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Research article

Neural networks-based event-triggered consensus control for nonlinear multiagent systems with communication link faults and DoS attacks

Yanming Wu[1,*], Zelun Wang[1], Guanglei Meng[1] and Jinguo Liu[2]

[1] College of Automation, Shenyang Aerospace University, Shenyang 110135, China
[2] State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China

* **Correspondence:** Email: yanmingwu@yeah.net; Tel: +008602489728773.

Abstract: This paper investigates the consensus control problem for a class of nonlinear multi-agent systems (MASs) with communication link faults and denial-of-service (DoS) attacks. First, considering simultaneously the communication link faults and DoS attacks, an adaptive event-triggered control strategy of MASs is proposed based on distributed adjacency error signals, and the avoidance of the Zeno phenomenon is analyzed. In addition, the unknown nonlinear functions can be approximated by the RBF neural networks. Then, based on Lyapunov stability analysis and induction, it is proved that all signals of MASs are uniformly ultimately bounded (UUB). Finally, the effectiveness of the proposed control scheme is verified by a simulation example.

Keywords: neural networks; event-triggered; multi-agent systems; communication link faults; DoS attacks

1. Introduction

The MASs have the advantages of a wide monitoring area, strong operation ability, and strong processing ability for complex tasks, which further attracts the interest of researchers [1–8]. Consensus control has always been an extremely important research topic of MASs, and has been widely used in practical projects, such as unmanned aerial vehicles [9], robots [10], smart grids [11], solar sailing [12], etc. Generally speaking, the consensus control problems of MASs are mainly divided into two types: leaderless and leader-follower.

With the tasks of MASs becoming more and more complex, the possibility of faults in the system is increasing. If a fault occurs in MASs, it will lead to serious and even irreversible consequences. This makes consensus control for MASs with faults becoming a vital research direction. At present, the faults research of MASs is mainly for internal component faults, such as sensor faults and actuator faults [13–19]. In [14], a new distributed fault-tolerant consensus tracking controller is proposed for MASs with abrupt and incipient actuator faults under fixed and switching topology. In [19], a class of fractional-order (FO) nonlinear MASs with serious sensor/actuator faults and time-varying delays is studied, and a new adaptive controller is designed to achieve consensus control. However, communication link faults usually occur in the information exchange between agents, which will seriously affect the stability and security of MASs. Therefore, the research on consensus control of MASs with communication link faults has also become a hot issue, which has attracted much attention from scholars. Currently, there is some research on the communication link faults of MASs. In [20] and [21], the resilience control problem is transformed into the design of distributed state observers, which solves the synchronous resilience control problem of MASs with unknown communication link faults. In [22], considering the communication faults between agents and their neighbors, the problem of adaptive distributed event-triggered fault-tolerant consensus for a class of MASs with time delays and external disturbances is solved. For nonlinear MASs with communication faults and asymmetric input saturation, an adaptive dynamic event-triggered cooperative control scheme is proposed in [23]. In addition, it is worth mentioning that the research in the above references does not consider the situation that the system suffers from cyber attacks. In practical applications, the interconnection characteristics of MASs make them vulnerable to cyber attacks, which leads to system performance degradation. If the cyber attacks the communication network for a long time, it may cause the communication link faults for MASs. When communication link faults and cyber attacks occur simultaneously, it leads to a rapid decline in the performance of MASs. Therefore, the research of MASs under communication link faults and cyber attacks is particularly important [24–26].

The main types of cyber attacks include denial-of-service (DoS) attacks [27] and deception attacks [28]. For DoS attacks, periodic or pulse width-modulated attacks are the simple type. From the viewpoint of energy constraints, periodic signals are easy to implement and represent a main type of jamming signal studied in the communications literature, such as the TCP protocol [29]. At present, consensus control of MASs under DoS attacks has led to many research achievements [30–32]. However, each agent is usually equipped with limited communication resources. In order to prolong the service life of the system, it is necessary to reduce the frequency of communication between agents. Compared with continuous communication between agents, event-triggered control strategy can effectively avoid the waste of communication resources, which is more practical [33–35]. Some scholars have proposed an event-triggered control strategy and achieved some results in view of the simultaneous existence of DoS attacks and faults in MASs. In [36], a class of stochastic nonlinear high-order MASs subject to DoS attacks and actuator faults is investigated, and a new fault-tolerant and antiattack security control method based on adaptive event-triggered is proposed. The author in [37] studies a class of heterogeneous nonlinear second-order MASs subject to DoS attacks, actuator faults, and integral quadratic constraints (IQC) and designs an event-triggered adaptive fault-tolerant migration control scheme to achieve cluster consensus. In [38], for a class of high-order uncertain nonlinear MASs with DoS attacks and actuator faults, a novel event-triggered controller based on the reliable attack detection mechanism is designed by the backstepping method. However, the references [36–38] focus on the faults of internal components in MASs under DoS attacks. However, in the aforementioned results, some references have concentrated on the DoS attacks and actuator faults of MASs. In the face of complex network environments, communication link faults are impossible to avoid. Especially, DoS attacks may increase the possibility of communication link faults. How to design the consensus control strategy for nonlinear MASs with communication link faults and DoS attacks is still a significant and challenging problem.

Based on the above analysis, this paper investigates the consensus control of a class of nonlinear MASs with communication link faults and DoS attacks. Specifically, the main contributions are as follows: In this paper, an event-triggered mechanism based on distributed adjacency error signals is designed. The main contributions of this paper are given as follows: 1) For communication link faults and DoS attacks, an adaptive event-triggered control strategy is proposed to ensure that all signals of MASs are uniformly ultimately bounded. 2) The effective factor of communication link faults is unknown. Compared with [22], the results of this paper are more general. In addition, different from the existing research [20–22], this paper proposes an adaptive event-triggered control strategy to solve simultaneous communication link faults and DoS attacks so that MASs can achieve consensus control in an insecure network environment.

