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BACKSTEPPING ATTITUDE COORDINATION CONTROL FOR SPACECRAFT FORMATION WITH MULTIPLE DELAYS

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This paper addresses attitude coordination control for spacecraft formation with multiple delays. A distributed angular velocity input law is firstly constructed for attitude synchronization and tracking under multiple communication delays. Introducing virtual auxiliary systems makes it possible to integrate the angular velocity input law with the true true control torque, and asymptotic stability of the system is guaranteed by Lyapunov theory. Moreover, by modifying the angular velocity input law, attitude coordination among spacecrafts can be guaranteed even under control input saturation constraints. Finally, effectiveness of the proposed methodology is illustrated by concrete simulations.

INTRODUCTION

Spacecraft formation(SF) is a promising concept for lots of 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 has received significant attention in recent years. The main idea behind attitude coordination control is to couple the spacecrafts' attitude states through a common control law.[2] The existing control strategies can be categorized broadly into leader-follower, virtual structure, and behavioral approaches.[3] In Reference 3, Ren points out the disadvantages of leader-follower approach, i.e., single point of failure and having no explicit feedback from followers, and introduces the decentralized formation control strategies based on virtual structure. Behavioral approach is natural to describe the formation-keeping and station-keeping behaviors and are utilized by many literatures.[4,5,6] Lawton[4] proposes velocity feedback and passivity-based damping approaches to maintain attitude alignment among a group of spacecraft. References 5 and 6 apply passivity-based design and call off the requirement of inertial frame information and angular velocity measurements, respectively.

Recently, robust attitude coordination and finite-time attitude synchronization have been addressed extensively.[7,8,9,10] Using sliding mode method, Reference 7 ensures that each spacecraft attains desired attitude and angular velocity while maintaining attitude synchronization with other spacecrafts even in presence of model uncertainties and external disturbances. Reference 8 extends robust attitude coordination to cases with actuator failures and control input constraints by developing a class of robust adaptive control laws. Du[9] and Zhou[10] investigate the finite-time attitude synchronization problem of spacecraft formation through constructing novel and suitable Lyapunov functions. Compared to these problems, in the available literatures, only few papers deal with attitude coordination control in presence of communication delays.[11] Nevertheless, since information exchange between spacecrafts plays an important role for attitude coordination, communication delays among spacecrafts needs to be seriously considered.

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Researchers have made particular significant effects to study the effects of communication delays in linear multi-agent systems described by first-order or second order dynamics,[12,13,14,15] and also nonlinear systems.[16,17] However, results of the above papers can't be extended to attitude coordination problem immediately due to the nonlinearity of the attitude dynamics.[11] To solve this problem, Reference 11 proposes a virtual systems approach to handle communication delays, i.e., driving the attitude of each rigid body to its corresponding virtual system. It should be noted that this approach has no explicitly feedback from each rigid body to its corresponding virtual system, thus rigid body may get out of formation due to control input saturation or too fast moving of the virtual system. Hatanake18 also considers attitude synchronization in presence communication delays, but only develops passivity-based distributed velocity input law. The main contribution of this paper is that of integrating the angular velocity input law with the true control torque, and giving explicit consideration of control input saturation constraints, by using backstepping design method. The backstepping control approach is a powerful tool to design attitude control of spacecraft,[19,20,21] whose design procedure is to construct a control law and a Lyapunov function recursively to guarantee stability. Similarly with communication delays, control input saturation constraints of spacecraft formation has not received much attention as well. For single spacecraft, control input saturation is an significant issue encountered in practice and affects the performance of attitude tracking.[22,23,24] Through designing velocity-free attitude controller, Reference 22 enforces actuator-magnitude and rate-saturation constraints, while Reference 24 develops a bounded controller using an adaptive scheme to tune the control parameters. As for attitude coordination control of spacecraft formation, control input saturation becomes an even more important issue to deal with. In fact, when some spacecrafts are saturated, while others not, the saturated spacecrafts will fall behind and thus degrade the performance of attitude coordination.

This paper presents a backstepping based control scheme of attitude coordination for spacecraft formation with multiple communication delays and control input saturation. We will first construct a distributed virtual angular velocity input law for each spacecraft, which based on the consensus algorithms proposed by Reference 13. Then, introducing virtual auxiliary systems and using backstepping design method, the actual control torques is obtained. Furthermore, we handle the control input saturation by modifying the virtual angular velocity input law. The main contribution of this work is to design attitude coordination control laws for spacecraft formation in presence of communication and saturation constraints, simultaneously.

