



Robust attitude consensus control of multi-spacecraft with stochastic link failure

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Abstract

This paper presents an adaptive attitude consensus controller for a group of space crafts subject to stochastic communication link failure and external disturbances. By leveraging the sliding-mode control technique and the super-martingales convergence method, the proposed adaptive controller is robust to the bounded but unknown disturbances and ensures almost sure consensus on the attitude among multi-spacecraft, respectively. Moreover, when compared with the existing results dealing with attitude consensus control with indeterministic communication topology, our approach can drive the attitude of multi-spacecraft to a desired attitude of a virtual spacecraft. To verify the effectiveness of the proposed approach, an attitude consensus control of a group of six spacecraft with a virtual leader is carried out.

Keywords Attitude consensus · Communication link failures · Adaptive control · Multi-spacecraft Systems

1 Introduction

In the recent decades, the development and application of a single spacecraft are constrained due to the gradually increased volume, weight, and cost. Due to the low cost, small volume, light weight, and low energy consumption, the multi-spacecraft system is developed to compensate for the disadvantages of a single spacecraft. The multi-spacecraft system can achieve or even exceed the capabilities of a single spacecraft. Moreover, the failure of a spacecraft will not lead

to the failure of the whole system. Thus, the multi-spacecraft system has attracted considerable attention. To accomplish complex space missions, it is critical for the multi-spacecraft systems to maintain an accurate relative attitude. Attitude consensus control of multi-spacecraft systems is one of the key factors for the success of space missions, especially for earth observation and universal exploration. For instance, the traditional single spacecraft is hard to conduct the large area Earth observation owing to its limited field of view. Therefore, it is worthwhile further investigating attitude consensus control for multi-spacecraft coordinated missions.

There have been numerous attitude consensus control schemes proposed to make attitude converge to a common attitude. In [1–4], adaptive attitude controllers using different techniques (e.g., sliding-mode control, backstepping control, robust control, etc.) were designed to achieve accurate relative orientation control among space crafts in either the undirected or directed topology, despite the existence of inertia uncertainties and external disturbances. When there exist input saturation constraints, terminal sliding-mode-based control methods were proposed to achieve attitude consensus [5–7]. In [8, 9], a relative position cooperative control problem was studied, where the proposed methods guarantee finite-time error convergence. However, the modeling uncertainties and disturbances are not considered, leading to limited robustness and degraded control performance.

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On the other hand, to achieve reliable attitude consensus control, it is of vital importance for spacecrafts to transmit information through inter-satellite communication links, and maintain a certain configuration and relative attitude. In the leader–follower control strategy, the spacecraft that is selected as a leader needs to reach the expected attitude, while the rest spacecrafts are regarded as the following ones to track the leader so as to complete the attitude consensus mission. In this control strategy, it is essential that the information of the leader can be transferred to any following spacecrafts through a deterministic communication link. In [10–12], the leader tracks the common attitude and the attitude information of the leader can be obtained by the followers to achieve the cooperative attitude control. In the virtual structure control strategy, the whole spacecraft tracks the virtual spacecraft which transfers the desired attitude. In [13–16], the multi-spacecraft system maneuvers to the specified attitude according to information transferred by the virtual leader through communication links. Based on consensus theory, spacecraft members utilize their own attitude information to cooperatively achieve the same attitude through communication link. In [17–19], the attitude consensus problem was addressed and a desired attitude can be reached through an undirected communication link. Although the aforementioned works can tackle the attitude consensus problem, the communication link failure is not considered in the controller design.

In practice, communication links are vulnerable to interference from various uncertain sources, which may lead to intermediate failure of the communication link. Under this situation, communication links may fail and rebuilt stochastically over time. In [20], the attitude consensus problem of multi-spacecraft system under stochastic communication link failure in a directed topology composed of four spacecraft was solved, where a stochastic variable associated with the link interconnection probability was used to model the information transmission of the spacecraft topology. Recently, taking into account the uncertain inertia matrix, a robust controller was designed under the directed communication topology composed of six spacecraft to make the attitude almost surely achieve consensus in [21]. However, these works can only achieve attitude consensus but cannot converge to a desired attitude.

In this paper, an adaptive attitude consensus control strategy for multi-spacecraft systems in the presence of stochastic communication link failure and interference of environmental disturbances is proposed and studied. The spacecraft topology consists of a virtual leader and a group of followers, where the motion of the virtual leader is governed by a desired attitude and the followers are to reach consensus and track the desired attitude. Based on the sliding-mode control and super-martingale convergence theorem, the designed controller not only achieves almost sure consensus, but also

suppresses the external disturbances. In contrast to the existing works in [20, 21], the proposed approach can handle a more complex communication topology and suppress the disturbance caused by external environment. The proposed control scheme can converge the attitude of all spacecraft to a specific desired attitude despite the existence of the environmental disturbances and stochastic communication link failure. Finally, numerical simulation results are given to verify the efficiency of the proposed attitude consensus controller.

The structure of this paper is organized as follows. In Sect. 2, the preliminaries used are introduced. In Sect. 3, the detailed problem is stated. In Sect. 4, the controller design and stability analysis are developed. In Sect. 5, an example case study is given to illustrate the effectiveness and performance of the proposed controller design method. Finally, conclusions are presented in Sect. 6.

2 Preliminaries

2.1 Notations

In the rest of this paper, the following notations are used. \mathbb{R} represents the set of real numbers. \mathbb{R}_+ represents the set of positive real numbers. $\|\cdot\|$ is the standard Euclidean norm. If a square matrix D is symmetric positive definite, the matrix D is represented as $D > 0$. We define $D = \text{diag}(D_1, D_2, \dots, D_n)$ as a block diagonal matrix with entries consisting of the matrices D_1, D_2, \dots, D_n . I_n denotes an $n \times n$ identity matrix. \otimes represents the Kronecker product. $\text{sgn}(\cdot)$ denotes the sign function. We use $\text{rank}(\cdot)$ to denote the rank of a matrix and use $\text{Null}(\cdot)$ to denote the null space.

2.2 Spacecraft attitude dynamics

The unit-quaternion form of attitude dynamics is used to describe the multi-spacecraft systems. The attitude kinematics and dynamics of the i th spacecraft can be expressed as

$$\dot{q}_i = Z(q_i)\omega_i,$$

$$J_i\dot{\omega}_i = S(\omega_i)J_i\omega_i + \tau_i + d_i, \quad (1)$$

where the subscript $i \in \{1, 2, \dots, n\}$ with n being the number of spacecrafts in the multi-spacecraft system, $q_i = [q_{1i} \ q_{2i} \ q_{3i} \ q_{4i}]^\top \in \mathbb{R}^4$ is the unit-quaternion of the body fixed frame \mathfrak{B} relative to the inertial frame \mathfrak{I} and satisfies the property $\|q_i\| = 1$, $\omega_i = [\omega_{xi} \ \omega_{yi} \ \omega_{zi}]^\top \in \mathbb{R}^3$ is angular

velocity of \mathfrak{B} relative to \mathfrak{I} , $Z(q_i) \in \mathbb{R}^{4 \times 3}$ is in the form of

$$Z(q_i) = \frac{1}{2} \begin{bmatrix} q_{4i} & -q_{3i} & q_{2i} \\ q_{3i} & q_{4i} & -q_{1i} \\ -q_{2i} & q_{1i} & q_{4i} \\ -q_{1i} & -q_{2i} & -q_{3i} \end{bmatrix},$$

$J_i \in \mathbb{R}^{3 \times 3} > 0$ is inertia matrix, $\tau_i \in \left[\tau_{xi} \ \tau_{yi} \ \tau_{zi} \right]^\top \in \mathbb{R}^3$

is the control torque, $d_i = [d_{xi} \ d_{yi} \ d_{zi}]^\top \in \mathbb{R}^3$ is the unknown but bounded disturbance torque, and $S(\omega_i)$ is the skew-symmetric matrix that is defined as follows:

$$S(\omega_i) = \begin{bmatrix} 0 & \omega_{zi} & -\omega_{yi} \\ -\omega_{zi} & 0 & \omega_{xi} \\ \omega_{yi} & -\omega_{xi} & 0 \end{bmatrix}.$$

Assumption 1 The disturbance torque is bounded by $\|d_i\| \leq d_{i,\max}$, where $d_{i,\max} \in \mathbb{R}_+$ is a positive constant.

