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Minimum sliding mode error feedback control for fault tolerant small satellite attitude control

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Abstract

This paper proposes a new control strategy (which we call "minimum sliding mode error feedback control, MSMEFC") for small satellite attitude control. As we know, the attitude control algorithm plays a significant role in the whole performance of the satellite, especially under the existence of uncertain disturbances from the space. Without loss of generality, the MSMEFC is presented based on the sliding mode theory. It is assumed that the equivalent control error is defined to offset the uncertain disturbances to improve the control performance. Hence, in order to estimate the optimal equivalent control error, a cost function is derived on the basis of the principle of minimum sliding mode error. Then, the equivalent control error wills feedback to the conventional sliding mode control to obtain the final MSMEFC. According to the theoretical analyzes, the sliding mode after the MSMEFC will approximate to the ideal sliding mode, resulting in enhancing the control performance. Moreover, an adaptive non-singular terminal sliding mode is employed to compare with the performance of MSMEFC. Several simulations are performed to verify the effectiveness of proposed MSMEFC in the presence of serious perturbations, even in some fault-tolerant scenarios.

Keywords: Attitude control; Sliding mode control; Minimum sliding mode error; Fault-tolerant

1. Introduction

Due to the existence of system uncertainties and external disturbances from the space, it is really difficult to design the spacecraft control system exactly, which greatly hinders the attitude control performance. Especially for the spacecrafts of long-time running on orbit, the serious perturbations or actuator faults will have detrimental effects on the spacecraft, or even leading to the mission failure and so on. Hence, the controllers with the performance of robust and fault tolerant are the key issues that need to be addressed. In recent years, some research institutes and scholars have paid attentions to develop reliable fault tolerant control schemes for various space missions. However, the previous study for small satellite is so limited expect for Cao et al. (2013), etc., who adopts adaptive non-singular terminal sliding mode (ANTSMC) to improve control precision in three types of actuator faults scenarios. Nevertheless, it also brings some disadvantages of heavy computational burden and more fuzzy parameters chosen. With a view to tackle these problems and enrich the correlational research, this paper presents the novel research findings of MSMEFC that can obtain the better control performance with serious system uncertainties and external disturbances, even in the presence of actuator faults.

The current literatures largely focus on developing nonlinear control algorithm to suppress system uncertainties and external disturbances. Obviously, the Sliding Mode Control (SMC) is an outstanding theoretical tool to tackle

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these problems, which is proposed by Emeleyanov and Utkin (Emelyanov and Taran, 1962; Emelyanov, 1970; Utkin, 1970) in 1950s. Because SMC is a robust nonlinear feedback control methodology that has some advantages of easy implementation, low computational costs and insensitive to external disturbances (Draznenovic, 1969); thereby receiving considerable attentions (Sanz and Etxebarria, 2005; Chen et al., 2003) in recent years. Take the research works of Cao et al. (2013), Iyer and Singh (1999), Wu and Yu (1999), Matthew et al. (2000), Terui (1998)for examples, the sliding mode controllers are designed to solve the spacecraft control problems. In the meantime, Wie et al. (1989), Hebertt et al. (1993), etc. developed robust steady controller and energy storage strategy for space station using sliding mode control theory. In order to enhance the control quality of SMC, many literatures largely focus on the integrated study of the SMC and other control theories, such as adaptive control (Hao et al., 2007; Sadati and Ghadami, 2008), fuzzy control (Hwang and Tomizuka, 1994; Wai, 2007; Wu and Ham, 1996), neural network (Fang et al., 1999; Tsai et al., 2004) and genetic algorithm (Lin and Chen, 1997). However, some defects and shortcomings of complex algorithm structures and heavy computational burden have also exposed at the same time.

With a view to overcome these limitations, the minimum sliding mode error feedback control (MSMEFC) is presented in this paper. For general SMC methodologies, it is reasonable to assume that SMC is composed of the equivalent control $\boldsymbol{u}_{eq}$ and the nonlinear switching control $\boldsymbol{u}_v$. The system uncertainties and external disturbances are defined as $\boldsymbol{\xi}$. More exactly, the MSMEFC is proposed based on the assumptions that we define the value of $(\boldsymbol{u}_v + \boldsymbol{\xi})$ as equivalent control error $\boldsymbol{d}$ and estimate it, then feedback it to the SMC. As a consequence, this strategy can offset or decrease the effect of $(\boldsymbol{u}_v + \boldsymbol{\xi})$, which will lead the actual sliding mode after MSMEFC to approximate to the ideal sliding mode in order to enhance the control precision. Obviously, the method to estimate equivalent control error is the core technology of the MSMEFC. Hence, an optimality criterion for determining the equivalent control error is developed based on the minimum sliding mode covariance constraint. The covariance constraint is proposed based solely on assumed knowledge of the error covariance between the actual sliding mode and the ideal sliding mode. Therefore, we present a strategy to determine the optimal equivalent control error which satisfies the requirements of the MSMEFC.

