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Research article

Velocity-free attitude coordinated tracking control for spacecraft formation flying

Qinglei Hu [a,*], Jian Zhang [b], Youmin Zhang [c]

[a] School of Automation Science and Electrical Engineering, Beihang University, Beijing, 100191, China
[b] College of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, China
[c] Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec, H3G 1M8, Canada

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A B S T R A C T

This article investigates the velocity-free attitude coordinated tracking control scheme for a group of spacecraft with the assumption that the angular velocities of the formation members are not available in control feedback. Initially, an angular velocity observer is constructed based on each individual's attitude quarternion. Then, the distributed attitude coordinated control law is designed by using the observed states, in which adaptive control method is adopted to handle the external disturbances. Stability of the overall closed-loop system is analyzed theoretically, which shows the system trajectory converges to a small set around origin with fast convergence rate. Numerical simulations are performed to demonstrate fast convergence and improved tracking performance of the proposed control strategy.

1. Introduction

During the last decades, spacecraft formation flying (SFF) has become an increasingly attractive research area. Instead of a single large and complex spacecraft, multiple small spacecraft are organized cooperatively to form a formation. This innovational operating pattern shows numerous superiorities while performing space missions. The attitude coordinated control problem for SSF has attracted a considerable amount of attention due to its practical and theoretical significance. Several nonlinear feedback control design methods have been applied to obtain good performance (i.e. high accuracy, rapid response, improved robustness, etc.), including sliding mode control approaches [1–3], adaptive control approaches [4,5], backstepping approaches [6–8], to name a few. In Ref. [4], the spacecraft formation subjected to parametric uncertainties and external disturbances was investigated, an adaptive control law was proposed based on neural networks. With the help of a modal observer and backstepping technique, a distributed attitude coordinated control strategy for a group of flexible spacecraft was developed in Ref. [6]. In Ref. [8], the relative position and attitude control law was designed, and input saturation was addressed by using backstepping and command filter technique. Based on the behavior-based structure, a decentralized coordinated control law was developed in Ref. [9]. Moreover, a robust attitude synchronization control law was proposed, where communication delays between formation members was explicitly addressed in Ref. [10].

In recent years, finite-time control has drawn intensive interest, for its inherent faster convergence rate, higher accuracy, and better robustness. In Ref. [11], a novel finite-time control scheme for robotic manipulators using fast terminal sliding modes was proposed. In Ref. [12], a fast terminal sliding mode control scheme for nonlinear dynamics was designed, and the singular problem was solved. Recently, the fast terminal sliding mode has been applied on a robot manipulator in Ref. [13], by which the tracking error could be suppressed within the predefined error boundary and finite-time convergence was obtained. As for attitude control of spacecraft, the advantages brought by finite-time control are also attractive. In Ref. [14], a global finite-time controller for attitude stabilization of a rigid spacecraft was presented. In Ref. [15], the attitude tracking problem for spacecraft has been investigated by designing a continuous terminal sliding mode control scheme. Adding a power integrator technique is adopted in Ref. [16], yet the parametric uncertainties and external disturbances have not been taken into consideration.

* Corresponding author. School of Automation Science and Electrical Engineering, Beihang University, Beijing, 100191, China.
E-mail address: huql_buaa@buaa.edu.cn (Q. Hu).

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Nevertheless, both attitude and angular velocity are assumed to be measureable in the above cited research works. In practical, precise measurements may be not accessible either subject to the failure of onboard sensors or the environmental perturbations. Thus, Kalman filter [17] has become a persuasive method to obtain accurate estimation due to its simplicity and robustness. Note that in some special cases, even imprecise measurement is unattainable. Hence, various observers have been developed for different estimation goals. In Ref. [18], a disturbance observer was designed by using the position and velocity information, thus the unexpected contact force was compensated and the operating accuracy of the ear surgical has been apparently upgraded. In Ref. [19], a high-gain observer was derived only rely on the position measurements, by which the uncertainties and velocities could be estimated. In Ref. [20], a speed sensorless control scheme for a five-phase permanent magnet synchronous motor drive was constructed by applying a sliding mode observer. Furthermore, to improve the response rate, a super-twisting second-order sliding mode observer was designed in Ref. [21]. In addition, assuming only a subset of the followers have access to the leader, the reference states are directly replaced by the estimated states in most existing works [21–25]. However, from the theoretical point of view, the stability analysis of the closed-loop system can still be enhanced by considering the influence of observer errors.

