Consensus of Nonlinear Multi-Agent Systems with Semi-Markov Switching Under DoS Attacks

Extended Abstract

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ABSTRACT

Denial of Service (DoS) attacks will destroy the communication channels between agents. How to reduce the impact of DoS attacks on system consensus of nonlinear multi-agent systems (MASs) with semi-Markov switching (SMS) is an important problem that has appeared in many applications. Existing work on consensus of nonlinear MAS with switching under DoS attacks can be divided into two categories: Markov switching (MS) and Semi-Markov Switching (SMS). There are many studies on MS, but very few on SMS. This is because the dwell time of the SMS obeys a more general probability distribution, which will bring new challenges to analysis. This paper proposes a novel approach that adopts a dynamic event-triggered strategy to reduce the frequency of control signals to complete the consensus on nonlinear MASs with SMS under DoS attacks. We use multiple Lyapunov functions established by stochastic techniques, and obtain sufficient conditions for MAS mean square consensus under aperiodic DoS attacks. The effectiveness of our strategy is verified by simulation results.

KEYWORDS

DoS attacks; Mean-square consensus; Nonlinear MASs; SMS

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1 INTRODUCTION

Multi-agent systems (MASs) composed of multiple subsystems have been widely used in Unmanned Aerial Vehicle (UAV) formation [9], small satellite groups [13], web services [12], alignment of satellites [7], and so on. Consensus is the most common phenomenon in those systems, and designing a control strategy is a fundamental research [8]. Some scholars addressed the Markov Switching (MS) by simulating the process of topologically random-switching of a network. Due to the interference of the external environment, the communication network of a MAS could change dynamically, so the consensus on MASs with MS has great practical significance.

How to use less control resources to make MASs under DoS attack converge to a stable state as quickly as possible has attracted significant research efforts [1, 2, 6]. Event-triggered strategies have been used as the main research method in the existing work: [11] designed an event-triggered function to reduce the use of communication resources and stabilize the entire system as quickly as possible after the attack disappears. [5] adopted a secure adaptive event-triggered strategy to study the consensus in systems with input constraints and hybrid network attacks. They used event-triggered strategies to achieve consensus on the system by saving limited communication resources. However, this kind of stability analysis of fixed topology have many limitations in real life. When the system is attacked, changes in topology may cause some randomness problems in connection loss. Therefore, equipping MASs with an ideal capability of random topology switching to minimize the connection loss under attacks is of particular importance.

For MASs equipped with switching systems, we focus on MASs with semi-Markov switching (SMS) because SMS possesses a greater capability of simulating random processes than the popular Markov switching (MS) deployed in MASs. As the result of extending from an MS to SMS [1, 2], the SMS state dwell time is subject to more general probability distribution and has a broader application space. However, during the switching process of this subsystem model, if there is an interference from external factors, the structure of the entire system will be damaged and the stability of the system will collapse. In response to this problem, [10] studied MASs with MS under attacks and gave a theoretical analysis and proof process. [4, 14] used event-triggered strategies for MASs with SMS under DoS attacks. However, they did not provide detailed explanations of the attack frequency and attack intensity.

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2 OUR WORK

2.1 Problem Formulation

We consider how to build event-triggered strategies that enable agents to reduce information exchanges to reach convergence states in which the interference of DoS attacks in SMS is minimized. We use state errors to build event-triggered functions to reduce the use of communication resources under DoS attacks to achieve consensus on SMS. The leader-follower MASs in this paper has 1 leader and N followers. For preliminary knowledge of SMS, please refer to the paper [2]. The leader agent can be written as follows [10]:

$$\dot{x}_0\left(t\right) = Ax_0\left(t\right) + Cf\left(x_0(t), t\right), i = 1, 2, 3, 4 \ldots, N. \tag{1}$$

where $x_0(t) \in \mathbb{R}^n$ represents the state of the leader. The notation $f\left(x_0(t)\right) : \mathbb{R}^n \times [0, +\infty) \to \mathbb{R}^n$ is a continuous nonlinear function, which satisfies the Lipschitz condition. The ith follower agent is as follows: The dynamic model for follower i can be described by [10] as

$$\dot{x}_i\left(t\right) = Ax_i\left(t\right) + Bu_i\left(t\right) + Cf\left(x_i(t)\right), i = 1, 2, 3, 4 \ldots, N. \tag{2}$$

where $x_i(t) \in \mathbb{R}^n$ is the state of the ith agent and $u_i(t) \in \mathbb{R}^n$ represents the control input of the ith agent. The notation $f(t, x_i(t)) = [f_1(t, x_1(t)), f_2(t, x_2(t)), ..., f_N(t, x_i(t))]^T \in \mathbb{R}^n$ is a continuous nonlinear function.

