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Tracking control of spacecraft formation flying with collision avoidance

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ABSTRACT

Study results of developing formation control system for multi-spacecraft that requires avoiding obstacles and maintaining the formation configuration are presented. In particular, nonlinear adaptive feedback control law is developed by employing special potential functions and a kind of time-varying sliding manifold, to enable the spacecraft formation in a specific configuration by taking into account the obstacle avoidance requirement while tracking a moving target in a way of cooperation or not. Moreover, capability for handling multiple tasks by the proposed control system is demonstrated in the presence of disturbances and parametric uncertainties. The stability proof is based on a Lyapunov-like analysis and the properties of the proposed potential functions. Numerical simulation of the proposed method is presented to demonstrate the advantages with respect to obstacle avoidance, fast tracking and formation flying configuration reconstruction capability.

1. Introduction

With more and more special requirements for spacecraft systems, the development of single traditional monolithic spacecraft system is restricted due to its shortcomings like long development cycle, huge cost and increased risk, etc. Comparatively, a space mission system with multiple smaller spacecraft under formation flying has several great advantages over the single one, such as enhanced adaptability, increased instrument resolution, reduced cost, shortened development cycle, increased overall system robustness, and so on. Both NASA and U.S. Department of Defense identified multi-spacecraft technology as a supporting technology for spacecraft system in the 21st century. Applications for spacecraft formation have been paying more attention to space-based interferometers, navigation and guidance instruments, synthetic aperture radars, military surveillance instruments, etc.

Formation maintaining and reconfiguration/reconstruction is one of the important issues for spacecraft formation system. In Ref. [31], a digital optimal control theory was proposed for satellites to maintain formation configuration, but one of the limitations of this work is that it can be only applied to satellites in circular orbits. For spacecraft in eccentric orbit, a formation control method and an initialization procedure have been proposed in Ref. [14]. Another work to reduce conservatism of orbit model is presented in Ref. [7], in which the authors proposed a nonlinear dynamic model to describe the relative positions of spacecraft in formation and developed an adaptive control law which guarantees the global asymptotic convergence of the position tracking error. In Ref. [29], a series of J_2 invariant relative orbits have been designed for spacecraft formation. Bando et al. [2] considered a formation problem with restricted control interval, and they designed feedback controllers to bring satellites in formation asymptotically to a given periodic orbit. In addition, Morgan et al. [25] proposed several open-loop guidance methods for spacecraft swarms composed of hundreds to thousands of agents, and they took into account the influence of J_2 and atmospheric drag perturbations. In Ref. [33], a nonlinear coupled dynamic model for formation flying spacecraft was established, and a relative orbit and attitude controller was developed via convex optimization. In addition, Cho et al. [5] presented and examined a general analytical solution to the optimal reconfiguration problem of satellite formation flying in an arbitrary elliptic orbit.

Target tracking is another common and important goal for spacecraft formation. Spacecraft formation is often required to maintain a specific configuration and track a moving leader at the same time. In Ref. [32], the leader–follower strategy was applied to spacecraft, and coordinating control laws with actuator saturation constraint was designed for formation keeping and attitude alignment. Following Ref. [32], Beard et al. [3] introduced an architecture for the multi-agent coordination system including the leader–follower strategy, agent behavioral and virtual-structure ap-

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proaches. Jiang et al. [15] studied the two-point boundary value problem of a leader–follower spacecraft formation flying in unperturbed elliptical reference orbits. They showed this problem can be solved just like the classical Lambert's problem, and the analytical solution of the problem was obtained. In Ref. [19], an output feedback control system using variable-structure model for the formation flying of satellites was designed to control a follower satellite for following a prescribed path with respect to the leader satellite. Bando et al. [1] designed L_1 suboptimal feedback controllers via the linear quadratic regulator theory to solve leader–follower formation and reconfiguration problems. In Ref. [35], adaptive tracking controls of relative position between two spacecrafts were presented, in which the uncertainties in the thrust alignments and gains, and the active spacecraft's mass are considered. Liu et al. [22] also developed a coordinated control scheme based on the leader–follower approach and sliding mode control to achieve formation maneuvers while keeping the internal formation intact.

In practical applications, flying safety requirements, such as relative distance keeping, collision avoidance, obstacle dodging and path constraints satisfying, etc., are the fundamental requirements for formation flying and the prerequisite for all the other tasks previously mentioned such as formation maintaining and reconstruction. The TanDEM task of Germany which uses helix conformation to guarantee the distance between satellites TerraSAR-X and TanDEM-X in the plane perpendicular to the orbital is never less than 200 m, such that flying safety is assured. Taur et al. [30] obtained minimum-fuel, impulsive, time-fixed solutions for the problem of orbital rendezvous, and they considered path constraints simultaneously. In Ref. [4], a schedule was presented for online generation of safe, fuel-optimized rendezvous trajectories. In addition, comparing with other methods like semi-definite programming [8] and model predictive control [28], artificial potential guidance (APG) is considered as one of the methods available to deal with safety issues, due to its clear physical meaning, sound theory, and effective solution, etc. In early time, APG was applied in robots systems [12,21,27] and then extended to spacecraft systems [23,24]. John-Olcayto et al. [16] considered the path constrains of spacecraft and developed a potential function guidance method to guarantee a secure autonomous spacecraft proximity. The problem of autonomous rendezvous and docking with a non-cooperative target is studied in Ref. [36], and a guidance-control method using potential function guidance and fuzzy logic was proposed to ensure safe approaching. In Ref. [6], velocity synchronization and collision avoidance were simultaneously achieved in nonlinear mechanical systems in the presence of communication delays and switching interconnection topologies. By combining artificial potentials and sliding mode control, Gazi et al. [9–11,34] presented stable and decentralized control strategies for multi-agent systems. The goals they achieved include leader tracking, collision avoidance, and formation maintaining. Pereira et al. [26] then extended this idea and proposed a formation control strategy for uncertain Euler–Lagrange mobile agents system.

