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Adaptive collision-free formation control for under-actuated spacecraft ☆

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A R T I C L E I N F O

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A B S T R A C T

This paper proposes an adaptive collision-free formation control strategy for a team of under-actuated spacecraft subject to parametric uncertainties. The objective is to drive follower spacecraft to form a prescribed shape around a leader, while collision avoidance is achieved among different spacecraft. To explore the under-actuated nature of the studied spacecraft, a hierarchical inner-outer loop strategy is adopted. First, in the outer position loop, a virtual force is synthesized by introducing negative gradients of novel potential functions with respect to the distances between spacecraft such that the collision-free formation objective is completed. Based on the synthesized virtual force, an applied thrust and a command attitude are extracted. Then, in the inner attitude loop, an applied torque is designed for each individual spacecraft to track the command attitude. Moreover, during the virtual force and applied torque syntheses, adaptive laws are developed to estimate and compensate the uncertain inertial parameters. In terms of Lyapunov theory, it is shown that the spacecraft trajectories driven by the proposed controller ultimately converges to a neighborhood of the desired formation. Finally, illustrative simulations are performed to verify the proposed theoretical results.

1. Introduction

During the past few decades, spacecraft formation flying has been considered as an important technique in advanced space applications including earth observation, deep-space exploration and synthetic aperture. Different spacecraft formation projects have been proposed, including Techsat-21, GRACE and PRISMA [1]. To accomplish these formation missions, controllers should be designed to drive the spacecraft to the desired formation. However, spacecraft are of high nonlinearity and are often subject to internal uncertainty and external perturbation. Therefore, there are still challenges in the high-performance formation control problem for spacecraft among research community.

Various control approaches have been developed for spacecraft formation flying in the existing literatures. For example, sliding mode control strategies were implemented in [2–5] to solve the relative motion control problem for the spacecraft formation maneuvering. In [6–8], 6-dof (degree-of-freedom) spacecraft formation flying control schemes were designed in terms of a backstepping technique. Without angular velocity measurements, attitude consensus control schemes were proposed in [9,10] using output feedback strategies. Based on the consensus idea, decentralized protocols using local information exchange were studied in [11–15]. Different communication situations including directed communication topology, switching communication topology and communication delay were studied respectively. Moreover, integrated position and attitude control approaches were presented in [16–19] using dual quaternions in describing coupled relative motion. However, in the above references, the control algorithms are developed based on a basic assumption that the considered spacecraft are fully actuated, namely, the dof of the inputs is equal to, or larger than, the dof of the controlled states.

In recent years, much attention has been paid to under-actuated spacecraft from the perspective of fuel saving. For various under-actuated forms, a number of control approaches have been developed such that the formation objective is achieved. Godard et al. [20] investigated the feasibility of formation maintenance and reconfiguration of the under-actuated spacecraft without either the radial or the in-track thrust using a nonlinear controller. Huang et al. [21] derived analytical solutions for the optimal under-actuated spacecraft formation reconfiguration problem using indirect opti-

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mization methods with the minimum principle. Then, Huang et al. [22] further designed another fast nonsingular terminal sliding mode controllers to deal with the under-actuated spacecraft formation reconfiguration problem in the presence of unmatched disturbances. However, in [20–22], the spacecraft is modeled as a mass point and its attitude dynamics is not studied. In addition, by considering the under-actuated model with the coupled translation and rotation dynamics, Wu et al. [23,24] designed fuel optimal control schemes for the spacecraft formation flying, Zhang et al. [25] proposed a robust adaptive backstepping scheme to solve the space interception problem, and Haghighi and Pang [26] developed a concurrent attitude-position control strategy consisting of three sub-levels for the formation flying of under-actuated nanosatellites. Nonetheless, the control schemes in [23–26] do not take the collision avoidance issue into account. This may lead to the destructive failure of missions. Although the collision-free control approaches have been proposed in [27–30] for fully actuated spacecraft, they are not applicable to the under-actuated ones.

This paper develops an adaptive collision-free formation control scheme for under-actuated spacecraft subject to inertial parameter uncertainties. The controller structure is based on a hierarchical inner-outer framework. Specifically, a virtual force introducing potential functions and an applied torque are synthesized in sequence such that the collision-free formation and the tracking to the command attitude are achieved, where the command attitude, together with an applied thrust, is extracted from the synthesized virtual force. In addition, adaptive strategies are introduced in the control scheme to deal with the issue caused by uncertain inertial parameters. Compared with the previous works associated with the spacecraft formation control, the main contributions of this paper are listed as follows. First, instead of the study for fully-actuated spacecraft [2–19], we propose a formation control approach for more intricate under-actuated spacecraft. Second, in contrast with [20–26], the proposed control scheme introducing novel potential functions guarantees that there are no collisions among spacecraft during the transient process. Third, adaptive algorithms are developed to compensate the uncertainties of inertial parameters such that the formation accuracy is improved.

The remaining parts of this paper are organized as follows: Section 2 introduces the nonlinear motion models of under-actuated spacecraft. Section 3 presents the controller development and stability analysis. Simulation results are presented in Section 4, and Section 5 concludes the paper.

Notations. In what follows, $\mathbb{R}$ and $\mathbb{R}^n$ denote the real number and real vector of dimension n, superscript T denotes the transpose of a vector or a matrix, $\|\cdot\|$ denotes the Euclidean norm of a vector, $\otimes$ denotes the multiplicative operation of unit quaternion, I_n denotes an $n\times n$ identity matrix, $\mathcal{N}\triangleq\{1,2,\cdots,n\}$ and $\bar{\mathcal{N}}=\{0\}\cup\mathcal{N}$. In addition, we define $\mathbb{L}_2=\{f:\mathbb{R}^+\to\mathbb{R}^n|f$ is locally integrable, $\int_0^\infty\|f(t)\|^2\mathrm{d}t<\infty\}$ and $\mathbb{L}_\infty=\{f:\mathbb{R}^+\to\mathbb{R}^n|f$ is locally integrable, $\mathrm{ess\,sup}_{t\in\mathbf{R}^+}\|f(t)\|<\infty\}$.