The remainder of this article is organized as follows: In Section 2, the problem statement and some preliminaries are given. Section 3 gives the main results. A numerical example is introduced in Section 4. A conclusion is drawn in Section 5.

Notations: For a square matrix $P \in R^{n\times n}$, the maximal and minimum eigenvalues of P are defined as $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$, respectively. $\otimes$ is the kronecker product. I_n is the identity matrix. $\|\cdot\|$ signifies the 2-norm of vectors or matrices. The symbol diag[.] is a diagonal matrix.

2. Preliminaries and problem statement

2.1. Graph theory

The communications among agents are indispensable to ensuring the normal operation of MASs. Graph theory is usually used to represent the communication topology between agents. An undirected graph with N nodes can be described as $\mathscr{G}(v, \varepsilon, \mathscr{A})$, where $v = \{v_1, v_2, \ldots, v_N\}$ is the node set and $\varepsilon = \left\{(v_i, v_j) | i \neq j, v_i, v_j \in v\right\}$ is the edge set, and $\mathscr{A} = \left[a_{ij}\right] \in R^{N\times N}$ is the weighted adjacency matrix, where $a_{ji} > 0$, if $(v_i, v_j) \in v$, and $a_{ji} = 0$ otherwise, $a_{ii} = 0$. The degree matrix is defined as $\mathscr{D} = \text{diag}\{d_1, d_2, \ldots, d_N\} \in R^{N\times N}$, where $d_i = \sum_{j=1}^{N} a_{ij}$. Define $\mathscr{L} = \left[l_{ij}\right] \in R^{N\times N}$ as the Laplacian matrix of the graph $\mathscr{G}$, and $\mathscr{L} = \mathscr{D} - \mathscr{A}$. In this paper, a group of $N+1$ agents has N followers and labels the leader node as node 0. If there is a directed edge from the leader to i-th follow, then $b_{i0} > 0$, otherwise $b_{i0} = 0$. Then, the adjacency matrix for the leader is defined as $\mathscr{B} = \text{diag}\{b_{10}, b_{20}, \ldots, b_{N0}\} \in R^{N\times N}$. Furthermore, define a matrix $H = \mathscr{L} + \mathscr{B}$.

Lemma 1 [39]: Assume that the undirected graph $\mathscr{G}$ is connected and at least one follower can obtain information from the leader. If $H = \mathscr{L} + \mathscr{B}$, then $H > 0$.

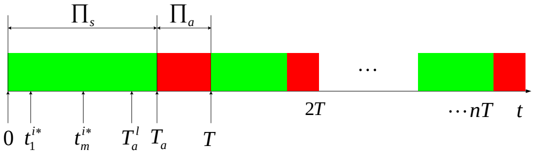

Figure 1. DoS attack strategy based on time sequence.

2.2. Problem statement

Considering a class of nonlinear MASs with a leader and N followers, the i-th agent can be described in the following form.

$$\dot{x}_i(t) = f_i(x_i(t)) + q_i(x_i(t))\,u_i(t) + d_i(t) \tag{2.1}$$

where $i = 1, 2, \ldots, N$. $x_i(t) \in R^n$ and $u_i(t) \in R^n$ are represent the state and control input of the i-th agent, respectively. $q_i(x_i(t)) \in R^n$ is a known control gain function. $f_i(x_i(t))$ is the unknown continuous nonlinear function. $d_i(t) \in R^n$ is the external disturbance. For the convenience of writing, $q_i(x_i(t))$ and $f_i(x_i(t))$ are denoted by $q_i(x_i)$ and $f_i(x_i)$ later. The dynamics of the leader are designed as follows:

$$\dot{x}_0(t) = r_d(t) \tag{2.2}$$

where $x_0(t) \in R^n$ represents the state of the leader agent, and $r_d(t) \in R^n$ is the unknown smooth function. Due to the existence of the unknown nonlinear function $f_i(x_i)$ in (2.1), radial-basis function neural networks (RBFNNs) are selected. According to the approximation principle, $f_i(x_i)$ has the following expression:

$$f_i(x_i) = \theta_i^{*\mathrm{T}}\varphi_i + \varepsilon_i \tag{2.3}$$

where θ_i^* is an ideal weight vector, φ_i is a basis function vector, ε_i represents an approximation error, and $\|\varepsilon_i\| \leq \bar{\varepsilon}_i$. Since the ideal weight θ_i^* is unknown, it needs to be estimated. Let $W = \|\theta_i^*\|^2$, $\hat{W}$ is an estimate of W. And then the estimated error $\tilde{W}$ is defined as $\tilde{W} = W - \hat{W}$.

In this paper, the framework of MASs is shown in Figure 2. The measurement channels of MASs suffer from the DoS attacks described in the previous subsection. In addition, the communication link faults between the agent and its neighbors are unknown, and the communication link fault model can be described as follows:

$$\begin{aligned} a_{ij}^F &= \rho \cdot a_{ij} \\ b_{i0}^F &= \rho \cdot b_{i0} \end{aligned} \tag{2.4}$$

where ρ is an unknown effective factor of the communication link faults model with the known lower bound, that is, $0 < \underline{\rho} \leq \rho \leq 1$. In the case of communication link faults, the weights a_{ij} and b_{i0} are converted to a_{ij}^F and b_{i0}^F.

Remark 1: In practical applications, the wireless network connection between sensors and controllers has been widely used, which has the advantages of easy deployment and low power consumption. However, this also makes the measurement channels of the system more vulnerable to DoS attacks, such as electromagnetic attacks and other attacks. In addition, there are few results that consider both communication link faults and DoS attacks on measurement channels for MASs.

