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Relative position coordinated control for spacecraft formation flying with communication delays

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ABSTRACT

This study addresses a relative position coordinated control problem for spacecraft formation flying subject to directed communication topology. Two different kinds of communication delay cases, including time-varying delays and arbitrarily bounded delays are investigated. Using the backstepping control technique, two virtual velocity control inputs are firstly designed to achieve coordinated position tracking for the kinematic subsystem. Furthermore, a hyperbolic tangent function is introduced to guarantee the boundedness of the virtual controller. Then, a finite-time control algorithm is designed for the dynamic subsystem. It can guarantee that the virtual velocity can be followed by the real velocity after finite time. It is theoretically proved that the proposed control scheme can asymptotically stabilize the closed-loop system. Numerical simulations are further presented that not only highlight closed-loop performance benefiting from the proposed control scheme, but also illustrate its superiority in comparison with conventional formation control schemes.

1. Introduction

During the past decade, spacecraft formation flying (SFF) has been proposed for various space missions, such as distributed aperture radar, earth stereo-imaging and deep-space observation [1–3]. To accomplish these missions, the relative positions in the spacecraft formation should be kept with high accuracy. For example, the configuration of the spacecraft formation for space-based laser interferometry mission must remain precisely intact when the formation intends to increase the baseline [4]. Inspired by these demands, the coordinated control problem of relative position for SFF has attracted more and more attention. Based on the leader-follower approach, Wang, et al. [5] firstly proposed a synchronized formation rotation and attitude control for multiple free-flying spacecraft. In [6], a virtual structure methodology was adopted to design a decentralized formation control scheme. The result in [6] was then extended by Ren et al. [4] where several decentralized controllers were designed to achieve relative position keeping and attitude alignment for spacecraft formation subject to a general directed communication topology. Taking uncertainties and disturbances into consideration, Zhang et al. [7] developed a robust coordinated control approach for spacecraft formation maneuver by looking into local information exchange. In [8], Belanger et al. reported an optimal decentralized position control method for SFF in the presence of measurement uncertainties. To handle possible collisions during formation maneuver, Lee et al. [9] presented a position tracking control scheme combined with the decentralized collision-avoidance capability. Considering that the velocity sensors would be faulty or with strong noises, Hu et al. [10] reported a finite-time coordinated controller of relative position for SFF only using the position measurements.

It should be emphasized that the preceding investigations of coordinated control did not consider the effects of unavoidable communication delays. However, such delays will inevitably deteriorate the control performance and even lead to system instability. To address this issue, several developments have been witnessed for consensus attitude control problem [11,12] and formation control problem [13,14] with communication delays. It is worth mentioning that the communication links among formation spacecraft in [11–14] were assumed to be undirected, i.e. bidirectional. However, in some missions with unidirectional laser communication system, the communication topology may be constrained to be directed, and the coordinated control problem under directed topology is more complicated when compared with the coordinated control problem with undirected topology [15]. In view of the directed communication topology case, Li et al. [16] proposed an attitude synchronization controller for rigid spacecraft formation based on the backstepping

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control methodology in the presence of time delays. Further, Du et al. [17] extended the work in [16] and designed a synchronized attitude controller for a group of flexible spacecraft. More recently, Nazair et al. [18] presented a decentralized position and attitude consensus control method for SFF with time delays. Nevertheless, all the above literatures only focused on the constant communication delays. Regarding to time-varying delays, Jin et al. [19,20] addressed the attitude synchronization control problem for SFF, in which the Lyapunov-Krasovskii function was adopted to obtain sufficient conditions of the control parameters. In [21], Abdessameud et al. proposed a position synchronization control law for the networked Euler-Lagrange system in the presence of unknown parameters. It should be pointed out that, although the coordinated control problem for SFF has been extensively investigated even in the presence of communication delays, either the constant delays or time-varying delays are assumed to be continuous and differentiable. Despite the interesting results cited above, the time delayed coordinated control problem for SFF still poses some challenges in more realistic applications. To the best of the author's knowledge, the issue of relative position coordinated control in the presence of directed communication topology and arbitrarily bounded delays is still an open one.

