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# Fault-Tolerant Platoon Control of Autonomous Vehicles Based on Event-Triggered Control Strategy

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**ABSTRACT** This paper is concerned with the issue of platoon fault-tolerant control of the system with time-varying actuator faults. By obtaining the relative state information of neighboring vehicles, two event-triggered fault-tolerant controllers are designed for the two cases of the leader vehicle speed. Then the vehicle platoon system is transformed into error system, and the event-triggered control strategy is designed, in an effort to further save resources. Moreover, by the related theory of Lyapunov, it is shown that the error system is bounded. Finally, two simulation examples are given to show the effectiveness of the proposed approach.

**INDEX TERMS** Autonomous vehicles, platoon fault-tolerant control, event-triggered control strategy, time-varying actuator failure.

## I. INTRODUCTION

The automatic driving of vehicle formation can improve the road utilization and alleviate the traffic congestion effectively. It is a strategic commanding point in the field of intelligent transportation research [1], [2]. Now the research on the platoon control of autonomous vehicles has attracted extensive attention and exploration in the research and engineering fields. For a long time, several platoon control methods have been developed, including leader-follower [3], virtual structures [4], behavior-based [5], artificial potentials [6], etc. Among them, the leader-follower method is widely used in autonomous vehicles. By arranging adjacent vehicles, the horizontal and vertical motion states are adjusted to achieve the desired safety distance and consistent travel speed (as shown in Fig.1).

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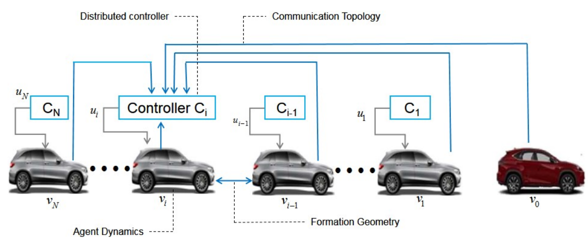


**FIGURE 1.** Schematic representation of a platoon as a multi-agent system.

In recent years, with the gradual deepening of theoretical research on multi-agent systems(MASs), the autonomous driving platoon control has been applied to the MASs gradually and a lot of research works on platoon control have been studied extensively. For example, Consolini et al. applied the leader-follower strategy to MASs in [7], [8]. The related literatures [9], [10] discussed the longitudinal platoon control and state estimation via communication channels with packed-dropout. A decentralized communication and control strategy was presented in [11]- [12] and a novel platoon model was established in [13]. Although the above literature have studied the platoon control, the driving environment and the inherent problems of the device itself have an important impact on the stable operation of the formation system. A real-time change of fleet topology [14], [15] or controller saturation [16], nonlinear [17], [18], actuator failure etc. will have an influence on platoon stability. In particular, actuator failure has a huge impact on formation control. The traditional formation plan is not ideal to apply to the automatic driving formation directly. So in order to guarantee the formation control for automatic driving, it is necessary to consider the various practical problems mentioned above comprehensively and establish a system model with low conservatism. This can provide guarantee for automatic driving platoon control.

The faults in the engineering system mainly include actuator faults, sensor faults, controller faults and faults of the controlled object itself. The actuator is the most prone to failure because it performs control tasks frequently. The failure of some actuators in the system may cause the system to lose the expected performance indicators, and even cause system instability. Therefore, it becomes more and more meaningful to study fault-tolerant control(FTC) of the automatic driving system. But it is only in recent years that considerable research efforts have been made with respect to the FTC of MASs in [19]- [23]. What is more, Deng et al. analyzed the characteristics of systems with actuator failures in [24]. In [25], finite-time fault-tolerant control (FTC) for trajectory tracking of an autonomous surface vehicle (ASV) was solved. A distributed adaptive control strategy to compensate for the effects of actuator failure and model uncertainty on MASs was studied in [26]. And Wu et al. addressed the adaptive fault-tolerant control (FTC) problem of uncertain switched nonaffine nonlinear systems in [27]. Reference [28] was on the analysis and design scheme of performance-based fault detection and fault-tolerant control and so on. Most of the current FTC methods focus on the continuous control. This type of control method will consume a large amount of resources, and lead to the problem of resource utilization degradation. From the perspective of resources conservation, the method of event-trigger control has been considered in this paper.

Since event-triggered control reduces energy loss to a certain extent, many scholars have applied it to consistency research in [29]- [32]. For the first-order MASs, Balador in [33] designed a centralized event triggering algorithm. In addition, based on the event-triggered mechanism, reference [34] also proposed a self-trigger control algorithm. For the second-order MASs, J. Hu studied a distributed event trigger control algorithm in [35]. The method proposed in [36] also used the distributed event trigger control, and based on this, it proved the solution to the consistency problem of the output. What is more, some event-triggered control have studied in [37]- [39]. Although the literatures aboved have studied the event-trigger control, they can't combined with the FTC to solve related problems. So combining the event-triggered algorithm with the intelligent vehicle fault-tolerant control problem will have great research significance.

Motivated by the above reasons, the main contributions of this paper are summarized as follows. Firstly, unlike the literature employing the FTC methods, a novel event-triggered fault-tolerant controller is proposed for the platoon model with time-varying actuator faults. And a distributed event-triggered control function considering the safe distance between vehicles is designed. Then on the basis of the designed distributed event-triggered control function, we consider two conditions of the leader's speed and verify separately. Finally, based on the Lyapunov stability analysis method, it is proved that the time interval is not equal to *0*, which effectively avoids Zeno behavior.

The rest of this paper is organized as follows. Preliminaries and problem formulation are given in Section II. The event-triggered control of vehicle platoon system with time-varying actuator failure are studied in Section III. Two numerical simulation experiments are presented in Section IV. Conclusions are drawn in Section V.

## II. PROBLEM STATEMENT AND PRELIMINARIES

In this section, some basic concepts and definitions about graph theory and model formulation are briefly introduced.

### A. GRAPY THEORY

The communication topology among the followers and the leader is described by a undirected graph $\mathcal{G} = (\mathcal{V}, \varepsilon, \mathcal{A})$, where $\mathcal{V} = \{1, 2 \ldots N\}$ is the node set, $\varepsilon \subseteq \mathcal{V} \times \mathcal{V}$ is the edge set and $\mathcal{A} = \left[a_{ij}\right]_{N\times N}$, $i = 1, 2 \ldots N, j = 1, 2 \ldots N$, is the adjacency matrix, $\left[a_{ij}\right]$ have the following definition:

$$a_{ij} = \begin{cases} 0, & \varepsilon_{ij} \notin \varepsilon, \\ 1, & \varepsilon_{ij} \in \varepsilon, \end{cases} \tag{1}$$

where $\varepsilon_{ij}$ is the eager between node $i$ and $j$. Clearly, $a_{ii} = 0$. Besides, $a_{i0}$ represents the communication between follower $i$ and the leader, if follower $i$ can get information from the leader, then $a_{i0} = 1$, otherwise $a_{i0} = 0$. The degree of node $i$ means the number of nodes connected with $i$, i.e., $d_i = \sum_{j=1}^{N} a_{ij}$. Moreover, $\mathcal{D} = diag\{d_1, d_2 \ldots d_N\}$ represent the degree matrix of $\mathcal{G}$.

$\mathcal{L} = \mathcal{D} - \mathcal{A}$ represents the Laplacian matrix of $\mathcal{G}$. Define the time interval constant $h_{ij} > 0$ to control the safe distance between vehicle $i$ and vehicle $j$. At the same time, define $h_i > 0$ to control the safe distance between vehicle $i$ and leader vehicle.

### B. SYSTEM CHARACTERISATION

To begin with, the dynamic models of follower agent $i$ of the autonomous platoon system with actuator fault can be described as:

$$\begin{cases} \dot{x}_i(t) = v_i(t), \\ \dot{v}_i(t) = p_i(t)\, u_i(t) + \theta_i(t) + f(t, x_i(t), v_i(t)), \end{cases} \tag{2}$$

where $x_i \in R^m$, $v_i \in R^m$, and $u_i \in R^m$ denote the position, velocity and control input vectors, respectively. The $p_i(t)$ and $\theta_i(t)$ are the time-varying actuator fault of agent $i$. Note that when $p_i(t) = 1$, there is no fault for the actuator, the $j$th actuator of the $i$th agent is healthy or normal; when $0 < p_i(t) < 1$, the $j$th actuator is subject to loss of effectiveness fault. The $\theta_i(t)$ is the actuator bias fault of agent $i$. $f(t, x_i(t), v_i(t))$ is the internal dynamic characteristic function of agent $i$.