The remainder of this paper is organized as follows. Preliminaries include attitude dynamics, graph theory and problem formulation are briefly described in the next section. Section 3 shows our main contribution of attitude coordination control with communication delays and saturation constraints. Some simulations are provided in section 4, and finally, section 5 concludes the paper.

PRELIMINARIES

Attitude Dynamics

Each spacecraft is assumed to be rigid with actuators providing torques about three mutually perpendicular axes that define a body-fixed frame $\mathcal{F}_i$. The motion of the ith spacecraft is given by

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

$$\dot{q}_i = \frac{1}{2}\left(q_i^{\times} + \eta_i I_3\right)\omega_i \tag{2}$$

$$\dot{\eta}_i = -\frac{1}{2}q_i^T\omega_i, i = 1, 2, \cdots, n \tag{3}$$

where $\omega_i \in \mathbb{R}^3$ denotes the inertial angular velocity of the ith spacecraft expressed in its body-fixed frame $\mathcal{F}_i$, $J_i \in \mathbb{R}^{3\times 3}$ denotes the positive definite actual inertia matrix of the ith spacecraft, $\eta_i \in \mathbb{R}$ and $q_i \in \mathbb{R}^3$ denote the quaternions that represent the orientation of $\mathcal{F}_i$ with respect to the inertial frame $\mathcal{F}_I$ and satisfy the constraint $\eta_i^2 + q_i^T q_i = 1$. And $\tau_i \in \mathbb{R}^3$ denote the vector of control input of the ith spacecraft. Further, the notation $v^\times$ for a vector $v = [v_1\ v_2\ v_3]^T \in \mathbb{R}^3$ is used to denote the skew-symmetric matrix

$$v^\times = \begin{bmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{bmatrix}$$

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 $\mathcal{V} = \{1, 2, \cdots, n\}$, an edge set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. An edge $(i, j) \in \mathcal{E}$ in a weighted directed graph indicates the ith spacecraft can receive information from the jth spacecraft and j is called parent node, while i the child node. The adjacency matrix A of a graph G is an $n \times n$ real matrix defined such that $A_{ij} = 1$ 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 $(i_1, i_2), (i_2, i_3), \cdots,$, where $i_k \in \mathcal{V}$. 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 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. In the case of directed graphs, having a rooted directed spanning tree is a weaker condition than being strongly connected.[25]

Problem Formulation

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

With the above assumptions, the control problem this paper addressed is that for spacecraft formation described by Eq. (1),(2) and (3), backstepping method is utilized to design a control law such that the following problems are solved:

(1) Attitude coordination with multiple communication delays: Spacecrafts in formation can synchronize their attitudes when no desired attitude is assigned to them. Meanwhile, when a desired attitude signal is only available to a part of the spacecrafts while having a directed path to all of the other spacecrafts, all the spacecrafts synchronize their attitudes to the desired attitude.

(2) Robust attitude coordination against control input saturation: Control problem (1) is solved even in face of control input saturation.

BACKSTEPPING BASED ATTITUDE COORDINATION CONTROL DESIGN

In this section, we propose our attitude coordination control design procedure, including the constructing of the angular velocity control law, the design of the true control torque for each spacecraft and handling the control input saturation.

Definition 1: A function $f : \mathbb{R} \to \mathbb{R}$ is locally passive, if there exist $\epsilon^- > 0$ and $\epsilon^+ > 0$ such that $yf(y) > 0$ for all $y \in [-\epsilon^-, \epsilon^+]$ apart from $y = 0$, where $f(0) = 0$.

Lemma 1: (see References 13) Consider the following systems

$$\dot{x}_i = k_i \sum_{j=1}^{N} A_{ij} f_{ij} \left(x_j(t - d_{ij}) - x_i(t)\right), i = 1, 2, \cdots, N \tag{4}$$

where k_i is a positive constant, the functions $f_{ij} : \mathbb{R} \to \mathbb{R}$ is locally passive on $\left(-\sigma_{ij}^-, \sigma_{ji}^+\right)$ with $\sigma_{ij}^- > 0$ and $\sigma_{ji}^+ > 0$ for all $i, j = 1, 2, \cdots, N$. Let $d = \max_{i,j=1,2,\cdots,N} d_{ij}$, and the initial conditions ψ_i satisfy

$$|\psi_i(\theta)| \leq \frac{\gamma}{2}, \forall i = 1, 2, \cdots, N,\ \theta \in [-d, 0] \tag{5}$$

where $|\cdot|$ denotes standard Euclidean vector norm(the 2-norm), $\gamma := \min\limits_{i,j=1,2,\cdots,N} \left\{\sigma_{ij}^-, \sigma_{ij}^+\right\}$. Then the consensus set χ_d is asymptotically attracting, which is defined by

$$\chi_d = \{x(t + \theta) = c\mathbf{1},\ c \in \mathbb{R}, \theta \in [-d, 0], t \geq 0\} \tag{6}$$

Angular Velocity input Law

Following the procedure of backstepping control design, we will firstly introduce the virtual angular velocity input law.