3 Stochastic process

A stochastic process $X = \{X(t), t \geq 0\}$ is to express the change in time of a stochastic phenomenon. The stochastic process can be described by the probability triple $(\Omega, \mathcal{F}, \mathbb{P})$, where Ω is a set of the events, \mathcal{F} is a σ -algebra and belongs to a subspace of Ω , and \mathbb{P} is the probability of event with $0 \leq \mathbb{P}\{\cdot\} \leq 1$ and $\mathbb{P}\{\Omega\} = 1$. Moreover, a filtration $\{\mathcal{F}_t, t \geq 0\}$ on $(\Omega, \mathcal{F}, \mathbb{P})$ is a set of sub σ -algebras of \mathcal{F} and satisfies the following conditions:

$$\mathcal{F}_0 \subset \mathcal{F}_1 \subset \cdots \subset \mathcal{F}_n \subset \cdots \subset \mathcal{F}.$$

If the stochastic process X is \mathcal{F}_t -measurable for all $t \geq 0$, then it is said to be adapted to the filtration $\{\mathcal{F}_t\}$. In addition, a process X is a super-martingale if the following conditions are satisfied [20]:

- (1) X is adapted to the filtration $\{\mathcal{F}_t\}$;
- (2) $\mathbb{E}\{|X(t)|\} < \infty, \forall t$;
- (3) $\mathbb{E}\{X(t) | \mathcal{F}_s\} \leq X(s), t > s$.

Now, it is ready to define the almost surely convergence of the stochastic variable $X(t)$ to a finite X_f if the following condition is satisfied:

$$\mathbb{P}\left\{\lim_{t \rightarrow \infty} X(t) = X_f\right\} = 1,$$

which is further equivalently defined as

$$\lim_{t \rightarrow \infty} X(t) \xrightarrow{a.s.} X_f.$$

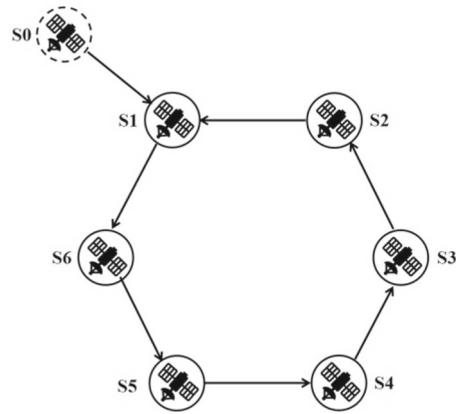


Fig. 1 The network topology of the multi-spacecraft systems

Then, the following super-martingale convergence lemma would be useful for the convergence analysis of stochastic variables.

Lemma 1 [22] If the stochastic process $X = \{X(t), t \geq 0\}$ is a nonnegative super-martingale, then there exists a finite X_f , such that $\lim_{t \rightarrow \infty} X(t) \xrightarrow{a.s.} X_f$.

4 Problem statement

As shown in Fig. 1, we assume that there are n spacecrafts and a virtual spacecraft in a multi-spacecraft system. The multi-spacecraft form a cyclic topology in which the i th spacecraft follows the $(i+1)$ th one and spacecraft i can obtain attitude information from spacecraft $i+1$, and the arrows in Fig. 1 indicate the information flow. It is worth noting that the $(n+1)$ th spacecraft is referred to spacecraft 1. In addition, we also assume that there is a virtual leader, i.e., spacecraft 0, whose attitude is denoted by $q_d \in \mathbb{R}^{4 \times 1}$. Here, the attitude of spacecraft 0 is known and stable. As a virtual leader, spacecraft 0 provides global reference attitude q_d in real time and transmits reference instructions to spacecraft 1 to realize attitude tracking of multi-spacecraft formation system. A controller is designed for the n spacecrafts to achieve consensus and achieve the desired attitude transmitted by the virtual spacecraft.

The communication link is easily affected by many stochastic uncertain sources during information transmission, such as the stochastic interference of external environment, communication equipment, or communication protocol. The uncertainty of the communication link makes the communication link fail or reconstruct in a stochastic way, which will not only affect the control accuracy of the formation, but also affect the stability and coordination of multi-spacecraft formation flight.

In addition to the virtual leader, the connectivity of the communication link between each two spacecraft may be stochastic due to the influence of uncertain sources. This parameter $p_i(t) \in [0,1]$ is used to describe the probability that the state information of the spacecraft $i+1$ can be transmitted to the spacecraft i . In each transmission process, the state information of the spacecraft $i+1$ can be transmitted to the spacecraft i with the probability of $p_i(t)$, and cannot be transmitted to the spacecraft with the probability of $1-p_i(t)$. In addition, we define a stochastic binary variable $a_i(p)$ to describe the effectiveness of the link as follows:

$$a_i(p) = \begin{cases} 1 & \text{with probability } p_i(t) \\ 0 & \text{with probability } 1 - p_i(t) \end{cases}.$$

It indicates that $a_i(p) = 0$ if there is no information transfer between two spacecrafts with probability $1 - p_i(t)$, while $a_i(p) = 1$ means that the communication link from spacecraft $i+1$ to i is connected with probability $p_i(t)$.

The purpose of this paper is to design an attitude controller, so that the attitude of multi-spacecraft system subject to communication failure and external disturbances can achieve consensus and stabilize to a desired attitude with

$$\lim_{t \rightarrow \infty} (q_i - q_d) \xrightarrow{a.s.} 0_{4 \times 1},$$

$$\lim_{t \rightarrow \infty} (q_i - q_j) \xrightarrow{a.s.} 0_{4 \times 1},$$

$$\lim_{t \rightarrow \infty} \omega_i \xrightarrow{a.s.} 0_{3 \times 1}, \quad (2)$$

where $i, j \in \{1, 2, \dots, N\}$. It is worth noting that q_i and $-q_i$ stand for the same attitude.

5 Adaptive attitude consensus controller

In this section, we propose a control law, such that the attitude of the multi-spacecraft system is able to achieve attitude consensus under the communication topology as follows:

$$\tau_i = -\gamma Z(q_i)^\top a_i(p)(q_i - q_{i+1}) - k_i \operatorname{sgn}(\omega_i) - \hat{d}_{i,max} \frac{\omega_i}{\|\omega_i\|} \quad (3)$$

$$-\beta K Z(q_1)^\top (q_1 - q_d)$$

with

$$\beta = \begin{cases} 1 & \text{if } i = 1 \\ 0 & \text{if } i \in \{2, \dots, n\} \end{cases}, \quad (4)$$

where $\gamma, K \in \mathbb{R}_+$ are positive constants, $q_d \in \mathbb{R}^{4 \times 1}$ is the desired attitude of the virtual leader with the property that

$\dot{q}_d = 0$, the constant $k_i \in \mathbb{R}_+$ is designed later, $\hat{d}_{i,max} \in \mathbb{R}$ is the estimate of the boundary of disturbance torque, which is obtained by

$$\hat{d}_{i,max} = r \|\omega_i\|, \quad i \in \{1, 2, \dots, n\}, \quad (5)$$

where the constant $r \in \mathbb{R}_+$ determines the convergence rate of the parameter estimate. In the above proposed attitude controller, $-k_i \operatorname{sgn}(\omega_i)$ and $-\hat{d}_{i,max} \frac{\omega_i}{\|\omega_i\|}$ are discontinuous items, which are used to handle the parameter uncertainties and counteract effects of the external disturbances. In the controller, $q_i - q_{i+1}$ represents the relationship between spacecrafts and is used to reduce the error between spacecrafts. The term $-\beta K Z(q_1)^\top (q_1 - q_d)$ represents that when the virtual spacecraft 0 transmits the reference information q_d to the spacecraft 1, the error between the spacecraft 1 and the specified attitude q_d is adjusted in real time, and is used to make the attitude point to the same desired attitude q_d .

The main result of this paper is summarized in the following theorem:

Theorem 1 Under the described stochastic communication topology, the attitude of multi-spacecraft systems can almost surely achieve consensus under the controller designed above, if the following conditions are satisfied:

$$k_i > \gamma, \quad p_i(t) \neq 0, \quad i \in \{1, 2, \dots, N\}. \quad (6)$$

Proof To prove the Theorem 1, the sliding surface is selected as $s = \omega$, and a candidate Lyapunov function is constructed as follows:

$$\begin{aligned} V = & \frac{1}{2} \omega^\top J \omega + \frac{1}{2} \gamma q^\top (\mathcal{T}^\top \otimes I_4) q \\ & + \frac{1}{2r} \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max})^2 \\ & + \frac{K}{2} (q_1 - q_d)^\top (q_1 - q_d), \end{aligned} \quad (7)$$

where $\omega = [\omega_1^\top, \omega_2^\top, \dots, \omega_N^\top]^\top \in \mathbb{R}^{3N \times 1}$, $J = \operatorname{diag}(J_1, J_2, \dots, J_N) \in \mathbb{R}^{3N \times 3N}$, $q = [q_1^\top, q_2^\top, \dots, q_N^\top]^\top \in \mathbb{R}^{4N \times 1}$, and the variable \mathcal{T} is defined as

$$\mathcal{T} = \begin{bmatrix} 1 & -1 & 0 & \dots & 0 \\ 0 & 1 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -1 & 0 & 0 & \dots & 1 \end{bmatrix}.$$

In the foregoing Lyapunov condition, the term $\frac{1}{2} \gamma q^\top (\mathcal{T}^\top \otimes I_4) q$ represents the attitude errors between two

spacecrafts, the term $\frac{1}{2r} \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max})^2$ is the error between the boundary of the disturbance and its estimate, and the last term $\frac{K}{2}(q_1 - q_d)^\top(q_1 - q_d)$ describes the error between the attitude and the desired attitude.

