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Low-complexity prescribed performance control for spacecraft attitude stabilization and tracking

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ABSTRACT

In this paper, the attitude stabilization and tracking control problem is investigated for spacecraft with consideration of unknown dynamics and external disturbance. A low-complexity prescribed performance attitude control scheme is presented to solve this problem. Different from existing works, there are threefold prominent advantages. The first one is the transient performance and the steady performance of the system is guaranteed by a user-defined function rather than depending on repeated adjustment of controller parameters. The second is that no information of the system and external disturbance is necessary in the developed control scheme, which means the method is model-free. Moreover, the developed low-complexity controller is calculated without any time-consuming iterative operations; thus it's significantly advantageous in engineering applications. It is proved that the state variables converge to the prescribed region at a prescribed exponential rate under the proposed control scheme. Four groups of numerical simulations are organized to validate the effectiveness of the method.

1. Introduction

Attitude stabilization and tracking control of spacecraft is very challenging on account of nonlinear and strong-coupled features, and therefore attracts considerable attention. Many significant developments related to attitude control are achieved in recent decades. Among these works, attitude control methods can be classified into two main types. The first type is model-dependent method, which is widely adopted for attitude control in the exiting works. Some typical methods are optimal control method [1–3], robust control method [4,5] and sliding mode control (SMC) method [6–11]. While there are many great developments of model-dependent attitude control methods, four problems are often encountered when applying these methods into practical attitude control systems. The first one is the requirements for precise models and parameters [12]. Control inputs of the model-dependent control methods are usually calculated on basis of the precise models and parameters. As a result, the inertial matrix of spacecraft is assumed to be known or can be estimated in advance. Strong uncertainties existing in parameters, however, always have serious effects on system performance and might even lead to the instability of the control system. The second prominent problem is the high computational complexity of some model-dependent control methods, such as optimal control method and robust control method. The iterative solving process (e.g. solving state-dependent Riccati equation in [1,2] and solving sum of squares programming problem in [5]) costs many valuable system resources and therefore restricts these methods' practical applications. Thirdly, it is costly to acquire accurate angular velocity information in practice as the use of gyroscopes is usually expensive to the system [13]. Without angular velocity information, full-state-based methods such as optimal control method and SMC method are usually ineffective. Last but not least, most of the model-dependent attitude control methods have no ability to simultaneously guarantee the transient and steady-state performance of attitude system with parameter uncertainties and external disturbance. The performance relies on the controller parameters' tuning and cannot be guaranteed theoretically in advance. These four problems are common in future space missions. For instance, the attitude control of a combined spacecraft after capturing a non-cooperative target is challenging as the center of mass and the inertial matrix are always unknown [14]. A low-complexity robust control method is expected to stabilize the combined spacecraft system without the priori knowledge of the system parameters. Besides, the transient and steady-state performance is expected to be guaranteed to satisfy the constraints such as the stabilization time and obstacle avoidance.

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Another type of attitude control methods is model-free method. This type makes use of the output feedbacks in controller design without priori knowledge of the real system parameters. The typical representative of model-free method is the Proportional-Integration-Derivative (PID) control method. Though PID control method has been proposed for almost one century, its dominance is still obvious now across all kinds of fields of the industry [15]. One of the most significant advantages of PID control method is its low-complexity properties. In the frontier fields, however, PID control method is too simple to achieve high performance. For improving the performance of PID control method, some PID-based control methods are presented, such as the adaptive PID method [16] and active disturbance rejection control (ADRC) method [15]. With the development of the aerospace technology, new space missions raise high requirements for controller design. PID-based methods are no longer attractive as performance of the systems under these methods are not controllable, which does not satisfy the high requirement of precision in future space missions. A model-free attitude control method is urgently needed, which not only has no need of the system parameters, but has ability to guarantee the performance of the system.

A low-complexity prescribed performance control (LCPPC) method is presented recently, in which the performance of the system is limited by a user-defined function [17–20]. The transient performance, including the convergence rate and overshoot, and the steady performance, mainly the stability region, are constrained. Moreover, the method is low-complexity as the controller is calculated without any time-consuming iterative operations. And specially, any system information is unnecessary in this method. Parameters estimation methods, including the least square method [21], neural network algorithm [22] and support vector machine method [23], are also needless in the controller. Thus far, the proposed method is mainly applied to tackle the tracking problem of robot joint position to obtain high precision compared with PID-based methods [24–30]. Theoretical analysis in [28] and experimental results in [30] demonstrated the superior tracking performance of the method with respect to model-free PID-based methods. In addition, the method is introduced to position tracking control of nonlinear multi-agent systems [31] and the control problem of large large-scale systems [32,33] and air-breathing hypersonic vehicles (AHV) [34,35], and achieved positive results.