Case 1: In case of attitude synchronization without desired attitude, virtual angular velocity input law of the ith spacecraft is designed as follows, which follows Lemma 1 directly.

$$\phi_i = k_i \Xi_i \sum_{j=1}^{n} A_{ij} F_{ij} \left(q_j \left(t - d_{ij}\right) - q_i \left(t\right)\right),\ i = 1, 2, \cdots, n \tag{7}$$

where k_i is a positive constant, $\Xi_i = \left(\frac{1}{2}\left(q_i^\times + \eta_i I_3\right)\right)^{-1}$, and the function $F_{ij} : \mathbb{R}^3 \to \mathbb{R}^3$ is defined such that $F_{ij}(s) = [f_{ij}(s_1)\ f_{ij}(s_2)\ f_{ij}(s_3)]^T$ for $s = [s_1\ s_2\ s_3]^T \in \mathbb{R}^3$, in which f_{ij} is defined as Lemma 1.

When ω_i of each each spacecraft converges to its virtual angular velocity input ϕ_i, attitudes of spacecraft formation satisfy the following differential equation.

$$\dot{q}_i = k_i \sum_{j=1}^{n} A_{ij} F_{ij} \left(q_j \left(t - d_{ij}\right) - q_i \left(t\right)\right),\ i = 1, 2, \cdots, n \tag{8}$$

Considering Lemma 1, Eq. (8) immediately implies that spacecrafts synchronize their attitudes in presence of multiple delays. One may wonder whether the use of Lemma 1 is proper, since $q_i \in \mathbb{R}^3, i = 1, 2, \cdots, n$ while $x_i \in \mathbb{R}$ in Eq. (4). In fact, considering the definition of F_{ij}, we can interpret each element of q_i independently as a system described by Eq. (4).

Case 2: In case of desired attitude tracking of the spacecraft formation, more practically, a desired attitude signal is available only to a part of the spacecrafts while having a directed path to all of the other spacecrafts. The desired attitude can be viewed as a reference spacecraft and we call it the 0th spacecraft. Adding with the 0th spacecraft, the new communication topology can be described by G', whose node set is $\mathcal{V}' = \{0, 1, 2, \cdots, n\}$. Further, the adjacency matrix of G' is denoted by $A' = [A'_{ij}]$, where $A'_{i0}, i = 1, 2, \cdots, n$ is 1 if the desired attitude is available to the ith spacecraft and 0 otherwise, and A'_{0i}=0 for all $i = 1, 2, \cdots, n$ since the 0th spacecraft gets no signal from other spacecrafts. Then, we propose the virtual angular velocity input law for the ith spacecraft as

$$\phi_i = k_i \Xi_i \sum_{j=0}^{n} A'_{ij} F_{ij} \left(q_j \left(t - d_{ij}\right) - q_i \left(t\right)\right),\ i = 1, 2, \cdots, n \tag{9}$$

To show that the attitude tracking of the spacecraft problem can be solved by Eq. (9), we need to recall the idea behind the novel proof methodology of Lemma 1. In Reference 13, the asymptotically attracting property of the consensus set χ_d in Eq. (6) is guaranteed by the fact that both the minimum and maximum of x_i are held by the root of the spanning tree. As for attitude tracking of the spacecraft formation, the 0th spacecraft act as the rooted one and thus holds the minimum and maximum attitude in formation, which implies that all the other spacecrafts attain the desired attitude.

Remark 1: It is needed to note that angular velocity input law can be designed by many existing time-delay consensus algorithms. Lemma 1 is chose since it is a relatively general one, where we only require that f_{ij} be locally passive and that the directed graph contains a spanning tree. Further, this paper only requires that the functions f_{ij} are locally passive on $[-2, 2]$ because the maximum element of q_i is bounded by 1(See References 13).

