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Fault-tolerant adaptive finite-time attitude synchronization and tracking control for multi-spacecraft formation

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A B S T R A C T

This paper addresses the attitude synchronization and tracking control (ASTC) for multi-spacecraft formation system (MFS) under undirected and directed graph. First, a new adaptive nonsingular fast terminal sliding mode surface (ANFTSMS) is developed. It has both the merits of the NFTSM avoiding singularity and the adaptive method regulating the relative weighting of parameters. This provides designers a new way to improve the control performance. Second, by applying ANFTSMS, the proposed ANFTSM-controllers (ANFTSMCs) provide high precision finite-time convergence, robust to time-varying disturbances, uncertainties and accommodate to actuator faults, limited inputs. Moreover, the ANFTSMCs also achieve simple structure, inexpensive computations and chattering-free for continuous design. Few studies have addressed these problems simultaneously. Finally, effectiveness of the algorithms are verified via simulations.

1. Introduction

Benefiting a variety of aerospace applications, such as satellite surveillance, space-based interferometry, pointing control [1], virtual co-observing, distributed aperture radar, stereo-imaging platforms for space science [2], ASTC has been vastly investigated which considers the synergic relations of multi-spacecraft and regards the MFS as one object to study so as to achieve the control objectives rapidly, flexibility, and reliability.

Recently, several control techniques are used to solve the ASTC problem [1–16]. In these algorithms, the sliding mode control (SMC) is an effective tool to deal with disturbances and uncertainties for nonlinear systems [3] and, the research issues have evolved from asymptotic convergence to finite-time convergence. By applying the rotation matrix and considering uncertainties and disturbances, Zheng et al. designed decentralized controllers through introducing an error variable and extended the results to time-varying communication delay case, moreover he studied the autonomous attitude coordination with input saturation [4,5]. Du et al. investigated flexible-MFS by using backstopping and neighbor-based approaches [6], then he pursued research on mixed-MFS which consists of rigid and flexible spacecraft models via an observer [7]. Liang et al. designed coordinated control laws by using behavior-based approach [8]. Asymptotical reachability of a given desired trajectory could be guaranteed by these controllers. Some solutions in the full state information case can be found in, e.g., [9,10], and references therein. Precise measurements of angular velocity are not always available due to budget limitations or implementation constraints [2]. There are studies devoted to velocity-free cases, for instance, Abdelkader et al. proposed a virtual systems-based approach which removes the requirement of angular velocity measurements and then proposed an attitude synchronization scheme to solve the leaderless problem under directed information flow [11]. Cheng et al. proposed a distributed finite-time observer to estimate the leader's attitude and then proposed a bounded finite-time controller to track the estimated attitude [12]. By applying lead filter so that the angular velocity is replaced with the filtered output, Lv et al. designed an asymptotically stable decentralized output feedback control scheme [13]. Several velocity-free investigations can be found in [14].

Finite-time control offers fast convergence and high-precision performance such that it attracted much attention more recently. However, the conventional finite-time SMC has singularity problems. Zhou et al. proposed an estimator-base nonsingular finite-time synchronization scheme [15], by using estimator to estimate the leader information. In [16], combining with the nonsingular terminal SMC and conventional one, Lu et al. proposed a sort of NFTSM surface (NFTSMS) with the feature of fast convergence and avoiding singularity. In [17], Wu proposed a type of robust adaptive synchronization control under directed information flow. Based on the investigations of Lu and Wu, Xia et al. [18] and Zhou

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et al. [3] applied the NFTSMS to ASTC and made several achievements, that they studied the finite-time ASTC under undirected and directed information flow case, respectively. By using the NFTSM and neutral network approximation, Zhao et al. designed finite-time controllers independent from the precise knowledge of inertia matrix [19], the adaptive finite-time bipartite consensus tracking control [20], and also investigated the time-varying terminal SMC which both eliminates the reaching phase and avoided singularity [21]. Hu et al. also used a time-varying SMC to do the investigation [22]. Nevertheless, problems still need to be investigated in depth for the reason that in practical applications, such as in unidirectional satellite laser communication system [3], the information flow among the spacecraft may be directed. And also that the actual system have saturation constraints and actuators may suffer unexpected fading or even completely failure. Failure of any member in the MFS, not only affects its own functionality, but also affects other members'. Without fault tolerance capability, an unforeseen occurrence of actuator faults could fail the space mission [23,24], fault tolerant control is a widely used technique to accommodate or manage component failures [25,26]. Thus, the ASTC for MFS with fault tolerant capability needs to be taken seriously. Recently, many new fault-tolerant studies have emerged such as [27,28]. Nevertheless, the amount of researches under the MFS attitude synchronization conditions is still insufficient. In [17], Wu et al. considered a directed information flow case but couldn't guarantee finite-time convergence. Then, based on the prior work of Wu, Zhou and Xia designed finite-time control schemes by using NFTSM to settle the singularity problem under undirected and directed information flow respectively [18,3], but haven't considered actuators unhealthy conditions. Moreover, equivalent control consumes much computation caused by the complex nonlinear terms. On this issue, Cai et al. proposed nonregressor-based approach owning a feature of reducing the usage of onboard resources in terms of computing power and memory size [29], which overcome the shortcomings of regressor-based adaptive control structurally complicated and computationally expensive leading to unfavorable for real-time implementation [30], and in [31], Xiao et al. use this ideology to design controller with fault-tolerant capability.