The dynamic models of leader agent can be described as:

$$\begin{cases} \dot{x}_0(t) = v_0(t), \\ \dot{v}_0(t) = f(t, x_0(t), v_0(t)), \end{cases} \tag{3}$$

where $x_0 \in R^m$ and $v_0 \in R^m$ denote the position and velocity of the leader agent. $u_0 \in R^m$ is the control input vector and $f(t, x_0(t), v_0(t))$ denotes the same implication as the $f(t, x_i(t), v_i(t))$ above. When $f(t, x_0(t), v_0(t)) = 0$, it means that the leader agent moves at a constant speed.

*Remark 1:* In order to describe the information organization form and the transmission process in the collaborative total process of autonomous vehicles, it is necessary to establish a multi-agent structure framework based on the behavior characteristics, in which each vehicle is an agent, and all unmanned vehicle systems constitute the whole multi-agent system.

*Assumption 1:* Assuming that the function $f$ satisfies Lipschitz, there are two non-negative constants $k_1$ and $k_2$ of the real number field, such that

$$\|f(t, x_i, v_i) - f(t, x_0, v_0)\| \le k_1 \|x_i - x_0\| + k_2 \|v_i - v_0\|. \tag{4}$$

*Assumption 2:* This directed graph $G$ has a directed spanning tree.

*Assumption 3:* There are an upper bound $\theta_{i0}$ and an lower bound $p_{i0}$ on the actuator additive fault $\theta_i$ and $p_i$. Namely, the inequality will be satisfied.

$$0 \le p_{i0} \le p_i(t) \le 1, 0 \le \|\theta_i(t)\| \le \theta_{i0}. \tag{5}$$

*Definition 1:* Define the local adjacency matrix

$$\hat{B} = \begin{bmatrix} a_{10} & & 0 \\ & \ddots & \\ 0 & & a_{N0} \end{bmatrix} \in R^{N \times N}, \tag{6}$$

where $a_{i0}$ is called the adjacency coefficient between the following vehicle $i$ and the leader vehicle. When the leader vehicle does not receive information from following vehicle $i$, $a_{i0} = 0$, else $a_{i0} = 1$.

*lemma 1:* Considering symmetric partitioned matrices

$$J = \begin{bmatrix} K & L \\ L^T & M \end{bmatrix}. \tag{7}$$

If $M$ is an invertible matrix, the necessary and sufficient condition for $J$ to be positive definite is

$$\begin{cases} K - LM^{-1}LM > 0, \\ K > 0. \end{cases} \tag{8}$$

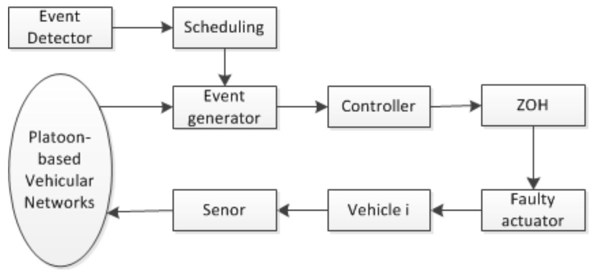


**FIGURE 2. The control framework diagram of the research ideas of this paper.**

*lemma 2:* The column vector $a$, $b$ satisfies that $|a^T b| \le \frac{\varepsilon}{2}\|a\|^2 + \frac{1}{2\varepsilon}\|b\|^2, \forall \varepsilon > 0$.

### C. PROBLEM FORMULATION

In this paper, both the leader speed and the leader-following consensus problem are considered. The objective is to construct a suitable distributed cooperative guaranteed cost controller which not only makes the consensus problem solvable but also provides an adequate level of performance.

*Definition 2:* Considering a fleet composed of $N+1$ vehicles, the dynamics of the first vehicle is shown as (2), and that of the following vehicle is shown as (3), for $i = 1, 2, \cdots N$, under any initial conditions and the action of controller $u(t)$, if satisfying the following equation

$$\begin{aligned} \lim_{t\to\infty} \|x_i(t) - x_j(t) - h_{ij}v_0\| &= 0, \\ \lim_{t\to\infty} \|v_i(t) - v_j(t)\| &= 0, \end{aligned} \tag{9}$$

the problem of Multi-Agent formation control is solved.

*Remark 2:* In order to ensure safety, the design basis of this paper is to adopt the workshop distance strategy with time constant. At this time, the workshop safety distance becomes a fixed distance workshop distance strategy. In this paper, defining interval constant $h_{ij} > 0$, to control the safe distance between vehicle $i$ and $j$. And defining $h_{i0} > 0$, to control the safe distance between vehicle $i$ and the leader.

## III. MAIN RESULT

In order to reduce the energy consumption caused by sensor data acquisition and frequent communication between vehicles, and to reduce the dependence on global state information in event trigger control, the event-triggered scheme is proposed to decide whether to send the sampled signal to the controller through wireless network or not. In this paper, a control framework diagram of the research ideas are shown as Fig.2. The event generator is designed between sensor and controller. It uses sampling information to determine whether the newly sampled signal will be sent to the controller through wireless network. The judgment condition is the trigger condition as below. In addition, we design a distributed event-triggered controller in this section. In the distributed event triggering mechanism, each following vehicle has a different triggering function and its controller is updated asynchronously.

### A. THE DESIGN OF THE FAULT-TOLERANT CONTROLLER BASED ON EVENT-TRIGGERED STRATEGY: THE SPEED OF THE LEADER CAR IS CONSTANT

In this part, we study the formation control problem of multi-agents with actuator fault in the case that the leader vehicle speed is constant. Then the following dynamical model (2) becomes:

$$\begin{cases}\dot{x}_i(t) = v_i(t), \\ \dot{v}_i(t) = p_i(t)u_i(t) + \theta_i(t).\end{cases} \tag{10}$$

The dynamic equation of the leader agent becomes:

$$\begin{cases}\dot{x}_0(t) = v_0(t), \\ \dot{v}_0(t) = 0.\end{cases} \tag{11}$$

Based on the system composed of (10) and (11), we will design the controller of the following vehicle $i$ as:

$$u_i(t) = u_{1i}(t) + u_{2i}(t), \tag{12}$$

where

$$\begin{aligned} u_{1i}(t) =& -\beta\left[v_i(t_k^i) - v_0\right] \\ & -\gamma a_{i0}\left[x_i(t_k^i) - x_0(t_k^i) - h_{i0}v_0\right] \\ & -\gamma\sum_{j\in N_i} a_{ij}\left[x_i\left(t_k^i\right) - x_j\left(t_k^j\right) - h_{ij}v_0\right] \end{aligned} \tag{13}$$

$$\begin{aligned} u_{2i}(t) =& -\frac{|1-p_{i0}|}{p_{i0}}\|u_{1i}\|\, sign\begin{bmatrix} v_i(t_k^i) - v_0 + x_i(t_k^i) \\ -x_0(t_k^i) - h_{i0}v_0\end{bmatrix} \\ & -sign\left[v_i(t_k^i) - v_0(t_k^i) + x_i(t_k^i) - x_0(t_k^i) - h_{i0}v_0\right]\frac{\theta_{i0}}{p_{i0}}, \end{aligned} \tag{14}$$

where $i = 1, 2, \cdots N$, $N_i$ is the set of neighbors of the vehicle $i$. $t_k^i$ is the trigger moment for vehicle $i$. $\beta$ and $\gamma$ are two undetermined normal numbers.

*Remark 3:* The controller is distributed and each follower has a controller. When the event trigger conditions are reached, followers exchange the position and velocity information through the topology diagram. If an event is not triggered, the control will be maintain the state of the previous moment. The neighbour $x_j$ in eq (13) achieve the stability control by obtaining location and speed information of its neighbors.