Backstepping Based Control Torque Design

This section integrates the angular velocity input law with the true control torque by introducing the virtual auxiliary systems. Motivated by Reference 11, we associate to each spacecraft the following virtual system

$$\begin{array}{l} \dot{q}_{vi} = \frac{1}{2}\left(q_{iv}^{\times} + \eta_{iv} I_3\right)\left(\omega_i - \phi_i\right) \\ \dot{\eta}_{iv} = -\frac{1}{2} q_{iv}^T \left(\omega_i - \phi_i\right), i = 1, 2, \cdots, n \end{array} \tag{10}$$

where $q_{iv} \in \mathbb{R}$ and $\eta_{iv} \in \mathbb{R}^3$ are the quaternions representing the attitude of the virtual system, which can be initialized arbitrarily, and ϕ_i is given by Eq. (7) or Eq. (9). The virtual systems can be seen as attitude errors between the ith spacecraft and the rigid body whose angular velocity is ϕ_i.

The true control torque is calculated by

$$\tau_i = \omega_i^{\times} J_i \omega_i - J_i \left(k_i^d \left(\omega_i + \phi_i\right) - k_i^p q_{iv} - \dot{\phi}_i\right), i = 1, 2, \cdots, n \tag{11}$$

Theorem 1: When the controller as Eq. (11) is introduced to each spacecraft, where k_i^d and k_i^p are positive constants, control problem 1 is solved.

Proof: Now consider the Lyapunov candidate

$$V_1 = \sum_{i=1}^{n} k_i^p \left[\left(\eta_{iv} - 1\right)^2 + q_{iv}^T q_{iv}\right] + \frac{1}{2} \sum_{i=1}^{n} \left(\omega_i - \phi_i\right)^T \left(\omega_i - \phi_i\right) \tag{12}$$

The time derivative of V_1 calculated using Eq. (1) and Eq. (10), is obtained as

$$\begin{aligned}\dot{V}_1 &= \sum_{i=1}^{n} k_i^p \left[-\left(\eta_{iv}-1\right) q_{iv}^T \tilde{\omega}_i + q_{iv}^T \left(q_{iv}^\times + \eta_{iv} I_3\right) \tilde{\omega}_i\right] + \sum_{i=1}^{n} \tilde{\omega}_i^T \left(\dot{\omega}_i - \dot{\phi}_i\right) \\ &= \sum_{i=1}^{n} k_i^p q_{iv}^T \tilde{\omega}_i + \sum_{i=1}^{n} \tilde{\omega}_i^T \left[J_i^{-1}\left(-\omega_i^\times J_i \omega_i + \tau_i\right) - \dot{\phi}_i\right] \end{aligned} \tag{13}$$

where $\tilde{\omega}_i = \omega_i - \phi_i$. Then substituting Eq. (11) into Eq. (13), we obtain

$$\dot{V}_1 = -k_i^d \sum_{i=1}^{n} \left(\omega_i - \phi_i\right)^T \left(\omega_i - \phi_i\right) \le 0 \tag{14}$$

Eq. (14) ensures the asymptotically convergence of q_{iv} and $(\omega_i - \phi_i)$ to zero. Then according to analysis in the previous section, we conclude that control problem 1 is solved, which ends the proof.

Remark 2: Considering the control torque of Eq. (11), ϕ_i is used to couple attitude dynamic of the ith spacecraft with other spacecrafts for attitude coordination control. To calculate the time derivative of ϕ_i, robust exact differentiator as Reference 21 is used.

Remark 3: Using Eq. (1) and Eq. (11), and after some algebraic manipulations, we have

$$\dot{\omega}_i - \dot{\phi}_i = -k_i^d \left(\omega_i - \phi_i\right) - k_i^p q_{iv} \tag{15}$$

Eq. (15) shows the fact that $k_i^d, i = 1, 2, \cdots, n$ specifies how fast the velocity errors $(\omega_i - \phi_i)$ stabilizes, and $k_i^p q_{iv}$ is a forcing function contributing to the control objective.

Remark 4: One significant problem the preceding control law faces is not taking account of the control input saturation. In Eq. (11), ϕ_i depends on the instantaneous response of the attitude dynamics of the spacecraft formation, which leads to the difficulty to obtain the upper bound of the calculated control torques. From this point of view, to handle the actuator saturation constraint, one feasible way is to modify the response of ϕ_i. This is the main motivation of the introducing of a tunable vector in next subsection.