Then, the time derivation of V is calculated to be

$$\begin{aligned}\dot{V} &= \omega^\top J\dot{\omega} + \gamma q^\top (T^\top \otimes I_4) \dot{q} \\ &+ \frac{1}{r} \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max}) \hat{d}_{i,max}^\top + K(q_1 - q_d)^\top \dot{q}_1.\end{aligned}\quad (8)$$

Substituting the equation of motion of multi-spacecraft into above yields

$$\begin{aligned}\dot{V} &= \omega^\top S(\omega) J\omega + \omega^\top \tau + \omega^\top d + \gamma q^\top (T^\top \otimes I_4) Z(q) \omega \\ &+ \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max}) ||\omega_i|| + K(q_1 - q_d)^\top Z(q_1) \omega_1,\end{aligned}\quad (9)$$

where the stacked variables $Z(q) = \text{diag}(Z(q_1), Z(q_2), \dots, Z(q_N))$, $S(\omega) = \text{diag}(S(\omega_1), S(\omega_2), \dots, S(\omega_N))$, $\tau = [\tau_1^\top, \tau_2^\top, \dots, \tau_N^\top]^\top$, and $d = [d_1^\top, d_2^\top, \dots, d_N^\top]$ are used. Since $S(\omega)$ is skew symmetric, one can further have that

$$\omega^\top S(\omega) J\omega = 0$$

$$\gamma q^\top (T^\top \otimes I_4) Z(q) \omega = \gamma \omega^\top Z(q)^\top (T \otimes I_4) q$$

$$K(q_1 - q_d)^\top Z(q_1) \omega_1 = K \omega_1^\top Z(q_1)^\top (q_1 - q_d).$$

Now, substituting the controller into \dot{V} results in

$$\begin{aligned}\dot{V} &= -\gamma \omega^\top Z(q)^\top (\mathcal{L}(p) \otimes I_4) q - \omega^\top (k \otimes I_3) \text{sgn}(\omega) \\ &- \sum_{i=1}^N \omega_i^\top \hat{d}_{i,max} \frac{\omega_i}{||\omega_i||} - K \omega_1^\top Z(q_1)^\top (q_1 - q_d) \\ &+ \omega^\top d + \gamma \omega^\top Z(q)^\top (T \otimes I_4) q \\ &+ \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max}) ||\omega_i|| + K \omega_1^\top Z(q_1)^\top (q_1 - q_d),\end{aligned}\quad (10)$$

where $k = \text{diag}(k_1, k_2, \dots, k_N)$ and a coupling matrix relating to the communication topology is

$$\mathcal{L}(p) = \begin{bmatrix} a_1(p) & -a_1(p) & 0 & \dots & 0 \\ 0 & a_2(p) & -a_2(p) & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -a_N(p) & 0 & 0 & \dots & a_N(p) \end{bmatrix}.$$

Then, the above equation can be rewritten as

$$\begin{aligned}\dot{V} &= \gamma \omega^\top Z(q)^\top ((T - \mathcal{L}(p)) \otimes I_4) q - \omega^\top (k \otimes I_3) \text{sgn}(\omega) \\ &- \sum_{i=1}^N \hat{d}_{i,max} ||\omega_i|| + \omega^\top d + \sum_{i=1}^N (\hat{d}_{i,max} - d_{i,max}) ||\omega_i||.\end{aligned}\quad (11)$$

Now, we define a vector $\mu = (\mu_1^\top, \mu_2^\top, \dots, \mu_N^\top)^\top = ((T - \mathcal{L}(p)) \otimes I_4) q \in \mathbb{R}^{4N \times 1}$, where

$$T - \mathcal{L}(p)$$

$$= \begin{bmatrix} 1 - a_1(p) & -1 + a_1(p) & 0 & \dots & 0 \\ 0 & 1 - a_2(p) & -1 + a_2(p) & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -1 + a_N(p) & 0 & 0 & \dots & 1 - a_N(p) \end{bmatrix}.$$

Consequently, we have

$$\begin{aligned}\dot{V} &= \gamma \omega^\top Z(q)^\top \mu - \omega^\top (k \otimes I_3) \text{sgn}(\omega) \\ &+ \omega^\top d - \sum_{i=1}^N d_{i,max} ||\omega_i|| \\ &= \sum_{i=1}^N \left(\gamma \omega_i^\top Z(q_i)^\top \mu_i - k_i \omega_i^\top \text{sgn}(\omega_i) + \omega_i^\top d_i - d_{i,max} ||\omega_i|| \right).\end{aligned}\quad (12)$$

Since $a_i(p) \in \{0, 1\}$, $||q_i|| = 1$, and $\|Z(q_i)^\top Z(q_i)\| = 1/4$, we can conclude that $\|Z(q_i)^\top \mu_i\| \leq 1$. As a result, it is clear that

$$\dot{V} \leq \sum_{i=1}^N \left(\gamma ||\omega_i|| - k_i \omega_i^\top \text{sgn}(\omega_i) + \omega_i^\top d_i - d_{i,max} ||\omega_i|| \right). \quad (13)$$

According to the assumption that $||d_i|| \leq d_{i,max}$ and $||\omega_i|| \leq \omega_i^\top \text{sgn}(\omega_i)$, we have

$$\dot{V} \leq \sum_{i=1}^N (\gamma - k_i) \omega_i^\top \text{sgn}(\omega_i). \quad (14)$$

From this inequality, we can see that as long as the condition $k_i > \gamma$ is satisfied, \dot{V} is negative semidefinite. By employing the generalized invariance principle, it is obtained that

$$\lim_{t \rightarrow \infty} \omega_i \equiv 0_{3 \times 1}, i \in \{1, 2, \dots, N\}. \quad (15)$$

Substituting the conclusion into the attitude dynamics model and controller leads to

$$\lim_{t \rightarrow \infty} Z(q_i)^\top a_i(p)(q_i - q_{i+1}) = 0_{3 \times 1}, i \in \{2, \dots, N\}. \quad (16)$$

Since $Z(q_i) \in \mathbb{R}^{4 \times 3}$ and $Z(q_i)^\top Z(q_i) = \frac{1}{4}I_3$, it can be obtained that $\text{rank}(Z(q_i)^\top) = 3$. Therefore, the following conclusion can be drawn:

$$a_i(p)(q_i - q_{i+1}) \in \text{Null}\left(Z(q_i)^\top\right).$$

Moreover, $Z(q_i)$ satisfies $Z(q_i)^\top q_i = 0$. As a consequence, we can transform the above condition as follows:

$$\lim_{t \rightarrow \infty} a_i(p)(q_i - q_{i+1}) = \eta_i q_i, \quad (17)$$

where η_i is a constant. Due to that $a_i(p)$ is uncertain, we make use of expectation to deal with the formula on both sides

$$\lim_{t \rightarrow \infty} \mathbb{E}\{a_i(p)(q_i - q_{i+1})\} = \mathbb{E}\{\eta_i q_i\}. \quad (18)$$

According to the property of expectation, we further have

$$\lim_{t \rightarrow \infty} \mathbb{E}\{a_i(p)\}(q_i - q_{i+1}) = \eta_i q_i,$$

which results in

$$\lim_{t \rightarrow \infty} (\mathbb{E}\{a_i(p)\} - \eta_i) q_i - \mathbb{E}\{a_i(p)\} q_{i+1} = \mathbf{0}_{4 \times 1}. \quad (19)$$

Because of the definition of $a_i(p)$, we have

$$\mathbb{E}\{a_i(p)\} = 1 \times p_i + 0 \times (1 - p_i) = p_i,$$

where $p_i(t)$ denotes the probability of the connection between agents. If $p_i(t) \neq 0$, we can obtain that

$$\mathbb{E}\{a_i(p)\} \neq 0.$$

Thus, we have

$$\lim_{t \rightarrow \infty} ((1 - \mathbb{E}\{a_i(p)\})^{-1} \eta_i) q_i - q_{i+1} = \mathbf{0}_{4 \times 1}.$$