In order to describe the displacement and speed tracking between the following vehicle $i$ and the leader vehicle and to control the safety distance between adjacent vehicles, we defined displacement error $\xi_i(t)$ and velocity error $\eta_i(t)$. We have

$$\begin{aligned} \xi_i(t) &= x_i(t) - x_0(t) - h_{i0}v_0, \\ \eta_i(t) &= v_i(t) - v_0(t). \end{aligned} \tag{15}$$

We define the measurement error $e_i^{\xi}(t)$ and $e_i^{\eta}(t)$ represent the displacement difference and velocity difference between the triggering moment and the measuring moment of the $i$th follower vehicle respectively. We have

$$\begin{aligned} e_i^{\xi}(t) &= \xi_i(t_k) - \xi_i(t), \\ e_i^{\eta}(t) &= \eta_i(t_k) - \eta_i(t). \end{aligned} \tag{16}$$

So the controller can be written as

$$u_i(t) = u_{1i}(t) + u_{2i}(t), \tag{17}$$

where

$$u_{1i}(t) = -\beta\eta_i\left(t_k^i\right) - \gamma a_{i_0}\xi_i\left(t_k^i\right) - \gamma\sum_{j\in N_i}\left(\xi_i\left(t_k^i\right) - \xi_j\left(t_k^j\right)\right), \tag{18}$$

$$\begin{aligned} u_{2i}(t) =& -\frac{|1-p_{i0}|}{p_{i0}}\|u_{1i}\|\, sign\left(\eta_i\left(t_k^i\right) + \xi_i\left(t_k^i\right)\right) \\ & -sign\left(\eta_i\left(t_k^i\right) + \xi_i\left(t_k^i\right)\right)\frac{\theta_{i0}}{p_{i0}}. \end{aligned} \tag{19}$$

The states and measurement errors of following vehicle are written in vector form, we have

$$\begin{aligned} \varepsilon(t) &= col\left(\varepsilon_1(t)\ldots\varepsilon_N(t)\right), \\ \eta(t) &= col\left(\eta_1(t)\ldots\eta_N(t)\right), \\ e^{\varepsilon}(t) &= col\left(e_1^{\xi}(t)\ldots e_N^{\xi}(t)\right), \\ e^{\eta}(t) &= col\left(e_1^{\eta}(t)\ldots e_N^{\eta}(t)\right). \end{aligned} \tag{20}$$

Then, the actuator faults $p_i(t)$ and $\theta_i(t)$ are written in vector form as

$$\begin{aligned} p(t) &= col\left(p_1(t)\ldots p_N(t)\right), \\ \theta(t) &= col\left(\theta_1(t)\ldots\theta_N(t)\right). \end{aligned} \tag{21}$$

From (20) and (21), the controller $u$ can be rewritten with compact form as below

$$\begin{aligned} u_1(t) =& -\beta\left[e^{\eta}(t) + \eta(t)\right] - \gamma\hat{B}\otimes I_m\left[e^{\xi}(t) + \xi(t)\right] \\ & -\gamma L\otimes I_m\left(e^{\xi}(t) + \xi(t)\right) \\ =& -\beta\left[e^{\eta}(t) + \eta(t)\right] - \gamma H\otimes I_m\left[e^{\xi}(t) + \xi(t)\right], \end{aligned} \tag{22}$$

$$\begin{aligned} u_2(t) =& -\frac{|1-p_{i0}|}{p_{i0}}\|u_1(t)\|\, sign\left(\eta(t) + \xi(t)\right) \\ & -sign\left(\eta(t) + \xi(t)\right)\frac{\theta_{i0}}{p_{i0}}, \end{aligned} \tag{23}$$

where $H = L + \hat{B}$.

From (20), (21), (22) and (23), we can get the error system

$$\begin{cases}\varepsilon(t) = \dot{\eta}(t), \\ \eta(t) = p(t)\left[u_1(t) + u_2(t)\right] + \theta(t).\end{cases} \tag{24}$$

If defining vectors

$$\chi(t) = \begin{bmatrix}\xi(t) \\ \eta(t)\end{bmatrix}, \quad e(t) = \begin{bmatrix}e^{\xi}(t) \\ e^{\eta}(t)\end{bmatrix}, \tag{25}$$

then, (25) can be expressed in a more concise form

$$\dot{\chi} = E\chi + Fe, \tag{26}$$

where

$$E = \begin{bmatrix}0_{N\times N} & I_N \\ -\gamma H & -\beta I_N\end{bmatrix}\otimes I_m, \tag{27}$$

$$F = \begin{bmatrix}0_{N\times N} & 0_{N\times N} \\ -\gamma H & -\beta I_N\end{bmatrix}\otimes I_m. \tag{28}$$

*Theorem 1:* Considering a fleet composed of $N+1$ vehicles, the dynamics of the first vehicle and the following vehicle are shown as (10). Under the action of the controller (11), if the system satisfies the following trigger condition

$$\sum_{j\in\mathcal{N}_i} a_i\left(\left\|e_i^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2+\left\|e_j^{\xi}\right\|^2\right)<b_i\left(\|\xi_i\|^2+\|\eta_i\|^2\right), \tag{29}$$

where $a_i=\gamma\left(a_{i0}+|N_i|\right)$, $b_i=\sigma_i\rho\,|N_i|\left(\gamma\lambda_{\min}(H)-\rho-\rho\gamma\,|N_i|\right)$, $\rho\leq\frac{\gamma\lambda_{\min}(H)}{1+\gamma|N_i|}$, $\sigma_i\in(0,1)$, all the vehicles reach the same state in the end. And at the same time, the existence of safe distance $h_{ij}v_0$ can avoid the collisions. The problem of multi-agent formation has been solved. That is for $i=1,2,\cdots N$, we have

$$\lim_{t\to\infty}\|\xi_i(t)\|=0,\qquad \lim_{t\to\infty}\|\eta_i(t)\|=0. \tag{30}$$

*Proof:* Please see Appendix A.

*Theorem 2:* Considering a fleet composed of $N+1$ vehicles, the dynamics of the first vehicle is shown as (10), and that of the following vehicle is shown as (11). Under the action of the controller (12), if the system satisfies the following trigger conditions (29), then there exists at least one agent $q\in N$,which has a positive lower $\tau$ bound on the trigger interval $\{t_{k+1}-t_k\}$, and $\tau$ satisfies

$$\tau=ln\left[\frac{\|E\|\left(\sqrt{N}\|D+A\|\|D\|+\sqrt{b_x/a_x}\right)}{\|D+A\|\|D\|\|E\|}\right]\frac{1}{\|E\|-\|F\|} \tag{31}$$

*Proof:* Taking the derivative of $\frac{\|e\|}{\|\chi\|}$

$$\begin{aligned}\frac{d}{dt}\frac{\|e\|}{\|\chi\|}&=\frac{d}{dt}\frac{\left(e^Te\right)^{\frac12}}{\left(\chi^T\chi\right)^{\frac12}}\\&=\frac{d}{dt}\frac{\left(e^Te\right)^{-\frac12}e^Te\left(\chi^T\chi\right)^{\frac12}-\left(\chi^T\chi\right)^{-\frac12}\chi^T\chi\left(e^Te\right)^{\frac12}}{\chi^T\chi}\\&=-\frac{e^T\chi}{\|e\|\,\|\chi\|}-\frac{\chi^T\dot\chi}{\|\chi\|^2}\frac{\|e\|}{\|\chi\|}\\&\leq\frac{\|e\|\,\|\dot\chi\|}{\|e\|\,\|\chi\|}+\frac{\|\chi\|\,\|\dot\chi\|}{\|\chi\|^2}\frac{\|e\|}{\|\chi\|}\\&=\left(1+\frac{\|e\|}{\|\chi\|}\right)\frac{\|\dot\chi\|}{\|\chi\|}\\&\leq\left(1+\frac{\|e\|}{\|\chi\|}\right)\left(\|E\|+\|F\|\frac{\|e\|}{\|\chi\|}\right).\end{aligned} \tag{32}$$

Defining $\omega=\frac{\|e\|}{\|\chi\|}$, from (31), we can obtain

$$\dot\omega\leq(1+\omega)\left(\|E\|+\|F\|\,\omega\right). \tag{33}$$

Then the upper bound of $\omega$ by the comparison theorem is

$$\omega\leq\psi\left(t,\psi_0\right), \tag{34}$$

where $\psi\left(t,\psi_0\right)$ is the solution to the differential equation

$$\begin{cases}\dot\psi=(1+\psi)\left(\|E\|+\|F\|\,\psi\right),\\ \psi\left(0,\psi_0\right)=\psi_0.\end{cases} \tag{35}$$

Then the general solution of (34) is

$$\psi\left(\tau,0\right)=\frac{\|E\|\,e^{(\|E\|-\|F\|)(\tau+C_1)}-1}{1-\|F\|\,e^{(\|E\|-\|F\|)(\tau+C_1)}}. \tag{36}$$

where $C_1$ is a constant.

Because this paper assumes that the first trigger occurs at the initial moment, that is $t_0=0$, and $e(0)=0$, then $\psi(0)=0$.

Substituting the initial value into the general solution

$$C_1=\frac{\ln\left(\|E\|\right)}{\|F\|-\|E\|}. \tag{37}$$

So we get a particular solution of equation (34)

$$\psi\left(\tau,0\right)=\frac{Q\,\|E\|-1}{1-Q\,\|F\|}, \tag{38}$$

where $Q=e^{(\|E\|-\|F\|)\left[\tau+\frac{\ln(\|E\|)}{\|F\|-\|E\|}\right]}$.

