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LPV gain-scheduled attitude control for satellite with time-varying inertia

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A B S T R A C T

The performance of an attitude control system is impacted by the inertia change, especially for small satellites. Although there are various control methods for satellites with inertia uncertainties, very few controllers are designed with consideration of time-varying inertia. In this paper, a linear parameter varying (LPV) model is established for a satellite with time-varying inertia. Moreover, because of their common occurrences, the actuator faults and saturation are considered during the controller design. A gain-scheduled controller is developed to guarantee the steady-state and transient performance of the system by limiting the steady-state variance and regional pole constraints. The simulations indicate that the proposed controller improves the stability performance by adjusting the gain with the inertia variations.

1. Introduction

Currently, the increasing requirements of satellite functions result in appreciable variations in the inertia. For example, an expanding solar array or movements of appendages cause obvious changes in the inertia, especially for small satellites. In addition, a capture or docking mission may bring out a great increase of the satellite mass. Therefore, it is meaningful to study satellite attitude control with consideration of significant changes in inertia.

Researchers have proposed various control methods for the satellite attitude control with inertia uncertainties. By considering the inertia as an uncertain matrix that satisfies specific boundary conditions, adaptive control [1–5] and sliding model control [6,7] were developed. Combined with linear matrix inequality (LMI) methods, adaptive attitude control was designed for a microsatellite with uncertain inertia, natural frequency and damping [3]. Combined with adaptive sliding mode control techniques, backstepping control was proposed in the presence of uncertain inertia matrices and unknown external disturbances in [5]. Iterative learning control was designed to improve the control accuracy of spacecraft attitude tracking control with model uncertainties [8]. A robust optimal attitude control with uncertain inertia was proposed using a minimal kinematic approach [9]. Fault-tolerant controllers were studied with consideration of the system uncertainties caused by the inertia and external disturbances [10–12]. All of the above controllers treat the inertia as uncertain parameters, which can be appropriate if the inertia changes slowly. However, if the inertia varies rapidly over a wide range, the system performance will be affected. Therefore, some researchers have considered time-varying inertia during the controller design. Time-varying inertia was treated as an explicit expression and a controller was designed by incorporating the prescribed performance control and adaptive estimation techniques into backstepping design [13]. Compared with adaptive controllers with uncertain inertia, controllers with time-varying inertia could provide better precisions [14]. Inspired by the results of [13,14], the time-varying inertia parameters are considered during the control design to improve the control system performance in this paper.

The linear parameter varying (LPV) model can accurately describe the time-varying characteristics of the system parameters. The LPV gain-scheduled controller can improve the performance of systems by using the information of the time-varying parameters. In addition, LPV control theory, an extension of linear control theory, enables easier design using the linear control method. With the development of LPV control theory [15–19], it has been applied to satellite attitude control systems [20–23]. In [20], the effectiveness factors were considered as time-varying parameters, and then the satellite attitude dynamics was transformed into the switched LPV system by separating the time-varying parameters. [21] and [22] established QLPV models for attitude control and attitude fault tolerant control, respectively. In addition, a virtual state variable and a coordinate transformation matrix were introduced to the

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attitude control LPV system to reduce the number of scheduling parameters in [23]. All the controllers above are gain-scheduled controllers. Therefore, the LPV gain-scheduled control is worthy of further development in satellite attitude control with time-varying parameters.

Moreover, the demand for satellite safety and reliability has spurred research on attitude control in the presence of actuator fault and actuator saturation. Researchers have obtained some results in this area. The controller was designed for spacecrafts with SGCMGs under partial actuator failure and actuator saturation in [24]. Attitude control with consideration of the actuator fault and actuator saturation was developed based on the reconstructed information using a slide-mode-based observer in [25]. An adaptive fast terminal sliding mode control law (AFTSMCL) was presented to resolve attitude tracking control problem for rigid spacecraft in [26]. There have also been some results on attitude control accounting for actuator faults, actuator saturation and inertia uncertainties together [10,27,28]. In [10], an attitude-stabilizing controller was proposed based on the smooth sliding-mode method. [27] proposed an indirect adaptive attitude control with limited thrusts. [28] investigated a finite-time attitude controller for spacecrafts. Considering time-varying inertia, actuator faults and actuator saturation together, adaptive attitude control for satellite reorientation was presented in [13]. Therefore, actuator faults and actuator saturation are also taken into consideration during the control design in this paper.

Based on the above, there are abundant research results in attitude control with consideration of the inertia uncertainties. However, the controllers considering time-varying inertia, which are more suitable for satellites with the inertia varying rapidly in a wide range, are very few. Moreover, controllers that consider the time-varying inertia, actuator faults and actuator saturation together are fewer. This study will provide a new possible solution to this problem. The main contributions and differences of this study relative to existing works are as follows:

1. The time-varying characteristic of the inertia is considered for satellites with the inertia changing rapidly over a wide range. In addition, actuator faults and actuator saturation are also considered during the controller design.
2. An LPV gain-scheduled controller is developed. The inertia parameters are considered as time-varying parameters in the LPV model. The gain of the controller is changed as the inertia parameters vary to improve the performance of the system.

The rest of the paper is organized as follows. In Section 2, a polytope uncertain LPV model is established for satellite attitude control with time-varying inertia, actuator faults and actuator saturation. A gain-scheduled controller is developed based on linear matrix inequalities (LMIs) in Section 3. Simulation results for the satellite attitude control system are provided in Section 4. Finally, conclusions based on the presented results are given in Section 5.