The purpose of this paper is to propose the MSMEFC for the attitude control of small satellite with the system uncertainties and external disturbances, even in the fault tolerant cases. In this study, the actuator of satellite attitude control relies on the three orthogonal reaction wheels without dumping the wheels' saturation. According to the reference Cao et al. (2013), three types of actuator faults are given and discussed, including actuator degradation (loss of effectiveness, LOE), actuator stuck fault (lock in unknown time, LIUT) and actuator failure for a short time (failure for a period time, FFPT). Moreover, the ANTSMC algorithm discussed in Cao et al. (2013) is employed to compare with the MSMEFC in order to verify the effectiveness of presented scheme.

The rest of this paper is organized as follows. In Section 2, the theoretical principles and design thoughts of MSMEFC are presented to make it easy to elaborate and understand. Then, the minimum sliding mode covariance constraint is proposed, which is the significant precondition to design the MSMEFC. In Section 3, the MSMEFC is derived with detailed proof of stability for the closed-loop system of small satellite attitude control. For a detailed assessment of the proposed control strategy, the numerical simulations are performed to verify the effectiveness of MSMEFC incorporating different fault scenarios in Section 4 and some concluding remarks are made in the Section 5.

2. Derivation of the MSMEFC

2.1. The proposal of the MSMEFC

The investigation is initiated by the theoretical basis and principles for deriving the MSMEFC. Without loss of generality, a class of MIMO nonlinear control system with uncertain disturbances can be described in the following form

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(t,\boldsymbol{x}) + \boldsymbol{g}(t,\boldsymbol{x})\boldsymbol{u} + \boldsymbol{\xi}(t,\boldsymbol{x}) \tag{1}$$

where $\boldsymbol{x}(t) \in \mathbb{R}^n$ is the system state vector and $\mathbb{R}^n$ is the real n-dimensional vector space, $\boldsymbol{u} \in \mathbb{R}^m$ is the input control, $\boldsymbol{f}(\bullet) \in \mathbb{R}^n$ is sufficiently differentiable vector fields, $\boldsymbol{g} \in \mathbb{R}^{n\times m}$ is the input control distribution matrix, which determines how the input control is introduced to the plant dynamics, $\boldsymbol{\xi}(t,\boldsymbol{x}) \in \mathbb{R}^n$ represents the system uncertainties and external disturbances, which satisfies the bounded condition $\|\boldsymbol{\xi}(t,\boldsymbol{x})\| \le \xi_M$.

Generally, the SMC algorithm begins with constructing a sliding manifold in the system state space. First of all, the sliding manifold $\boldsymbol{S}(t, \boldsymbol{x})$ is designed as the smooth and continuous switching function. According to Eq. (1), taking the derivative of $\boldsymbol{S}$ is given

$$\dot{\boldsymbol{S}} = \frac{\partial \boldsymbol{S}}{\partial t} + \frac{\partial \boldsymbol{S}}{\partial \boldsymbol{x}}[\boldsymbol{f}(t,\boldsymbol{x}) + \boldsymbol{g}(t,\boldsymbol{x})\boldsymbol{u} + \boldsymbol{\xi}(t,\boldsymbol{x})] \tag{2}$$

Based on Eq. (2), the control laws can be derived as follows

$$\begin{aligned} &\boldsymbol{u} = \boldsymbol{u}_{eq} + \boldsymbol{u}_v \\ &\boldsymbol{u}_{eq} = -\left(\tfrac{\partial \boldsymbol{S}}{\partial \boldsymbol{x}}\boldsymbol{g}\right)^{-1}\left(\tfrac{\partial \boldsymbol{S}}{\partial t} + \tfrac{\partial \boldsymbol{S}}{\partial \boldsymbol{x}}\boldsymbol{f}\right) \\ &\boldsymbol{u}_v = -\varepsilon \mathrm{sgn}(\boldsymbol{S}) \end{aligned} \tag{3}$$

where $\boldsymbol{u}_{eq}$ is the equivalent control, $\boldsymbol{u}_v$ is the nonlinear switching control and there constant $\varepsilon > 0$ exists. It is worth pointing out that the nonlinear switching control can be chosen different types of switching control such as the nonlinear exponential switching control. For simplicity,