It is easily find $\sum_{j\in\mathcal{N}_i}\left(\left|e_i^{\xi}\right|+\left|e_j^{\xi}\right|+\left|e_i^{\eta}\right|\right)$ is the $i$th row of the vector $\left|\left[\,D+A\;\;D\,\right]\right|\,|e|$.Then we can obtain

$$\sum_{j\in\mathcal{N}_i}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2\right)\leq\left\|\left|\left[\,D+A\;\;D\,\right]\right|\,|e|\right\|^2. \tag{39}$$

Supposing that the $i$th following car makes $\|\xi_i\|^2+\|\eta_i\|^2$ reach the maximum. Then

$$\frac{\sum_{j\in\mathcal{N}_i}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2\right)}{\|\xi_i\|^2+\|\eta_i\|^2}\leq\frac{N\|D+A\|^2\|D\|^2\|e\|^2}{\|\chi\|^2}. \tag{40}$$

From (37) and (39), the lower bound $\tau$ of the event trigger interval can be as follows

$$\frac{\sqrt{N}\,\|D+A\|\,\|D\|\,\|Q\,\|E\|-1\|}{1-Q\,\|F\|}=\sqrt{\frac{b_x}{a_x}}. \tag{41}$$

From the above equation,we have

$$\tau=ln\left[\frac{\|E\|\left(\sqrt{N}\|D+A\|\|D\|+\sqrt{b_x/a_x}\right)}{\|D+A\|\|D\|\|E\|}\right]\frac{1}{\|E\|-\|F\|}>0. \tag{42}$$

The theorem is proved.

### *B. THE DESIGN OF THE FAULT-TOLERANT CONTROLLER BASED ON EVENT-TRIGGERED STRATEGY: THE SPEED OF THE LEADER CAR IS TIME-VARYING*

In this part, we study the formation control problem of multi-agents with actuator fault in the case that the leader vehicle speed time-varying.

Based on the system composed of (2) and (3), we will design the controller of the following vehicle $i$ as:

$$u_i\left(t\right)=u_{1i}(t)+u_{2i}(t), \tag{43}$$

where

$$u_{1i}(t) = -\beta\left[v_i(t_k^i) - v_0\right] - \gamma a_{i0}\left[x_i(t_k^i) - x_0(t_k^i) - h_{i0}v_0\right] - \gamma\sum_{j\in N_i} a_{ij}\left[x_i\left(t_k^i\right) - x_j\left(t_k^j\right) - h_{ij}v_0\right], \tag{44}$$

$$u_{2i}(t) = -\frac{|1-p_{i0}|}{p_{i0}}\|u_{1i}(t)\|\, sign\left(\eta(t)+\xi(t)\right) - sign\left(\eta(t)+\xi(t)\right)\frac{\theta_{i0}}{p_{i0}} - sign\left(\eta(t)+\xi(t)\right) \times \frac{f(t,x(t),v(t)) - f(t,x_0(t),v_0(t))}{p_{i0}} \tag{45}$$

From (20) and (21), the controller $u(t)$ can be rewritten with compact form as below

$$u_1(t) = -\beta\left[e^{\eta}(t)+\eta(t)\right] - \gamma\hat{B}\otimes I_m\left[e^{\xi}(t)+\xi(t)\right] - \gamma L\otimes I_m\left(e^{\xi}(t)+\xi(t)\right) = -\beta\left[e^{\eta}(t)+\eta(t)\right] - \gamma H\otimes I_m\left[e^{\xi}(t)+\xi(t)\right], \tag{46}$$

$$u_{2i}(t) = -\frac{|1-p_{i0}|}{p_{i0}}\|u_1(t)\|\, sign\left(\eta(t)+\xi(t)\right) - sign\left(\eta(t)+\xi(t)\right)\frac{\theta_{i0}}{p_{i0}} - sign\left(\eta(t)+\xi(t)\right) \times \frac{f(t,x(t),v(t)) - f(t,x_0(t),v_0(t))}{p_{i0}}. \tag{47}$$

From (20), (21), (22) and (23), we can get the error system

$$\left\{\varepsilon(t) = \dot{\eta}(t), \quad \eta(t) = p(t)\left[u_1(t)+u_2(t)\right]+\theta(t). \right. \tag{48}$$

If defining vectors

$$\chi(t) = \begin{bmatrix}\xi(t)\\ \eta(t)\end{bmatrix}, \quad e(t) = \begin{bmatrix}e^{\xi}(t)\\ e^{\eta}(t)\end{bmatrix}, \tag{49}$$

then, (48) can be expressed in a more concise form

$$\dot{\chi} = E\chi + Fe, \tag{50}$$

where

$$E = \begin{bmatrix}0_{N\times N} & I_N\\ -\gamma H & -\beta I_N\end{bmatrix}\otimes I_m, \tag{51}$$

$$F = \begin{bmatrix}0_{N\times N} & 0_{N\times N}\\ -\gamma H & -\beta I_N\end{bmatrix}\otimes I_m. \tag{52}$$

*Theorem 3:* Considering a fleet composed of $N+1$ vehicles, the dynamics of the first vehicle is shown as (3), and that of the following vehicle is shown as (2). When the leader's speed is time varying, under the action of the controller (43), if the system satisfies the following trigger conditions as below

$$\sum_{j\in\mathcal{N}_i} a_i\left(\left\|e_i^{\xi}\right\|^2 + \left\|e_i^{\eta}\right\|^2 + \left\|e_j^{\xi}\right\|^2\right) < b_i\left(\|\xi_i\|^2 + \|\eta_i\|^2\right), \tag{53}$$

where $a_i = \gamma\left(a_{i0}+|N_i|\right)$, $b_i = \sigma_i\rho\,|N_i|\left(\gamma\lambda_{\min}(H) - \rho - \rho\gamma\,|N_i|\right)$, $\rho \leq \frac{\gamma\lambda_{\min}(H)}{1+\gamma|N_i|}$, $\sigma_i \in (0,1)$, all the vehicles reach the same state in the end. The platoon problem can be solved

*Proof:* Please see Appendix B.

*Remark 4:* Because event trigger interval greater than zero can rule out Zeno behavior. It has nothing to do with the speed of the leader. The poof of Zeno behavior for Theorem 3 is same to Theorem 2. So it is omitted.

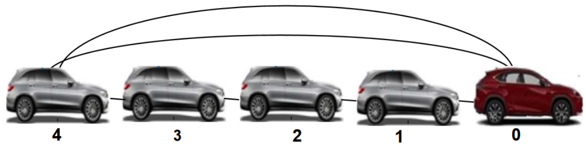


**FIGURE 3.** The vehicle queue topology diagram.

## IV. SIMULATION

In this section, we will give two numerical experiments to verify the correctness and the validity of the above theorem. Both experiments are based on a leader-follower vehicle formation system consisting of a leader vehicle and four follower vehicles. The system topology of the fleet is shown in Fig.4.

Firstly, we verify that the speed of the leader vehicle is constant. The dynamic equation of leader and follower is shown as below:

$$\begin{cases}\dot{x}_0(t) = v_0(t),\\ \dot{v}_0(t) = 0,\end{cases} \tag{54}$$

$$\begin{cases}\dot{x}_i(t) = v_i(t),\\ \dot{v}_i(t) = p_i(t)\,u_i(t) + \theta_i(t),\end{cases} \tag{55}$$

where $u_i(t)$ is defined in (11).

Taking the local adjacency matrix $B = diag\{1,0,1,1\}$, then $\lambda_{min}(H) = 0.6443$. Taking $\beta = 1.2$, $\gamma = 1.4$, $\varsigma = 0.25$. And the actuator failure $p_i(t)$ and $\theta_i(t)$ are as follows:

$$p_i = col(1, 0.2, \sqrt{0.2\cos(0.1t)}+0.3, 0.6),$$
$$\theta_i = col(0,0,0,0,0,0,0.05\sin(0.05\pi t), 0, 0.25, 0.3-0.05\sin(0.2\pi t)) \tag{56}$$

The safe distance between vehicle $i$ and the leader $h_{i0} = (0.1, 0.2, 0.3, 0.4)$.The initial values of the leader vehicle and the follower vehicle are defined as follows:

$$x_i(0) = col(-4,-4,-4,-3,-3,-2,-2,-1),$$
$$v_i(0) = col(15,10,20,10,15,10,18,20),$$
$$x_0(0) = col(0,0),$$
$$v_0(0) = col(10,10). \tag{57}$$

It can be seen from Fig.4 and Fig.5 that the change of displacement state of *0 − 4* vehicles. It is easily find that the status gradually reach consensus and the motorcade forme initially. But in the case of a normal controller, the queue is chaotic. This effectively verifies the effectiveness of the controller proposed in this paper. Fig.6 shows the real-time distance between each follower car and the leader car as we previously set. And Fig.7 and Fig.8 show that the