The control goal is to design an adaptive event-triggered control scheme so that the follower agents can track the leader with ideal accuracy under communication link faults and DoS attacks. To solve the consensus problem, the following assumptions and lemma need to be satisfied:

Assumption 1 [43]: The unknown smooth function $r_d(t) \in R^n$ satisfies $\|r_d(t)\| \leq \bar{r}_d$, where $\bar{r}_d > 0$.

Assumption 2 [44]: The external disturbance $d_i(t) \in R^n$ is bounded satisfying $\|d_i(t)\| < D$, where $D > 0$.

Lemma 2 [45]: For a continuous function $\Phi(t) \geq 0$, the initial condition $\forall\ t \in R^+$ and $\Phi(0)$ is bounded, if the following inequality holds:

$$\dot{\Phi}(t) \leq -\psi\Phi(t) + \vartheta \tag{2.5}$$

where ψ, ϑ are positive constants, then $\Phi(t)$ is bounded.

3. Main result

The tracking error of the i-th agent is defined as

$$\delta_i = x_i - x_0 \tag{3.1}$$

The distributed error is defined as

$$e_i(t) = \sum_{j=1}^{N} a_{ij}\left(x_i - x_j\right) + b_i(x_i - x_0) \tag{3.2}$$

Let $e(t) = \left[e_1^{\mathrm{T}}(t), e_2^{\mathrm{T}}(t), \cdots, e_N^{\mathrm{T}}(t)\right]^{\mathrm{T}}$, $\delta(t) = \left[\delta_1^{\mathrm{T}}(t), \delta_2^{\mathrm{T}}(t), \cdots, \delta_N^{\mathrm{T}}(t)\right]^{\mathrm{T}}$. If the communication link faults exist, the communication weights are affected by the unknown factor ρ. According to (2.1) and (3.2), the distributed error $e(t)$ is converted to

$$e_F(t) = \rho e(t) = \rho(H \otimes I_n)\delta(t) \tag{3.3}$$

where $e_F(t) = \left[e_{1F}^{\mathrm{T}}(t), e_{2F}^{\mathrm{T}}(t), \cdots, e_{NF}^{\mathrm{T}}(t)\right]^{\mathrm{T}}$.

Besides, in order to avoid the waste of resources, an event-triggered mechanism is introduced, and the event-triggered measurement error is defined as follows:

$$z_i(t) = e_i(t) - e_i\left(t_k^i\right), t \in \left[t_k^i, t_{k+1}^i\right) \tag{3.4}$$

where $i = 1, 2, \cdots, N$, $k = 0, 1, 2, \ldots$, t_k^i is the sampling time of $e_i(t)$, Then the event-triggered mechanism is

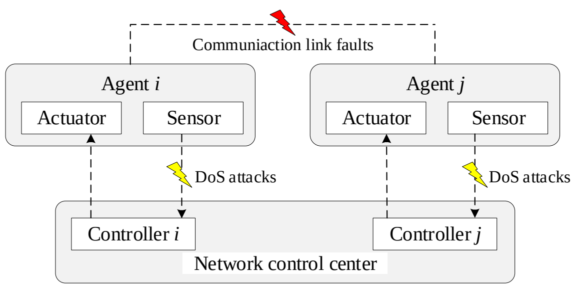

Figure 2. The framework of MASs.

$$\|z_i(t)\| \le \frac{\kappa_i \underline{\rho}^2}{c_i} \|e_i(t)\| \tag{3.5}$$

where c_i and κ_i are two positive constants with $c_i > \kappa_i + 3$.

The trigger time can be determined as

$$t_{k+1}^i = \left\{ \inf\left\{ t > t_k^i : \|z_i(t)\| > \frac{\kappa_i \underline{\rho}^2}{c_i} \|e_i(t)\| \right\} \middle| t \in \prod\nolimits_s \right\} \cup \{nT\} \tag{3.6}$$

Remark 2: In this paper, the designed event-triggered mechanism is different from the traditional trigger mechanism, which is designed by distributed adjacency error signals and state signals. In addition, compared with the trigger mechanism in the traditional secure network environment [21–23], the event-triggered mechanism designed (3.6) adds restrictions. This is because when MASs is attacked by DoS attacks, the data transmission in the measurement channels is interrupted, and the control strategy cannot update the data. It is worth noting that, in order to avoid the instability of the MAS caused by the control strategy failing to be updated for a long time, the proposed control strategy of MASs will be triggered immediately at the end of periodic DoS attacks.

Afterwards, based on (2.1), (2.2), (3.1)-(3.3), the dynamic equation of the error system can be obtained as follows:

$$\begin{aligned} \dot{\delta}_i(t) =& \dot{x}_i(t) - \dot{x}_0(t) \\ =& f_i(x_i(t)) + q_i(x_i(t)) u_i(t) + d_i(t) - r_d(t) \end{aligned} \tag{3.7}$$

$$\dot{e}_{iF}(t) = \rho \dot{e}_i(t) = \rho(\sum_{j=1}^{N} a_{ij}\left(\dot{\delta}_i(t) - \dot{\delta}_j(t)\right) + b_i \dot{\delta}(t)) \tag{3.8}$$

To proved that all follower agents can track the trajectory of the leader, the following theorem is given based on the above definition.

Theorem 1: Suppose that assumptions 1 and 2 hold. Considering the nonlinear MASs (2.1) and (2.2) with the communication link faults (2.3) and DoS attacks, the event-triggered control strategy and neural network adaptive rate are designed as

$$u_i(t) = \frac{c_i}{q_i(x_i)\underline{\rho}^2}\left(-e_i\left(t_k^i\right) - e_i(t_k^i)\|\varphi_i\|^2 \hat{W}_i sgn(\hat{W}_i)\right) \tag{3.9}$$

$$\dot{\hat{W}}_i = \alpha_i\left(-\sigma_i \hat{W}_i + \|\varphi_i\|^2 \|e_i(t)\|^2\right) \tag{3.10}$$

where c_i, β_i, κ_i, α_i and σ_i are positive constants with $c_i > \kappa_i + 3$. Then, all signals are uniformly ultimately bounded.

