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Attitude tracking control for spacecraft formation with time-varying delays and switching topology

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ABSTRACT

This paper investigates attitude dynamic tracking control for spacecraft formation in the presence of unmeasurable velocity information with time-varying delays and switching topology. Based on an extended state observer, a nonlinear attitude tracking control approach is developed for spacecraft attitude model formulated by Euler–Lagrangian equations. The attitude tracking controller allows for external disturbances and absence of angular velocity information. Both auto-stable region techniques and a Lyapunov function approach are developed to prove ultimately bounded tracking. Simulation results demonstrate effectiveness of the nonlinear control techniques proposed in this paper.

1. Introduction

The past two decades have witnessed burgeoning interest in cooperative control for multi-agent systems because of potential advantages over a single body, including greater flexibility, adaptability and performance. The typical applications of cooperative control for multi-agent systems including wireless sensor networks [1], multi-manipulator collaborative assembly [2], satellite formation [3], multiple autonomous underwater vehicles [4], deep space exploration [5], and so on. In space industry, spacecraft formation flying is a concept of that multiple satellites cooperate in a group to accomplish a mission objective. Promising and on-going applications include meteorological/environmental observations, high resolution space interferometry, synthetic apertures, etc, [6,7]. With the rapid development of on-board autonomous orbit/attitude control technologies, it has become very feasible to replace a single large and costly spacecraft with a group of small and affordable spacecrafts while maintaining or improving operational efficiency and performance.

For attitude control of spacecraft formation, two types of uncertainties are paid attention widely. The first one is that external disturbances arises from unexpected environmental torques. The other one is that information and communication situations are embodied in time-varying delays and switching topology. Therefore, to explore the advanced control strategy which is suitable to characteristics of spacecrafts, an extended state observer (ESO) is introduced in spacecraft formation flying control with switching topology and time varying delays in this paper. The ESO is a key link for active disturbance rejection control which is firstly proposed by Jingqing Han [8]. It is taken off as an efficient technology in numerous successful engineering applications [9,10]. Unlike traditional linear or nonlinear observers, the ESO estimates uncertainties, unmodeled dynamics and external disturbances as an extended state of original systems [11,12]. Some problems on attitude tracking control for spacecraft formation have been investigated by ESOs, however, the constraints on switching topology have not considered both in [13] and [14].

For spacecraft formation, coordinated attitude control is a significant research topic for its application in both space-based interferometry and synthetic-aperture imaging. Attitude coordination control can be reduced to attitude tracking control for a single spacecraft by a leader-follower approach [15] or a reference projection method [16]. For instance, many results have been obtained on the attitude tracking control for spacecraft formation, such as [17,18] and the references therein. Usually, angular velocities have to be known and disturbance torques are assumed to be constants [19,20]. However, these requirements are not always satisfied with in reality [21]. In practice, networked individuals need to cooperate with each other to make a formation exhibit a harmonious behavior. Therefore, it is required intercommunication for sharing knowledge to make control decisions. During information exchanging, time delay inevitably exists in communication links and communication topology switch over time for

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the reason of the possible message dropouts in the communication channels or even failures of spacecrafts. Both time delays and switching topology degrade control performances of formation and even destabilize the entire system [22]. Consensus control for multi-agent systems with switching topology and time delay has been attracted great attentions [23,24]. However, to the best of our knowledge, very few results are available on Lagrangian formulated systems for attitude coordination control of spacecraft formation. In addition, model parameters of a spacecraft in formation can't be known exactly, and spacecrafts are always subject to external disturbances. Therefore, there are also a lot of space to be improved on realizing high attitude control performance, which motivates us to make an effort in this paper.

Notation: In the following, if not explicitly stated, matrices are assumed to have compatible dimensions. $\|\cdot\|$ is the Euclidean norm of a vector. $\mathbb{R}$:=$(-\infty, \infty)$, $\mathbb{R}_{>0}$:=$(0, \infty)$, $\mathbb{R}_{\geq 0}$:=$[0, \infty)$. $\mathbb{R}^n$ denotes the n-dimension Euclidean space. For any function $\boldsymbol{f}: \mathbb{R}_{\geq 0} \to \mathbb{R}^n$, the $\mathcal{L}_\infty$-norm is defined as $\|\boldsymbol{f}\| = \sup_{t\geq 0}|\boldsymbol{f}(t)|$, and the $\mathcal{L}_\infty$ space is defined as the set $\{\boldsymbol{f}: \mathbb{R}_{\geq 0} \to \mathbb{R}^n: \|\boldsymbol{f}\|_\infty < \infty\}$. $\lambda_{\min}\{\boldsymbol{A}\}$ and $\lambda_{\max}\{\boldsymbol{A}\}$ represent the minimum and maximum eigenvalues. $\otimes$ is the standard Kronecker product. $\boldsymbol{I}_N$ is the identity matrix with dimension N. $\mathbf{1}_N = (1, 1, \ldots 1)^T$ is the unit vector with N-dimension. For any vector $\boldsymbol{x} = [x_1, \ldots, x_N]^T$, define $[\boldsymbol{x}]^\gamma = [|x_1|^\gamma \mathrm{sign}(x_1), \ldots, |x_N|^\gamma \mathrm{sign}(x_N)]^T$. In addition, define $|\boldsymbol{x}|^\gamma = [|x_1|^\gamma, \ldots, |x_N|^\gamma]^T$. The notation $\boldsymbol{x} \to \boldsymbol{y}$ means that there exists a constant ε such that $\|\boldsymbol{x} - \boldsymbol{y}\| \leq \varepsilon$. The symmetric terms in a symmetric matrix are denoted by *.