It also can be rewritten as follows:

$$\lim_{t \rightarrow \infty} ((1 - \mathbb{E}\{a_i(p)\})^{-1} \eta_i) q_i^\top - q_{i+1}^\top = \mathbf{0}_{1 \times 4}.$$

Multiplying $(1 - \mathbb{E}\{a_i(p)\})^{-1} \eta_i$ on both sides, it can be transformed into

$$\lim_{t \rightarrow \infty} ((1 - \mathbb{E}\{a_i(p)\}) - \eta_i)^2 q_i^\top q_i - q_{i+1}^\top q_{i+1} = \mathbf{0}_{1 \times 4}. \quad (20)$$

On account of unit-quaternion vector satisfying the property $q_i^\top q_i = 1$ and $q_{i+1}^\top q_{i+1} = 1$, we have

$$\lim_{t \rightarrow \infty} \left(1 - \mathbb{E}\{a_i(p)\}^{-1} \eta_i\right)^2 = 1.$$

Hence, we can obtain two situations based on above condition

$$\lim_{t \rightarrow \infty} \eta_i = 0 \quad (21)$$

or

$$\lim_{t \rightarrow \infty} \eta_i = 2\mathbb{E}\{a_i(p)\}. \quad (22)$$

Then, we analyze the two situations, respectively:

1) For the first situation:

If η_i satisfies the equation $\lim_{t \rightarrow \infty} \eta_i = 0$, then we have

$$\lim_{t \rightarrow \infty} \mathbb{P}\{|q_i - q_{i+1}| > \varepsilon\} = 0. \quad (23)$$

Now, we define filtration $\mathcal{F}_t = \{[q(\rho)^\top \omega(\rho)^\top], 0 < \rho < t\}$. The following three conditions can be obtained in the first situation:

- a) For spacecraft 2, ..., N, owing to that the external disturbance has been compensated, we regard Lyapunov candidate $V(t) = \frac{1}{2}\omega^\top J\omega + \frac{1}{2}\gamma q^\top (T^\top \otimes I_4)q$ as a stochastic process. $V(t)$ is \mathcal{F}_t -measurable for each time t . Apart from $q(t)$ and $\omega(t)$, $V(t)$ is also determined by their history, so $V(t)$ only depends on $\{\mathcal{F}_s, 0 \leq s \leq t\}$. As a consequence, $V(t)$ is adapted to the filtration \mathcal{F}_t .
- b) Because of the time derivation of Lyapunov candidate $\dot{V}(t) \leq 0$, $V(t)$ is getting smaller. In addition, $q(t)$ and $\omega(t)$ are bounded; consequently, $V(t)$ is also bounded. Thus, we know that $\mathbb{E}\{V(t)\}$ is also bounded.
- c) Due to that $\dot{V}(t) \leq 0$, we know $V(t) \leq V(s)$ if $t \geq s$. In view of the fact that $V(t)$ is measurable for each t and the property of expectation, we have

$$\mathbb{E}\{V(t)|\mathcal{F}_s\} \leq V(s), t \geq s.$$

As a consequence, the above conditions yield that $V(t)$ is a super-martingale. Then, making use of the conclusion in Lemma 1, we know that

$$\lim_{t \rightarrow \infty} V(t) \rightarrow V_f, \quad (24)$$

where V_f is a finite nonnegative real number. From the equation $V(t) = \frac{1}{2}\omega^\top J\omega + \frac{1}{2}\gamma q^\top (T^\top \otimes I_4)q$ and $\lim_{t \rightarrow \infty} \omega_i = \mathbf{0}_{3 \times 1}$, it is clear that

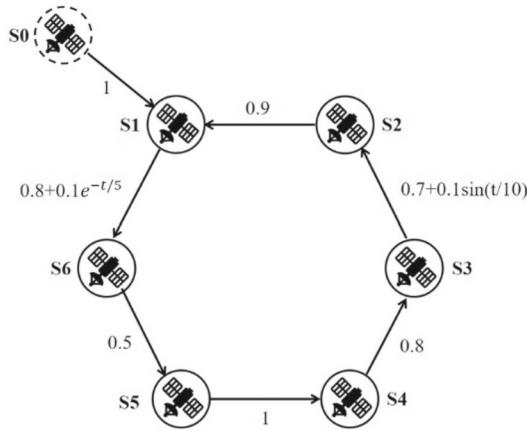


Fig. 2 The probabilities of the connectivity of the multi-spacecraft systems

Table 1 Initial conditions of each spacecraft

Spacecraft	q_i^\top	ω_i^\top [rad/s]
S1	$[\sqrt{2}/2 - \sqrt{2}/200]$	$[0.1 - 0.050.2]$
S2	$[-0.6 \ 0 \ 0 \ -0.8]$	$[0.0060.2]$
S3	$[-0.5 \ 0.5 \ 0.5 \ 0.5]$	$[-0.02 - 0.05 - 0.1]$
S4	$[0 \ 0 \ -1 \ 0]$	$[0.100.04]$
S5	$[0.5 \ -0.5 \ -0.5 \ 0.5]$	$[-0.01 - 0.030.1]$
S6	$[0 \ 1 \ 0 \ 0]$	$[0 - 0.1 - 0.1]$

$$\lim_{t \rightarrow \infty} \frac{1}{2} \gamma q^\top (\mathcal{T}^\top \otimes I_4) q \xrightarrow{a.s.} V_f. \quad (25)$$

Due to the fact that $\frac{1}{2} \gamma q^\top (\mathcal{T}^\top \otimes I_4) q$ is the attitude errors between space crafts and $\lim_{t \rightarrow \infty} \mathbb{P}\{||q_i - q_{i+1}|| > \varepsilon\} = 0$, it follows that $V_f = 0$. Therefore, we have

$$\lim_{t \rightarrow \infty} (q_i - q_{i+1}) \xrightarrow{a.s.} 0, \forall i = 1, \dots, n. \quad (26)$$

It also can be said that

$$\mathbb{P}\left\{\lim_{t \rightarrow \infty} (q_i - q_{i+1}) = 0\right\} = 1, \forall i = 1, \dots, n, \quad (27)$$

which implies that the attitude errors between space crafts almost surely converge to zero.

2) For the second situation:

If η_i satisfies the equation $\lim_{t \rightarrow \infty} \eta_i = 2\mathbb{E}\{a_i(p)\}$, then we have

$$\lim_{t \rightarrow \infty} \mathbb{P}\{||q_i + q_{i+1}|| > \varepsilon\} = 0. \quad (28)$$

We also define a filtration $\mathcal{F}_t = \{[q(\rho)^\top \omega(\rho)^\top], 0 < \rho < t\}$. Similar to the first situation, the following three conditions can be obtained:

a) We regard Lyapunov candidate $\bar{V}(t) = \frac{1}{2} \omega^\top J \omega + \frac{1}{2} \gamma q^\top (M^\top \otimes I_4) q$ as a stochastic process with

$$M = \begin{bmatrix} 1 & 1 & 0 & \dots & 0 \\ 0 & 1 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & \dots & 1 \end{bmatrix}.$$

$\bar{V}(t)$ is \mathcal{F}_t -measurable for each time t and is also adapted to the filtration \mathcal{F}_t .