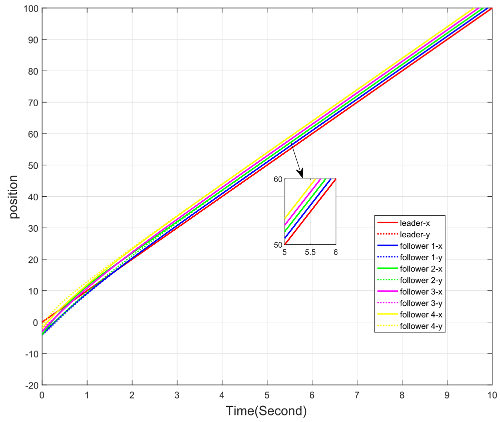


**FIGURE 4.** Positions for four follower vehicles and the leader under the controller proposed in this paper.

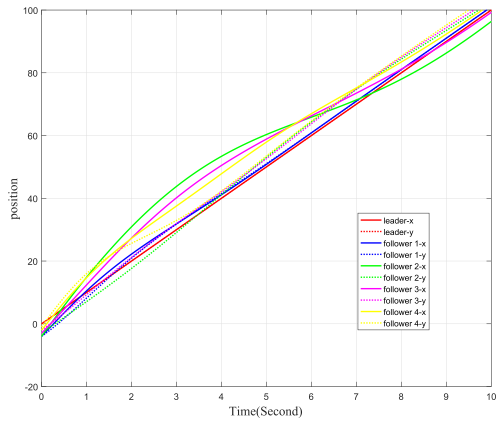


**FIGURE 5.** Positions for four follower vehicles and the leader without fault tolerant controller.

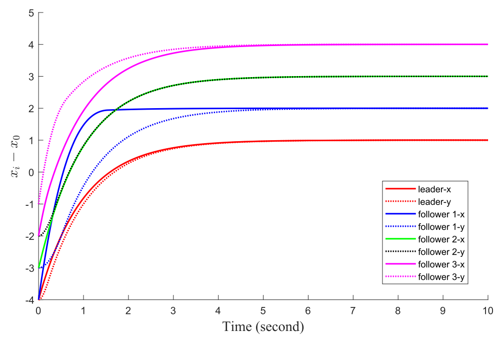


**FIGURE 6.** Inter-vehicle spaces between four follower vehicles and the leader.

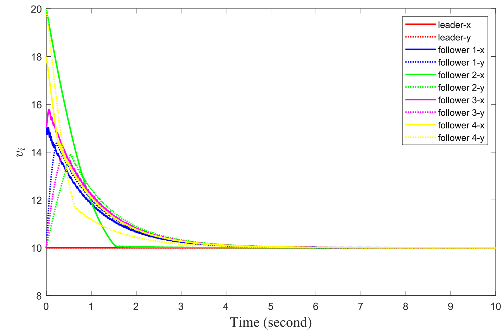


**FIGURE 7.** Velocity for four follower vehicles and the leader under the controller proposed in this paper.

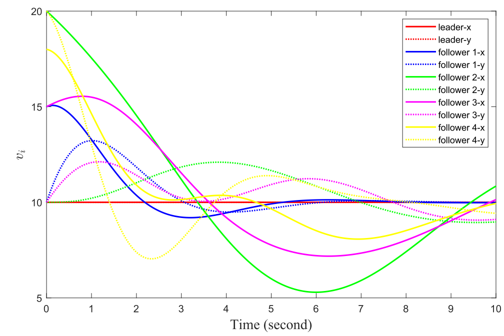


**FIGURE 8.** Velocity for four follower vehicles and the leader without fault tolerant controller.

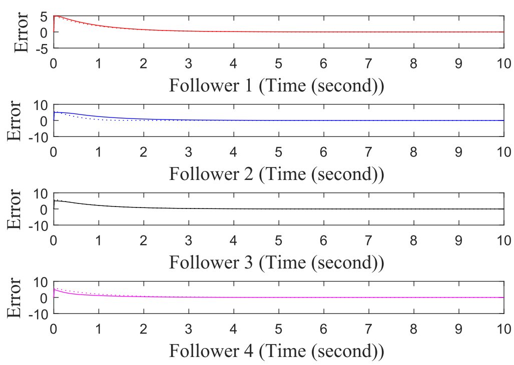


**FIGURE 9.** The measurement error of states $\xi_i$.

changing in the velocity of the system. Under the action of the controller proposed in this paper, the speed of the following vehicle gradually approaches the target speed, and finally reaches the consistency. With the ordinary controller, the speed of the following vehicle can't reach the speed of the target vehicle. From Fig.9, we can obtain that the state error($\xi_i(t) = x_i(t) - x_0(t) - h_{i0}v_0$) gradually converges to zero. And the triggering instants are displayed in Fig.10.

Secondly, we verify that the speed of the leader vehicle is time-varying. The dynamic equation of the leading vehicle and the dynamic equation of the follower's vehicle are as below:

$$\begin{cases} \dot{x}_0(t) = v_0(t), \\ \dot{v}_0(t) = -\sin x_0(t) - 0.25 v_0(t) + 1.5\cos(2.5t), \end{cases} \tag{58}$$

$$\begin{cases} \dot{x}_i(t) = v_i(t), \\ \dot{v}_i(t) = p_i(t) u_i(t) + \theta_i(t) \\ \qquad -(\sin x_i(t) + 0.25 v_i(t) - 1.5\cos(2.5t)). \end{cases} \tag{59}$$

The initial state is the same as before. Then, Fig.11 and Fig.12 show that when the speed of the leader vehicle changes, the follower vehicles also can quickly adapt to the

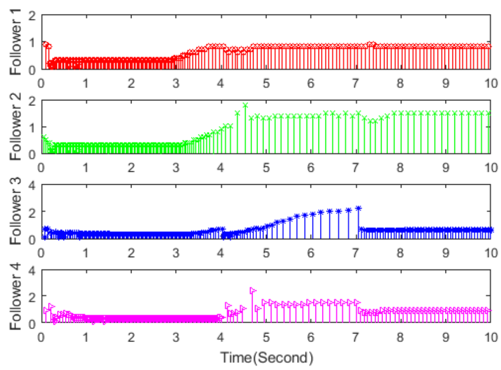


**FIGURE 10.** **The event trigger interval of each follower.**

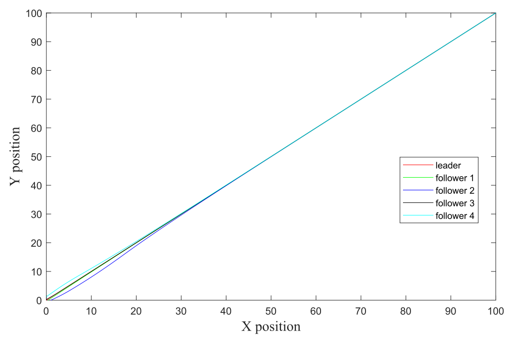


**FIGURE 11.** **Positions for four follower vehicles and the leader for leader in time-varying situations.**

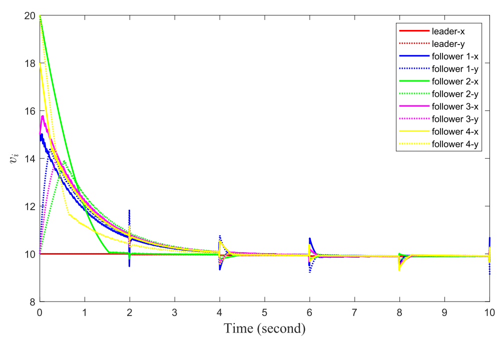


**FIGURE 12.** **Velocities for four follower vehicles and the leader for leader in time-varying situations.**

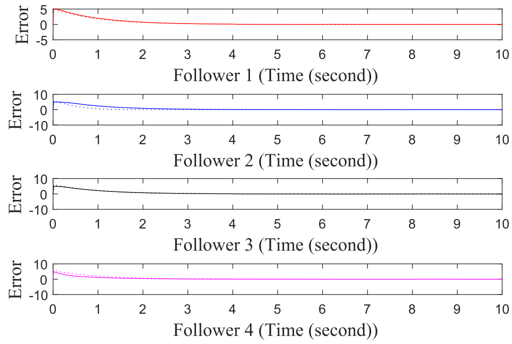


**FIGURE 13.** **The measurement error of states $\xi$ for leader in time-varying situations.**

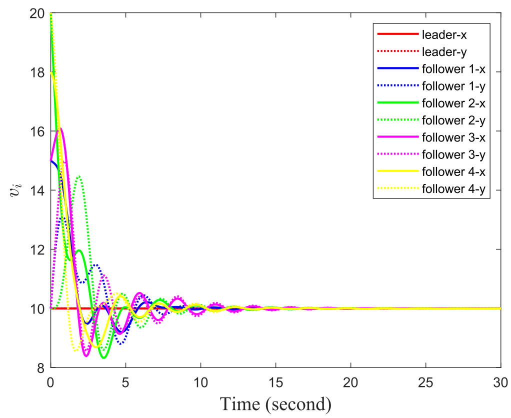


**FIGURE 14.** **Velocities for four follower vehicles and the leader with time-delay.**

change. Their position and velocity also reach the desired condition. From Fig.13, we can obtain that the state error gradually converges to zero.