2. Attitude dynamics of rigid spacecraft

In this paper, we consider a team of N networked spacecraft indexed by set $\ell = \{1, \ldots, N\}$. Suppose that in addition to the N spacecrafts, called followers hereafter, there exists a virtual leader labeled as spacecraft d. Note that the virtual leader acts as a command generator giving bounded time-varying reference to a small portion of networked spacecrafts [13,20]. The reference frames are shown in Fig. 1.

Using Euler rotational equations of motion, the following equation describes the angular velocity vector $\boldsymbol{\omega} \in \mathbb{R}^3$ of the spacecraft in its body axes

$$\boldsymbol{J}_{s/c}\dot{\boldsymbol{\omega}} - (\boldsymbol{J}_{s/c}\boldsymbol{\omega}) \times \boldsymbol{\omega} = \boldsymbol{u} + \boldsymbol{d}_{ext} \quad (1)$$

where the matrix $\boldsymbol{J}_{s/c} \in \mathbb{R}^3$ is the rotational inertia of the spacecraft, expressed in its body frame, and is symmetric positive definite. Besides, $\boldsymbol{u} \in \mathbb{R}^3$ and $\boldsymbol{d}_{ext} \in \mathbb{R}^3$, all expressed in the spacecraft body-fixed frame, denote the control input and the external disturbance torque, respectively. In practice, the spacecraft masses vary slowly in time due to fuel consumption and payload variations, and the disturbance forces also slowly vary in time because

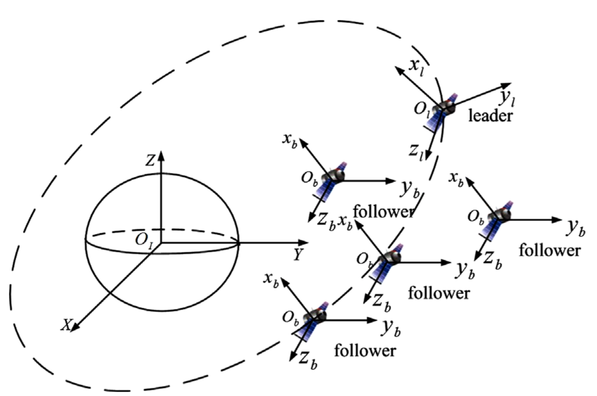

Fig. 1. Schematic representation of coordinate frame.

of solar radiation, aerodynamics and magnetic fields [15]. Therefore, the following reasonable assumptions are given out in this paper.

Assumption 1 (*Wang et al. [15]*). The change of $\boldsymbol{J}_{s/c}$ is negligible, i.e., $\dot{\boldsymbol{J}}_{s/c} = 0$.

Assumption 2 (*Wang et al. [15]*). The change of angular acceleration of spacecraft is small and bounded, i.e., 0.98,0.00,0.00 there exists a positive constant $\tilde{\delta}$ such that $\|\boldsymbol{\omega}^{(2)}\| < \tilde{\delta}$.

Assumption 3 (*Wang et al. [15]*). There exists a differentiable function $\boldsymbol{d}(t)$ which is the approximation of the slowly changed actual external disturbance torque $\boldsymbol{d}_{ext,i}$. Furthermore, the differential of $\boldsymbol{d}(t)$ is assumed to be bounded.

