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Research Article

Relative position finite-time coordinated tracking control of spacecraft formation without velocity measurements

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ABSTRACT

This paper investigates finite-time relative position coordinated tracking problem by output feedback for spacecraft formation flying without velocity measurement. By employing homogeneous system theory, a finite-time relative position coordinated tracking controller by state feedback is firstly developed, where the desired time-varying trajectory given in advance can be tracked by the formation. Then, to address the problem of lack of velocity measurements, a finite-time output feedback controller is proposed by involving a novel filter to recover unknown velocity information in a finite time. Rigorous proof shows that the proposed control law ensures global stability and guarantees the position of spacecraft formation to track a time-varying reference in finite time. Finally, simulation results are presented to illustrate the performance of the proposed controller.

1. Introduction

Recent years have witnessed a prosperous development of spacecraft formation flying (SFF), which is expected to be an applicable technology for many space and Earth science missions, such as distributed aperture radar, enhanced stellar and extension planet detection optical interferometry, virtual co-observation and stereo-imaging platforms for space science and Earth observing [1–3], etc. Details of current and future spacecraft formation flying missions have been recently collected and presented in Ref. [4]. By replacing a large spacecraft with a group of small cooperative spacecrafts, SFF possesses many advantages over the traditional single spacecraft, such as lower cost, higher system reliability, and more flexibility. In near future, NASA will deploy many smaller spacecrafts in highly controlled spatial configurations [5,6]. It should be noted that most prior research is limited to one-leader-one-follower configuration, which is not a reliable case, since the follower depends only on the information of the leader. However, coordinated control for multiple spacecrafts in a formation has been an important issue in practice. Relative position of the formation should be kept a precise accuracy, during some missions (e.g., space interferometry, etc.), which requires the spacecraft to reach specified formation with zero relative velocity [7,8]. To meet these missions, coordinated tracking control of relative motion for spacecraft formation has been an interesting topic.

Great deals of literatures focused on translational coordinated control of SFF have been carried out [9–16]. Grøtli et al. [9] studied a controller–observer scheme for the spacecraft formation relative position tracking problem based on the leader–follower architecture, which guarantees uniform global exponential stability of the closed-loop system. By introducing formation feedback from the spacecraft to the virtual structure, Ren et al. [10] made an improvement for spacecraft formation control, which provided faster convergence speed than previous control law via virtual structure. Lv et al. [16] proposed a robust control law for spacecraft formation with consideration of both translational and rotational control in presence of parameter uncertainties and input constraints. Note that the above-mentioned literatures can only guarantee asymptotical convergence of closed-loop system, which means the convergence rate is at best exponential with infinite settling time. In other words, the coordination of SFF cannot be reached in a finite time. Obviously, the coordination control laws of SFF with finite-time convergence are more desirable. Besides faster convergence rate, the closed-loop systems under finite-time control usually demonstrates higher accuracies, better disturbance rejection properties, and better robustness against uncertainties. In addition, some orbiting missions of SFF require fast and even finite time operations. Motivated by this circumstance, a control method with faster convergence rate for SFF is in urgent request.

Finite-time control technique has attracted increasing attention due to its fast convergence rate and robustness to disturbances

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[17–24]. Bhat et al. [17,20] addressed the relationship between finite-time stability and homogenous system. In view point of homogenous theory, tracking control problem of robot manipulators is discussed in Refs. [18,19]. Yu et al. [21] proposed a continuous finite-time control scheme for robotic manipulators using fast terminal sliding modes. Chen et al. [22] developed a disturbance observer and finite-time control law for a class of SISO system using terminal sliding mode technique. Mondal et al. [23] designed an adaptive second order sliding mode to obtain a shorter settling time and less overshoot of uncertain system. Besides this, finite-time control has been applied to solve control problem for spacecraft [25–31] to achieve better performance and higher accuracy. Song et al. [25] developed a fast terminal sliding mode control law with an inner control loop and an outer control loop to drive the spacecraft tracking a desired attitude trajectory. Zhou et al. [26] investigated finite-time attitude synchronization and stabilization problem by using a fraction power. Sun et al. [28] developed a finite-time control law to stabilize the closed-loop 6DOF spacecraft formation control system, and a disturbance observer is derived to reject the external disturbance. It should be noted that these previous works carried out almost concentrate on attitude and/or coordinated attitude control problem rather than the position control of spacecraft. This leads to an insistent demand to solve the relative position coordinated control strategies for SSF in sense of finite time, which is key step for the successful spacecraft formation.

In addition, most of the existing finite-time control schemes are developed assuming that the measurement of full states are accessible [18,26], which may not be the common case in reality. As for SFF, most research has been carried out under the assumption that both position and velocity of SFF can be measured. However, from the view point of reducing implementation cost and spacecraft weight, the question of how to design a control law without velocity measurement becomes imperative, especially, when the velocity sensors are fault or with heavy noises. To this, Hong [32] derived a finite-time observer for double integrator system. Then, Zhang et al. [33] solved finite-time consensus tracking for harmonic oscillators by doing further research with the observer given in [32]. Zhao et al. [34] considered both finite-time tracking problem for multiple second-order dynamic agents with an active leader and finite-time containment tracking problem as well, and the control schemes rely on the position measurements of an agent and its neighbors. Whereas research on finite-time output feedback control protocol for the robot manipulators remains open. It is even hard for SFF due to the inherent nonlinearity in the dynamic model of spacecraft formation tracking problem, especially, when the time-varying trajectory is considered. Hence, to study the finite-time output control scheme for SFF is not only theoretically challenging but also practical imperativeness.

