Chinese Journal of Aeronautics, (2015),28(2): 527–534

Chinese Society of Aeronautics and Astronautics & Beihang University
Chinese Journal of Aeronautics

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Attitude coordination for spacecraft formation with multiple communication delays

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Received 11 April 2014; revised 17 July 2014; accepted 28 September 2014
Available online 23 February 2015

KEYWORDS

Attitude coordination;
Backstepping;
Delay control systems;
Formation;
Lyapunov–Krasovskii

Abstract Communication delays are inherently present in information exchange between spacecraft and have an effect on the control performance of spacecraft formation. In this work, attitude coordination control of spacecraft formation is addressed, which is in the presence of multiple communication delays between spacecraft. Virtual system-based approach is utilized in case that a constant reference attitude is available to only a part of the spacecraft. The feedback from the virtual systems to the spacecraft formation is introduced to maintain the formation. Using backstepping control method, input torque of each spacecraft is designed such that the attitude of each spacecraft converges asymptotically to the states of its corresponding virtual system. Furthermore, the backstepping technique and the Lyapunov–Krasovskii method contribute to the control law design when the reference attitude is time-varying and can be obtained by each spacecraft. Finally, effectiveness of the proposed methodology is illustrated by the numerical simulations of a spacecraft formation.

1. Introduction

Spacecraft formation (SF) technology experiences much attention and research in recent years due to its potential use in scientific and military missions, to name a few, monitoring of the earth and its surroundings, deep space imaging and exploration, and military surveillance instruments.[1,2] Attitude coordination control is one of its enabling technologies and needs in-depth study.[3–5]

The main idea behind attitude coordination is to couple the spacecraft's attitude states through a common control law.[2] This control problem can be solved by several existing control strategies, which can be categorized broadly into leader-follower, virtual structure and behavior-based approaches. In Ref.[6], Ren and Beard pointed out the disadvantages of leader-follower approach, i.e., single point of failure and having no explicit feedback from followers, and introduced the decentralized formation control strategies based on virtual structure. They presented formation control ideas for multiple spacecraft using virtual structure; more importantly, introduce formation feedback from spacecraft to the virtual structure. Later, Ren and Beard[7] combined the strength of decentralized control and virtual structure approach to improve the virtual structure formation control strategy. Behavioral approach is natural to describe the coordination behavior of the spacecraft formation and is utilized in many researches.[8–10] Lawton and Beard[8]

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.02.007

proposed velocity feedback and passivity-based damping approaches to maintain attitude alignment among a group of spacecraft. Bai et al.[9] and Ren[10] applied passivity-based design to call off the requirement of inertial frame information and angular velocity measurements.

Recently, robust attitude coordination[11,12] and finite-time attitude synchronization[13,14] have been addressed extensively. Compared to these topics, in the available literatures, only few papers deal with attitude coordination for spacecraft formation in the presence of multiple communication delays.[15] Nevertheless, since information exchange between spacecraft plays an important role for attitude coordination, communication delays between spacecraft need to be seriously considered.

Researchers have made particular significant efforts to study the effects of communication delays in linear multi-agent systems described by first-order or second-order dynamics[16–19] and also nonlinear systems[20,21]. However, results of the above papers cannot be extended to spacecraft formation control problem immediately due to the nonlinearity of the attitude and translational dynamics.[15] To solve this problem, in Ref.[15], the authors proposed a virtual system-based approach to handle communication delays, i.e., driving the attitude of each rigid body to its corresponding virtual system. But feedback from each rigid body to its corresponding virtual system is not considered; therefore, rigid bodies may get out of formation due to control input saturation or too fast moving of the virtual system. Hatanaka et al. also considered attitude synchronization in the presence of communication delays,[22] but only develops passivity-based distributed velocity input law.

This paper presents attitude coordination control law for spacecraft formation with multiple communication delays in two cases. In the first case, the reference is constant and available to only a part of the spacecraft. The virtual systems for the spacecraft formation will be constructed firstly, which is based on the consensus algorithms proposed by Ref.[17] Then a velocity free attitude tracking control law is proposed with consideration of feedback from the virtual systems to spacecraft formation system. In another case that the attitude reference is time-varying, attitude coordination (attitude synchronization to the desired reference) can be hardly achieved if some of the spacecraft can only receive delayed information from neighbors, not from the leader. Hence, in the second case, it is assumed that each spacecraft can obtain the desired attitude from their leader. Then backstepping[23,24] and Lyapunov–Krasovskii method makes it possible for us to design the attitude coordination control law.