Proof. Due to the existence of DoS attacks, the whole time can be divided into two different time intervals, namely, non-attack area $\prod_s$ and attack area $\prod_a$. Firstly, the stability of MASs in the first period $[0, T)$, which can be divided into non-attack area $\left[0, T_a^l\right)$ and attack area $\left[T_a^l, T\right)$ is analyzed. According to Figure 1, t_m^{i*} is defined as the last trigger time of the i-th agent, and $\left[t_k^i, t_{k+1}^i\right)$ is the trigger sequence generated by the event-triggered mechanism (3.5). It is worth noting that $0 \leq t_k^i, t_{k+1}^i \leq t_m^{i*} \leq T_a^l$.

1). In the non-attack area case,

In this area, the DoS attacks are in the sleep zone, which provides energy for the next attack. At this time, agents can communicate with each other through topology. However, due to the existence of communication link faults, the efficiency of information transmission has been affected. Therefore, the stability of MASs in this area is analyzed. Consider the Lyapunov function as follows:

$$\begin{aligned} V(t) &= V_1(t) + V_2(t) \\ &= \frac{1}{2} e_F^{\mathrm{T}}(t) \left(H^{-1} \otimes I_n\right) e_F(t) + \frac{1}{2} \sum_{i=1}^{N} \alpha_i^{-1} \tilde{W}_i^{\mathrm{T}} \tilde{W}_i \end{aligned} \tag{3.11}$$

where

$$V_1(t) = \frac{1}{2} e_F^{\mathrm{T}}(t) \left(H^{-1} \otimes I_n\right) e_F(t) \tag{3.12}$$

$$V_2(t) = \frac{1}{2} \sum_{i=1}^{N} \alpha_i^{-1} \tilde{W}_i^{\mathrm{T}} \tilde{W}_i \tag{3.13}$$

For ease of writing, the following process is omitted (t). Then, the time derivative of (3.9) along the trajectory (2.2) is given by

$$\begin{aligned} \dot{V} =& e_F^{\mathrm{T}} \left(H^{-1} \otimes I_n\right) \dot{e}_F - \sum_{i=1}^{N} \alpha_i^{-1} \tilde{W}_i^{\mathrm{T}} \dot{\hat{W}}_i \\ =& \rho e_F^{\mathrm{T}} \dot{\delta} - \sum_{i=1}^{N} \alpha_i^{-1} \tilde{W}_i^{\mathrm{T}} \dot{\hat{W}}_i \\ =& \sum_{i=1}^{N} (\rho e_{iF}^{\mathrm{T}} \theta_i^{*\mathrm{T}} \varphi_i + \rho e_{iF}^{\mathrm{T}} \varepsilon_i + \rho e_{iF}^{\mathrm{T}} q_i(x_i) u_i \\ &+ \rho e_{iF}^{\mathrm{T}} d_i - \rho e_{iF}^{\mathrm{T}} r_d - \alpha_i^{-1} \tilde{W}_i^{\mathrm{T}} \dot{\hat{W}}_i) \end{aligned} \tag{3.14}$$

According to Assumptions 1 and 2, it has

$$\rho e_{iF}^{\mathrm{T}} \varepsilon_i \leq \rho \|e_{iF}\| \|\varepsilon\| \leq \|e_i\|^2 + \frac{1}{4} \bar{\varepsilon}^2 \tag{3.15}$$

$$\rho e_{iF}^{\mathrm{T}} d_i \leq \rho \|e_{iF}\| \|d_i\| \leq \|e_i\|^2 + \frac{1}{4} D^2 \tag{3.16}$$

$$-\rho e_{iF}^{\mathrm{T}} r_d \leq \rho \|e_{iF}\| \|r_d\| \leq \|e_i\|^2 + \frac{1}{4} \bar{r}_d^2 \tag{3.17}$$

$$
\begin{aligned}
\rho e_{iF}^{\mathrm{T}}\theta_i^{*\mathrm{T}}\varphi_i &\leq \|\rho e_{iF}^{\mathrm{T}}\theta_i^{*\mathrm{T}}\varphi_i\|\cdot 1 \\
&\leq \|\rho e_{iF}^{\mathrm{T}}\theta_i^{*\mathrm{T}}\varphi_i\|^2 + \frac{1}{4} \\
&\leq W\|\varphi_i\|^2\|e_i\|^2 + \frac{1}{4}
\end{aligned} \tag{3.18}
$$

Then, by substituting formulas (3.15)-(3.18) into (3.14), it can be concluded that

$$
\begin{aligned}
\dot{V} \leq& \sum_{i=1}^{N}(W\|\varphi_i\|^2\|e_i\|^2 + \rho^2 e_i^{\mathrm{T}} q_i(x_i)u_i + 3\|e_i\|^2 \\
&- \alpha_i^{-1}\tilde{W}_i^{\mathrm{T}}\dot{\hat{W}}_i + \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2))
\end{aligned} \tag{3.19}
$$

Subsequently, based on the expressions of the controller (3.9) and adaptive law (3.10), further results can be obtained as follows:

$$
\begin{aligned}
\dot{V} \leq& \sum_{i=1}^{N}(W\|\varphi_i\|^2\|e_i\|^2 - c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}e_i(t_k^i)\|\varphi_i\|^2\hat{W}_i sgn(\hat{W}_i) \\
&- c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}e_i(t_k^i) + 3\|e_i\|^2 + \sigma\tilde{W}_i^{\mathrm{T}}\hat{W}_i - \tilde{W}_i\|\varphi_i\|^2\|e_i\|^2 \\
&+ \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2))
\end{aligned} \tag{3.20}
$$

