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Robust adaptive spin-axis stabilization of a symmetric spacecraft using two bounded torques

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Abstract

The spin-axis stabilization of an axisymmetric spacecraft by two control torques perpendicular to the symmetry axis is addressed. Two control laws are designed to align the symmetry axis along a desired inertial direction despite the revolution around the symmetry axis. The first controller takes a saturated proportional-derivative form and can stabilize the spin-axis to the desired direction with a priori bounded torques in the absence of modeling uncertainties. In order to achieve better robustness, an adaptive controller is then designed to account for the inertia uncertainties and disturbances, in addition to actuator saturation. Numerical examples are presented to demonstrate the advantageous features of the proposed algorithm compared with conventional spin-axis stabilization methods.

Keywords: Adaptive control; Input saturation; Spin-axis stabilization; Symmetric spacecraft; Two torques

1. Introduction

The attitude control of a spacecraft by fewer than three control torques has attracted considerable attention in recent years (e.g., Crouch, 1984; Byrnes and Isidori, 1991; Brockett, 1983), due to the benefits of a reduced number of actuators and resulting cost reduction, and to fault-tolerance to actuator failures. Fewer than the full number of control inputs introduces nonholonomic constraint to a spacecraft system and, as shown in Byrnes and Isidori (1991), its full attitude motion cannot be stabilized with continuous feedback laws by only two torques, due to the violation of the Brockett necessary condition (Brockett, 1983). This is quite different from the fully actuated attitude control (Hu, 2009; Hu and Zhang, 2015), where three control torques are assumed to be available. Partial failures of a control moment gyro (CMG) array were approached by Zhang et al. (2008, 2013) and a novel reconfiguration scheme was designed to sufficiently utilize the remaining capability of the active CMGs. Despite of occurrence of actuator faults, the study in Zhang et al. (2008, 2013) still assumes the spacecraft to be fully actuated, similar to conventional fault-tolerant attitude control (Cao et al., 2014).

In order to stabilize the full attitude of a spacecraft by means of two torques, time-invariant discontinuous and time-varying continuous control techniques are employed. Discontinuous feedback methods were designed in Krishnan et al. (1994) and Tsiotras and Luo (2000) to stabilize the attitude of an axisymmetric spacecraft when the initial angular velocity along the symmetric axis is zero. Attitude stabilization of an asymmetric spacecraft was attained in Morin and Samson (1997), by periodically time-varying feedback, and in Casagrandea et al. (2008) by discontinuous feedback. Other work considered the underactuated attitude stabilization issue with two torques provided by momentum exchange devices (Krishnan et al., 1995; Horri and Palmer, 2012; Gui et al., 2015, in press),

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where symmetry or asymmetry of the spacecraft is not a factor.

Another method to circumvent the Brockett necessary condition is to adjust the full attitude stabilization objective to partial attitude stabilization, such as spin-axis stabilization (Tsiotras and Longuski, 1994; Tsiotras, 1997), which allows nonzero spin rate about the spin axis, or line-of-sight (LOS) pointing control (Kwon et al., 2011; Jin and Hwang, 2011), which necessitates zero terminal angular velocity. In these cases, the spin axis or the LOS axis of the spacecraft is controlled to a desired direction while there is no requirement on the angular velocity about the spin axis or the rotation angle about the LOS axis. It was shown in Tsiotras and Longuski (1994), Tsiotras (1997) that even linear feedbacks can be used to stabilize the spin axis of an axisymmetric spacecraft with two torques spanning a plane perpendicular to the symmetry axis. In Cheon (2010), the spin-axis stabilization of an asymmetric spacecraft was considered. These papers, however, assume that there exist no disturbance torques and inertia uncertainties. In order to account for these practical factors, a nonlinear $\mathcal{H}_\infty$ control law was proposed in Zheng and Wu (2009) with a constraint on system states, thus ensuring local stability. Recently, another spin-axis stabilization controller with disturbance rejection was designed in Zhang et al. (2008) via internal modal principle (IMP) but the proposed method relies on an accurate system model and the disturbance torque is limited to only sinusoidal types. In addition, actuator saturation is another important issue that arises during practical applications and thus should be considered.