This paper focuses on solving the relative position coordinated control problem for SFF in the presence of communication delays, while the communication links in the spacecraft formation are subject to a directed topology. A novel control approach is presented based on the combination of backstepping control method and finite-time control technique. Firstly, two virtual velocity control laws are designed to achieve coordinated position tracking for the kinematic subsystem in the presence of different time delays. Then, a finite-time controller is proposed for the dynamic subsystem to guarantee that the designed virtual velocity can be followed by the real velocity after finite time. With application of this approach, asymptotically coordinated position tracking can be achieved. The designed coordinated control scheme is an extension of the existing results in [12,16,17]. However, in comparison with [12,16,17], the main contributions of this study are: (1) Two different kinds of time delay cases, i.e. time-varying delays and arbitrarily bounded delays, are addressed, which are largely unexplored in the existing literatures; (2) A hyperbolic tangent function is introduced to achieve the boundedness of the controller, which makes it generally difficult to analyze the delay effects of those schemes.

The reminder of this paper is organized as described next. In Section 2, the mathematical model of SFF and the problem formulation are introduced. The main results of relative position coordinated control scheme designed for spacecraft formation maneuver are presented in Section 3. Numerical simulations are presented on a generic SFF model in Section 4. Finally, the paper ends with concluding remarks.

Notations: Throughout the paper, for $\mathbf{x} = [x_1, x_2, \ldots, x_n]^T \in \mathbf{R}^n$, define $\mathbf{x} \odot \mathbf{x} = [x_1^2, x_2^2, \ldots, x_n^2]^T$, $\tanh(\mathbf{x}) = [\tanh(x_1), \tanh(x_2), \ldots, \tanh(x_n)]^T$, $\mathrm{sgn}^\alpha(\mathbf{x}) = [\mathrm{sgn}^\alpha(x_1), \mathrm{sgn}^\alpha(x_2), \ldots, \mathrm{sgn}^\alpha(x_n)]^T$ with $\mathrm{sgn}^\alpha(x_i) = |x_i|^\alpha$. In addition, the arguments of time-dependent parameters are omitted, e.g. $\tilde{\boldsymbol{\rho}}_i \leftrightarrow \tilde{\boldsymbol{\rho}}_i(t)$, except for the parameters which are time delayed, e.g. $\tilde{\boldsymbol{\rho}}_i(t - T_{ij})$.

2. Preliminaries and problem formulation

2.1. Dynamic model of spacecraft formation flying

In this subsection, the relative motion model of SFF is introduced, and a schematic representation of SFF system is presented in Fig. 1. Assume that the investigated SFF system consists of a virtual leader and n followers. The orbital motion of the virtual leader spacecraft is described by a true anomaly θ and a radial distance R_c from the Earth center to the virtual leader. The inertial coordinate frame C_{ECI} is attached to the Earth center, and $\mathbf{R}_c$ represents the distance vector from the origin of C_{ECI} to the virtual leader. In addition, a local-vertical-

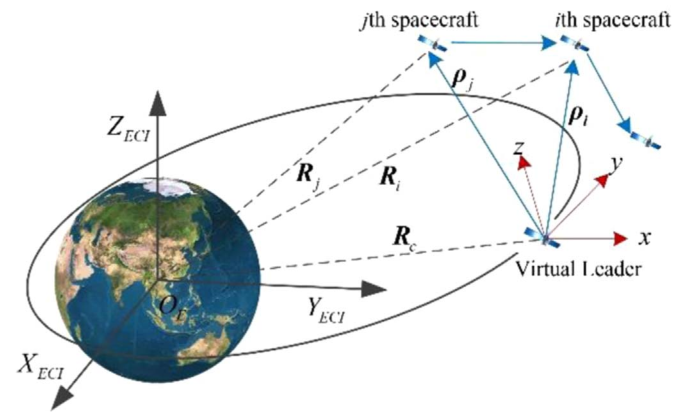

Fig. 1. Schematic representation of SFF system.

local-horizontal (LVLH) frame located at the center of the virtual leader is introduced to investigate the relative motion problem, where x axis points in the radial direction (along $\mathbf{R}_c$), z axis points normal to the orbital plane, and y axis denotes the third axis of the right-handed frame.