Based on the event-triggered mechanism (3.5), it can be concluded that

$$
\begin{aligned}
&-c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}e_i(t_k^i)\|\varphi_i\|^2\hat{W}_i sgn(\hat{W}_i) \\
&\quad= - c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}(e_i + z_i)\|\varphi_i\|^2\hat{W}_i sgn(\hat{W}_i) \\
&\quad\leq - c_i|\hat{W}_i|\|e_i\|^2\|\varphi_i\|^2 + c_i\frac{\kappa_i}{\underline{\rho}^2}|\hat{W}_i|\|e_i\|\cdot\|z_i\|\cdot\|\varphi_i\|^2 \\
&\quad\leq - (c_i - \kappa)|\hat{W}_i|\|e_i\|^2\|\varphi_i\|^2
\end{aligned} \tag{3.21}
$$

$$
\begin{aligned}
-c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}e_i(t_k^i) &= -c_i\frac{\rho^2}{\underline{\rho}^2}e_i^{\mathrm{T}}(e_i - z_i) \\
&\leq -c_i\|e_i\|^2 + \frac{c_i}{\underline{\rho}^2}\|e_i\|\|z_i\| \\
&\leq -(c_i - \kappa_i)\|e_i\|^2
\end{aligned} \tag{3.22}
$$

By substituting formulas (3.21) and (3.22) into (3.20), it can be concluded that

$$
\dot{V} \leq \sum_{i=1}^{N}(\hat{W}_i\|\varphi_i\|^2\|e_i\|^2 - (c_i - \kappa_i)|\hat{W}_i|\|\varphi_i\|^2\|e_i\|^2
$$

$$
\begin{aligned}
&- (c_i - \kappa_i)\|e_i\|^2 + 3\|e_i\|^2 + \sigma \tilde{W}_i^{\mathrm{T}} \hat{W}_i \\
&+ \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2)) \\
\leq& \sum_{i=1}^{N} ((\hat{W}_i - (c_i - \kappa_i)|\hat{W}_i|)\|\varphi_i\|^2\|e_i\|^2 + \sigma \tilde{W}_i^{\mathrm{T}} \hat{W}_i \\
&- (c_i - (\kappa_i + 3))\|e_i\|^2 + \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2))
\end{aligned} \tag{3.23}
$$

Since $c_i \geq \kappa_i + 3$, it is easy to obtain that $\hat{W}_i - (c_i - \kappa_i)|\hat{W}_i| < 0$. Furthermore, (3.23) is transformed into

$$
\begin{aligned}
\dot{V} \leq& \sum_{i=1}^{N} (-(c_i - (\kappa_i + 3))\|e_i\|^2 + \sigma \tilde{W}_i^{\mathrm{T}} \hat{W}_i \\
&+ \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2))
\end{aligned} \tag{3.24}
$$

Since

$$
\begin{aligned}
\sigma \tilde{W}_i^{\mathrm{T}} \hat{W}_i =& \sigma \tilde{W}_i^{\mathrm{T}} \left(W_i - \tilde{W}_i \right) \\
\leq& - \sigma \tilde{W}_i^{\mathrm{T}} \tilde{W}_i + \frac{1}{2}\sigma \tilde{W}_i^{\mathrm{T}} \tilde{W}_i + \frac{1}{2}\sigma W_i^{\mathrm{T}} W_i \\
=& - \frac{1}{2}\sigma \tilde{W}_i^{\mathrm{T}} \tilde{W}_i + \frac{1}{2}\sigma W_i^{\mathrm{T}} W_i
\end{aligned} \tag{3.25}
$$

Then, it has

$$
\begin{aligned}
\dot{V} \leq& \sum_{i=1}^{N} (-(c_i - (\kappa_i + 3))\|e_i\|^2 - \frac{1}{2}\sigma_i \tilde{W}_i^{\mathrm{T}} \tilde{W}_i \\
&+ \frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2) + \frac{1}{2}\sigma W_i^{\mathrm{T}} W_i) \\
\leq& - \frac{c_i - (\kappa_i + 3)}{\lambda_{max}(H^{-1})} V_i - \frac{1}{2}\alpha_i V_2 + \eta \\
\leq& - \zeta V(t) + \eta
\end{aligned} \tag{3.26}
$$

where $\zeta = min(\frac{c_i - (\kappa_i + 3)}{\lambda_{max}(H^{-1})}, \frac{1}{2}\alpha_i)$, $\eta = \sum_{i=1}^{N} (\frac{1}{4}(1 + \bar{\varepsilon}^2 + D^2 + \bar{r}_d^2) + \frac{1}{2}\sigma W_i^{\mathrm{T}} W_i)$, $i = 1, 2, ..., N$.

By using Lemma 2, it has

$$
V(t) \leq V(0) e^{-\zeta t} + \frac{\eta}{\zeta}\left(1 - e^{-\zeta t}\right) \tag{3.27}
$$

It verifies that all signals of systems are bounded via selecting the appropriate parameters, that is, $\|e_i(t)\|$, $\|\delta_i(t)\|$, $\left\|\tilde{W}_i\right\|$ are bounded, and it has

$$
\|e_i(t)\| \leq \sqrt{\frac{2\left(V(0) + \eta/\zeta\right)}{\lambda_{\min}(H^{-1})\underline{\rho}^2}} \tag{3.28}
$$

2) In the attack area case:

In this area, the attacker is active, and the control strategy will maintain the value of the last trigger time t_m^{i*} in the non-attack area. Therefore, it is necessary to discuss the upper bound of error $e_i(t)$ in the attack area.

