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Adaptive fault-tolerant attitude control for satellite reorientation under input saturation

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ABSTRACT

This paper studies the rest-to-rest attitude reorientation problem of a three-axis stabilized satellite subject to inertia uncertainties, external disturbances, actuator faults and input saturation. An arc tangent function is first adopted to model the constrained control input, and meanwhile an augmented plant is constructed to facilitate the control law derivation. Then, a novel adaptive fault-tolerant control scheme is proposed by incorporating the prescribed performance control and adaptive estimation techniques into backstepping design. Exploiting the dynamic surface control method, the complexity problem residing in traditional backstepping approaches is effectively averted. It is shown that the control algorithm developed is not only robust against environmental disturbances and adaptive to unknown time-varying inertia properties caused by the mass displacement of large-scale deployable appendages, but also able to steer the attitude reorientation errors along prescribed transient and steady-state behavioral bounds, despite the presence of actuator faults and input saturation. Based on standard Lyapunov synthesis, all signals in the closed-loop system are proved to be semi-globally uniformly ultimately bounded. Finally, simulation experiments carried out on a miniature satellite testify the effectiveness of the proposed control approach.

1. Introduction

The modern satellites are widely equipped with large-scale, lightweight deployable appendages (such as antennas, sunshields, solar arrays, etc.). To perform special and urgent missions, such kind of satellites are always expected to carry out large-angle attitude maneuvers with high precision and stability. In fact, the performance of attitude control system is directly bearing upon whether a satellite can be orientated to the desired attitude rapidly and accurately, and to some extent determines the operational lifespan of the satellite. However, in practice the satellite's inertia properties inevitably change during its attitude maneuvers due to the mass displacement of the appendages (e.g., boom or antennas deployment); on the other hand, the environmental disturbances arising from solar radiation pressure, gravity gradient torque, etc., are likely to have an adverse impact on attitude control precision. With the aforesaid reasons in mind, when the satellite performs attitude maneuvers, its attitude is possible to suffer from deviation in the case of both inertia uncertainties and external disturbances. Such a deviation may give rise to undesirable performance degradation or even lead to instability which, in turn, may result in aborting the given space missions. Thus, it is necessary to develop effective control schemes for satellite attitude maneuvers in the presence of inertia uncertainties and external disturbances.

In recent years, extensive results related to the attitude control design and analysis of spacecraft with inertia uncertainties have been reported in the literature (e.g., [1–5], just name a few). In these works, the adaptive control was used in conjunction with some advanced control methods such as inverse optimal, fuzzy approach, sliding mode control, etc., to account for the unknown but constant inertia parameters. It is noteworthy, however, that the inertia properties always vary over time in practice owing to onboard payloads variations, fuel consumption, and rotation of deployable appendages in particular, and thus the aforementioned control strategies are not applicable anymore. Taking explicit account of time-varying inertia uncertainties, Thakur et al. [6] proposed an adaptive attitude tracking control scheme for a deployable spacecraft to guarantee asymptotic convergence of the tracking errors for any initial condition and all reference trajectories, in the presence of fuel depletion or mass displacement. Furthermore, from a practical viewpoint, another important problem that deserves more attention is actuator faults. Despite various efforts have been devoted to improving satellite reliability, multiple anomalies do occur in actuators during their long operational life. Actuator faults may lead to malfunctions of the attitude control system, which may

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further result in aborting the scheduled missions. So far, significant efforts have been invested into the attitude control problem of rigid spacecraft with actuator faults. In this direction, a review paper by Yin et al. [7] provided excellent overviews for the recent development of the attitude fault-tolerant control (FTC) of spacecraft. In general, the existing methods for FTC systems design can be classified into two types, i.e., active FTC [8–10] and passive FTC [11–13]. The active FTC system, which is composed of a fault detection and diagnosis (FDD) mechanism and a reconfiguration control process, can actively react to the detected system faults instead of a class of presumed potential faults and reduce the control conservativeness. However, to maintain the stability and acceptable performance of the system, the active FTC system relies heavily on on-line and real-time FDD to provide the most up-to-date status information, thus posing an extremely challenging task for the active FTC system design. In contrast to the active FTC, the passive FTC approach is robust against some types of system faults and simple for implementation without any control structure or parameter adjustment. In the light of this, in this work, we will devote our main efforts toward the fault-tolerant attitude control design for the rest-to-rest attitude reorientation of a three-axis stabilized satellite using the passive FTC approach. In this respect, a promising solution has been presented in [11], where a nonregressor-based robust fault-tolerant control strategy was developed to achieve stable and high precise attitude tracking in the presence of modeling uncertainties, external disturbances, actuator faults and limited resources. Recently, motivated by the result of [11], several methods on fault-tolerant control of spacecraft can be found in the literature [14–16]. In [16], an adaptive actuator faults and disturbances compensation scheme was presented with a composite parameter adaptation strategy to achieve attitude tracking of spacecraft. In [17], a command filter was first designed to generate a virtual velocity error signal and then an adaptive fault-tolerant controller was derived, which ensures insensitivity to inertia uncertainties and robustness against unknown external disturbances without requiring model information.

