Neurocomputing 171 (2016) 230–241

Contents lists available at ScienceDirect

Neurocomputing

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

Neural network-based distributed adaptive attitude synchronization control of spacecraft formation under modified fast terminal sliding mode

Lin Zhao [a,*], Yingmin Jia [a,b]

[a] The Seventh Research Division, Beihang University (BUAA), Beijing 100191, PR China
[b] State Key Laboratory of Robotics and System (HIT), Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 2 September 2014
Received in revised form
16 June 2015
Accepted 20 June 2015
Communicated by Long Cheng
Available online 10 July 2015

Keywords:
Spacecraft formation flying (SFF)
Attitude synchronization
Terminal sliding mode (TSM)
Neural network (NN)
Input constraint

ABSTRACT

This paper investigates the distributed attitude synchronization control of spacecraft formation flying (SFF) in the presence of unknown external disturbances. A novel multi-spacecraft modified fast terminal sliding mode (MFTSM) is designed, which not only avoids the singularity problem, but also contains the advantages of fast terminal sliding mode (FTSM). Based on the MFTSM and neutral network (NN) approximation techniques, a distributed MFTSM control law with adaptive tuning law is proposed. Moreover, a distributed MFTSM control law considering input constraint is also given. Both the two control laws can guarantee the attitude tracking errors that converge to the regions containing the origin in finite time and are independent on the precise knowledge of inertia matrix. Simulation results are presented to demonstrate the effectiveness of designed schemes.

Introduction

Spacecraft formation flying (SFF) is a promising concept to replace a large spacecraft with a group of smaller, less-expensive, and cooperative spacecrafts. Precise formation of spacecraft makes possible applications such as large-scale distributed sensing (radar, interferometry, and imaging). Recently, various approaches have been proposed for the spacecraft formation control. For example, a leader–follower approach was developed for attitude synchronization in [1], which results in a centralized control law. Centralized and decentralized implementation of a virtual structure coordination strategy was developed for attitude synchronization in [2] and [3], respectively. In [4], a behavioral approach was used for attitude synchronization. Graph-theoretical approach has been actively studied for cooperative control of a multi-agent system using limited local interaction [10–15] and it has been investigated for attitude synchronization problems in [5–9].

In practical formation flying, various uncertainties are acting on the spacecraft due to imprecise measurements and external disturbances. The neural network (NN) has been used in the robust control of nonlinear uncertain multi-agent systems [16–21], due to its learning and adaptive abilities, such as the NN-based adaptive approach was proposed in [17] for the leader–following control of multiagent systems; the NN was used in [18] at each node to approximate the distributed dynamics for a group of Lagrangian vehicle systems. Recently, the NN-based distributed attitude coordination control for a group of spacecrafts with input saturation was investigated in [21] for SFF, however, the proposed attitude coordination control laws are asymptotically stable control laws.

The significant requirement in spacecraft formation synchronization control is a high convergence rate, and the control laws with finite-time convergence are more desirable. Several kinds of finite-time coordination protocols have been developed for first-order and second-order multi-agent formation systems [22–25]. Recently, the finite-time control techniques have been applied to study the spacecraft formation synchronization control, such as a distributed finite-time attitude control law was proposed for a group of spacecraft with a leader–follower architecture [31], the quaternion-based finite time attitude synchronization and stabilization problem for satellite formation flying was investigated in [32]. Inertia matrix uncertainty is not considered in [31,32]. Terminal sliding mode control (TSMC) [26] is considered to be an effectiveness finite-time control scheme, especially for systems with uncertainty and external disturbance [29]. The initial TSMC has two disadvantages [30]. The first is the singularity problem, and the second is that it has slower convergence to the equilibrium than the traditional linear sliding mode control (LSMC)

* Corresponding author.
E-mail addresses: zhaolin1585@163.com (L. Zhao), ymjia@buaa.edu.cn (Y. Jia).

http://dx.doi.org/10.1016/j.neucom.2015.06.063
0925-2312/

when the system state is far away from the equilibrium. A nonsingular TSMC was proposed in [27] to eliminate the first problem, and the fast TSMC (FTSMC) was proposed in [28] to eliminate the second problem. Based on TSMC, the robust decentralized attitude control problem was studied in [33] for spacecraft formations under model uncertainties and disturbances. The distributed attitude coordination control schemes using a fast terminal sliding mode (FTSM) are proposed in [34,35] for a group of spacecraft in the presence of external disturbances. However, all of the works in [31–35] give the control laws dependent on the precise knowledge of inertia matrix, in practical spacecraft systems, the inertia matrix may particularly time-varying and uncertain. Moreover, in [35], the control signals are required to be available for exchange among neighbor spacecrafts, which not only increases the communication flow among neighbor agents but also yields an algebraic loop problem. In [34], the undirected communication topology is considered, which can eliminate the assumption that control signals are available for exchange among neighbor agents. However, cooperative control for attitude synchronization under directed communication topology is more challenging. At last, the above literatures do not consider the case where spacecrafts in formation are subject to input constraint. In almost every physical application, the actuator has bound on its input, and thus control saturation limit is important to study [21,36,37].