In this paper, the orientations of the rigid bodies with respect to the inertial frame will be described in terms of the Modified Rodriguez Parameters (MRPs) [25]. The MRP vector $\boldsymbol{q} \in \mathbb{R}^3$ is defined by

$$\boldsymbol{q} = \boldsymbol{e} \tan\frac{\theta}{4}, \theta \in (-2\pi, 2\pi)$$

where $\boldsymbol{e} \in \mathbb{R}^3$ is the Euler axis of rotation expressed in the body frame and θ is the rotation angle about $\boldsymbol{e}$. Then, the attitude of the ith spacecraft has the following relation

$$\dot{\boldsymbol{q}}_i = \boldsymbol{Z}(\boldsymbol{q}_i)\boldsymbol{\omega}_i \quad (2)$$

where $\boldsymbol{\omega}_i \in \mathbb{R}^3$ is the angular velocity for the ith spacecraft and

$$\boldsymbol{Z}(\boldsymbol{q}_i) = \frac{1}{2}\left[\boldsymbol{I}\left(\frac{1 - \boldsymbol{q}_i^T\boldsymbol{q}_i}{2}\right) + \boldsymbol{q}_i\boldsymbol{q}_i^T + \boldsymbol{S}(\boldsymbol{q}_i)\right]$$

Note that the skew-symmetric matrix function $\boldsymbol{S}(\boldsymbol{x})$ for an arbitrary $\boldsymbol{x} = [x_1, x_2, x_3]^T \in \mathbb{R}^3$ is defined as

$$\boldsymbol{S}(\boldsymbol{x}) = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}$$

By combining Eqs. (1) and (2), the following Lagrangian formulation of attitude dynamics is obtained with respect to the MRPs for the ith spacecraft ($i \in \ell$) [26]:

$$\boldsymbol{M}_i(\boldsymbol{q}_i)\ddot{\boldsymbol{q}}_i + \boldsymbol{C}_i(\boldsymbol{q}_i, \dot{\boldsymbol{q}}_i)\dot{\boldsymbol{q}}_i = \boldsymbol{\tau}_{u,i} + \boldsymbol{\tau}_{ext,i}, \ i \in \ell \quad (3)$$

where

$$\boldsymbol{\tau}_{u,i} = \boldsymbol{Z}^{-T}(\boldsymbol{q}_i)\boldsymbol{u}_i, \ \boldsymbol{\tau}_{ext,i} = \boldsymbol{Z}^{-T}(\boldsymbol{q}_i)\boldsymbol{d}_{ext,i}, \ \boldsymbol{M}_i(\boldsymbol{q}_i) = \boldsymbol{Z}^{-T}(\boldsymbol{q}_i)\boldsymbol{J}_{s/c,i}\boldsymbol{Z}^{-1}(\boldsymbol{q}_i)$$

$$\boldsymbol{C}_i(\boldsymbol{q}_i, \dot{\boldsymbol{q}}_i) = -\boldsymbol{Z}^{-T}(\boldsymbol{q}_i)\boldsymbol{J}_{s/c,i}\boldsymbol{Z}^{-1}(\boldsymbol{q}_i)\dot{\boldsymbol{Z}}(\boldsymbol{q}_i)\boldsymbol{Z}^{-1}(\boldsymbol{q}_i) - \boldsymbol{Z}^{-T}(\boldsymbol{q}_i)\boldsymbol{S}(\boldsymbol{J}_{s/c,i}\boldsymbol{Z}^{-1}(\boldsymbol{q}_i)\dot{\boldsymbol{q}}_i) \boldsymbol{Z}^{-1}(\boldsymbol{q}_i)$$

Some fundamental properties of Euler Lagrangian system (3) are given as follows.

Property 1 (*Min et al. [20]*). *The inertial matrix $\boldsymbol{M}_i(\boldsymbol{q}_i)$ is lower and upper bounded, i.e.,*

$$0 < \lambda_{\min}\{\boldsymbol{M}_i(\boldsymbol{q}_i)\}\boldsymbol{I} \leq \boldsymbol{M}_i(\boldsymbol{q}_i) \leq \lambda_{\max}\{\boldsymbol{M}_i(\boldsymbol{q}_i)\}\boldsymbol{I} < \infty$$

Property 2 (*Min et al. [20]*). *The matrix $\dot{\boldsymbol{M}}_i(\boldsymbol{q}_i) - 2\boldsymbol{C}_i(\boldsymbol{q}_i, \dot{\boldsymbol{q}}_i)$ is skew symmetric. That is, we have $\boldsymbol{r}^T(\dot{\boldsymbol{M}}_i(\boldsymbol{q}_i) - 2\boldsymbol{C}_i(\boldsymbol{q}_i, \dot{\boldsymbol{q}}_i))\boldsymbol{r} = 0$ for a given vector $\boldsymbol{r} \in \mathbb{R}^3$.*

Property 3 (*Min et al. [20]*). *For all $\boldsymbol{q}_i \in \mathbb{R}^n$, there exists $k_{c_i} \in \mathbb{R}_{>0}$: $|\boldsymbol{C}_i(\boldsymbol{q}_i, \dot{\boldsymbol{q}}_i)\dot{\boldsymbol{q}}_i| \leq k_{c_i}|\dot{\boldsymbol{q}}_i|^2$.*

3. Communication topology

In this paper, a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is used to describe the