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Robust attitude coordinated control for spacecraft formation with communication delays

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Abstract In this paper, attitude coordinated tracking control algorithms for multiple spacecraft formation are investigated with consideration of parametric uncertainties, external disturbances, communication delays and actuator saturation. Initially, a sliding mode delay-dependent attitude coordinated controller is proposed under bounded external disturbances. However, neither inertia uncertainty nor actuator constraint has been taken into account. Then, a robust saturated delay-dependent attitude coordinated control law is further derived, where uncertainties and external disturbances are handled by Chebyshev neural networks (CNN). In addition, command filter technique is introduced to facilitate the backstepping design procedure, through which actuator saturation problem is solved. Thus the spacecraft in the formation are able to track the reference attitude trajectory even in the presence of time-varying communication delays. Rigorous analysis is presented by using Lyapunov-Krasovskii approach to demonstrate the stability of the closed-loop system under both control algorithms. Finally, the numerical examples are carried out to illustrate the efficiency of the theoretical results.

1. Introduction

Spacecraft formation flying has become an attractive topic during the last decade, and extensive effort has been put on this novel technique theoretically and practically. From the existing research literatures, a large number of advantages of the decentralized control algorithms have been shown, such as better system reliability and higher robustness. The control architectures for formation coordination can be categorized into four types, namely, the leader-follower structure,[1] the behavioral based approach,[2] the virtual structure[3] and graph-theoretical based technique.[4]

Practically speaking, the spacecraft formation subjects to various uncertainties such as the unknown disturbance and the time-varying inertia moment. Yang et al.[5] accomplished accuracy estimation of the external disturbances by using an

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extended observer. Considering parametric uncertainties and disturbances, Zhang et al.[6] proposed a sliding mode and adaptive coordinated tracking controller for multiple rigid spacecraft. As for a group of flexible spacecraft, Du and Li[7] employed backstepping control approach to solve the attitude synchronization problem. Neural networks (NNs) show effective performance to approximate the continuous functions over any arbitrary accuracy, which makes it be a favorable technique in nonlinear system controller design. Based on Chebyshev neutral network, Zou et al.[8] proposed a robust control law for the spacecraft in the presence of unknown inertia moment and external disturbances. Fazlyab et al.[9] designed an adaptive fault-tolerant controller for a rigid spacecraft by three-layered neutral network approximation technique. Zhao and Jia[10] developed a finite-time attitude synchronization control algorithm for multiple spacecraft formation by utilizing neural networks and modified fast terminal sliding mode.

Apart from the issues stated above, input saturation caused by the limitation of actuator is another challenge for spacecraft attitude maneuver.[11–20] Su and Zheng[13] proposed globally asymptotic saturated control laws for spacecraft attitude stabilization by modifying traditional proportional-derivative controller. Boskovic et al.[14] constructed a time-varying sliding mode control scheme to achieve attitude stabilization for spacecraft under input saturation and uncertainties. Bustan et al.[15] applied the similar approach to design fault-tolerant attitude tracking control law for a rigid spacecraft. Loria and Nijeijer[16] adopted hyperbolic tangent function to derive bounded output feedback for Euler-Lagrange system. Homogenous system theory combined with hyperbolic tangent function was used to obtain the finite-time coordinated control algorithms for a group of spacecraft formation in Refs. [18, 19]. Zou and Kumar[20] investigated attitude coordinated control problem for multiple spacecraft, where neural network was employed and an auxiliary signal was used to compensate the exceeding value of control torque.