In the LVLH frame, the relative position and relative velocity vectors from the virtual leader to the ith spacecraft are represented as $\boldsymbol{\rho}_i = [\rho_{i,x}, \rho_{i,y}, \rho_{i,z}]^T$ and $\mathbf{v}_i = [v_{i,x}, v_{i,y}, v_{i,z}]^T$, respectively. The distance from the Earth center to the ith spacecraft is denoted as $R_i = [(R_c + \rho_{i,x})^2 + \rho_{i,y}^2 + \rho_{i,z}^2]^{1/2}$. Let a_c and e_c respectively represent the semi-major axis and the orbital eccentricity of the elliptical orbit of the virtual leader, μ represents the gravitational constant, and $n_c = \sqrt{\mu / a_c^3}$ denotes the mean orbital angular velocity, then $R_c = a_c(1 - e_c^2)/[1 + e_c\cos(\theta)]$ and $\dot{\theta} = n_c[1 + e_c\cos(\theta)]^2/(1 - e_c^2)^{3/2}$ can be obtained. The relative motion model for the ith spacecraft in the LVLH frame can be described by [22].

$$\dot{\boldsymbol{\rho}}_i = \mathbf{v}_i \tag{1}$$

$$m_i\dot{\mathbf{v}}_i + \mathbf{C}_i\mathbf{v}_i + \mathbf{N}_i + \mathbf{F}_{di} = \mathbf{u}_i \tag{2}$$

where m_i denotes the mass of the ith spacecraft, $\mathbf{u}_i = [u_{i,x}, u_{i,y}, u_{i,z}]^T$ represents the control force applied on the ith spacecraft, $\mathbf{F}_{di} = [F_{di,x}, F_{di,y}, F_{di,z}]^T$ is the bounded disturbance force with $\|\mathbf{F}_{di}\| \le \bar{d}$, where $\bar{d}$ is a positive constant. In addition, $\mathbf{C}_i$ is a Coriolis-like anti-symmetric matrix and $\mathbf{N}_i$ is a nonlinear term defined as

$$\mathbf{C}_i = 2m_i\begin{bmatrix} 0 & \dot{\theta} & 0 \\ -\dot{\theta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$
$$\mathbf{N}_i = m_i\begin{bmatrix} -\ddot{\theta}\rho_{i,y} - \dot{\theta}^2\rho_{i,x} + \mu(\rho_{i,x} + R_c)/R_i^3 - \mu/R_c^2 \\ \ddot{\theta}\rho_{i,x} - \dot{\theta}^2\rho_{i,y} + \mu\rho_{i,y}/R_i^3 \\ \mu\rho_{i,z}/R_i^3 \end{bmatrix} \tag{3}$$

2.2. Communication topology description

The communication topology among n follower spacecraft in the formation is modelled as a weighted digraph $G(A) = \{V, E, A\}$, where $V = [v_1, v_2, \ldots, v_n]$ is a finite set of nodes, $E \subseteq \{V \times V\}$ is a set of edges, $(v_j, v_i) \in E$ means that there is an edge from node v_j to node v_i. The weighted adjacency matrix of $G(A)$ is represented as $\mathbf{A} = [a_{ij}] \in \mathbf{R}^{n\times n}$ with non-negative adjacency elements a_{ij}, and $a_{ij} > 0$ if $(v_j, v_i) \in E$; otherwise $a_{ij} = 0$. Self-edges are not allowed, which means $a_{ii} = 0$. The neighborhood of node v_i is defined as $N_i = \{v_j | (v_j, v_i) \in E\}$. The out-degree of node v_i is denoted by $\deg_{\mathrm{out}}(v_i) = d_i = \sum_{j\in N_i} a_{ij}$. Then the out-degree matrix of $G(A)$ is denoted by $\mathbf{D} = \mathrm{diag}\{d_1, d_2, \ldots, d_n\}$. The Laplacian matrix of $G(A)$ is defined as $\mathbf{L} = \mathbf{D} - \mathbf{A}$. A path in $G(A)$ from node v_i to node v_j is a sequence of distinct nodes starting at v_i and