Motivated by the above facts and a reasonable need for providing more reliable solutions, the attitude coordinated tracking algorithm with fast convergence rate is proposed for the spacecraft formation. The angular velocity of each spacecraft is assumed to be unmeasurable, and the reference attitude is accessible for only a subset for the formation members. Hence, an angular velocity observer is designed to compensate the lack of information. Then, a distributed attitude control law is developed via local interaction, which stabilizes the attitude errors. It is worthwhile to mention that finite-time control method is applied to accelerate the response speed of the observer and the distributed control law, and thus the fast convergence rate of the closed-loop system is guaranteed. A novel Lyapunov function is constructed to analyze system stability with consideration of observer errors, attitude errors and observed errors.

The rest of this paper is organized as follows: Section 2 summarizes the mathematical model of spacecraft formation and necessary preliminaries for problem formulation. The main results of the work are presented in Section 3. Firstly, an angular velocity observer is constructed to compensate the unmeasurable information. Based on the observed states, a distributed velocity-free controller with fast convergence rate is designed. Adaptive method is applied to deal with the external disturbances. Rigorous proof is carried out to analyze the stability of the closed-loop system, and finite-time control theory is used to show the fast convergence rate of system states. Finally, numerical simulation results are shown in Section 4 to support the theoretical development, followed by concluding remarks in Section 5.

2. Preliminaries and problem formulation

2.1. Notations

Throughout this paper, the norm of a vector $\|\boldsymbol{x}\| = \sqrt{\boldsymbol{x}^{\mathrm{T}}\boldsymbol{x}}$ and the induced norm for a matrix $\boldsymbol{X} \in \Re^{n\times n}$ is defined as $\|\boldsymbol{X}\| = \sqrt{(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X})_M}$. It should be noted that $\boldsymbol{X}_M$ and $\boldsymbol{X}_m$ indicate the maximum and minimum eigenvalues of matrix $\boldsymbol{X}$, respectively. In addition, for a given vector $\xi \in \Re^n, \xi_w$ denotes the wth entry of vector ξ. The function $\mathrm{sig}(\xi)^r = (|\xi_1|^r \mathrm{sgn}(\xi_1), \ldots, |\xi_n|^r \mathrm{sgn}(\xi_n))^{\mathrm{T}} \in \Re^n$ is defined with a positive scalar r.

2.2. Spacecraft formation attitude kinematics and dynamics

The attitude kinematics and dynamics of the ith spacecraft using quaternion are as follows [26].

$$\dot{q}_{0i} = -\frac{1}{2}\boldsymbol{q}_i^{\mathrm{T}}\omega_i \tag{1a}$$

$$\dot{\boldsymbol{q}}_i = \boldsymbol{Q}_i(\boldsymbol{q}_i)\omega_i \tag{1b}$$

$$\boldsymbol{J}_i\dot{\omega}_i + \omega_i^{\times}\boldsymbol{J}_i\omega_i = \boldsymbol{u}_i + \boldsymbol{d}_i \tag{1c}$$

where $\overline{\boldsymbol{q}}_i = [q_{0i}, \boldsymbol{q}_i^{\mathrm{T}}]^{\mathrm{T}}$ is the quaternion denoting the rotation from the body-fixed frame of the spacecraft to the inertial frame, the matrix $\boldsymbol{Q}_i(\boldsymbol{q}_i)$ can be expressed as $\boldsymbol{Q}_i(\boldsymbol{q}_i) = \frac{1}{2}(q_{0i}I_{3\times 3} + \boldsymbol{q}_i^{\times}), \omega_i \in \Re^3$ is the angular velocity vector expressed in the body-fixed frame for ith spacecraft. $\boldsymbol{J}_i \in \Re^{3\times 3}$ denotes the inertia tensor of the ith spacecraft, $\boldsymbol{u}_i \in \Re^3$ is the control torque of ith spacecraft. $\boldsymbol{d}_i \in \Re^3$ denotes environmental disturbances acting on the ith spacecraft.