On the basis of equality (3.3) and (3.8), it has

$$\dot{e}_i(t) = \sum_{j=1}^{N} a_{ij}\left(\dot{\delta}_i(t) - \dot{\delta}_j(t)\right) + b_i\dot{\delta}(t) \tag{3.29}$$

Afterwards, we have

$$\begin{aligned}\left\|\dot{\delta}_i\right\| =& \left\|f_i\left(x_i\right) - \frac{c_i}{\underline{\rho}^2}e_i(t_m^{i*}) - \frac{c_i}{\underline{\rho}^2}e_i(t_m^{i*})\|\varphi_i\|^2\hat{W}_i sgn(\hat{W}_i) - r_d\right\| \\ \leq& \|\theta_i^{*\mathrm{T}}\varphi_i + \varepsilon_i\| + \|\frac{c_i}{\underline{\rho}^2}e_i(t_m^{i*})\| + \|r_d\| \\ &+ \|\frac{c_i}{\underline{\rho}^2}e_i(t_m^{i*})\|\varphi_i\|^2\hat{W}_i sgn(\hat{W}_i)\|\end{aligned} \tag{3.30}$$

Based on Theorem 1, we can get that $\|\tilde{W}_i\|$ and $e_i(t_m^{i*})$ are bounded. Afterwards, it can be concluded that $\|\theta_i^*\|$ and $\|\hat{W}_i\|$ are bounded. On the basis of Assumptions 1 and 2, $\left\|\dot{\delta}_i\right\|$ is bounded. Then, $\left\|\sum_{j=1}^{N}\left(a_{ij}\left(\dot{\delta}_i - \dot{\delta}_j\right) + b_i\dot{\delta}_i\right)\right\|$ is also bounded. Thus, there is a positive constant ϖ, so that

$$\left\|\sum_{j=1}^{N}\left(a_{ij}\left(\dot{\delta}_i - \dot{\delta}_j\right) + b_i\dot{\delta}_i\right)\right\| \leq \varpi \tag{3.31}$$

Integrating both sides of (3.25), it obtains

$$\int_{T_a^l}^{t} \dot{e}_i\left(t\right) d\tau = \int_{T_a^l}^{t} \sum_{j=1}^{N}\left(a_{ij}\left(\dot{\delta}_i - \dot{\delta}_j\right) + b_i\dot{\delta}_i\right) d\tau \tag{3.32}$$

Then, it gets

$$\left\|e_i\left(t\right) - e_i\left(T_a^l\right)\right\| \leq \varpi\left(t - T_a^l\right) \tag{3.33}$$

While $t = T$, it has

$$\|e_i\left(T\right)\| \leq \left\|e_i\left(T_a^l\right)\right\| + \varpi\left(T - T_a^l\right) \tag{3.34}$$

According to (3.28), the errors of $\|e_i\left(T\right)\|$ are bounded. Then, for other cycles based on (3.34), it can be derived that

$$\|e_i\left(nT\right)\| \leq \left\|e_i\left(\left(n-1\right)T + T_a^l\right)\right\| + \varpi\left(T - T_a^l\right) \tag{3.35}$$

Therefore, $\|e_i\left(nT\right)\|$ is also bounded, so the proof is complete.

Remark 3: In a complex network environment, the wireless channels between agents are vulnerable to damage. Compared with the research on the damage of a single channel, this paper studies the situation that the measurement channels and communication channels are subject to DoS attacks and communication link faults simultaneously. In particular, the communication link faults considered in this paper are different from those in [21] and [22]. Comparing with [22], the unknown effective factor of communication link faults and DoS attacks of MASs is simultaneously considered, which makes our research more applicable in a wider range of scenarios. In addition, the proposed event trigger mechanism (3.6) can compensate for the effect of DoS attacks, which effectively avoids the instability of MASs caused by the control strategy without updating under DoS attacks. Under the action of event-triggered control strategy (3.9) and adaptive law (3.10), the consensus control of MASs with communication link faults and DoS attacks is realized.

Under the event-triggered mechanism (3.6), the Zeno phenomenon is inevitable. In order to avoid the continuous triggering, theoretical proof is proposed in the following theorem:

Theorem 2: Consider the nonlinear MASs (2.1) and (2.2) with the event-triggered control strategy (3.9) under assumptions 1and 2. The lower bound of the trigger interval constant $\Delta_i = t_{k+1}^i - t_k^i$ defined by the event-triggered mechanism (3.6) is a positive value, that is, the Zeno phenomenon does not exhibit.

Proof. If $t \in \left[t_k^i, t_{k+1}^i\right)$, it has

$$\begin{aligned} \frac{d}{dt}\|z_i(t)\| \le & \frac{z_i^{\mathrm{T}}(t)\dot{z}_i(t)}{\|z_i(t)\|} \le \|\dot{z}_i(t)\| \le \frac{1}{q_i(x_i)}\|\dot{e}_i(t)\| \\ & = \frac{1}{q_i(x_i)}\left\|\sum_{j=1}^{N}\left(a_{ij}\left(\dot{\delta}_i - \dot{\delta}_j\right) + b_i\dot{\delta}_i\right)\right\| \end{aligned} \tag{3.36}$$

On the basis of (3.31), there are further

$$\|\dot{z}_i(t)\| \le c_i\|z_i(t)\| + \frac{1}{q_i(x_i)}\varpi \tag{3.37}$$

And then, it has

$$\|z_i(t)\| \le \frac{\varpi}{q_i(x_i)c_i}\left(e^{c_i(t-t_k^i)} - 1\right) \tag{3.38}$$

Define a trigger interval constant Δ_i ,moreover, Δ_i satisfies

$$\Delta_i = t_{k+1}^i - t_k^i \ge \frac{1}{c_i}\ln\left(1 + \frac{q_i(x_i)c_i\left\|z_i\left(t_{k+1}^i\right)\right\|}{\varpi}\right) \tag{3.39}$$