2. LPV model of satellite attitude control

In this section, with consideration of the time-varying inertia, actuator multiplicative faults and actuator saturation, an uncertain LPV model with input constraints is established for the satellite attitude control system.

2.1. Satellite attitude dynamics model with time-varying inertia

A growing number of missions have to incorporate satellites with rapidly deployable appendages, which results in appreciable variations in the inertia parameters. For example, for a deployable satellite, an expanding solar array or sensor boom causes the change of the inertia. In addition, a capture or docking mission may increase the satellite mass significantly. As a result, time-varying inertia is considered in the satellite attitude dynamics model.

The satellite actuators are three orthogonally installed reaction flywheels, and the attitude sensors are gyros and star sensors. The attitude dynamics of a satellite can be described as

$$\boldsymbol{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{I}\boldsymbol{\omega} = \boldsymbol{u} + \boldsymbol{T}_g + \boldsymbol{T}_d \tag{1}$$

where $\boldsymbol{\omega}$ is the angular velocity, $\boldsymbol{u} = [u_1, u_2, u_3]^{\mathrm{T}}$ is the control input, $\boldsymbol{T}_g = \left[T_{g1}, T_{g2}, T_{g2}\right]^{\mathrm{T}}$ is the gravitational torque, $\boldsymbol{T}_d = [T_{d1}, T_{d2}, T_{d2}]^{\mathrm{T}}$ is the external disturbance torque and $\boldsymbol{I}$ is the satellite rotational inertia, which can be written as

$$\boldsymbol{I} = \begin{bmatrix} I_1 & I_{12} & I_{13} \\ I_{12} & I_2 & I_{23} \\ I_{13} & I_{23} & I_3 \end{bmatrix} \tag{2}$$

I_1, I_2 and I_3 are the moments of the inertia around the three coordinate axes of the satellite body coordinate system, and other elements of the inertia matrix are the products of the inertia.

Under the small angle approximation, the angular velocity is given as follows

$$\boldsymbol{\omega} = \begin{bmatrix} \dot{\phi} - \omega_0\psi \\ \dot{\xi} - \omega_0 \\ \dot{\psi} + \omega_0\phi \end{bmatrix} \tag{3}$$

where ϕ, ξ and ψ denote the roll angle, the pitch angle and the yaw angle respectively, and ω_0 is the orbital angular velocity.

As is known

$$\boldsymbol{T}_g = \begin{bmatrix} -3\omega_0^2(I_2 - I_3)\phi \\ -3\omega_0^2(I_1 - I_3)\xi \\ 0 \end{bmatrix} \tag{4}$$

Substituting Eqs. (2)–(4) into Eq. (1), the attitude dynamics can be rewritten as the following matrix differential equation:

$$\tilde{\boldsymbol{A}}_2\ddot{\boldsymbol{\Phi}} + \tilde{\boldsymbol{A}}_1\dot{\boldsymbol{\Phi}} + \tilde{\boldsymbol{A}}_0\boldsymbol{\Phi} = \boldsymbol{G}_u\boldsymbol{u} + \boldsymbol{G}_d\boldsymbol{T}'_d \tag{5}$$

where $\boldsymbol{\Phi} = [\phi, \xi, \psi]^{\mathrm{T}}$ is the vector containing Euler angles, and $\tilde{\boldsymbol{A}}_0$, $\tilde{\boldsymbol{A}}_1$ and $\tilde{\boldsymbol{A}}_2$ are given as follows:

$$\tilde{\boldsymbol{A}}_0 = \omega_0^2 \begin{bmatrix} 4(I_2 - I_3) & 0 & I_{13} \\ -I_{12} & 3(I_1 - I_3) & -I_{23} \\ I_{13} & 0 & I_2 - I_1 \end{bmatrix}$$
$$\tilde{\boldsymbol{A}}_1 = \omega_0 \begin{bmatrix} 0 & -2I_{23} & -I_1 + I_2 - I_3 \\ 2I_{23} & 0 & -2I_{12} \\ I_1 - I_2 + I_3 & 2I_{12} & 0 \end{bmatrix}$$
$$\tilde{\boldsymbol{A}}_2 = \boldsymbol{I}$$
$$\boldsymbol{G}_u = \boldsymbol{G}_d = \boldsymbol{E}_3$$
$$\boldsymbol{T}'_d = \boldsymbol{T}_d - \omega_0^2 \begin{bmatrix} I_{23} \\ 0 \\ -I_{12} \end{bmatrix}$$

where $\boldsymbol{E}_n$ is a unit matrix of order n.

Define state variables $\boldsymbol{x} = \left[\dot{\boldsymbol{\Phi}}^{\mathrm{T}}, \boldsymbol{\Phi}^{\mathrm{T}}\right]^{\mathrm{T}}$ and the state space expression of satellite attitude control system with time-varying inertia can be expressed as

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{A}(\boldsymbol{I}(t))\boldsymbol{x} + \boldsymbol{B}(\boldsymbol{I}(t))\boldsymbol{u} + \boldsymbol{D}\boldsymbol{w} \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} \end{cases} \tag{6}$$

where $\boldsymbol{w}$ is the zero-mean white noise with unit variance, $\boldsymbol{D} \in \mathbf{R}^6$, and $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ can be shown as follows.

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