- b) $\mathbb{E}\{\bar{V}(t)\}$ is also bounded.
- c) In addition, we can get that

$$\mathbb{E}\{\bar{V}(t)|\mathcal{F}_s\} \leq \bar{V}(s), t \geq s.$$

As a consequence, the above conditions yield that $\bar{V}(t)$ is a super-martingale. Then, making use of the conclusion in Lemma 1, we know that

$$\lim_{t \rightarrow \infty} \bar{V}(t) \rightarrow \bar{V}_F, \quad (29)$$

where \bar{V}_F is a finite nonnegative real number. Combined with the Lyapunov candidate and the conclusion $\lim_{t \rightarrow \infty} \omega_i = \mathbf{0}_{3 \times 1}$, it yields that

$$\lim_{t \rightarrow \infty} \frac{1}{2} \gamma q^\top (M^\top \otimes I_4) q \xrightarrow{a.s.} \bar{V}_F. \quad (30)$$

Due to the fact that $\frac{1}{2} \gamma q^\top (M^\top \otimes I_4) q$ is with respect to $(q_i + q_{i+1}), \forall i = 1, \dots, n$ and $\lim_{t \rightarrow \infty} \mathbb{P}\{||q_i + q_{i+1}|| > \varepsilon\} = 0$, it follows that $\bar{V}_F = 0$. Therefore, we have

$$\lim_{t \rightarrow \infty} (q_i + q_{i+1}) \xrightarrow{a.s.} 0, \forall i = 1, \dots, n. \quad (31)$$

It also can be said that

$$\mathbb{P}\left\{\lim_{t \rightarrow \infty} (q_i + q_{i+1}) = 0\right\} = 1, \forall i = 1, \dots, n, \quad (32)$$

which implies that the attitude errors between space crafts almost surely converge to zero. It means that spacecraft $i + 1$ can transfer information to spacecraft i , and spacecraft i

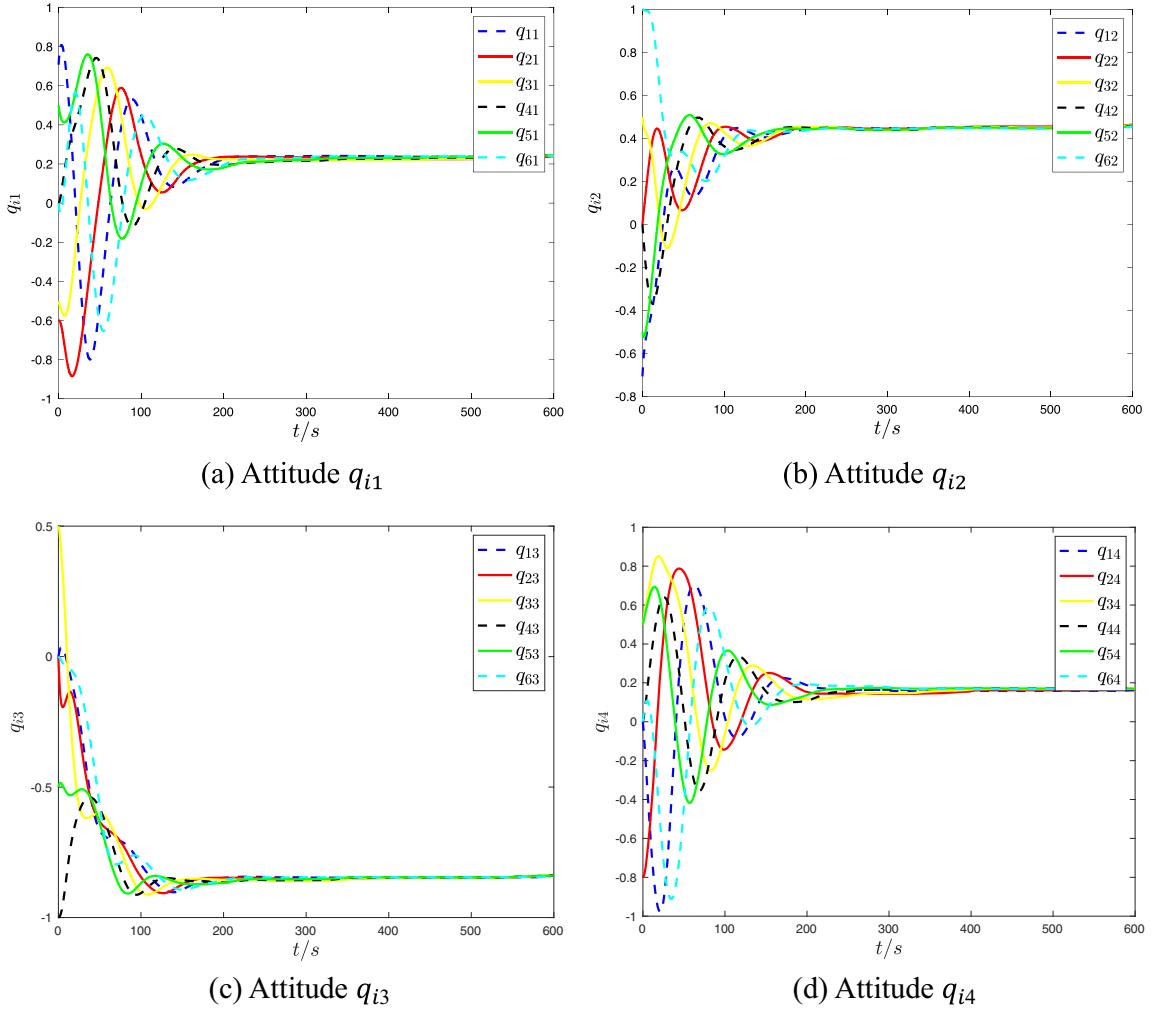


Fig. 3 Attitude under the proposed attitude controller

is capable of tracking spacecraft $i + 1$, resulting in attitude consensus.

Since $Z(q_1)$ satisfies the property $Z(q_1)^\top q_1 = 0$, we have

$$\lim_{t \rightarrow \infty} Z(q_1)^\top q_d = \mathbf{0}_{3 \times 1}. \quad (33)$$

Hence, we know that $\text{Null}(Z(q_1)^\top) = \bar{\eta}_1 q_d$ with $\bar{\eta}_1$ being a constant. As a result, we obtain that as $t \rightarrow \infty$, we have

$$qd = \eta_1 q_1.$$

Since $\|q_d\|=1$ and $\|q_1\|=1$, we can further obtain $\eta_1=1$. Therefore, it is clear that

$$\lim_{t \rightarrow \infty} (q_1 - q_d) \rightarrow \mathbf{0}_{4 \times 1}. \quad (34)$$

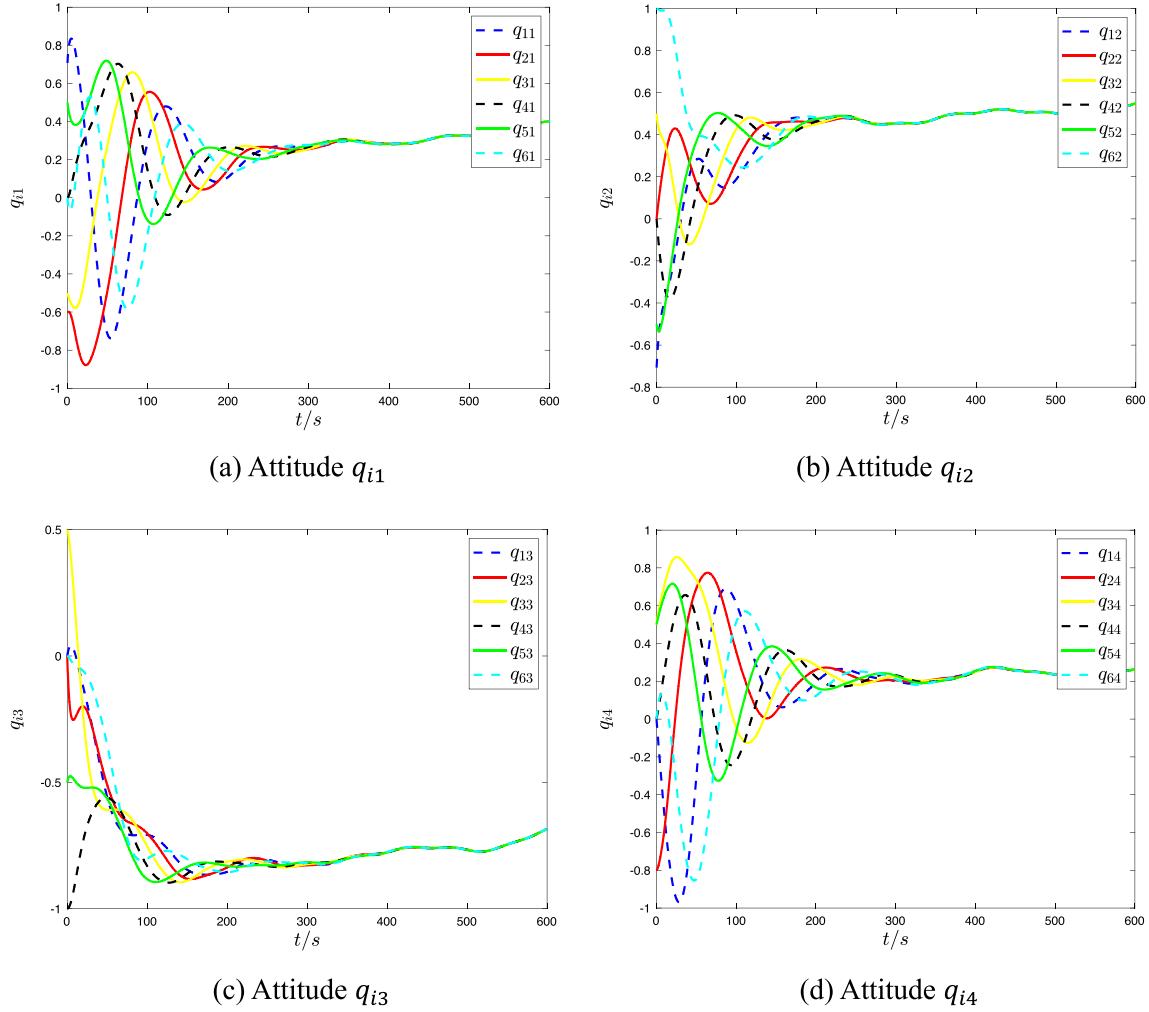
Moreover, since $\lim_{t \rightarrow \infty} (q_i - q_{i+1}) \xrightarrow{a.s.} 0$, $\forall i = 1, \dots, n$, it is obtained that

$$\lim_{t \rightarrow \infty} (q_i - q_d) \xrightarrow{a.s.} 0_{4 \times 1}, \forall i = 1, \dots, n. \quad (35)$$

This implies that the attitude errors between spacecrafts and the virtual spacecraft almost surely converge to zero, and all spacecrafts are capable of achieving the desired attitude almost surely. This completes the proof.

