performance of CEACS was examined using optimal controls such as H_2 and H_∞, the pointing accuracy degraded significantly (Ban and Varatharajoo, 2013; Ban et al., 2012).

One of the well-known approaches that deal with perturbations and model uncertainty in complex nonlinear dynamic systems is sliding mode control (SMC). The high robustness and insensitivity to perturbations and uncertainties as well as rapid response, simplicity of implementation and order reduction are amongst advantages of SMC (Slotine and Li, 1991). The limitations of classical control techniques have inspired many researchers to adopt this robust control scheme for spacecraft's attitude control specifically for attitude-tracking missions (Crassidis and Markley, 1996; Lo and Chen, 1995). The emphasis of the preceding studies and other similar works is mainly on resolving the SMC drawbacks that are chattering and stability problems. The chattering phenomenon is observed in practical applications when the system's error trajectory does not slide along the sliding manifold smoothly but with a high-frequency oscillation. High-frequency switching control utilized for tackling the disturbances and uncertainties and the imperfection of the switching devices make the system's error trajectory to chatter in some neighborhood of the switching surface (Slotine and Li, 1991; Young et al., 1999). This oscillation, highly undesirable, is the major drawback of pure SMC (Utkin and Lee, 2006). This dangerous vibration is critical for the spacecraft's control performance; hence, if not completely avoided, the switching frequencies should be restraint