As a matter of fact, input saturation is also a practical and unavoidable issue that should be considered in developing attitude controller for satellites. Indeed, the onboard actuators used for spacecraft attitude control (e.g., reaction wheels, thrusters and CMGs) are easy to suffer from input magnitude constraints, especially when some of them undergo severe faults. To ensure the control input remains within a physically reasonable bound, several methods have already been presented in the literature. For instance, in [18], two globally stable control schemes based on variable structure control and adaptive technique were proposed to explicitly account for control input saturation, and then an improved version with continuous control was additionally proposed in [19] by adjusting dynamically a single parameter. Subsequently, a new kind of saturated proportional-derivative method consisting of hyperbolic tangent functions is presented in [20] to enforce limitations on the actuator control authority. In a recent paper [21], a robust nonlinear controller was proposed for the tethered space robot-target combination, where a feedback term was designed to compensate the saturation of the thruster. In [22], the actuator saturation problem was tackled via incorporating radial basis function neural network, whilst the angular velocity was restricted in a permitted range of operation based on a typical hyperbolic tangent function. It is remarkable that, in [23], a smooth hyperbolic tangent function was employed to model the magnitude and rate saturations, and then an adaptive control method integrating an augmented plant was developed that guarantees the stability of the resulted closed-loop system.

In practical engineering, the science objectives of space missions usually impose rigorous performance requirements on the spacecraft attitude control system. However, it is a quite challenging task to develop an effective attitude control scheme for spacecraft to achieve consistent control performance necessary to meet those requirements, especially in the presence of actuator faults and input saturation. Bechlioulis and Rovithakis [24] proposed the prescribed performance control for uncertain nonlinear systems, which guarantees that the system output error converges to a predefined arbitrarily small residual set with prescribed transient performance. Later, this promising control technique has been extensively applied to different kinds of nonlinear systems to guarantee prescribed transient and steady-state tracking performance in [25–27]. Recently, in [27], a robust prescribed performance tracking control was designed for spacecraft attitude tracking with uncertain dynamics and disturbances. Most recently, an adaptive attitude tracking control scheme with prescribed performance guarantees was proposed in [28] for a rigid spacecraft with unknown inertia, external disturbances, actuator faults and control input saturation. However, it is notable that, in [28], the inertia matrix is assumed to be unknown but constant and the total actuator failure is not considered. Thus far, it still remains an open problem how to achieve prescribed performance guarantees in the presence of unknown and time-varying inertia properties, external disturbances, actuator faults and input saturation.

In this paper, we concentrate on the rest-to-rest attitude reorientation problem of a three-axis stabilized satellite in the event of time-varying inertia parameters, unexpected environmental disturbances, actuator faults and input saturation. By incorporating prescribed performance control and backstepping design, a novel adaptive fault-tolerant control scheme is proposed to achieve prescribed transient and steady-state behavior bounds for the attitude reorientation errors. The main contributions of this work are summarized as follows:

1) The designed controller is capable of steering the attitude reorientation errors to predefined arbitrar-ily small residual sets with prescribed convergence rate and maximum overshoot, even if time-varying inertia properties, external disturbances, actuator faults and input saturation are simultaneously taken into account.

2) As opposed to existing works in the relevant literature, the norm estimation approach is used to estimate the time-varying inertia parameters that have both unknown rigid components and only partially determined variable components, rather than the unknown but constant ones. In addition, by employing the dynamic surface control, the complexity problem inherent in traditional backstepping is effectively eliminated. As such, the proposed control scheme is ready to be implemented in practical engineering.

The rest of the paper is organized as follows. Sec. 2 provides the problem description and preliminaries. The main results of this work are presented in Sec. 3, where the adaptive fault-tolerant attitude controller design for a three-axis stabilized satellite and the corresponding stability analysis are in order. Sec. 4 demonstrates the effectiveness of the proposed control scheme via numerical simulations performed on a microsatellite. Finally, conclusions are summarized in Sec. 5.

2. Problem statement and preliminaries

Notations: For the sake of brevity, we define the following fairly standard notations that are needed throughout this paper. $\|\cdot\|$ denotes Euclidean norm of a vector or the induced norm of a matrix, while $\lambda_{\min}(\boldsymbol{A})$ represents the minimum eigenvalue of a matrix $\boldsymbol{A}$. $(\cdot)' = \partial(\cdot)/\partial t$ represents the derivative with respect to time of any given variable. In addition, the operation $\boldsymbol{\vartheta}^{\times} \in \Re^{3\times 3}$ denotes a skew-symmetric matrix with the following form $\boldsymbol{\vartheta}^{\times} = [0, -\vartheta_3, \vartheta_2; \vartheta_3, 0, -\vartheta_1; -\vartheta_2, \vartheta_1, 0]$ for any given vector $\boldsymbol{\vartheta} = [\vartheta_1, \vartheta_2, \vartheta_3]^T$.

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