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Autonomous attitude coordinated control for spacecraft formation with input constraint, model uncertainties, and external disturbances

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Abstract To synchronize the attitude of a spacecraft formation flying system, three novel autonomous control schemes are proposed to deal with the issue in this paper. The first one is an ideal autonomous attitude coordinated controller, which is applied to address the case with certain models and no disturbance. The second one is a robust adaptive attitude coordinated controller, which aims to tackle the case with external disturbances and model uncertainties. The last one is a filtered robust adaptive attitude coordinated controller, which is used to overcome the case with input constraint, model uncertainties, and external disturbances. The above three controllers do not need any external tracking signal and only require angular velocity and relative orientation between a spacecraft and its neighbors. Besides, the relative information is represented in the body frame of each spacecraft. The controllers are proved to be able to result in asymptotical stability almost everywhere. Numerical simulation results show that the proposed three approaches are effective for attitude coordination in a spacecraft formation flying system.

1. Introduction

The problems of attitude coordinated control of spacecraft formation flying (SFF) have been studied intensively during the past decades. Deep space exploration, Earth monitoring, in-orbit servicing, and military operations are involved in the potential applications of attitude coordinated control of SFF. Attitude coordinated control indicates controlling a fleet of spacecraft so that their orientations and angular velocities converge to equal asymptotically. A common reference is usually needed in some literatures[1–6] to synchronize the attitude of spacecraft. Generally speaking, it is called cooperative attitude tracking[1] if all the spacecraft are synchronized to a common reference trajectory. However, attitude coordination using local relative information is more challenging. In this condition, a spacecraft can only measure the relative attitude and angular velocity to its neighbors in the body frame, and no common reference trajectory is considered. This situation is more realistic because the availability of a common reference may be difficult to obtain in many cases.

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Various strategies for attitude coordinated control of SFF have been proposed, including multi-input multi-output, leader-follower, virtual structure, and behavioral approaches.[2–11] However, external disturbances and model uncertainties are not considered simultaneously in these literatures. Jin et al.[12] proposed robust decentralized attitude coordination controllers of SFF to deal with external disturbances and model uncertainties. Nevertheless, the stability analysis is complicated and the parameters of the controllers are restricted strictly. Liang et al.[13] put forward an attitude coordinated controller considering external disturbances and parameter uncertainties by using sliding mode control, but the chattering problem of sliding mode control may appear due to the sign function in the controller. Zhang et al.[14,15] presented robust attitude coordination and six degree-of-freedom coordination controllers of SFF to tackle external disturbances, model uncertainties, and communication delays. Zou and Kumar[16] examined robust attitude coordination control for SFF under actuator failures and obtained uniformly ultimately bounded stability of the closed-loop system. Li and Liu[17] proposed attitude synchronization schemes with communication delays, model uncertainties, disturbances, and actuator saturation was also considered by selecting control gains appropriately. Abdessameud et al.[18] solved leaderless and leader-follower attitude synchronization problems with time delay using a virtual system approach. Zou and Kumar[19] designed observers with finite-time convergence to obtain distributed output feedback coordinated controllers, however, the communication topology graph was restricted with a hierarchical structure.

Another practical problem in attitude coordinated control of SFF is the input constraint. The actuators of spacecraft can usually afford limited control torque, so it is necessary to design a controller considering the input constraint. Backstepping control with a command filter[20] is an effective tool to overcome the input constraint problem. This filter structure can provide bounded output signals, which is helpful to conquer the input constraint problem. By incorporating the command filter, Farrell[21] and Sonneveldt[22] et al. solved the input constraint problem in adaptive flight control design. However, the design procedures are only applicable for a particular model in these literatures. Li et al.[23] presented an adaptive backstepping controller for optimal descent tracking. Recently, Lv et al.[24] proposed backstepping-based synchronized control schemes for SFF with coupled attitude and orbit, input constraint, and parameter uncertainties. Meanwhile, it should be noted that autonomous attitude coordinated control of SFF with input constraint, model uncertainties, and external disturbances, was not considered.

Quaternions are usually adopted in attitude control of spacecraft. However, the mapping from S^3 (three-sphere) to SO(3) (three-dimentional special orthogonal group) is two-to-one due to the parameterization of the attitude by the quaternions. This property may lead to an unwinding phenomenon[25] in attitude control with quaternions. Such a phenomenon is highly undesirable from the viewpoint of fuel consumption and vibration suppression. A quaternion-based hybrid control approach[26] of SFF is adopted to overcome unwinding, but the controller is discontinuous. Recently, researchers have investigated attitude coordinated control developed directly on SO(3) to conquer the unwinding with quaternions. Wang and Xie[27] presented an attitude synchronization approach with time delays. Lee[28] derived the exponential stability of attitude tracking control directly developed on SO(3) with strict Lyapunov stability analysis. A robust adaptive attitude tracking control method based on SO(3) was established in Ref.[29], and the controllers were applied to the experiment of attitude control of a quadrotor unmanned aerial vehicle. However, autonomous attitude coordinated control of SFF using SO(3) has seldom been presented.