In this paper, the spin-axis stabilization of a symmetric spacecraft with two torques perpendicular to the symmetry axis is revisited. The study is along the same line with Tsiotras and Longuski (1994), Tsiotras (1997), Cheon (2010), Zheng and Wu (2009) and Zhang et al. (2008), where the spin rate of the spacecraft about the symmetry axis is completely uncontrollable, but is different from the control of a conventional spin-stabilized satellite (Sidi, 1997), for which additional torques are required to adjust the rotation rate about the spin axis (typically, a symmetry axis of the satellite). In practice, many spacecraft have an almost symmetric mass distribution about a certain axis, such as the Cosmic Background Explorer (COBE), Microwave Anisotropy Probe (MAP), Plank spacecraft, some micro/pico-satellites, etc. When a symmetric spacecraft encounters actuator failures and loses the control torque along the symmetry axis, the spacecraft will remain rotating about the symmetry axis at a constant rate. The method proposed in the following can then work as a contingency mode and be applied to stabilize the spin axis to any direction of interest. This is particular useful in cases when the symmetry axis is a communication antenna or the line-of-sight of an onboard telescope, camera, or sensor, etc. In these cases, the rotation speed about the symmetry axis is irrelevant when the objective is to point it toward a desired direction.

In order to describe the direction of the spin-axis, the attitude parameter proposed by Tsiotras and Longuski (1995) is adopted and the system is modeled in the presence of external disturbances, inertia uncertainties as well as actuator saturation. First, a saturated proportional-derivative controller (SPDC) is proposed in the uncertainty-free case to align the spin-axis to any desired inertial direction. By restricting the upper bounds of the proportional term and derivative term respectively, the SPDC can produce bounded control torque a priori while ensuring asymptotic stability of the closed-loop system. To deal with the unknown disturbance torques and uncertain spacecraft inertia, an adaptive controller is then designed based on a sliding-mode-like function. The total uncertainties are compensated by an adaptive algorithm, which removes the requirement for the upper bound of the uncertainties. It is shown that the adaptive controller ensures global asymptotic convergence of the system states even under actuator saturation. Illustrative numerical examples are presented to demonstrate the advantages of the proposed method over previous spin-axis stabilization laws of Tsiotras (1997) and Zhang et al. (2008).

The remainder of this paper is organized as follows. In the next section, the mathematical models are presented to describe the motion of an axisymmetric spacecraft with two torques. In Section 3, the SPDC and an adaptive controller are designed in sequence. Section 4 compares the proposed controllers with the proportional-derivative controller (PDC) in Tsiotras (1997) and the controller in Zhang et al. (2008) via numerical simulations. The conclusion is given in Section 5.

2. Mathematical models

The attitude dynamics of a rigid spacecraft are given by

$$\boldsymbol{J}\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times \boldsymbol{J}\boldsymbol{\Omega} = \mathrm{sat}(\boldsymbol{u}) + \boldsymbol{d} \tag{1}$$

where $\boldsymbol{J} \in \mathbb{R}^{3\times3}$ is the inertia matrix of the spacecraft system. $\boldsymbol{\Omega} \in \mathbb{R}^3$ is the spacecraft angular velocity expressed in the spacecraft body frame $\mathcal{B}$, which is denoted by the set of three orthogonal unit vectors $\{\boldsymbol{b}_1, \boldsymbol{b}_2, \boldsymbol{b}_3\}$ with its origin located at the center-of-mass of the spacecraft. $\boldsymbol{u} \in \mathbb{R}^3$ is the control torque and $\boldsymbol{d} \in \mathbb{R}^3$ is the disturbance torque. In addition, $\mathrm{sat}(\boldsymbol{u}) = [\mathrm{sat}(u_1), \mathrm{sat}(u_2), \mathrm{sat}(u_3)]^T$, where $\mathrm{sat}(u_i) = \mathrm{sgn}(u_i)\min\{|u_i|, u_{\max}\}$, $i = 1, 2, 3$ with $u_{\max}$ being the maximum control torque, denotes the saturation constraint of actuators.

Since we are interested in an axisymmetric spacecraft, we assume, without loss of generality, that $\boldsymbol{b}_3$ is aligned with the symmetric axis and only two control torques perpendicular to $\boldsymbol{b}_3$ are available, i.e., $\boldsymbol{u} = [u_1, u_2, 0]^T$. Let $\boldsymbol{b}_1$, $\boldsymbol{b}_2$, and $\boldsymbol{b}_3$ be three principle axes of the spacecraft, i.e., $\boldsymbol{J} = \mathrm{diag}(J_1, J_2, J_3)$, where J_1, J_2, and J_3 are the principal moments of inertia of the spacecraft. Then, the attitude dynamics can be written as