Angular Velocity Input Modifying for Control Input Saturation

As shown in Remark 3, control input saturation problem can be handled by modifying angular velocity input law ϕ_i in Eq. (7) or Eq. (9). Hence, we introduce vectors $\phi_i', i = 1, 2, \ldots, n$ given by

$$\dot{\phi}_i' = \dot{\phi}_i + J_i^{-1}\delta_i - k_i^d \left(\phi_i' - \phi_i\right) \tag{16}$$

The term $\delta_i, i = 1, 2, \cdots, n$ is the vector errors between the calculated control torques and the actual ones introduced to spacecraft. And δ_i is defined such that $\delta_i = 0$ if $|\tau_i'| \le \tau_{im}$ and $\delta_i = \tau_i' - \tau_{im}\mathrm{sgn}\left(\tau_i'\right)$ otherwise, with τ_{im} denotes the bound of the control authority of the ith spacecraft, sgn denotes the sign function, and τ_i' is given by

$$\tau_i' = \omega_i^\times J_i \omega_i - J_i \left(k_i^d \left(\omega_i - \phi_i\right) + k_i^p q_{iv}' - \dot{\phi}_i\right) \tag{17}$$

where q_{iv}' is obtained similarly as q_{iv}, excepting that ϕ_i in Eq. (10) be replaced by ϕ_i'. We now show that modifying angular velocity input law can handle the control input saturation constraints.

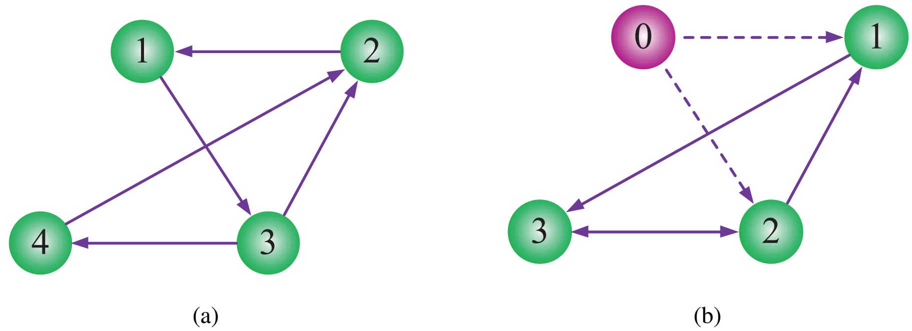

Figure 1. Communication Topology of Spacecraft Formation

Theorem 2: If we apply control torques given by $\tau_i' - \delta_i, i = 1, 2, \cdots, n$ to each spacecraft, control problem 2 can be solved.

Proof: Submitting $\tau_i' - \delta_i$ into Eq. (1), we get

$$\dot{\omega}_i - \dot{\phi}_i = -k_i^d \left(\omega_i - \phi_i\right) - k_i^p q_{iv}' - J^{-1}\delta_i \tag{18}$$

Using Eq. (16), Eq. (18) can be written as

$$\dot{\omega}_i - \dot{\phi}_i' = -k_i^d \left(\omega_i - \phi_i'\right) - k_i^p q_{iv}' \tag{19}$$

Then choose the Lyapunov functional candidate as

$$V_2 = \sum_{i=1}^{n} k_i^p \left[\left(\eta_{iv}' - 1\right)^2 + q'^T_{iv} q_{iv}'\right] + \frac{1}{2}\sum_{i=1}^{n}\left(\omega_i - \phi_i'\right)^T\left(\omega_i - \phi_i'\right) \tag{20}$$

The time derivative of V_i along the trajectory Eq. (19) can be evaluated as

$$\dot{V}_2 = -k_i^d \sum_{i=1}^{n}\left(\omega_i - \phi_i'\right)^T\left(\omega_i - \phi_i'\right) \leq 0 \tag{21}$$

Obviously, q_{iv} and $(\omega_i - \phi_i')$ asymptotically converge to zero, which is the equilibrium solution of the system. Furthermore, generally speaking, δ_i in Eq. (16) should be zero for some period of time since control saturates for the entire time duration is impractical. Therefore, it can be concluded that the modifying angular velocity input can track the desired one, which combining Theorem 1 finishes the proof.

SIMULATIONS

This section presents simulations to illustrate the effectiveness of our attitude coordination controller design under communication delays and control input saturation constraints.

Case 1: Attitude coordination of spacecraft formation without desired attitude trajectory. In this case, the communication topology has a spanning tree rooted by the 1th spacecraft, as shown in Fig.1(a). Table. 1 gives the system parameters for the spacecraft formation, including inertial matrices and initial conditions. The other numerical parameters are given in Table. 2.

Fig. 2 shows that the 4 spacecrafts synchronize their attitudes at about 20s. The history of the virtual systems' attitudes and the actual control torques of the spacecraft formation are shown in Fig. 3 and Fig. 4, respectively. It is seen that the stability of the system and the attitude synchronization are ensured, although the control inputs are saturated before 8s. Furthermore, Fig. 5 shows us the attitudes of the spacecrafts when time delays among spacecrafts are doubled, which implies the feasibility of our proposed control law in presence of even larger communication delays.