The simulation results show that the proposed controller have good performance in the case of a time-varying actuator failure in the system and whether the pace of leadership changes, it can make the vehicle platoon system reach stable state.

*Remark 5:*The robustness test of the model is vital to the system. We have supplemented Fig.14 to show the impact of delay on the system. It can be seen that the system can also be ultimately bounded. This verifies the model in this paper is robust and verifies the effectiveness of event-triggered fault-tolerant control proposed in this paper. And we will do more on robustness tests such as random perturbations and noise in subsequent work.

*Remark 6:* Most of the current fault-tolerant control methods for the platoon system focus on the continuous control like [27], [28]. This type of control method will send many unnecessary signals to the controller, thus increasing the network communication burden and vehicle fuel consumption. Unlike the literature employing the FTC methods, we proposed a novel event-triggered fault-tolerant controller for the platoon model with time-varying actuator faults which could reduce energy loss to a certain extent under the condition that the system is stable.

*Remark 7:* In fact, there are many modelling methods of state-space to handle with event- triggered problem. But the current methods like [35]–[37], [39] can not deal with formation problems with event-triggered mechanism and actuator failure at the same time. The presented control scheme can also keep the system stable in the event of some failures or attacks and the complexity is not increased. So the system is more conservative.

*Remark 8:* Although the proposed event-triggered fault-tolerant controller proves the stability of the system. It should be pointed that, for simplicity, the disturbance and measurement noise are not considered in system. If those issues

**TABLE 1. The control flow chart of Theorem 1.**

| Control flow of the controller. |
| --- |
| **Input:** $u_i(t)$ |
| **Output:** $x_i(t)$ |
| **Initialization:** $x_i(0), v_i(0), x(0), x(0)$ |
| 1: **while** the System(2) and (3) is running do |
| 2: $u_i\ (t) = u_{1i}(t) + u_{2i}(t)$, |
| 3: $\begin{matrix} \xi_i(t) = x_i(t) - x_0(t) - h_{i0}v_0 \\ \eta_i(t) = v_i(t) - v_0(t) \end{matrix}, \begin{matrix} e_i^{\xi}(t) = \xi_i\ (t_k) - \xi_i(t) \\ e_i^{\eta}(t) = \eta_i\ (t_k) - \eta_i(t) \end{matrix}$ |
| 4: **if** $\sum_{j\in\mathcal{N}_i} a_i \left( \left\| e_i^{\xi} \right\|^2 + \left\| e_i^{\eta} \right\|^2 + \left\| e_j^{\xi} \right\|^2 \right) < b_i \left( \|\xi_i\|^2 + \|\eta_i\|^2 \right)$ **then** |
| 5: $x_i(t) = x_i(t_k)$. |
| 6: $\lim_{t\to\infty} \|\xi_i(t)\| = 0,\ \lim_{t\to\infty} \|\eta_i(t)\| = 0$. The system is stable. |
| 7: **else** |
| 8: $x_i(t) = x_i(t_k - 1)$. Waiting for the next moment. |
| 9: **end if** |
| 10: **end while** |

are considered, the event-triggered control problem becomes much more complicated. This is also the subject for our future research. In addition, we can't calculate the complexity accurately. The system model parameters are related to the state and control inputs of the system. Therefore, the specific computational complexity is also related to the system.

## V. CONCLUSION

In this paper, we studied the leader-follower consistency in autonomous vehicle platoon systems with time-varying actuator failure under event-triggering mechanism. The difference between our work and other scholars in the past is that we designed the even-triggered fault-tolerant controller, which avoids continuous calculation and measurement and reduces the loss of communication resources. At the same time, we have proved the consistency of the system under the control of the trigger function. In addition, we also studied the fault-tolerant of vehicle platoon when leader speed is time-varying. Finally, the effectiveness of the proposed controller is verified by numerical experiments.

## APPENDIXES

## APPENDIX A

## PROOF OF THEOREM 1

In order for readers to better understand the proof process of Theorem 1, we have designed the control flow of Theorem 1 as shown Table.1.

Based on the system (24), constructing the common Lyapunov function candidate

$$V(\chi(t)) = \frac{1}{2}\chi(t)^T\ (\Omega \otimes I_m)\ \chi(t), \tag{60}$$

where $\Omega = \begin{bmatrix} \beta I_N + \gamma H & I_N \\ I_N & I_N \end{bmatrix}$. In order to ensure that $V$ is positive, there should be $\Omega > 0$. By *lemma 1*, we can get the necessary and sufficient condition for $\Omega > 0$,

$$\begin{cases} \beta I_N + \gamma H > 0, \\ \beta I_N + \gamma H - I_N > 0. \end{cases} \tag{61}$$

Then the Lyapunov's expansion is

$$\begin{aligned} V &= \frac{1}{2}\left(\xi^T \quad \eta^T\right) \begin{bmatrix} \beta I_N + \gamma H & I_N \\ I_N & I_N \end{bmatrix} \otimes I_m \begin{bmatrix} \xi \\ \eta^T \end{bmatrix} \\ &= \frac{1}{2}\xi^T\ (\beta I_N + \gamma H) \otimes I_m \xi + \frac{1}{2}\eta^T\eta + \xi^T\eta. \end{aligned} \tag{62}$$

Taking the derivative with respect to $v$, we get

$$\begin{aligned} &\dot{V}\ (\chi(t))| \\ &\quad = \xi^T\ (\beta I_N + \gamma H) \otimes I_m \eta + \eta^T\dot{\eta} + \xi^T\dot{\eta} + \eta^T\eta \\ &\quad = \xi^T\ (\beta I_N + \gamma H) \otimes I_m \eta + \eta^T\tilde{\eta} + \left(\xi^T + \eta^T\right)\dot{\eta} \\ &\quad = \xi^T\ (\beta I_N + \gamma H) \otimes I_m \tilde{\eta} + \eta^T\tilde{\eta} + \left(\xi^T + \eta^T\right) u_1\ (t) \\ &\qquad + \left(\xi^T + \eta^T\right) \begin{pmatrix} (p\ (t) \otimes I_m - I_{mN})\ u_1\ (t) \\ + p\ (t) \otimes I_m u_2\ (t) + \theta\ (t) \otimes{}_m \end{pmatrix} \\ &\quad = \xi^T\ (\beta I_N + \gamma H) \otimes I_m \eta + \eta^T\eta \\ &\qquad + \left(\xi^T + \eta^T\right) u_1\ (t) + A \end{aligned} \tag{63}$$

where

$$\begin{aligned} A &= \left(\xi^T + \eta^T\right) \begin{pmatrix} (p\ (t) \otimes I_m - I_{mN})\ u_1\ (t) \\ + p\ (t) \otimes I_m u_2\ (t) + \theta\ (t) \end{pmatrix} \\ &= \sum\nolimits_{i=1}^N \left(\xi_i^T + \eta_i^T\right) \begin{bmatrix} (p_i\ (t) - 1)\ u_{1i}\ (t) \\ + p_i\ (t)\ u_{2i}\ (t) + \theta_i\ (t) \end{bmatrix} \\ &\le \sum\nolimits_{i=1}^N \left\|\xi_i^T + \eta_i^T\right\| \|u_{1i}\ (t)\|\ |p_i\ (t) - 1| \\ &\quad + \sum\nolimits_{i=1}^N \left\|\xi_i^T + \eta_i^T\right\| \theta_{i0} \\ &\quad + \sum\nolimits_{i=1}^N p_i\ (t) \left(\xi_i{}^T + \eta_i{}^T\right) \begin{pmatrix} -\frac{|1-p_{i0}|}{p_{i0}} \|u_{1i}\|\ sign\ (\eta_i\ (t) + \xi_i\ (t)) \\ -sign\ (\eta_i\ (t) + \xi_i\ (t))\ \frac{\theta_{i0}}{p_{i0}} \end{pmatrix} \\ &\le \sum\nolimits_{i=1}^N \left\|\xi_i^T + \eta_i^T\right\| \|u_{1i}\ (t)\|\ |p_{i0} - 1| \\ &\quad + \sum\nolimits_{i=1}^N \left\|\xi_i^T + \eta_i^T\right\| \theta_{i0} \\ &\quad - \sum\nolimits_{i=1}^N |1 - p_{i0}|\ \|u_{1i}\| \left(\xi_i{}^T + \eta_i{}^T\right) sign\ (\eta_i\ (t) + \xi_i\ (t)) \\ &\quad - \sum\nolimits_{i=1}^N \left(\xi_i{}^T + \eta_i{}^T\right) sign\ (\eta_i\ (t) + \xi_i\ (t))\ \theta_{i0}. \end{aligned} \tag{64}$$

Because $\left(\xi_i{}^T + \eta_i{}^T\right) sign\ (\eta_i\ (t) + \xi_i\ (t)) \ \ge\ \left\|\xi_i^T + \eta_i^T\right\|$, we can easily get $A < 0$.