According to (3.6) and (3.28), it can further derive that

$$\begin{aligned} \Delta_i = & t_{k+1}^i - t_k^i \\ \ge & \frac{1}{c_i}\ln\left(1 + \frac{\kappa_i\underline{\rho}^2}{\varpi}\sqrt{\frac{2\left(V(0) + \eta/\zeta\right)}{\lambda_{\min}(H^{-1})\underline{\rho}^2}}\right) > 0 \end{aligned} \tag{3.40}$$

□

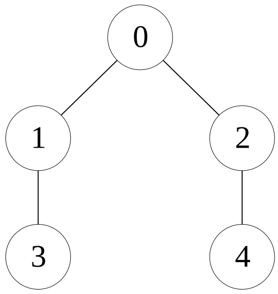

Figure 3. The topology graph $\mathscr{G}$.

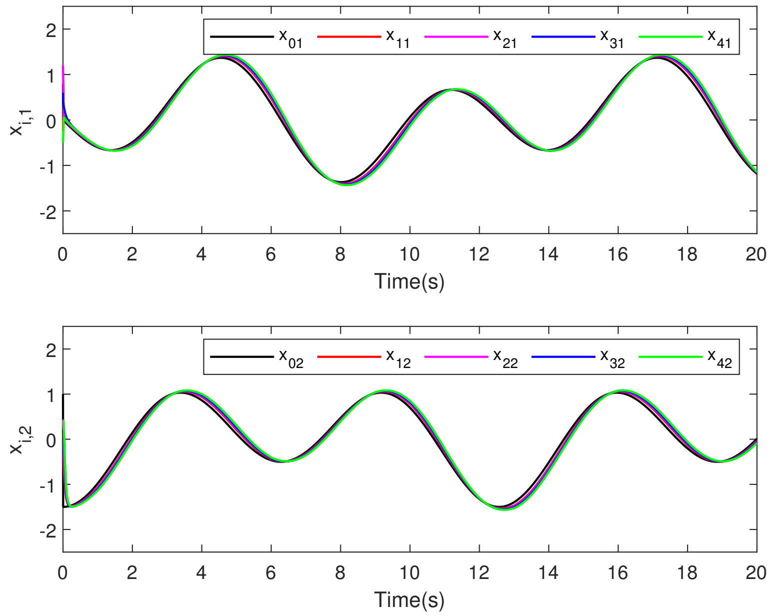

Figure 4. The trajectory of all agents' states x_0, x_1, x_2, x_3, x_4.

4. Numerical simulation

In this section, a numerical simulation example will be provided to verify the feasibility and effectiveness of the proposed control strategy. The simulated MASs has four followers and one leader under the undirected graph $\mathscr{G}$ shown Figure 3. The adjacency matrix $\mathscr{A}$ and the Laplacian matrix $\mathscr{L}$ are

$$\mathscr{A} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \mathscr{L} = \begin{bmatrix} 2 & 0 & -1 & 0 \\ 0 & 2 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}$$

The matrix $\mathscr{B}$ is $\mathscr{B} = diag\{1, 1, 0, 0\}$. The unknown effectiveness factor of communication networks is $\rho = 0.85$.

The relevant parameters of systems (2.1) and (2.2) are given as $f_i(x_i) = \sin(x_i)$, $q_i(x_i) = 2 + 0.5\sin(x_{i1} + x_{i2})$, $d_i(t) = [0.5\sin(t)\ 0.5\cos(t)]^{\mathrm{T}}$. The dynamic input of the leader is $r_d(t) =$

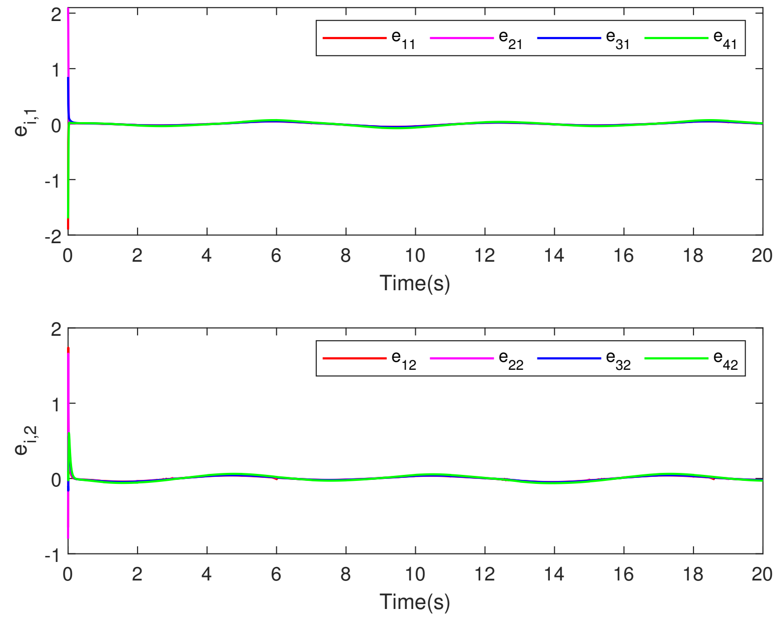

Figure 5. The trajectory of distributed error, e_1, e_2, e_3, e_4.