Moreover, time-delay is unavoidable whenever information transfers between neighboring spacecraft due to communication bandwidth limitation and obstructions in space. The ignorance of such phenomenon may degrade control performance and bring unpredictable effect to system stability. Under such circumstance, the need for developing control algorithms with consideration of the communication delays arises. Li and Liu[21] derived the adaptive sliding mode control laws for spacecraft formation with uncertainties and constant non-uniform delays. Zhou et al.[22] proposed a velocity-free decentralized attitude synchronization algorithm with time-varying delays. On basis of the previous research works, coordinated control schemes for spacecraft formation under directed communication topology were carried out. Regardless of external disturbance and parametric uncertainties, Li et al.[23] designed control law by using backstepping technique and finite-time method. The uncertain factors were also neglected in Ref. [24]. For the purpose of handling system uncertainties and unknown disturbances, adaptive attitude synchronization control laws were investigated in the presence of communication delays.[25–27] Especially, Du and Li[27] proposed attitude synchronized control law for multiple flexible spacecraft, where finite-time control technique was also involved. More recently, input saturation has been considered in the time-delay systems as well. Xu et al.[28] proposed a robust controller for uncertain discrete time-delay system with bounded external disturbances and input saturation. Abdessameud and Tayebi[29] studied synchronization algorithm for Euler-Lagrange systems with communication delays, where the upper bound of control input was related to control gains and the number of formation members. It is worth emphasizing that extending these results to spacecraft formation attitude coordinated problem is not straightforward owing to the inherent coupled nonlinear dynamics of spacecraft.

Inspired by the previous research works, we concentrate on developing attitude coordinated tracking control laws for spacecraft formation with communication delay, external disturbance, inertia uncertainties and even actuator constraints. Although attitude coordinated control problem for spacecraft formation has been widely studied, control strategy taking these above factors into consideration simultaneously can hardly be found, especially when the communication topology is directed. First, a sliding mode attitude coordinated controller is presented for a formation subjected to environmental disturbance, where communication delays are considered explicitly. Then, CNN approximation approach is applied to enhance system robustness to uncertainties and disturbances. Backstepping technique with command filter has been adopted to develop the robust saturated control law. Additionally, the information exchange topology between neighboring spacecraft is supposed to be directed, which not only leads to practical significance but also poses more challenges on controller design.

The organization of this paper is as follows. In Section 2, mathematical model of spacecraft formation attitude system and some preliminaries on graph theory are presented. The main work is stated in Section 3, where two novel attitude coordinated control laws are derived and sufficient conditions for system stability are obtained. Then, the effectiveness of the theoretical results is verified by numerical examples in the following section. Finally, the conclusion and remarks are made in Section 5.

2. Preliminaries

2.1. Spacecraft formation attitude kinematics and dynamics

Unit quaternion is introduced for attitude kinematics of the ith spacecraft[30]

$$\dot{q}_{i0} = -\frac{1}{2}\boldsymbol{q}_i^{\mathrm{T}}\boldsymbol{\omega}_i \tag{1}$$

$$\dot{\boldsymbol{q}}_i = \boldsymbol{Q}(\boldsymbol{q}_i)\boldsymbol{\omega}_i = \frac{1}{2}(q_{i0}\boldsymbol{I}_{3\times3} + \boldsymbol{q}_i^{\times})\boldsymbol{\omega}_i \tag{2}$$

The dynamic model of the ith spacecraft is governed by

$$\boldsymbol{J}_i\dot{\boldsymbol{\omega}}_i + \boldsymbol{\omega}_i^{\times}\boldsymbol{J}_i\boldsymbol{\omega}_i = \boldsymbol{u}_i + \boldsymbol{d}_i \tag{3}$$

where $\bar{\boldsymbol{q}}_i = [q_{i0}, \boldsymbol{q}_i^{\mathrm{T}}]^{\mathrm{T}} \in \mathbf{R}^4$ is the quaternion denoting the rotation from the body frame of the spacecraft to the inertial frame, q_{i0} and $\boldsymbol{q}_i \in \mathbf{R}^3$ satisfy $\boldsymbol{q}_i^{\mathrm{T}}\boldsymbol{q}_i + q_{i0}^2 = 1$; $\boldsymbol{\omega}_i \in \mathbf{R}^3$ is the angular velocity expressed in the body frame; $\boldsymbol{J}_i \in \mathbf{R}^{3\times3}$ represents the inertia tensor; $\boldsymbol{u}_i \in \mathbf{R}^3$ and $\boldsymbol{d}_i \in \mathbf{R}^3$ denote the control torque and environmental disturbances acting on the ith spacecraft, respectively.

As attitude coordinated tracking problem is addressed in this article, the reference trajectory for the spacecraft forma-