Nevertheless, to the best of authors' knowledge, it should be noted that all of the above-mentioned results few considered the requirement of obstacle avoidance. Furthermore, the problem for combining obstacle avoidance with target tracking and formation maintaining simultaneously poses considerable complexity and difficulty in the spacecraft formation control system design, and it remains an open issue. Motivated by the above facts, the above multiple-task problem, including target tracking, obstacle avoidance, and formation keeping for applications with multi-spacecraft in formation flying, is to be tackled in this paper. Specifically, a nonlinear adaptive feedback control law combining APG in conjunction with sliding mode technique is proposed, novel special artificial potential functions and a kind of time-varying sliding manifold are adopted in the proposed control method. The control objective achieved enables spacecraft in formation flying being able to maintain a special configuration and take into account the requirement of obstacle avoidance while tracking a moving target in a cooperative way or non-cooperative way. Moreover, it is showed that by adoption of adaptive updating law, the rejection of disturbances and parametric uncertainties can also be achieved.

The paper is organized as follows: Section 2 states the mathematical model of spacecraft formation system and the potential functions used in this paper. The control method combining APG with sliding mode technique is designed in Section 3. Numerical simulations and 3D illustrations are presented in Section 4 to demonstrate various features and effectiveness of the proposed control methods. Finally, the paper is completed with some concluding comments.

2. Spacecraft modeling and potential functions

2.1. Relative orbital model for spacecraft in formation flying

The spacecraft is assumed to be a rigid body, and the reference orbital coordinate system is denoted by $\{X_r, Y_r, Z_r\}$, with its origin at the centroid of the reference spacecraft. The X_r axis is along to the local vertical, the Y_r axis is along to the local horizontal, and the Z_r axis can be obtained according to the right-hand rule. One issue needs to be pointed out is that the reference spacecraft is just a standard/reference used to describe the relative positions of the spacecraft in formation. In this paper, the reference spacecraft is not a real spacecraft, and it can be regarded as a "virtual spacecraft" running on the particular orbit. Noting that throughout the paper, except special explanation, every three-dimensional column vector can be written as the decomposition form $\boldsymbol{l}_{3\times 1} = [l_x \quad l_y \quad l_z]^{\mathrm{T}}$ to represent the component of each axis with respect to the reference orbital coordinate system.

Let $\boldsymbol{\rho}_i$ and $\boldsymbol{v}_i$ denote the position and the velocity of the i-th spacecraft in the formation with respect to the reference orbital coordinate system, respectively, then the relative motion of the i-th spacecraft can be described by [18]

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

$$m_i \dot{\boldsymbol{v}}_i = \boldsymbol{C}_i(\dot{\theta}_c)\boldsymbol{v}_i + \boldsymbol{D}_i(\dot{\theta}_c, \ddot{\theta}_c, r_c)\boldsymbol{\rho}_i + \boldsymbol{n}_i(r_i, r_c) + \boldsymbol{d}_i + \boldsymbol{f}_i \tag{2}$$

where

$$\boldsymbol{C}_i(\dot{\theta}_c) \triangleq 2m_i\dot{\theta}_c \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{D}_i(\dot{\theta}_c, \ddot{\theta}_c, r_i) \triangleq -m_i\frac{\mu}{r_i}\mathbf{I}_{3\times 3} + m_i \begin{bmatrix} \dot{\theta}_c^2 & \ddot{\theta}_c & 0 \\ -\ddot{\theta}_c & \dot{\theta}_c^2 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{n}_i(r_i, r_c) \triangleq \mu m_i \left[-\frac{r_c}{r_i^3} + \frac{1}{r_c^2} \quad 0 \quad 0 \right]^{\mathrm{T}},$$

and also θ_c is the true anomaly of the reference, $r_c = \|\boldsymbol{r}_c\|$ ($\|\bullet\|$ presents the Euclidean norm of vector throughout the paper) is the distance between the centroid of the reference and the Earth's center, μ is the gravitational constant of the Earth, m_i is the mass of the i-th spacecraft, $\boldsymbol{d}_i$ is the disturbance vector which includes some disturbances like J_2 perturbation and so on, $\boldsymbol{f}_i$ is the control force vector of the i-th spacecraft, $r_i = [(r_c + \rho_{ix})^2 + \rho_{iy}^2 + \rho_{iz}^2]^{1/2}$ is the distance between the centroid of the i-th spacecraft and the Earth's center, $i = 1, 2, \ldots, n$, where n is the total number of the spacecraft in formation. Note that the spacecraft relative orbital model introduced above has high accuracy and is adaptive to spacecraft in any eccentric orbits when the distance between the spacecraft and the reference is not very far.