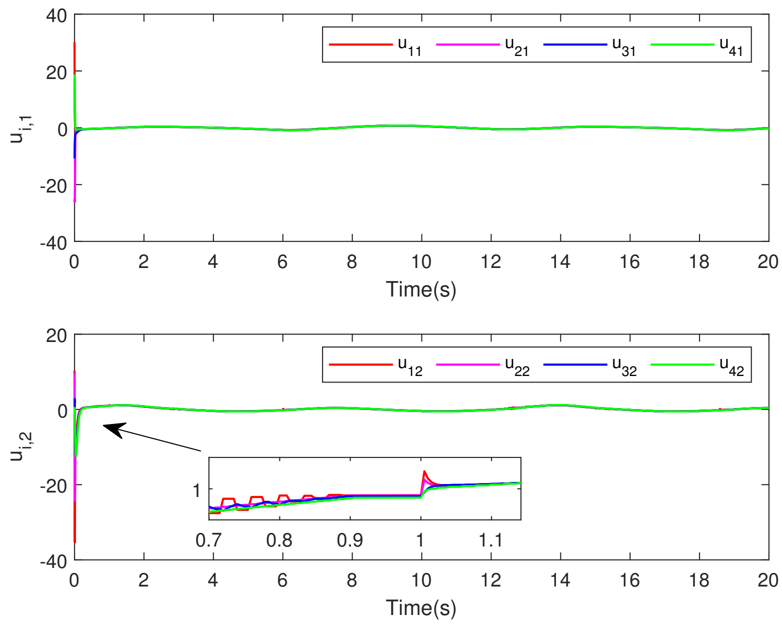

Figure 6. The trajectory of event-triggered controller with DoS attacks, u_1, u_2, u_3, u_4.

$\begin{bmatrix} 0.5\sin(0.5t) - \sin(t) \\ -0.5\cos(0.5t) - \cos(t) \end{bmatrix}$. The initial states of MASs are given as $x_1(0) = [-0.25\ 0.25]^{\mathrm{T}}$, $x_2(0) = [1.2\ 0.3]^{\mathrm{T}}$, $x_3(0) = [0.6\ 0.15]^{\mathrm{T}}$, $x_4(0) = [-0.5\ 0.4]^{\mathrm{T}}$. The design parameters are selected as $\underline{\rho} = 0.4$, $\kappa_1 = 0.27$, $\kappa_2 = 0.25$, $\kappa_3 = 0.26$, $\kappa_4 = 0.25$. The parameters of the adaptive rate of neural networks are selected as $\alpha_1 = 15$, $\alpha_2 = 15$, $\alpha_3 = 15$, $\alpha_4 = 15$, $\sigma_1 = 0.12$, $\sigma_2 = 0.13$, $\sigma_3 = 0.12$, $\sigma_4 = 0.15$.

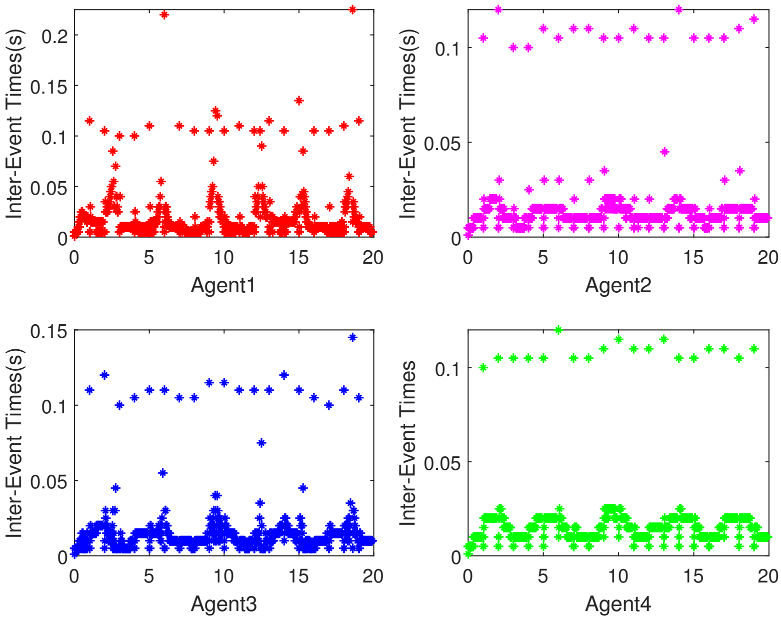

Figure 7. The inter-event times of four followers.

The period of DoS attacks is $T = 1$, and the attack time, $T_a = 0.9$. At this time, the non-attack area is $\prod_s = [(n-1), (n-1) + 0.9)$ and the attack area is $\prod_a = [(n-1) + 0.9, n)$, where $n = 1, 2, \ldots, n$.

Based on Theorem 1 and Theorem 2, the simulation results are shown in Figures 4–7. Figure 4 shows the trajectory of all agents. It can be seen that all followers can accurately track the state of leader under DoS attacks. Figure 5 shows the trajectory of the distributed error. Figure 6 shows the trajectory of the event-triggered controller with DoS attacks on each agent. Figure 7 shows the trigger interval time of four followers, and it can be seen that there is no Zeno phenomenon under the event-triggered condition (3.6). Therefore, the method proposed in this paper is feasible and effective.

5. Conclusions

This paper investigates the consensus control of a class of nonlinear MASs with communication link faults and DoS attacks. Firstly, RBFNNs are used to approximate the nonlinear function of MASs. Then, based on the distributed adjacency error signals, an event-triggered mechanism is designed to solve the problem of wasting communication resources. In order to deal with the communication link faults and DoS attacks in the system, an adaptive event-triggered control strategy is designed. The stability of the system is proved by selecting an appropriate Lyapunov function, and the avoidance of the Zeno phenomenon is analyzed. In the future, the benchmark for control strategy and the protocol for MASs with DoS attacks between controller and actuator will be established to validate the effectiveness of the developed protocol.

Author contributions

Yanming Wu, Zelun Wang: Theoretical derivation, Writing-review and editing, Simulation analysis; Guanglei Meng, Jinguo Liu: Writing-review and editing; All authors: Methodology, Simulation, Validation. All authors have read and agreed to the published version of the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The author declares no conflict of interest in this paper.

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