6 Simulation results

In this section, we carry out a numerical simulation of a multi-spacecraft system including six spacecrafts in a ring topology to verify the effectiveness of the proposed adaptive sliding-mode control law and analyze its performance. For each spacecraft in the system, the inertia matrix and external

**Fig. 4** Attitude under the existing controller in 21

disturbances are assumed as follows:

$$J_i = \begin{bmatrix} 60 & 0 & -5 \\ 0 & 65 & 0 \\ -5 & 0 & 70 \end{bmatrix} \text{kg} \cdot \text{m}^2, i \in \{1, 2, \dots, 6\}$$

$$d_i = 10^{-2} \begin{pmatrix} -1 + 3 \sin(0.1t + \frac{\pi}{2}) + 4 \sin(0.03t) \\ 1.5 - 1.5 \sin(0.02t) - 3 \sin(0.05t + \frac{\pi}{2}) \\ 1 + 2 \sin(0.1t) - 1.5 \sin(0.04t + \frac{\pi}{2}) \end{pmatrix},$$

$$i \in \{1, 2, \dots, 6\}.$$

The probabilities of information transmission between six spacecrafts and a virtual spacecraft are shown in Fig. 2. The communication probability can be the same or different, constant or time-varying. That is to say, the stochastic communication failure of each link is independent and indeterministic. The initial attitudes and initial angular velocities are illustrated in Table 1. For the proposed controller, the control gains are selected with $\gamma = 65$, $K = 110$, $k_i = 65$,

$r = 0.02$, $i \in \{1, 2, \dots, 6\}$. The desired attitude of the virtual is set as $q_d = [0.1105, -0.468, -0.854, 0.1433]^\top$. In the following, two simulation cases are considered.

6.1 Case 1: attitude consensus of multi-spacecraft system without a virtual leader

For comparison, the attitude controller in 21 is also simulated. To have a fair comparison, the leaderless attitude consensus of the multi-spacecraft system is considered in Case 1, as follows:

$$\tau_i = -\gamma Z(q_i)^\top a_i(p)(q_i - q_{i+1}) - k_i \operatorname{sgn}(\omega_i) - \hat{d}_{i,\max} \frac{\omega_i}{\|\omega_i\|}. \quad (36)$$

As shown in Figs. 3 and 4, the attitude errors among spacecrafts under the proposed controller can gradually converge to the common attitude with a high accuracy, while

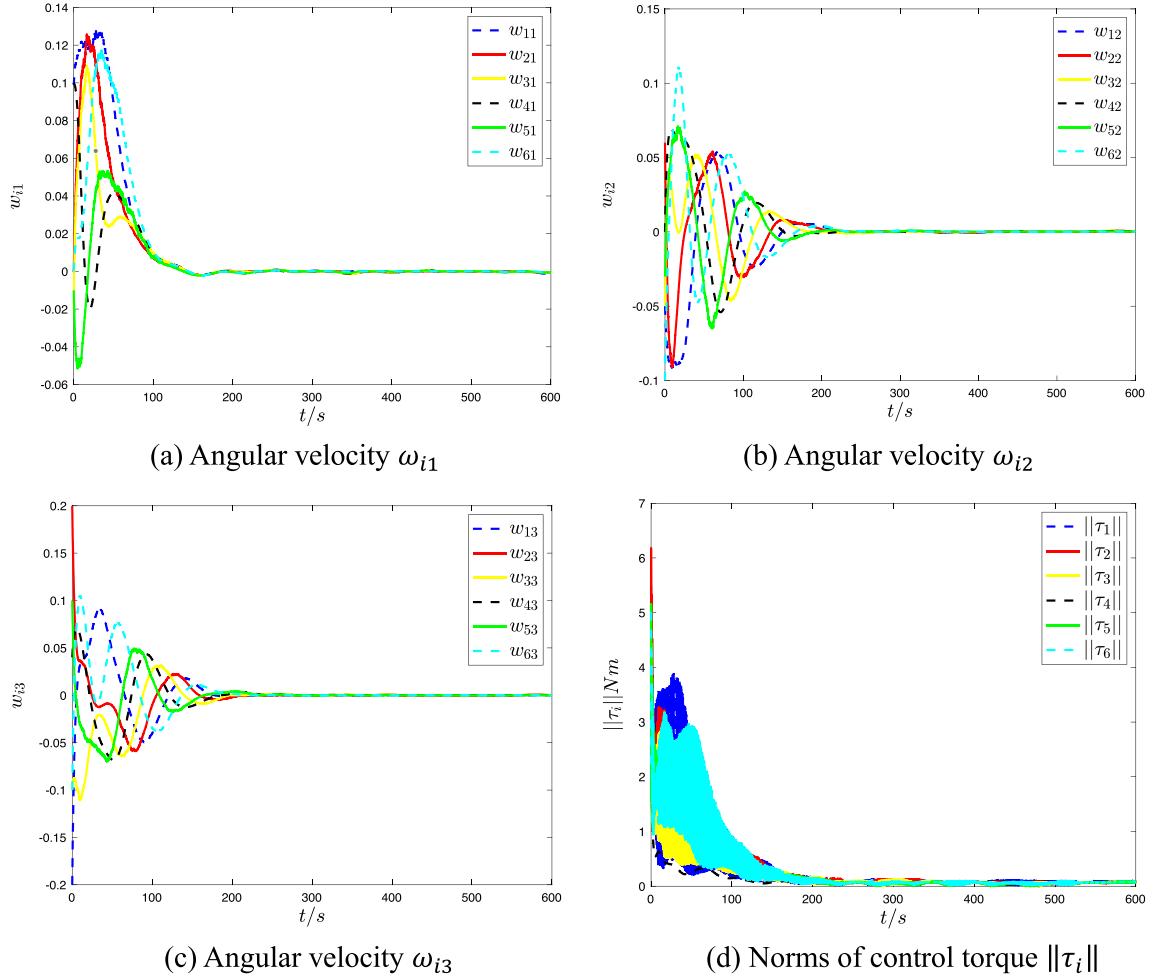


Fig. 5 Angular velocities and norms of control inputs under the proposed attitude controller

the steady-state consensus errors under the existing controller in [21] are much worse than that under our proposed approach. This is due to the fact that the existing controller in [21] does not consider external disturbances in the design process, and hence has limited robustness. The time history of angular velocity and norm of the commanded control torque of each spacecraft in the topology under the two controllers are depicted in Figs. 5 and 6, from which it is clear that the proposed attitude consensus control approach achieves better angular velocity convergence accuracy than that of the existing control approach in [21].

From Table 2, we can see the difference of impact made by proposed control vs existing one of multi-spacecraft system without a virtual leader in case 1. Compared with the stable attitude in [21], the controller we proposed can make the attitude converge to a stable value and the angular velocity converge to 0. However, the controller in [21] cannot converge to a stable value, the angular velocity will fluctuate. Therefore, the relative errors under the existing controller in [21] are much worse than that under our proposed approach and

the proposed attitude consensus control approach achieves better angular velocity convergence accuracy than that of the existing control approach in [21]. It means that the proposed controller can better suppress the adverse impact caused by disturbance.