In this paper, we investigate the autonomous attitude coordinated control problem of SFF using local information. The qualifier "autonomous" refers to that no leader or no external reference tracking exists in the SFF system. This assumption may increase robustness and lower cost when the orientation in the inertial frame is not relevant.[30] We use the backstepping technique and the relative attitude error resolved in SO(3) to solve the attitude coordinated control problem in this study. Autonomous attitude coordinated controllers are proposed in three cases, which are the ideal case, the case with model uncertainties and external disturbances, and the case with input constraint, model uncertainties, and external disturbances. Only angular velocity and local information of relative attitude expressed in the body frame are used in these controllers. Besides, by using LaSalle's invariance principle, it is proven that asymptotical convergence of the closed-loop system can be achieved with the presented controllers under some conditions.

2. Mathematical model and preliminaries

2.1. Spacecraft attitude model based on rotation matrix

The attitude dynamics and kinematics equations of the ith spacecraft are given as[28–31]

$$\boldsymbol{J}_i\dot{\boldsymbol{\omega}}_i = -\boldsymbol{\omega}_i^{\times}\boldsymbol{J}_i\boldsymbol{\omega}_i + \boldsymbol{\tau}_i + \boldsymbol{d}_i \tag{1}$$

$$\dot{\boldsymbol{R}}_i = \boldsymbol{R}_i\hat{\boldsymbol{\omega}}_i \tag{2}$$

where $i = 1, 2, \ldots, n$; $\boldsymbol{J}_i \in \mathbf{R}^{3\times3}$ is the inertia matrix of the spacecraft; $\boldsymbol{\omega}_i \in \mathbf{R}^3$ is the angular velocity resolved in the body frame; $\boldsymbol{\tau}_i \in \mathbf{R}^3$ and $\boldsymbol{d}_i \in \mathbf{R}^3$ are the control torque and the disturbance torque, respectively; $\boldsymbol{R}_i \in \mathrm{SO}(3)$ is the rotation matrix that transforms the body frame into the inertial frame. The hat map $\wedge$ transforms a vector in $\mathbf{R}^3$ to a 3×3 skew-symmetric matrix so that $(\boldsymbol{x})^\wedge\boldsymbol{y} = \boldsymbol{x}\times\boldsymbol{y}$. The inverse of the hat map is denoted by $\vee$ which transforms a 3×3 skew-symmetric matrix to a 3-dimensional vector. Several properties of the map $\vee$ are given as follows:[28]

$$\mathrm{tr}(\boldsymbol{A}(\boldsymbol{x})^\wedge) = \frac{1}{2}\mathrm{tr}[(\boldsymbol{x})^\wedge(\boldsymbol{A}-\boldsymbol{A}^{\mathrm{T}})] = -\boldsymbol{x}^{\mathrm{T}}(\boldsymbol{A}-\boldsymbol{A}^{\mathrm{T}})^\vee \tag{3}$$

$$(\boldsymbol{x})^\wedge\boldsymbol{A} + \boldsymbol{A}^{\mathrm{T}}(\boldsymbol{x})^\wedge = [(\mathrm{tr}(\boldsymbol{A})\boldsymbol{I}_3 - \boldsymbol{A})\boldsymbol{x}]^\wedge \tag{4}$$

$$\boldsymbol{R}(\boldsymbol{x})^\wedge\boldsymbol{R}^{\mathrm{T}} = (\boldsymbol{R}\boldsymbol{x})^\wedge \tag{5}$$

where, for any $\boldsymbol{x} \in \mathbf{R}^3$, $\boldsymbol{A} \in \mathbf{R}^{3\times3}$, and $\boldsymbol{R} \in \mathrm{SO}(3)$, $\mathrm{tr}(\cdot)$ is the trace of a matrix. We need to design controllers to synchronize the attitude of spacecraft, namely, $\boldsymbol{R}_i \to \boldsymbol{R}_j$, $\boldsymbol{\omega}_i \to \boldsymbol{\omega}_j$ as $t \to \infty$.

2.2. Basic graph theory

Weighted undirected graphs can be used to describe local information exchanges between spacecraft within a formation.[3,4] A weighted undirected graph $G = (v,\varsigma,\boldsymbol{C})$ is composed of a node set $v = \{1, 2, \ldots, n\}$, an edge set $\varsigma \subseteq v\times v$, and a weighted adjacency matrix $\boldsymbol{C}$. If there exists information transmission from the jth node to the ith node, then there is an edge from the jth node to the ith node, denoted as $(i, j) \in \varsigma$. In an undirected graph, if $(i, j) \in \varsigma$, then $(j, i) \in \varsigma$. The