Then

$$\begin{aligned} &\dot{V}\ (\chi(t))| \\ &\quad \le \xi^T\ (\beta I_N + \gamma H) \otimes I_m \eta + \eta^T\eta \\ &\qquad + \left(\xi^T + \eta^T\right) u_1\ (t) \\ &\quad \le \xi^T\ (\beta I_N + \gamma H) \otimes I_m \eta + \eta^T\eta \\ &\qquad + \left(\xi^T + \eta^T\right) \begin{pmatrix} -\beta\ [e^{\eta}(t) + \eta(t)] \\ -\gamma H \otimes I_m \left[e^{\xi}(t) + \xi(t)\right] \end{pmatrix} \\ &\quad = -\gamma\xi^T\ (H \otimes I_m)\ \xi + (1 - \beta)\eta^T\eta \\ &\qquad - \left(\xi^T + \eta^T\right) \left(\gamma H \otimes I_m e^{\xi} + \beta e^{\eta}\right) \\ &\quad \le -\gamma\lambda_{\min}(H)\|\xi\|^2 + (1 - \beta)\|\eta\|^2 \\ &\qquad - \left(\xi^T + \eta^T\right) \left(\gamma H \otimes I_m e^{\xi} + \beta e^{\eta}\right) \end{aligned}$$

$$
\begin{aligned}
&= -\gamma\lambda_{\min}(H)\sum_{i=1}^{N}\|\xi_i\|^2 + (1-\beta)\sum_{i=1}^{N}\|\eta_i\|^2 \\
&\quad -\left(\xi^T+\eta^T\right)\left(\gamma H\otimes I_m e^{\xi}+\beta e^{\eta}\right) \\
&= -\gamma\lambda_{\min}(H)\sum_{i=1}^{N}\|\xi_i\|^2 + (1-\beta)\sum_{i=1}^{N}\|\eta_i\|^2 + B
\end{aligned} \tag{65}
$$

where

$$
\begin{aligned}
B &= -\left(\xi^T+\eta^T\right)\left(\gamma H\otimes I_m e^{\xi}+\beta e^{\eta}\right) \\
&= \sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)\left(\gamma\sum_{j\in N_i}\left(e_j^{\xi}-e_i^{\xi}\right)-\gamma a_{i0}e_i^{\xi}-\beta e_i^{\eta}\right) \\
&= -\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)\left(\gamma a_{i0}e_i^{\xi}+\beta e_i^{\eta}\right) \\
&\quad +\gamma\sum_{i=1}^{N}\left[\left(\xi_i^T+\eta_i^T\right)\sum_{j\in N_i}\left(e_j^{\xi}-e_i^{\xi}\right)\right].
\end{aligned} \tag{66}
$$

From lemma 2, we have

$$
\begin{aligned}
&\gamma\sum_{i=1}^{N}\left[\left(\xi_i^T+\eta_i^T\right)\sum_{j\in N_i}\left(e_j^{\xi}-e_i^{\xi}\right)\right] \\
&= -\gamma\sum_{i=1}^{N}|N_i|\left(\xi_i^T+\eta_i^T\right)e_i^{\xi}+\gamma\sum_{i=1}^{N}\sum_{j\in N_i}\left(\xi_i^T+\eta_i^T\right)e_j^{\xi} \\
&= -\gamma\sum_{i=1}^{N}|N_i|\xi_i^T e_i^{\xi}-\gamma\sum_{i=1}^{N}|N_i|\eta_i^T e_i^{\xi} \\
&\quad +\gamma\sum_{i=1}^{N}\sum_{j\in N_i}\xi_i^T e_j^{\xi}+\gamma\sum_{i=1}^{N}\sum_{j\in N_i}\eta_i^T e_j^{\xi} \\
&\le \rho\gamma\sum_{i=1}^{N}|N_i|\left(\left\|\tilde{\xi}_i\right\|^2+\|\tilde{\eta}_i\|^2\right) \\
&\quad +\frac{\gamma}{\rho}\sum_{i=1}^{N}\sum_{j\in N_i}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2\right),
\end{aligned} \tag{67}
$$

$$
\begin{aligned}
&-\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)\left(\gamma a_{i0}e_i^{\xi}+\beta e_i^{\eta}\right) \\
&= -\left(\begin{array}{l}\sum_{i=1}^{N}\gamma a_{i0}\xi_i^T e_i^{\xi}+\sum_{i=1}^{N}\beta\xi_i^T e_i^{\eta}+\sum_{i=1}^{N}\gamma a_{i0}\eta_i^T e_i^{\xi} \\ +\sum_{i=1}^{N}\beta\eta_i^T e_i^{\eta}\end{array}\right) \\
&\le \frac{1}{2}\sum_{i=1}^{N}\left(\rho\left\|\xi_i^T\right\|^2+\gamma^2 a_{i0}^2\frac{1}{\rho}\left\|e_i^{\xi}\right\|^2\right) \\
&\quad +\frac{1}{2}\sum_{i=1}^{N}\left(\rho\left\|\xi_i^T\right\|^2+\beta^2\frac{1}{\rho}\left\|e_i^{\eta}\right\|^2\right) \\
&\quad +\frac{1}{2}\sum_{i=1}^{N}\left(\rho\left\|\eta_i^T\right\|^2+\gamma^2 a_{i0}^2\frac{1}{\rho}\left\|e_i^{\xi}\right\|^2\right) \\
&\quad +\frac{1}{2}\sum_{i=1}^{N}\left(\rho\left\|\eta_i^T\right\|^2+\beta^2\frac{1}{\rho}\left\|e_i^{\eta}\right\|^2\right) \\
&= \rho\sum_{i=1}^{N}\left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right) \\
&\quad +\frac{1}{\rho}\sum_{i=1}^{N}\left(\gamma^2 a_{i0}^2\left\|e_i^{\xi}\right\|^2+\beta^2\left\|e_i^{\eta}\right\|^2\right) \\
&= \rho\sum_{i=1}^{N}\left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right) \\
&\quad +\frac{1}{\rho}\sum_{i=1}^{N}\frac{1}{|N_i|}\sum_{j\in N_i}\left(\gamma^2 a_{i0}^2\left\|e_i^{\xi}\right\|^2+\beta^2\left\|e_i^{\eta}\right\|^2\right),
\end{aligned} \tag{68}
$$

so

$$
\begin{aligned}
B &\le \rho\sum_{i=1}^{N}\left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right) \\
&\quad +\frac{1}{\rho}\sum_{i=1}^{N}\frac{1}{|N_i|}\sum_{j\in N_i}\left(\gamma^2 a_{i0}^2\left\|e_i^{\xi}\right\|^2+\beta^2\left\|e_i^{\eta}\right\|^2\right) \\
&\quad +\rho\gamma\sum_{i=1}^{N}|N_i|\left(\left\|\tilde{\xi}_i\right\|^2+\|\tilde{\eta}_i\|^2\right) \\
&\quad +\frac{\gamma}{\rho}\sum_{i=1}^{N}\sum_{j\in N_i}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2\right).
\end{aligned} \tag{69}
$$