Case 2: Attitude coordination of spacecraft formation when the desired attitude is only available to a set of spacecrafts, while having a directed path to all of the other spacecrafts. In this case, we numbered the desired attitude model as the 0th spacecraft, as shown in Fig.1(b). As with case 1, Table. 3 and Table. 4 give the system parameters and other numerical parameters, respectively. Fig. 6 shows the attitudes of the 3 spacecrafts and their reference trajectory, and the attitudes of virtual systems corresponding to each spacecraft are shown in Fig. 7. We can conclude that the stability of the system and the attitude synchronization are ensured, although the control inputs are saturated for some period of time, as shown by Fig. 8.

Table 1. System Parameters of Case 1

Spacecraft	Inertial Matrix	Initial q_j	Initial ω_j
1	$\mathrm{diag}(20, 25, 15)$	$[-0.1\ 0.9\ 0.2]^T$	$[0.02\ 0\ 0]^T$
2	$\mathrm{diag}(12, 15, 25)$	$[0.2\ 0.3\ 0.1]^T$	$[0\ 0\ \ -0.04]^T$
3	$\mathrm{diag}(20, 15, 15)$	$[-0.2\ 0.1\ 0.3]^T$	$[0.08\ 0.05\ 0.04]^T$
4	$\mathrm{diag}(15, 15, 20)$	$[0.4\ 0.0\ 0.8]^T$	$[0.1\ 0.05\ \ -0.04]^T$

Table 2. The Other Parameters of Case 1

Parameter Name	Values
Time Delays	$d_{12} = 0.5$s, $d_{24} = 1$s,$d_{23} = 1.5$s $d_{31} = 1.2$s, $d_{43} = 0.8$s
Control Parameters	$k_j^d = 1$, $k_j^p = 0.5$, for $j = 1, 2, 3, 4$
Initial Attitudes of Virtual Systems	$[0\ 0\ 0]^T$ for $j = 1, 2, 3, 4$
The Function $f_ij(x)$	$\tanh(x)$
Maximum Torque	5N.m

CONCLUSIONS

This paper proposes a backstepping based attitude coordination control method for spacecraft formation in presence of multiple communication delays. Particularly, through introducing the virtual auxiliary systems, we integrate angular velocity input law with the true true control torque. Control input saturation is also considered by modifying the angular velocity. The numerical simulation results illustrate the performance of our control law for attitude coordination among 4 spacecrafts with and without desired attitude.

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Table 3. System Parameters

Spacecraft	Inertial Matrix	Initial q_j	Initial ω_j
1	$\mathrm{diag}(12, 15, 25)$	$[0.2\ 0.3\ 0.1]^T$	$[0\ 0\ -0.04]^T$
2	$\mathrm{diag}(20, 15, 15)$	$[-0.2\ 0.1\ 0.3]^T$	$[0.08\ 0.05\ 0.04]^T$
3	$\mathrm{diag}(15, 15, 20)$	$[0.4\ 0.0\ 0.8]^T$	$[0.1\ 0.05\ -0.04]^T$

Table 4. The Other Parameters

Parameter Name	Values
Time Delays	$d_{12} = 0.8\mathrm{s}$, $d_{23} = 1\mathrm{s}$, $d_{31} = 1.4\mathrm{s}$, $d_{32} = 1.5\mathrm{s}$
Control Parameters	$k_j^d = 1$, $k_j^p = 0.5$, for $j = 1, 2, 3$
The Function $f_i j(x)$	$\tanh(x)$
Maximum Torque	$5\mathrm{N.m}$
Vector Part of Desired Quaternion	$[-0.1\ 0.9\ 0.2]^T$
Initial attitudes of Virtual System	$q_{jv} = [0\ 0\ 0]^T$, for $j = 1, 2, 3$

