Information Sciences 328 (2016) 144–157

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Distributed finite-time attitude regulation for multiple rigid spacecraft via bounded control

Yingying Cheng[a], Haibo Du[a,*], Yigang He[a], Ruting Jia[b]

[a] School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, Anhui 230009, China
[b] Department of Electrical and Computer Engineering, California State University at Northridge, Northridge, CA 91330, USA

ARTICLE INFO

Article history:
Received 16 October 2014
Revised 25 July 2015
Accepted 5 August 2015
Available online 28 August 2015

Keywords:
Spacecraft
Attitude control
Finite-time control
Distributed control

ABSTRACT

The problem of finite-time attitude regulation for multiple rigid spacecraft with leader–follower architecture is studied. The desired attitude for spacecraft formation is represented by the attitude of a leader. A distributed finite-time convergent observer is first proposed to estimate the leader's attitude in a finite time. By using the technique of finite-time saturation control, a bounded finite-time attitude controller is designed to track the estimated attitude and then the leader's attitude in a finite time. A simulation example is finally given.

1. Introduction

Recently, the problem of distributed attitude control has attracted a great deal of attention. The interest is motivated by its many applications, such as formation flying, satellite surveillance, etc [20,28,36,41,49]. The advantages of distributed control strategy lie in its greater efficiency, higher robustness, and reduced communication requirement [12,17,30]. For these reasons, the distributed control has been applied in many areas, e.g., formation control of underwater vehicles [26], decentralized control of stochastic nonlinear large-scale systems [44], network synchronization [4,37], etc. Nevertheless, it is well-known that the attitude dynamics of spacecraft are coupled and highly non-linear [21], which means that the distributed control of multiple spacecraft is more challenging than that of linear multi-agent systems. To this end, there have been some reports about the distributed control for multiple spacecraft in the literature.

In order to achieve attitude synchronization, the work [18] proposed two distributed control laws that require the communication topology to take on the form of a ring graph. The work [29] demonstrated that this ring topology can be extended to more general cases. In the case that the angular velocity is unavailable, the corresponding attitude synchronization control algorithms via output feedback were proposed in [1,18,45]. When there is a single leader or multiple leaders, the problem of distributed attitude tracking control was discussed in [5,31,38]. In [39], based on the adaptive sliding mode control, two decentralized attitude control laws were proposed to address inertia uncertainties and environmental disturbances. In [24], the distributed cooperative controllers with and without angular velocity feedback were designed for spacecraft formation flying missions.

Note that the previously listed distributed attitude control laws are asymptotically stable control laws, which only guarantee that the attitude synchronization is achieved asymptotically with infinite settling time. In order to increase the convergent rate of closed-loop systems, the technique of finite-time control has been recently developed, which can guarantee that the systems'

* Corresponding author. Tel.: +86 18256956759.
E-mail address: haibo.du@hfut.edu.cn (H. Du).

http://dx.doi.org/10.1016/j.ins.2015.08.042
0020-0255/

states converge to equilibrium within a finite time [3]. The finite-time control of dynamic systems is of interest due to its faster convergence rate, and better robustness and disturbance rejection properties [3,43]. Because of these advantages, the finite-time attitude control problems for single spacecraft have been extensively discussed in [6,14,19,47,48] and for multiple spacecraft in [8,25,46,49]. In [8,46], the problem of distributed finite-time attitude tracking control for a group of spacecraft with single leader was investigated. The work [25] considered the case of multiple leaders. In [49], the terminal sliding mode control method was employed to design a finite-time attitude cooperative control law. Nevertheless, it should be pointed out that actuator saturation is not explicitly taken into account in these proposed distributed finite-time attitude control laws [8,25]. From the viewpoint of practical application, saturation nonlinearity will definitely have an important influence on system performance. To this end, in [23], a distributed finite-time control law was designed under input constraints, which requires the precise information of the inertia matrix. Based on a fast terminal sliding mode and Chebyshev neural network, the work [22] proposed a distributed finite-time control law which only guarantees that the tracking error converges to a small region in a finite time. In [13], based on a finite-time convergent observer, a bounded finite-time coordinated attitude control law via output feedback was designed. However, the results are about semi-global.