The main contribution of this work is to solve the problem of finite-time coordinated position tracking via output feedback for spacecraft formation flying (SFF) without velocity measurement. First of all, based on the homogeneous system theory, a finite-time control law by state feedback is designed. Then, by exploiting some structural properties of the SFF model, a filter is proposed to estimate the velocity in a finite time and under this, a global finite time coordinated position tracking control law without velocity measurement is developed. The rest of this paper is organized as follows. In Section 2, some preliminaries refer to our work and the control objective is introduced. Our major result is presented in Section 3, based on the homogenous theory, a full state feedback finite-time control scheme is developed, with which the spacecraft formation can track a time-varying reference trajectory in finite time. Then, an output feedback finite-time control scheme combined with a filter has been derived, and in this case the request of the velocity sensor is unavailable. Finally, simulation examples are shown to illustrate the effectiveness of proposed control scheme.

2. Preliminaries

2.1. Model of relative motion

In this section, nonlinear model of relative motion of spacecraft formation is introduced, and a schematic drawing of the SSF is given in Fig. 1. Let C_{ECI} be the inertial coordinate frame $\{X, Y, Z\}$, with its origin attached to the center of the Earth. Assuming a virtual leader is in an ideal, elliptical orbit around the Earth, and each spacecraft is a mass. $\boldsymbol{R}_c$ denotes the distance vector from origin of C_{ECI} to the virtual leader. To study relative motion problem of SSF, a local-vertical-local-horizontal (LVLH) coordinate C_L attached to the virtual leader is introduced, with x axis pointing along the direction of $\boldsymbol{R}_c$, y-axis pointing along the velocity vector and normal to x, z axis being mutually perpendicular to x and y axes such that the frame C_L forms a right-hand coordinate frame.

In the LVLH coordinate, relative vector from the virtual leader to the ith spacecraft denoted as $\boldsymbol{\rho}_i = [x_i, y_i, z_i]^{\mathrm{T}} \in \mathbf{R}^3$, and $R_i = [(R_c+x_i)^2 + y_i^2 + z_i^2]^{3/2}$ denotes the distance from center of the Earth to the ith spacecraft. μ is gravity constant, a_c is the semi-major axis of the elliptical orbit of virtual leader, e_c is orbital eccentricity of the reference orbit, θ is true anomaly of virtual leader, and $n = \sqrt{\mu/a_c^3}$ is average orbital angular velocity. Thus, $R_c = (a_c(1-e_c^2)/1 + e_c \cos\theta)$ and $\dot\theta = (n_c(1-e_c \cos\theta)^2/(1-e_c^2)^{3/2})$ can be obtained for further analysis. The nonlinear relative motion model of the spacecraft formation in the LVLH coordinate frame is then given as Eqs. (1a)–(1c):

$$\ddot{x}_i = 2\dot\theta\dot{y}_i + \ddot\theta y_i + \dot\theta^2 x_i - \frac{\mu(x_i+R_c)}{R_i} + \frac{\mu}{R_c^2} + \frac{1}{m_i}(u_{xi}+f_{dxi}), \quad i = 1,\dots,n \tag{1a}$$

$$\ddot{y}_i = -2\dot\theta\dot{x}_i - \ddot\theta x_i + \dot\theta^2 y_i - \frac{\mu y_i}{R_i} + \frac{1}{m_i}(u_{yi}+f_{dyi}) \tag{1b}$$

$$\ddot{z}_i = -\frac{\mu z_i}{R_i} + \frac{1}{m_i}(u_{zi}+f_{dzi}) \tag{1c}$$

where n is total number of spacecrafts in the formation, m_i denotes the mass of the ith spacecraft, $\boldsymbol{f}_d = [f_{dxi} \;\; f_{dyi} \;\; f_{dzi}]^{\mathrm{T}} \in \mathbf{R}^3$ is external disturbance, and $\boldsymbol{u} = [u_{xi} \;\; u_{yi} \;\; u_{zi}]^{\mathrm{T}} \in \mathbf{R}^3$ is actual control force. Thus, nonlinear kinematic and dynamic model of the ith spacecraft in LVLH can be arranged into the following advantageous form [35]:

$$\boldsymbol{M}_i\ddot{\boldsymbol{\rho}}_i + \boldsymbol{C}_i\dot{\boldsymbol{\rho}}_i + \boldsymbol{N}_i + \boldsymbol{F}_{di} = \boldsymbol{u}_i \tag{2}$$

where $\boldsymbol{\rho}_i \in \mathbf{R}^3$ denotes the relative position between the ith spacecraft and virtual leader, $\boldsymbol{M}_i = m_i\boldsymbol{I}_3$, $\boldsymbol{I}_3$ represents an identity matrix, $\boldsymbol{F}_{di} \in \mathbf{R}^3$ and $\boldsymbol{u}_i \in \mathbf{R}^3$ represent disturbance and control force acting on with the ith spacecraft, respectively. $\boldsymbol{C}_i$ is a Coriolis-like matrix defined as Eq. (3), which is anti-symmetric, $\boldsymbol{N}_i$ is a nonlinear term

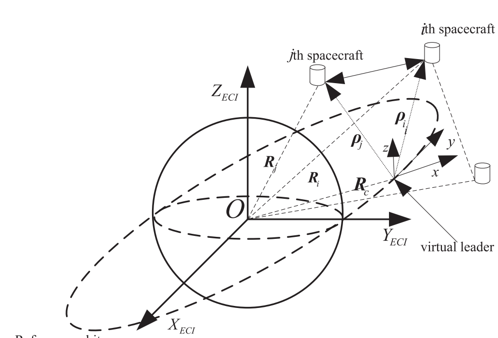

Fig. 1. Schematic representation of the SSF system.