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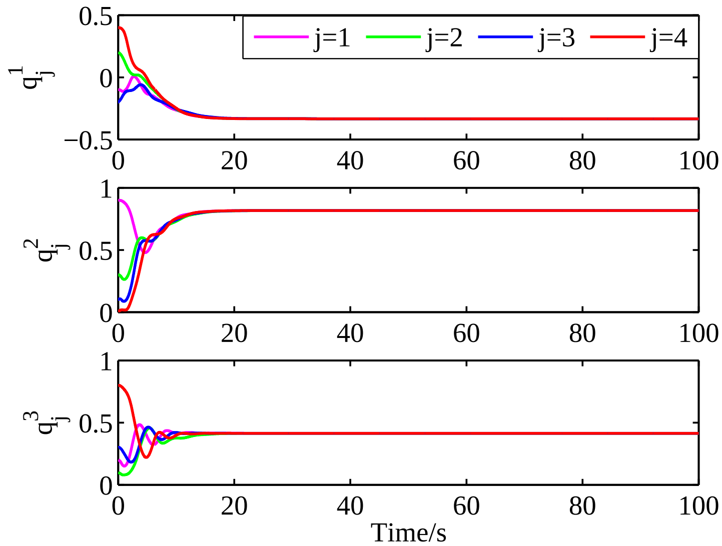

Figure 2. Attitudes of Spacecraft Formation in Case 1

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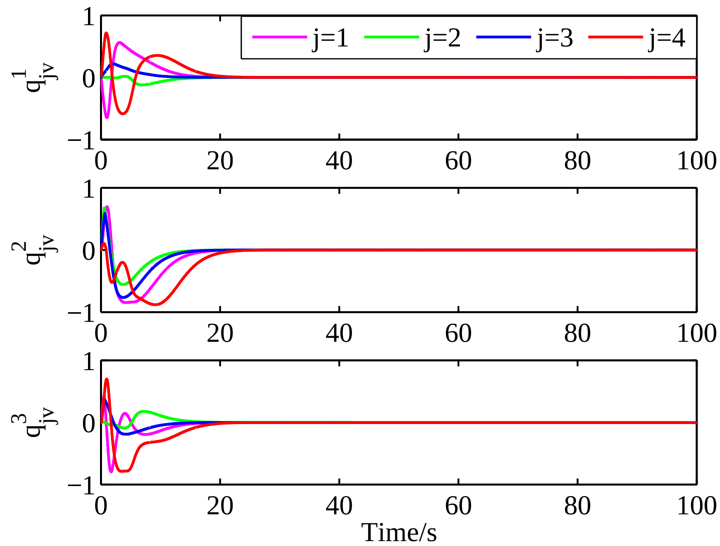