6.2 Case 2: attitude consensus of multi-spacecraft system with a virtual leader

In this case, we consider the spacecraft topology that there is a virtual leader connected with the spacecraft 1, as the topology shown in Fig. 2. Under this spacecraft topology, the time history of the attitude with each spacecraft is shown in Fig. 7. We can see that the proposed controller can ensure the asymptotic convergence of attitude errors between follower spacecrafts and the virtual spacecraft. Figure 8 shows the angular velocity and the norms of the commanded control torques of each spacecraft. With proposed controller, we can see that the angular velocity of the multi-spacecraft system tends to be stable over time. In the simulation, the control

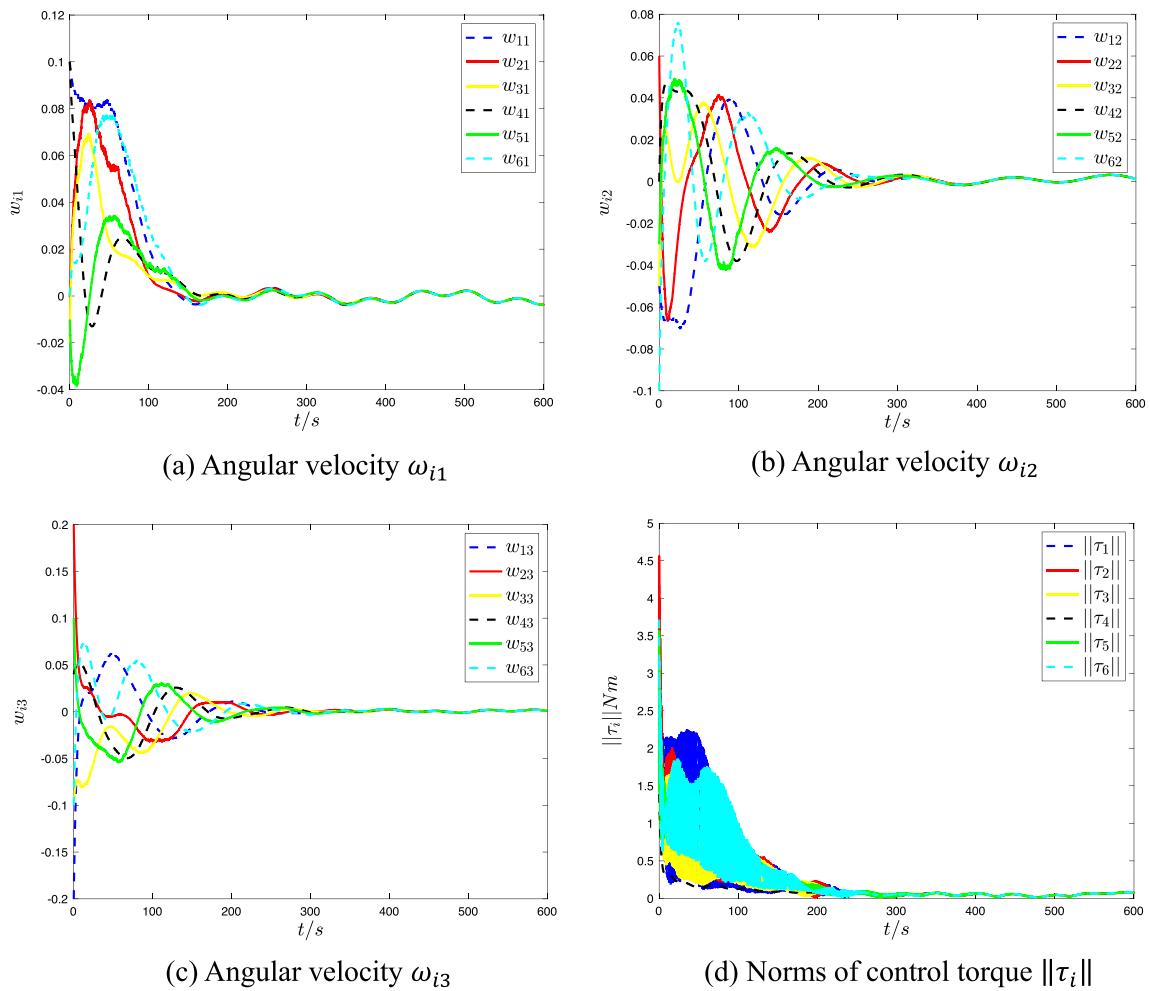


Fig. 6 Angular velocities and norms of control inputs under the existing controller in [21]

Table 2 Comparison of [21] and proposed controller under disturbance

	Relative attitude error				Relative angular velocity error		
	q_{i1}	q_{i2}	q_{i3}	q_{i4}	ω_{i1}	ω_{i2}	ω_{i3}
[21]	0.114	0.096	0.108	0.035	0.003	0.003	0.001
Proposed scheme	0.001	0.005	0.002	0.002	0.001	0.001	0.0001

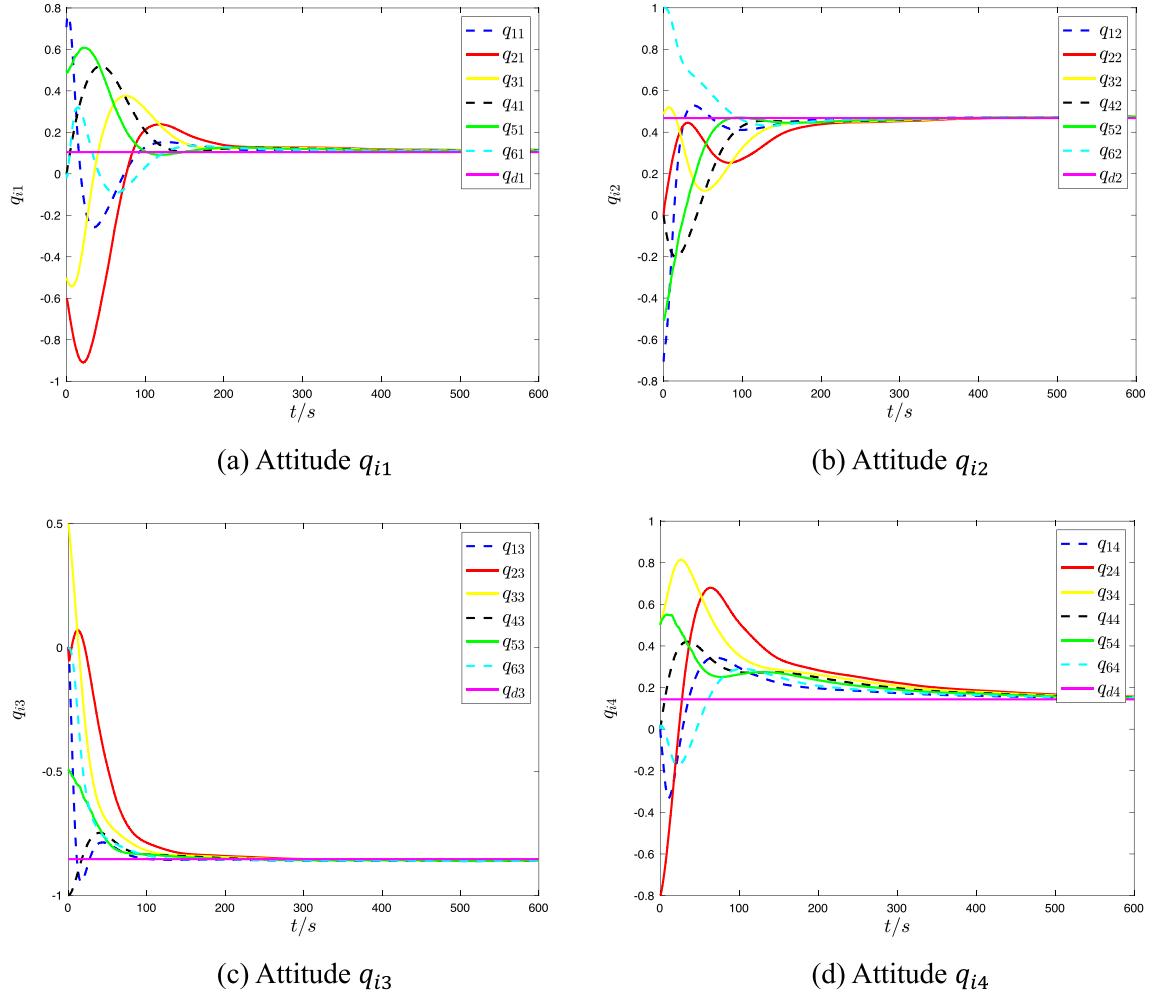


Fig. 7 Attitude under the proposed attitude controller when there is a virtual leader in the topology

torque curve of each follower spacecraft is shown. In addition, it can be observed that the control torque is only large in the initial stage and there is a certain oscillation. When the attitude consensus errors become small, the control torque can be kept in a small range. Due to the physical limitation of actuators, we add a constraint that the control input torque cannot exceed $10N \cdot m$ in the simulation process.