Definition 2.1. [1]. The control objective of consensus is to use an event-triggered protocol such that nonlinear MASs with SMS satisfy the following equation under DoS attacks.

$$\mathbb{E}\left\{\|\delta_i\left(t\right)\|^2\right\} \le \omega \mathbb{E}\left\{\|\delta_i\left(0\right)\|^2\right\} e^{-\sigma t}, \forall t \ge 0, \tag{3}$$

where $\omega > 0, \sigma > 0$ represent two positive constants, respectively.

2.2 Main Results

We design an event-triggered controller to achieve consensus in nonlinear MASs with SMS in the presence of DoS attacks. For the DoS attack process described in paper [3], our controller is designed as: $u_i\left(t\right) = \begin{cases} K_{r(t)}\theta_i\left(t_k^i\right), t \in \left[\hat{T}_{k-1}, \hat{t}_k\right) \\ 0, t \in [\hat{t}_k, \hat{T}_k) \end{cases}$,where $\theta_i(t) = \sum_{j=1}^{N} a_{ij,r(t)}\left(x_j(t) - x_i(t)\right) + b_{i0,r(t)}\left(x_0(t) - x_i(t)\right)$. Here, t_k^i is the triggering instant of agent i, $a_{ij,r(t)}$ is the coupling weight value between agent i and agent j, $b_{i0,r(t)}$ is the coupling weight value between agent i and the leader, and $K_{r(t)}$ is the feedback gain matrix of different subsystems.

We define the event-trigger error as: $e_i\left(t\right) = \theta_i\left(t_k^i\right) - \theta_i\left(t\right), t \in \left[t_k^i, t_{k+1}^i\right)$, and express the event-trigger instant sequence of the agent as: $t_{k_i+1}^i = \inf\left\{t | t > t_{k_i}^i : \Gamma_i(t) \ge 0\right\}$. In order to exclude Zeno behavior, we adopt the method proposed in [3]. We improve the event-triggered strategy in [11] and apply it to nonlinear MASs with SMS. We define the event-trigger function is defined as: $\Gamma_i\left(t\right) = \|e_i\left(t\right)\| - \beta_1\|\theta_i\left(t\right)\|$,where $\beta_1 = \frac{\hat{\gamma}\hat{\beta}_1}{2\|Q_r BB^T Q_r\|\left(2|N_i| + b_{0i(r)}\right)}$, $0 < \hat{\gamma} < 1$. Based on our event-triggered control strategy, the status information will be sent only after the state measurement error of the agent reaches a predetermined threshold to avoid frequent updates of the controller.

For given positive scalars $\hat{\beta} > 0, \alpha_1 > 0, 0 < \vartheta < \alpha_1, \alpha_2 > 0, \rho > 0$, and $\gamma > 0$, the mean square consensus can achieve in leader-following MASs under the triggering condition. If there are matrices $Q_r > 0, Q > 0, C > 0$ with appropriate dimensions, the following matrix inequalities hold:

$$\begin{bmatrix} {Q_r}^{-1}A^T + A{Q_r}^{-1} - 2\lambda_* BB^T + CC^T + \hat{\beta}I_N + \sum_{n=1}^{s}\pi_{rq}(h)\left(I_N \otimes Q_q\right) & {Q_r}^{-1} \\ * & -\rho^{-2}I_N \end{bmatrix} < 0, \tag{4}$$

$$\begin{bmatrix} Q^{-1}A^T + AQ^{-1} + CC^T - \alpha_2 Q^{-1} & Q^{-1} \\ * & -\rho^{-2}I_N \end{bmatrix} < 0, \tag{5}$$

$$\Gamma\left(t_0, t\right) \le \frac{\vartheta}{\ln\gamma + (\alpha_1 + \alpha_2)\Delta_*}, \varsigma < \frac{\alpha_1 - \vartheta}{\alpha_1 + \alpha_2} \tag{6}$$

where $r = 1, 2, 3 \ldots s$. $\Gamma\left(t_0, t\right)$ and ς respectively represent the attack length and attack intensity. Their definitions can be found in the paper [3].

The proof is omitted due to the space limit.

3 CONCLUSIONS

This paper studied the consensus of nonlinear multi-agent systems (MASs) with semi-Markov switching (SMS) under DoS attacks. Different from existing research [10], we used an event-triggering strategy to reduce the communication between agents. We provide an upper limit of attacks on the system to ensure that the proposed event triggering strategy can be effectively implemented. We verified the effectiveness of our algorithm through experimental results. We will further study the consensus issue of MASs with SMS and other types of switching systems under external interferences.

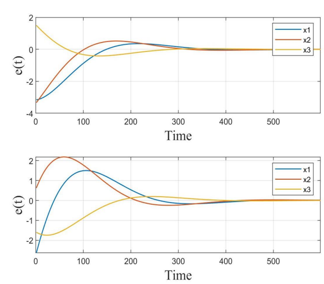

Figure 1: State error of MASs.

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