Motivated by the above discussions, in this paper, we will further consider a more interesting attitude synchronization problem for SFF in the presence of unknown inertia matrices and external disturbances. The main contributions are stated as follows:

(1) Our analysis is based on a kind of directed graph, which is more challenging than the undirected communication topology.
(2) A novel multi-spacecraft modified fast terminal sliding mode (MFTSM) is designed, which not only avoids the singularity problem, but also contains the advantages of fast terminal sliding mode (FTSM).
(3) Based on the MFTSM and neutral network (NN) approximation techniques, a distributed MFTSM control law with adaptive tuning law is proposed, which can guarantee the attitude tracking errors converge to the regions containing the origin in finite time. Moreover, the control law for each spacecraft does not require any information about inertia matrix, external disturbance torque. At last, the control signals are not required to be available for exchange among neighbor spacecrafts.
(4) The distributed MFTSM control law considering input constraint is further proposed, which can also guarantee the attitude tracking errors converge to the regions containing the origin in finite time.

The rest of the paper is organized as follows. In Section 1, the attitude dynamics, graph theory and some useful lemmas are presented, and system descriptions along with necessary assumptions are given. The main results are presented in Section 2. Simulation results and conclusion are given in Sections 3 and 4, respectively.

Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote the n-dimensional and the $n\times m$-dimensional Euclidean spaces, respectively; I denotes the identity matrix with appropriate dimensions; $X<0$ represents that X is the symmetric negative definite matrix; the superscripts T and -1 stand for matrix transposition and matrix inverse, respectively; $|\cdot|$ refers to the absolute value, $\|\cdot\|$ refers to the Euclidean vector norm or the induced matrix 2-norm, $\|\cdot\|_\infty$ refers to the vector ∞-norm or the induced matrix ∞-norm and $\|\cdot\|_F$ refers to the Frobenius matrix norm; $\otimes$ denotes the Kronecker product; $\mathrm{sig}^r(\cdot)=\mathrm{sgn}(\cdot)|\cdot|^r$, $\mathrm{sgn}(\cdot)$ and $\tanh(\cdot)$ are the sign, and standard hyperbolic tangent functions, respectively.

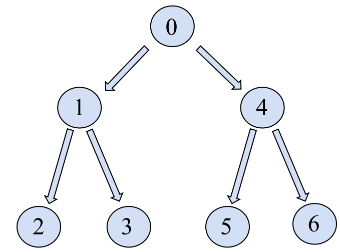

Fig. 1. The interaction topology of SFF.

Table 1
Numerical simulation parameters.

Initial attitude	$q_1(0)=[0.1,0.6,0.7]^T,\ q_2(0)=[-0.2,0.8,0.5]^T$
	$q_3(0)=[0.2,0.8,-0.3]^T,\ q_4(0)=[-0.3,-0.9,0.3]^T$
	$q_5(0)=[0.25,0.5,0.3]^T,\ q_6(0)=[-0.4,0.75,0.6]^T$
Initial angular velocity	$\omega_i(0)=[0,0,0]^T,\ i=1,\dots,6$
Desired trajectory [34]	$q_d=0.2[\cos(0.2t),\ \sin(0.2t),\sqrt{3}]$
External disturbance	$d_i=0.01[\sin(it),\ \cos(it),\sin(2it)]^T,\ i=1,\dots,6$
MFTSM	$\sigma_{i1}=2,\ \sigma_{i2}=2,\ i=1,\dots,6$
	$r=3/5,\ r_1=6/5,\ \phi=0.5$

1. Attitude dynamics and mathematical preliminaries

1.1. Spacecraft attitude dynamics

The individual spacecraft in the formation is modeled as rigid bodies. The equations of motions for the ith spacecraft in the formation are described as follows [34]:

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

$$\dot{q}_i=T_i(q_i)\omega_i,\quad i=1,\dots,n \tag{2}$$

where n is the total number of the spacecraft in the formation, $J_i\in\mathbb{R}^{3\times3}$ is the symmetric inertia matrix of the i-th spacecraft, $u_i\in\mathbb{R}^3$ is the control torque and $d_i\in\mathbb{R}^3$ is the unknown external disturbance torque, $\omega_i=[\omega_{i1},\omega_{i2},\omega_{i3}]^T\in\mathbb{R}^3$ is the angular velocity of the ith spacecraft system, $q_i\in\mathbb{R}^3$ represents the modified Rodrigues parameters (MRPs) of the ith spacecraft in the formation describing the spacecraft attitude with respect to an inertial frame, defined by

$$q_i(t)=\rho_i\tan\left(\frac{\epsilon_i(t)}{4}\right),\quad \epsilon_i(t)\in[0,2\pi)\ \mathrm{rad} \tag{3}$$

where ρ_i and ϵ_i denoting the Eular eigenaxis and eigenangle, respectively. The notation $a^\times$ for a vector $a=[a_1,a_2,a_3]^T\in\mathbb{R}^3$ is used to denote the skew-symmetric matrix, that is $a^\times=[0,-a_3,a_2;a_3,0,-a_1;-a_2,a_1,0]$. The Jacobian matrix $T_i(q_i)\in\mathbb{R}^{3\times3}$ for the MRPs is given by [38]

$$T_i(q_i)=\frac{1}{2}\left(\frac{I-q_i^Tq_i}{2}I+q_i^\times+q_iq_i^T\right),\quad T_i(q_i)^TT_i(q_i)=\left(\frac{1+q_i^Tq_i}{4}\right)^2I \tag{4}$$

Remark 1. It should be noted that if $q_i\to0$, the orientation has returned back to the origin. As a complete revolution is performed (i.e., $\epsilon_i\to 360^\circ$), this particular MRPs set goes singular. As shown in [38], it is possible to map the original MRPs vector q_i to its corresponding shadow counterpart $q_i^s=-\frac{q_i}{q_i^Tq_i}$. By choosing to switch the MRPs when $q_i^Tq_i>1$, the MRPs vector remains