2. Motion models of spacecraft

Suppose that there is a team of $n+1$ spacecraft consisting of a leader and n followers. The leader (labeled by 0) follows a desired orbit and followers (labeled by 1 to n) are supposed to maintain a desired formation with respect to the leader. In this section, the motion models of spacecraft are established. Firstly, three underlying coordinate frames are presented. Secondly, the relative orbit motions of the follower spacecraft with respect to the leader are given. Thirdly, the relative attitude motions of the follower spacecraft are modeled. Finally, the anti-collision formation of spacecraft is formally formulated.

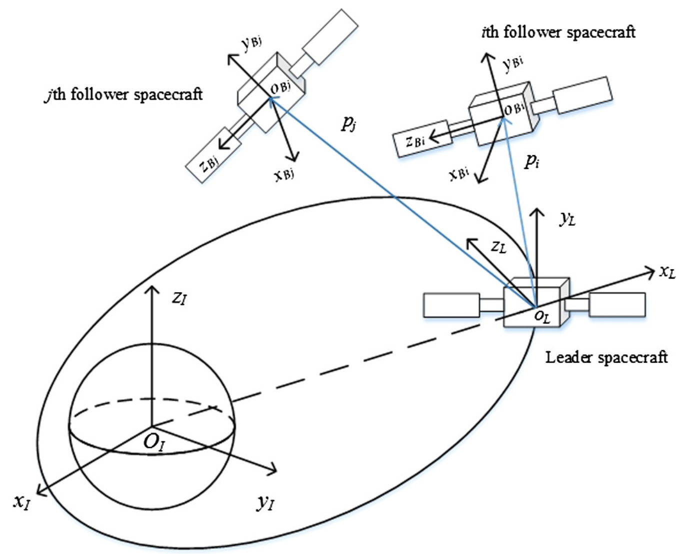

Fig. 1. Coordinate sketch.

2.1. Coordinate frames

Three coordinate frames are introduced to establish the motion models of spacecraft [31]. They are sketched in Fig. 1 and their definitions are given as follows.

Earth centered (EC) frame $\mathcal{F}_I=\{O_Ix_Iy_Iz_I\}$. This frame, considered also as the inertial frame, is attached to the earth, where origin O_I is the earth center, axis O_Ix_I points to the vernal equinox, axis O_Iz_I points to the north pole, and axis O_Iy_I is in the equatorial plane and complies with the right-hand rule.

Body centered (BC) frame $\mathcal{F}_{Bi}=\{O_{Bi}x_{Bi}y_{Bi}z_{Bi}\}$. This frame is attached to each spacecraft, where origin O_{Bi} is the spacecraft center, and three axes $O_{Bi}x_{Bi}$, $O_{Bi}y_{Bi}$ and $O_{Bi}z_{Bi}$ are along with the inertial principal axes of the spacecraft, respectively, where $i\in\bar{\mathcal{N}}$.

Local vertical local horizontal (LVLH) frame $\mathcal{F}_L=\{O_Lx_Ly_Lz_L\}$. This frame is attached to the leader spacecraft, where origin O_L is the leader center, O_Lx_L points from the earth center to O_L, axis O_Lz_L is perpendicular to the orbit plane, and axis O_Ly_L is in the orbit plane and complies with the right-hand rule.

2.2. Relative orbit motions of spacecraft

The n spacecraft are supposed to form and maintain a pattern with respect to a leader spacecraft. Suppose that the leader spacecraft moves along an elliptical orbit, which is determined by six elements: semi-major axis a_0, eccentricity e_0, orbit inclination i_0, argument of perigee ω_p, right ascension of ascending node Ω_0 and true anomaly f_0. To facilitate the analysis, the orbit motions of the follower spacecraft are described in the LVLH frame.

Define $\mathbf{p}_i=[x_i,y_i,z_i]^T$ as the position of the i-th follower spacecraft relative to the leader spacecraft in the LVLH frame. According to [32], the relative orbit motion equation is expressed as follows:

$$m_i\big(\ddot{\mathbf{p}}_\mathbf{i}+2\mathrm{S}(\dot{\theta}_0)\dot{\mathbf{p}}_\mathbf{i}+\mathrm{G}(\dot{\theta}_0,\ddot{\theta}_0,\mathbf{p}_\mathbf{i},r_0)\big)=R_E^LR_B^E\mathbf{u}_\mathbf{i}^\mathbf{b},\tag{1}$$

where $m_i\in\mathbb{R}$ denotes the spacecraft mass, $\mathbf{u}_\mathbf{i}^\mathbf{b}=T_ie_1$ with $e_1\triangleq[1,0,0]^T$ denotes the applied force in the i-th BC frame, representing that the force $T_i\in\mathbb{R}$ generated by the only thruster is along axis $O_{B_i}x_{B_i}$, matrix $\mathrm{S}(\dot{\theta}_0)$ and vector $\mathrm{G}(\dot{\theta}_0,\ddot{\theta}_0,\mathbf{p}_\mathbf{i},r_0)$ are defined as

$$\mathrm{S}(\dot{\theta}_0)=\begin{bmatrix}0&-\dot{\theta}_0&0\\\dot{\theta}_0&0&0\\0&0&0\end{bmatrix},\tag{2}$$

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