This paper presents fault tolerant control schemes for ASTC of MFS with multiple constraints and the contributions are summarized as follows:

1) The ANFTSMS can regulate relative weighting between angular velocity error and attitude error adaptively with parameters a_i, b_i used to adjust the tracking and synchronization behaviors, and the requirement of b_i is relaxed from $b_i > 0$ to $b_i \geq 0$ compared with [3,18].
2) The ANFTSMCs are designed for undirected and directed cases respectively, and provide finite-time convergence with disturbances, uncertainties, actuator faults, input saturations and achieve low-cost computations, simple structures, chattering free for continuous design simultaneously, with few prior info requirements of uncertainties, faults etc. thus the design process is user-friendly.

The rest is organized as: Section 2 states system model, problem formulation and preliminaries. In Section 3, the ANFTSMS is proposed to design robust and fault tolerant controllers achieving ASTC in finite-time, accompanied by system stability proofs. Numerical simulations are provided in Section 4. Finally, conclusion is drawn in Section 5.

2. Mathematical model and problem formulation

2.1. Notions

To reduce repeated explanation, unless otherwise indicated, $i = 1, \ldots, n$ denote the serial number of each spacecraft in the n-element MFS. R^n and $R^{n\times m}$ represent the Euclidean space with corresponding dimension and $\|\cdot\|$ represents the Euclidean norm of vectors and the induced norm. A given vector $x \in R^{3\times 1}$ is defined as $x = [x_1, x_2, x_3]^T$ and $x^r \triangleq [x_1^r, x_2^r, x_3^r]^T$. The derivation of x^r is given by $(x^r)' \triangleq r \cdot diag(x_1^{r-1}, x_2^{r-1}, x_3^{r-1})[\dot{x}_1, \dot{x}_2, \dot{x}_3]^T$. The maximum and minimum eigenvalue of a matrix is denoted as $\lambda_{\max}(\cdot)$ and $\lambda_{\min}(\cdot)$. $x^\times$ is a skew-symmetric matrix of $x \in R^{3\times 1}$ in the form of

$$x^\times = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}.$$

2.2. Mathematical system model

2.2.1. Spacecraft attitude dynamics and kinematics

Assume each spacecraft in MFS is rigid with three reaction flywheels (or actuators) on the perpendicular axis respectively to provide control torque. The attitude dynamics and kinematics of the ith spacecraft are given in chapter 4 of [32]

$$J_i\dot{\omega}_i = -\omega_i^\times J_i\omega_i + u_i + d_i \tag{1}$$

$$\dot{q}_i = \frac{1}{2}(q_i^\times + q_{0,i}I_3)\omega_i, \qquad \dot{q}_{0,i} = -\frac{1}{2}q_i^T\omega_i, \quad i = 1, \ldots, n \tag{2}$$

where $J_i \in R^{3\times 3}$ is a symmetric positive definite matrix denoting the inertia matrix with respect to its body-fixed frame $(\mathcal{B})$. $\omega_i \in R^3$ represents the angular velocity with respects to an inertia coordinate system $(\mathcal{I})$. $u_i \in R^3$ denotes the control torque. $I \in R^{3\times 3}$ is the identity matrix. $d_i \in R^3$ represents the external disturbances. $(q_i \in R^3,\ q_{i,0} \in R)$ denotes the unit quaternion which is used to describe the orientation of $\mathcal{B}$ with respect to $\mathcal{I}$, and is expressed in $\mathcal{B}$. In addition, the constraint $q_i^Tq_i + q_{0,i}^2 = 1$ exists according to the unit quaternion operational laws.

Assumption 1. Denote $J_i = \bar{J}_i + \Delta J_i$ where $\bar{J}_i$ and ΔJ_i are the nominal portion and time-varying uncertain portion (caused by, such as fuel burning, payload loading or releasing etc. [30]) of the inertia matrix respectively. $\|\Delta J_i\|$ and $\|d\Delta J_i/dt\|$ are practically assumed to be bounded.

Assumption 2. [29] External disturbance d_i caused by gravitation, solar radiation, magnetic forces (all could be assumed bounded), and aerodynamic drags (proportional to the square of angular velocity) is assumed to be bounded with satisfying $\|d_i\| \leq c_1 + c_2\|\omega\|^2$ where $c_1 \geq 0$ and $c_2 \geq 0$ are unknown constants.

Assumption 3. $\|\omega_i^d\|$ and $\|\dot{\omega}_i^d\|$ are bounded.

2.2.2. Error dynamics and kinematics

Denoting the desired attitude as $(q_i^d, q_{0,i}^d)$ which signifies a target frame $(\mathcal{D})$ with respect to $\mathcal{I}$ then, the error quaternion $(\tilde{q}_i, \tilde{q}_{0,i})$ is given by the unit quaternion operational laws [33]

$$\tilde{q}_i = q_{0,i}^d q_i - \left(q_i^d\right)^\times q_i - q_{0,i}q_i^d \tag{3}$$

$$\tilde{q}_{0,i} = \left(q_i^d\right)^T q_i + q_{0,i}^d q_{0,i} \tag{4}$$