Motivated by the foregoing discussions, this paper aims at developing a low-complexity prescribed performance control method for spacecraft attitude stabilization and tracking problem with unknown dynamics and external disturbance. To the authors' best knowledge, there exist few researches reported on the robust model-free attitude control of rigid spacecraft with prescribed transient and steady performance. Compared with the existing methods, the contributions of this study are as follows:

- The equations of spacecraft attitude motion are converted into a Lagrangian form by means of differential algebra method in order to combine attitude control system in the modified Rodrigues parameters (MRP) with LCPPC.
- The prescribed performance control scheme developed by Bechlioulis and Rovithakis in [19] is extended to spacecraft with partial-state-based control scheme by means of Tracking Differentiator (TD). For spacecraft, the precise angular velocity is hard to obtain from the measurement devices and therefore the contribution is of practical significance.
- The attitude control scheme in this paper is model-free, estimation-free, adaptation-free and low-complexity, which is different from most of the current attitude control methods. Firstly, any information of the system nonlinearities and external disturbance is unnecessary in the proposed controller. Besides, parameters estimation methods are also needless in the proposed controller. Lastly, the low-complexity property is realized as the solution of the controller is solved without any complicated iteration process.

The rest of this paper is organized as follows. Section 2 gives the spacecraft attitude kinematics and dynamics in MRP. Main work of this paper is provided in Section 3, including model transforming, low-complexity prescribed performance controller design and stability analysis. Four groups of numerical simulations are organized in Section 4 to validate the efficiency of the proposed method. Finally, some conclusions are drawn in Section 5.

2. System description

In this section, the attitude of a rigid spacecraft is formulized by MRP for its nonsingularity of attitude representation [36]. The MRP $\boldsymbol{\sigma}$ is defined by

$$\boldsymbol{\sigma} = \boldsymbol{\Phi} \tan(\varphi/4) \tag{1}$$

where $\boldsymbol{\Phi} \in \mathbb{R}^3$ is the transient Euler axis, $\varphi \in \mathbb{R}$ is the transient Euler angle, $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & \sigma_2 & \sigma_3 \end{bmatrix}^T \in \mathbb{R}^3$ is the MRP.

Spacecraft attitude kinematics is defined using MRP as

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{B}(\boldsymbol{\sigma})\,\boldsymbol{\omega}, \tag{2}$$

where $\boldsymbol{B}(\boldsymbol{\sigma}) = (1/4)\left(\left(1-\boldsymbol{\sigma}^T\boldsymbol{\sigma}\right)\boldsymbol{I}_{3\times3} + 2\boldsymbol{\sigma}\boldsymbol{\sigma}^T + 2\left[\boldsymbol{\sigma}^\times\right]\right) \in \mathbb{R}^{3\times3}$, $\boldsymbol{\omega} \in \mathbb{R}^3$ is the angular velocity of the spacecraft, $\boldsymbol{I}_{3\times3} \in \mathbb{R}^{3\times3}$ is a identity matrix. For any vector $\boldsymbol{\gamma} = \begin{bmatrix} \gamma_1 & \gamma_2 & \gamma_3 \end{bmatrix}^T \in \mathbb{R}^3$, the operator $\left[\boldsymbol{\gamma}^\times\right]$ denotes a 3×3 skew-symmetric matrix which is given by

$$\left[\boldsymbol{\gamma}^\times\right] = \begin{bmatrix} 0 & -\gamma_3 & \gamma_2 \\ \gamma_3 & 0 & -\gamma_1 \\ -\gamma_2 & \gamma_1 & 0 \end{bmatrix}.$$

Spacecraft attitude dynamics of a rigid spacecraft is defined by

$$\dot{\boldsymbol{\omega}} = -\boldsymbol{J}^{-1}\left[\boldsymbol{\omega}^\times\right]\boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{J}^{-1}\left(\boldsymbol{u}(t) + \boldsymbol{d}(t)\right) \tag{3}$$

where $\boldsymbol{J} \in \mathbb{R}^{3\times3}$ represents the symmetric positive definite inertia matrix of the spacecraft, $\boldsymbol{u} \in \mathbb{R}^3$ and $\boldsymbol{d} \in \mathbb{R}^3$ are control input and unknown external disturbance, respectively.

To facilitate the controller design, the state variables and the external disturbance are assumed to satisfy the following Assumptions.

Assumption 1. Throughout the space mission, attitude MRP $\boldsymbol{\sigma}$ is measurable and available for the feedback in control design.

Assumption 2. The desired attitude MRP $\tilde{\boldsymbol{\sigma}} = \begin{bmatrix} \tilde{\sigma}_1 & \tilde{\sigma}_2 & \tilde{\sigma}_3 \end{bmatrix}^T$ and its derivative $\dot{\tilde{\boldsymbol{\sigma}}}$ as well as the second derivative $\ddot{\tilde{\boldsymbol{\sigma}}}$ are bounded, continuous with respect to t and locally Lipschitz, which means the space mission is expected to generate continuously smooth tracking trajectory for the attitude control system.

Assumption 3. The external disturbance $\boldsymbol{d}$ is bounded, and the bound limit is not known in advance.

Remark 1. The above assumptions are common and reasonable in the practical spacecraft system.