To solve the problem of distributed finite-time attitude control for a group of spacecraft under input saturation, an observer-based distributed control strategy is employed in the present study. First, a distributed finite-time observer is designed to estimate the leader's attitude in a finite time by imposing certain assumptions. Then, the distributed finite-time attitude control problem for multiple spacecraft is transformed to a finite-time attitude control problem for a single spacecraft. In order to satisfy the requirement of control saturation in practice, the physical structural features of the attitude control system were fully exploited, and a Lyapunov function was constructed and a bounded finite-time attitude controller was designed. Under the proposed controller, based on homogeneous systems theory, it is shown that the leader's attitude can be tracked in a finite time. Hence, the problem of distributed finite-time attitude control of multiple spacecraft via bounded control is solved. In addition, given that the physical structural features of the attitude control system are fully exploited, the proposed finite-time control law does not need the precise information of the inertia matrix. Thus, it is easy to tune the control gains by satisfying the actuation bound in practice.

2. Preliminaries and problem formulation

2.1. Kinematics and dynamics of spacecraft attitude

Without loss of generality, n rigid spacecraft will be considered in the present study. Let $\Gamma = \{1, \ldots, n\}$. Modified Rodrigues Parameters (MRPs) were used to describe the orientation of i-th spacecraft with respect to the inertial frame [15,32]. For i-th spacecraft, $\sigma_i = \eta_i \tan(\phi_i/4) \in R^3, -2\pi < \phi_i < 2\pi$, represent the MRPs, and η_i, ϕ_i represent the Euler axis and the Euler angle. Given a vector $v = [v_1, v_2, v_3]^T$, the symbol $(\cdot)^\times$ denotes a 3×3 skew-symmetric matrix, which is defined by $v^\times = [0, -v_3, v_2; v_3, 0, -v_1; -v_2, v_1, 0]$.

Based on the MRPs, the dynamics of spacecraft is presented as that in [32]:

$$\dot{\sigma}_i = G(\sigma_i)\omega_i, \; J_i\dot{\omega}_i = -\omega_i^\times J_i\omega_i + \tau_i, \tag{1}$$

where $\omega_i \in R^3$ is the angular velocity , $J_i \in R^{3\times 3}$ and $\tau_i \in R^3$ are, respectively, the positive definite inertia matrix, and the control torque of spacecraft. In addition, the matrix $G(\sigma_i)$ is defined by $G(\sigma_i) = \frac{1}{2}[(\frac{1-\sigma_i^T\sigma_i}{2})I_3 + \sigma_i^\times + \sigma_i\sigma_i^T]$, which has the following property [34]:

$$\begin{aligned} \sigma_i^T G(\sigma_i)\omega_i &= \left(\frac{1+\sigma_i^T\sigma_i}{4}\right)\sigma_i^T\omega_i, \\ G(\sigma_i)G^T(\sigma_i) &= \left(\frac{1+\sigma_i^T\sigma_i}{4}\right)^2 I_3. \end{aligned} \tag{2}$$

Remark 1. Note that the attitude description based on MRPs has a geometric singularity when ϕ_i approaches $\pm 2\pi$. As in [35], the stability analysis of this paper refers to the attitude system described by Modified Rodrigues Parameters. Thus, it means that the basin of attraction of the proposed control law is for all initial attitudes except for the singular point.

2.2. Control objective

The goal of this paper is to design a bounded distributed finite-time attitude control law for a group of spacecraft such that all the attitudes can reach synchronization in a finite time and the final attitude is the desired constant attitude. This problem is called the distributed finite-time attitude regulation problem under the constraint condition that the control torque is required to be bounded. Motivated by [11], the definition of thefinite-time regulation problem is extended from the case of single agent to multiple agents.

Definition 1. (**Distributed finite-time attitude regulation problem.**) Given a desired constant attitude $\sigma^d \in R^3$, find an attitude control law that is based on the local state information from itself and its neighbors, such that all the attitudes of system (1) can