Deonte $\boldsymbol{F}_i(\boldsymbol{q}_i) = \boldsymbol{Q}_i(\boldsymbol{q}_i)^{-1}$, and $\boldsymbol{g}(\boldsymbol{q_i}) = \boldsymbol{Q}_i(\boldsymbol{q}_i)\boldsymbol{J}_i^{-1}$. In the following, $\boldsymbol{F}_i(\boldsymbol{q}_i)$ and $\boldsymbol{Q}_i(\boldsymbol{q}_i)$ are denoted as $\boldsymbol{F}_i$ and $\boldsymbol{Q}_i$, respectively. Then, system (1a)-(1c) are rewritten as

$$\dot{\boldsymbol{q}}_i = \boldsymbol{v}_i, \dot{\boldsymbol{v}}_i = \boldsymbol{f}_i(\boldsymbol{q}_i, \boldsymbol{v}_i) + \boldsymbol{g}(\boldsymbol{q_i})\boldsymbol{u}_i + \boldsymbol{g}(\boldsymbol{q_i})\boldsymbol{d}_i \tag{2}$$

where $\boldsymbol{f}_i(\boldsymbol{q}_i, \boldsymbol{v}_i) = \dot{\boldsymbol{Q}}_i\boldsymbol{F_i}\dot{\boldsymbol{q}}_i - \boldsymbol{Q}_i\boldsymbol{J}_i^{-1}(\boldsymbol{F_i}\dot{\boldsymbol{q}}_i)^{\times}\boldsymbol{J_i}\boldsymbol{F_i}\dot{\boldsymbol{q}}_i$.

Remark 1. To guarantee the existence of $\boldsymbol{F}_i$, the matrix $\boldsymbol{Q}_i$ should be invertible, which implies that $\det(\boldsymbol{Q}_i) = \frac{1}{2}q_{i0}(t) \neq 0$ for $t \geq 0$. Thus, the initial state and control strategy should be chosen to guarantee $q_{i0}(t) \neq 0$ for all time. In fact, the initial attitudes can be always selected as $q_{i0}(0) \neq 0$ and the control parameters are tunable to ensure $q_{i0}(t) \neq 0$ for $t > 0$. Therefore, this restriction is mild and reasonable.

Assumption 1. The external disturbance $\boldsymbol{d}_i$ is assumed to be bounded and satisfy $\|\boldsymbol{d}_i\| \leq \overline{d}$ with $\overline{d} > 0$. Noticing that $\|\boldsymbol{g}(\boldsymbol{q_i})\| = \left\|\boldsymbol{Q_i}\boldsymbol{J}_i^{-1}\right\| \leq (\boldsymbol{J}_i)_m^{-1}$, it leads to $\|\boldsymbol{g}(\boldsymbol{q_i})\boldsymbol{d_i}\| \leq (\boldsymbol{J}_i)_m^{-1}\overline{d}$. Denote $\varphi_d = (\boldsymbol{J}_i)_m^{-1}\overline{d}$, we have $\left\|\boldsymbol{d}_i^*\right\| \leq \varphi_d$ with φ_d being a positive scalar.

2.3. Graph theory

To describe the communication links between spacecraft in the formation flying, fundamental graph theory is to be used [27]. Let $\boldsymbol{G}@(N, E, \boldsymbol{A})$ be a graph, in which $N = \{n_1, n_2, \ldots, n_n\}$ is a finite nonempty set of nodes and $E \subseteq N \times N$ is a set of ordered pairs of nodes, called edges. An edge $(n_i, n_j) \in E$ denotes that node n_j can obtain information from node n_i, thus n_i is a parent of n_j, and n_j is a child of n_i. Then the set of the neighbors of node n_i is denoted by $N_i = \{j : (n_i, n_j) \in E\}$. If a graph has the property that $(n_i, n_j) \in E \Leftrightarrow (n_j, n_i) \in E$, the graph is called an undirected graph. A adjacency matrix $\boldsymbol{A} = [a_{ij}] \in \Re^{n\times n}$ associated with $\boldsymbol{G}$ represents the communication between each node, in which $a_{ij} > 0$ if $(n_i, n_j) \in E$, while $a_{ij} = 0$ otherwise. The Laplacian matrix $\boldsymbol{L} = [l_{ij}] \in \Re^{n\times n}$ associated with $\boldsymbol{A}$ is defined as $l_{ii} = \sum_{i\neq j} a_{ij}$ and $l_{ij} = -a_{ij}$, where $i \neq j$. Moreover, it is assumed that $a_{ii} = 0$, for all $i = 1, 2, \cdots, n$. A graph $\boldsymbol{G}$ is said to be connected if there exists a path between each pair of distinct nodes.

Throughout this paper, the formation flying with n spacecraft is considered, each spacecraft denotes as a node in the graph.