Figure 3. Attitudes of Virtual Systems in Case 1

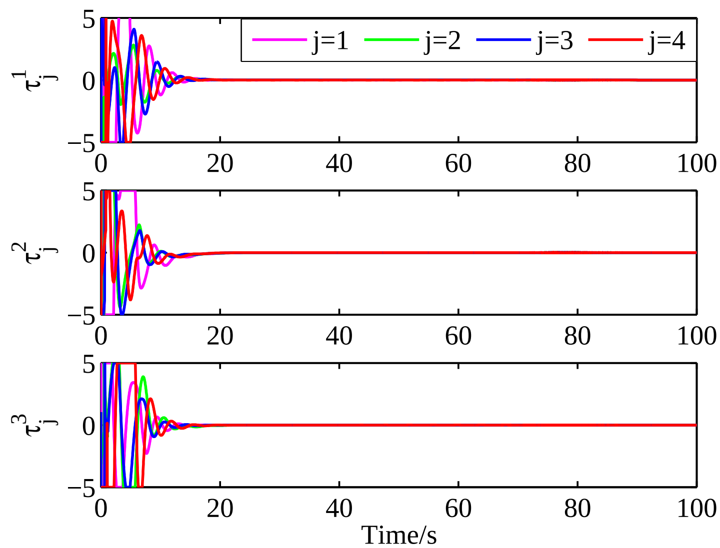

Figure 4. Actual Control Torques of Spacecraft Formation in Case 1

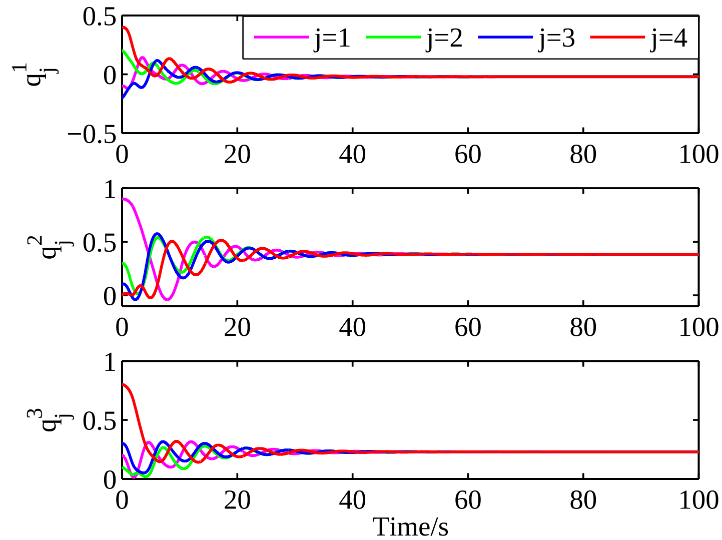

Figure 5. Attitudes of Spacecraft Formation When Communication Delay is Doubled

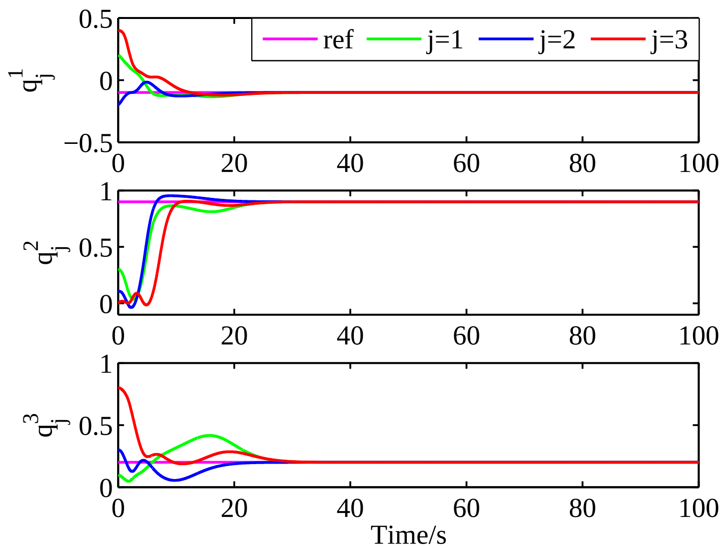

Figure 6. Attitudes of Spacecraft Formation in Case 2

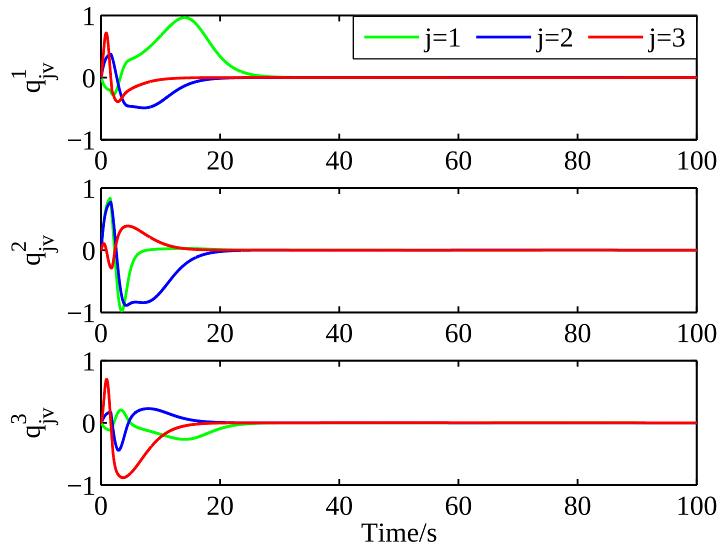

Figure 7. Attitudes of Virtual Systems in Case 2

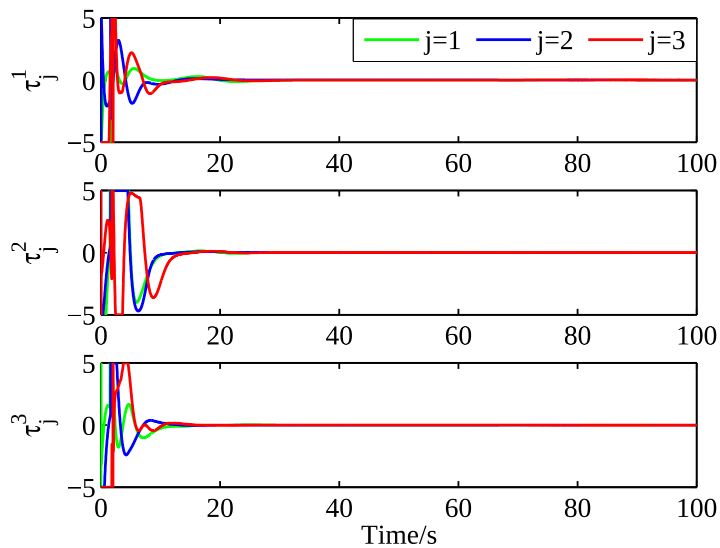

Figure 8. Actual Control Torques of Spacecraft Formation in Case 2