2. Preliminaries

2.1. Spacecraft dynamics

Spacecraft attitude kinematics and dynamics are given by

$$\begin{cases} \dot{\boldsymbol{Q}}_i = \left[\dot{\eta}_i,\ \dot{\boldsymbol{q}}_i^{\mathrm{T}}\right]^{\mathrm{T}} = \frac{1}{2}\begin{bmatrix} -\boldsymbol{q}_i^{\mathrm{T}} \\ \boldsymbol{q}_i^{\times} + \eta_i \boldsymbol{I}_{3\times 3} \end{bmatrix}\boldsymbol{\omega}_i \quad (i = 1, 2, \ldots, n) \\ \boldsymbol{J}_i\dot{\boldsymbol{\omega}}_i = -\boldsymbol{\omega}_i^{\times}\boldsymbol{J}_i\boldsymbol{\omega}_i + \boldsymbol{\tau}_i \end{cases} \tag{1}$$

where $\boldsymbol{Q}_i = \left[\eta_i,\ \boldsymbol{q}_i^{\mathrm{T}}\right]^{\mathrm{T}}$ denotes the quaternions representing the orientation of body-fixed frame with respect to the inertial frame and satisfy the constraint $\eta_i^2 + \boldsymbol{q}_i^{\mathrm{T}}\boldsymbol{q}_i = 1$, with $\eta_i \in \mathbf{R}$ and $\boldsymbol{q}_i \in \mathbf{R}^{3\times 1}$ the scalar part and the vector part of the unit quaternion, respectively; $\boldsymbol{\omega}_i \in \mathbf{R}^{3\times 1}$ denotes the inertial angular velocity of the ith spacecraft expressed in its body-fixed frame; $\boldsymbol{J}_i \in \mathbf{R}^{3\times 3}$ denotes the positive definite inertia matrix of the ith spacecraft; and $\boldsymbol{\tau}_i \in \mathbf{R}^{3\times 1}$ denotes the vector of control input of the ith spacecraft. Further, the notation $\boldsymbol{\upsilon}^{\times}$ for a vector $\boldsymbol{\upsilon} = [\upsilon_1, \upsilon_2, \upsilon_3]^{\mathrm{T}}$ is used to denote the skew-symmetric matrix:

$$\boldsymbol{\upsilon}^{\times} = \begin{bmatrix} 0 & -\upsilon_3 & \upsilon_2 \\ \upsilon_3 & 0 & -\upsilon_1 \\ -\upsilon_2 & \upsilon_1 & 0 \end{bmatrix} \tag{2}$$

2.2. Graph theory

Let $G = (\mathcal{V}, \mathcal{E})$ be a weighted directed graph describing the communication topology of the spacecraft formation, which consists of a node set $\mathcal{V} = \{1,\ 2,\ \ldots,\ n\}$ and an edge set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. An edge $(i, j) \in \mathcal{E}$ in a weighted directed graph indicates that the ith spacecraft can receive information from the jth spacecraft and j is called parent node, while i is the child node. The adjacency matrix $\boldsymbol{A}$ of a graph G is an $n \times n$ real matrix defined as A_{ij} if and only if $(i, j) \in \mathcal{E}$ and $A_{ij} = 0$ otherwise. A directed path is a sequence of edges in a directed graph of the form $(i_1, i_2), (i_2, i_3), \ldots, (i_k, i_{k+1}), \ldots$, with $i_k \in \mathcal{V}$. The directed graph G is said to be strongly connected if there is a directed path between any two vertices in it. And we call that G has a rooted directed spanning tree if and only if there exists at least one node having a directed path to all of the other nodes (an example with six nodes and seven edges is shown by Fig. 1, where $e_1, e_2, \ldots, e_7$ denote the seven edges). In the case of directed graphs, having a rooted directed spanning tree is a weaker condition than being strongly connected.[25]

2.3. Problem formulation

To achieve attitude coordination of spacecraft formation, communication between spacecraft plays an important role. The graph of communication topology is assumed to be directed and contains a rooted spanning tree. We also assume that each spacecraft can sense its own states with no delays, and communication between the ith and jth spacecraft, with $(i, j) \in \mathcal{E}$, is delayed by d_{ij}, and $d_{ij} \geqslant 0$ refers to time delays that model the propagation of state information from node j to i.

With the above assumptions, the main objective of this paper is that: for spacecraft formation system described by Eq. (1), two control methods are designed.

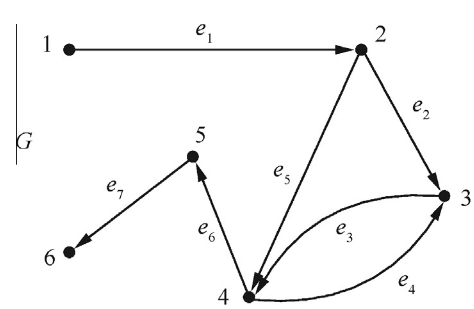

Fig. 1 An example of a rooted directed spanning tree with 1 as its root node.