7 Conclusion and future work

An adaptive attitude consensus control strategy is proposed for multi-spacecraft systems subject to stochastic communication link failure and environmental disturbances. The

spacecraft topology of interest is made up with multiple follower spacecrafts and a virtual leader. Taking advantages of the sliding-mode control technique and super-martingale convergence theorem, the proposed adaptive attitude controller guarantees that the attitudes of all follower spacecrafts almost surely converge to a desired attitude in spite of the disturbances and indeterministic information exchange channels. Simulation results for a group of six spacecrafts with a virtual leader are shown to validate the proposed attitude consensus controller with an improved performance. In the future, input saturation, inertia uncertainties, and a more general communication topology can be incorporated in the adaptive stochastic attitude consensus controller design.

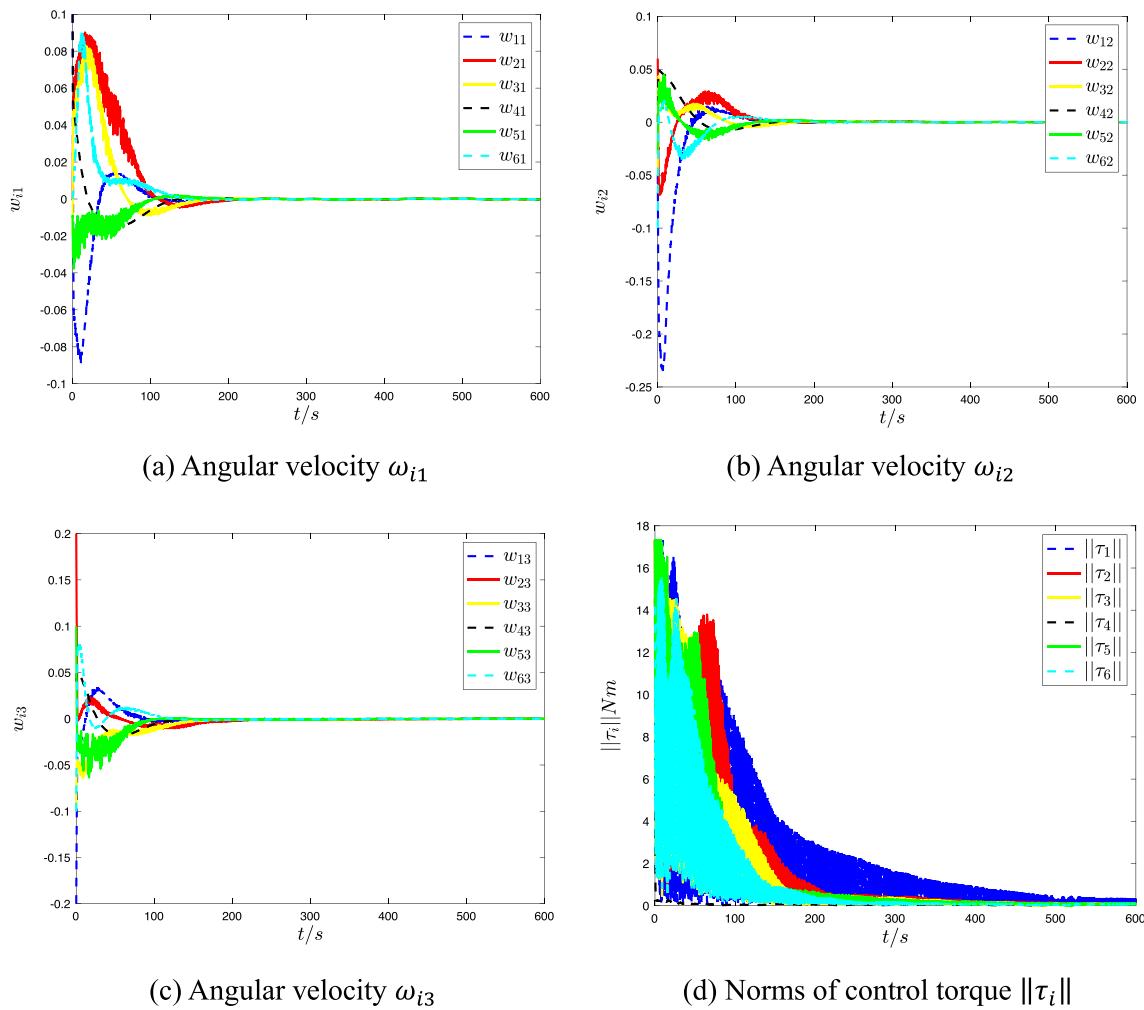


Fig. 8 Angular velocity and norms of the control torque under the proposed attitude controller when there is a virtual leader in the topology

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Declaration

Conflict of interest The authors have not disclosed any competing interests.

References

1. Liang H, Wang J, Sun Z (2011) Robust decentralized coordinated attitude control of spacecraft formation. *Acta Astronaut* 69(5):280–288
2. Liu X, Guo Y, Lu P (2014) Robust attitude coordination control for satellite formation with matched perturbations and measurement noises. In: 2014 American control conference, pp 3893–3898
3. Ma C, Zeng Q, Zhao X (2015) Distributed adaptive attitude synchronization for spacecraft formation flying with sampled-data information flows. *J Franklin Inst* 352(7):2796–2809
4. Zhu Z, Guo Y (2019) Adaptive coordinated attitude control for spacecraft formation with saturating actuators and unknown inertia. *J Franklin Inst* 356(2):1021–1037
5. Zhang C, Wang J, Zhang D, Shao X (2019) Synchronization and tracking of multi-spacecraft formation attitude control using adaptive sliding mode. *Asian J Control* 21(2):832–846

6. Zhao L, Jia Y (2016) Neural network-based distributed adaptive attitude synchronization control of spacecraft formation under modified fast terminal sliding mode. *Neurocomputing* 171:230–241
7. Zou A-M, Kumar KD (2012) Neural network-based distributed attitude coordination control for spacecraft formation flying with input saturation. *IEEE Trans Neural Netw Learn Syst* 23(7):1155–1162
8. Hu Q, Zhang J, Friswell MI (2015) Finite-time coordinated attitude control for spacecraft formation flying under input saturation. *J Dyn Syst Meas Control* 137:061012
9. Zou A-M, de Ruiter AHJ, Kumar KD (2016) Distributed finite-time velocity-free attitude coordination control for spacecraft formations. *Automatica* 67:46–53
10. Cai H, Huang J (2017) Leader-following attitude consensus of multiple rigid body systems by an adaptive distributed observer approach. *IFAC-PapersOnLine* 50(1):15446–15451
11. Du H, Chen MZQ, Wen G (2016) Leader-following attitude consensus for spacecraft formation with rigid and flexible spacecraft. *J Guid Control Dyn* 39(4):944–951
12. Lee D (2018) Nonlinear disturbance observer-based robust control for spacecraft formation flying. *Aerospace Sci Technol* 76:82–90
13. Boskovic JD, Li S-M, Mehra RK (2004) Robust tracking control design for spacecraft under control input saturation. *J Guidance Control Dyn* 7:627
14. Cong B-L, Liu X-D, Chen Z (2011) Distributed attitude synchronization of formation flying via consensus-based virtual structure. *Acta Astronaut* 68(11–12):1973–1986
15. Wang Q, Duan Z, Lv Y (2018) Distributed attitude synchronization control for multiple flexible spacecraft without modal variable measurement
16. Xu C, Wu B, Wang D, Zhang Y (2020) Distributed fixed-time output-feedback attitude consensus control for multiple spacecraft. *IEEE Trans Aerosp Electron Syst* 56(6):4779–4795
17. Li S, Du H, Shi P (2014) Distributed attitude control for multiple spacecraft with communication delays. *IEEE Trans Aerosp Electron Syst* 50(3):1765–1773
18. Lyu J, Gao D (2014) Attitude synchronization for multiple spacecraft with input constraints. *Chin J Aeronaut* 27(2):321–327
19. Min H, Wang S, Sun F, Gao Z, Zhang J (2012) Decentralized adaptive attitude synchronization of spacecraft formation. *Syst Control Lett* 61(1):238–246
20. Rezaee H, Abdollahi F (2017) Almost sure attitude consensus in multispacecraft systems with stochastic communication links. *IFAC-PapersOnLine* 50(1):9392–9397
21. Rezaee H, Abdollahi F (2020) Robust attitude alignment in multispacecraft systems with stochastic links failure. *Automatica* 118:109033
22. Bauer H (1981) Probability theory and elements of measure theory. Academic Press, London

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