Then $\dot{V}$ can become

$$
\begin{aligned}
&\dot{V}\left(\chi(t)\right)| \\
&\le -\gamma\lambda_{\min}(H)\sum_{i=1}^{N}\|\xi_i\|^2+(1-\beta)\sum_{i=1}^{N}\|\eta_i\|^2 \\
&\quad +\rho\sum_{i=1}^{N}\left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right) \\
&\quad +\frac{1}{\rho}\sum_{i=1}^{N}\frac{1}{|N_i|}\sum_{j\in N_i}\left(\gamma^2 a_{i0}^2\left\|e_i^{\xi}\right\|^2+\beta^2\left\|e_i^{\eta}\right\|^2\right) \\
&\quad +\rho\gamma\sum_{i=1}^{N}|N_i|\left(\|\xi_i\|^2+\|\eta_i\|^2\right) \\
&\quad +\frac{\gamma}{\rho}\sum_{i=1}^{N}\sum_{j\in N_i}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2\right) \\
&= \frac{1}{\rho}\sum_{i=1}^{N}\sum_{j\in N_i}\left(\begin{array}{l}\left(\frac{\gamma^2 a_{i0}^2}{|N_i|}+\gamma\right)\left\|e_i^{\xi}\right\|^2 \\ +\frac{\beta^2}{|N_i|}\left\|e_i^{\eta}\right\|^2+\gamma\left\|e_j^{\xi}\right\|^2\end{array}\right) \\
&\quad +\sum_{i=1}^{N}\left(\begin{array}{l}\left(\rho+\rho\gamma\,|N_i|-\gamma\lambda_{\min}(H)\right)\left\|\xi_i^T\right\|^2 \\ +\left(\rho+\rho\gamma\,|N_i|+(1-\beta)\right)\left\|\eta_i^T\right\|^2\end{array}\right) \\
&\le \sum_{i=1}^{N}\left(\begin{array}{l}\left(\rho+\rho\gamma\,|N_i|-\gamma\lambda_{\min}(H)\right) \\ \left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right)\end{array}\right) \\
&\quad +\frac{\gamma}{\rho}\sum_{i=1}^{N}\sum_{j\in N_i}\frac{a_{i0}+|N_i|}{|N_i|}\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2\right)
\end{aligned} \tag{70}
$$

To make the derivative of lyapunov function negative definite, by introducing parameter $\sigma\epsilon(0,1)$, and making the measurement error meet:

$$\sum_{j\in\mathcal{N}_i} a_i\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2\right)<b_i\left(\|\xi_i\|^2+\|\tilde{\eta}_i\|^2\right), \tag{71}$$

where $a_i=\gamma\left(a_{i0}+|N_i|\right)$, $b_i=\sigma_i\rho\left|N_i\right|\left(\gamma\lambda_{\min}(H)-\rho-\rho\gamma\left|N_i\right|\right)$, $\rho\le\frac{\gamma\lambda_{\min}(H)}{1+\gamma|N_i|}$, $\sigma_i\in(0,1)$. From (41) and (42), then we can get

$$\begin{aligned}\dot{V}\left(\chi(t)\right)| &\le \sum_{i=1}^{N}\begin{array}{c}\left(\rho+\rho\gamma\left|N_i\right|-\gamma\lambda_{\min}(H)\right)\\ \left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right)\end{array}\\ &\quad+\sum_{i=1}^{N}\begin{array}{c}\left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right)\\ \sigma_i\left(\gamma\lambda_{\min}(H)-\rho-\rho\gamma\left|N_i\right|\right)\end{array}\\ &=\sum_{i=1}^{N}\begin{array}{c}\left(\sigma_i-1\right)\left(\gamma\lambda_{\min}(H)-\rho-\rho\gamma\left|N_i\right|\right)\\ \left(\left\|\xi_i^T\right\|^2+\left\|\eta_i^T\right\|^2\right)\end{array}\\ &\le 0\end{aligned} \tag{72}$$

The event-triggered function is designed by (42)

$$\begin{aligned}f_i(t)=&\sum_{j\in\mathcal{N}_i} a_i\left(\left\|e_i^{\xi}\right\|^2+\left\|e_j^{\xi}\right\|^2+\left\|e_i^{\eta}\right\|^2\right)\\ &-b_i\left(\|\xi_i\|^2+\|\eta_i\|^2\right).\end{aligned} \tag{73}$$

Trigger time $t_k^i$ is obtained from the solution of equation $f(t)=0$. At the same time $e_i^{\xi}\left(t_k^i\right)=e_i^{\eta}\left(t_k^i\right)=0$. To sum up, Theorem 1 is proved.

## APPENDIX B
## PROOF OF THEOREM 3

Based on the system (61), we construct the common Lyapunov function candidate

$$V(\chi(t))=\frac{1}{2}\chi(t)^T\left(\Omega\otimes I_m\right)\chi(t). \tag{74}$$

Then the Lyapunov's expansion is

$$\begin{aligned}V&=\frac{1}{2}\begin{pmatrix}\xi^T & \eta^T\end{pmatrix}\begin{bmatrix}\beta I_N+\gamma H & I_N\\ I_N & I_N\end{bmatrix}\otimes I_m\begin{bmatrix}\xi\\ \eta^T\end{bmatrix}\\ &=\frac{1}{2}\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\xi+\frac{1}{2}\eta^T\eta+\xi^T\eta.\end{aligned} \tag{75}$$

Taking the derivative with respect to $V$, we get

$$\begin{aligned}&\dot{V}\left(\chi(t)\right)|\\ &=\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\eta+\eta^T\dot{\eta}+\xi^T\dot{\eta}+\eta^T\eta\\ &=\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\eta+\eta^T\eta+\left(\xi^T+\eta^T\right)\dot{\eta}\\ &=\xi^T\left(I_N+\gamma H\right)\otimes I_m\eta+\ \eta^T\eta+\left(\xi^T+\eta^T\right)u_1(t)\\ &\quad+\left(\xi^T+\eta^T\right)\begin{pmatrix}\left(p(t)\otimes I_m-I_{mN}\right)u_1(t)\\ +p(t)\otimes I_m u_2(t)+\theta(t)\otimes_m\end{pmatrix}\\ &=\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\eta+\eta^T\eta+\left(\xi^T+\eta^T\right)u_1(t)+A,\end{aligned} \tag{76}$$

where

$$\begin{aligned}A&=\left(\xi^T+\eta^T\right)\left(\left(p(t)\otimes I_m-I_{mN}\right)u_1(t)+M\right)\\ &=\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)\left[\left(p_i(t)-1\right)u_{1i}(t)+M\right]\\ &\le\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\left\|u_{1i}(t)\right\|\left|p_i(t)-1\right|+M\\ &\quad+\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)p_i(t)\\ &\quad\times\left(-\frac{\left|1-p_{i0}\right|}{p_{i0}}\left\|u_{1i}\right\|sign\left(\eta_i(t)+\xi_i(t)\right)\right)\\ &\le\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\left\|u_{1i}(t)\right\|\left|p_{i0}-1\right|+M\\ &\quad-\sum_{i=1}^{N}\left|1-p_{i0}\right|\left\|u_{1i}\right\|\left(\xi_i^T+\eta_i^T\right)sign\left(\eta_i(t)+\xi_i(t)\right),\end{aligned} \tag{77}$$

where

$$\begin{aligned}M&=\left(\xi^T+\eta^T\right)\left(p(t)\otimes I_m u_2(t)+\theta(t)+f_i-f_0\right)\\ &\le\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\cdot\theta_{i0}+\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\cdot f_i\\ &\quad-\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\cdot f_0\\ &\quad+\sum_{i=1}^{N}\begin{array}{c}\left(\xi_i^T+\eta_i^T\right)\\ p_i(t)\end{array}\begin{pmatrix}-sign\left(\eta_i(t)+\xi_i(t)\right)\frac{\theta_{i0}}{p_{i0}}\\ -sign\left(\eta_i(t)+\xi_i(t)\right)\frac{f_i-f_0}{p_{i0}}\end{pmatrix}\\ &\le\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\cdot\theta_{i0}+\sum_{i=1}^{N}\left\|\xi_i^T+\eta_i^T\right\|\cdot\left(f_i-f_0\right)\\ &\quad-\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)sign\left(\eta_i(t)+\xi_i(t)\right)\theta_{i0}\\ &\quad-\sum_{i=1}^{N}\left(\xi_i^T+\eta_i^T\right)sign\left(\eta_i(t)+\xi_i(t)\right)\left(f_i-f_0\right).\end{aligned} \tag{78}$$

Because $\left(\xi_i^T+\eta_i^T\right)sign\left(\eta_i(t)+\xi_i(t)\right)\ \ge\ \left\|\xi_i^T+\eta_i^T\right\|$, we can easily get $A<0$.

Then

$$\begin{aligned}&\dot{V}\left(\chi(t)\right)|\\ &\le\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\eta+\eta^T\eta+\left(\xi^T+\eta^T\right)u_1(t)\\ &\le\xi^T\left(\beta I_N+\gamma H\right)\otimes I_m\eta+\eta^T\eta\\ &\quad+\left(\xi^T+\eta^T\right)\begin{pmatrix}-\beta\left[e^{\eta}(t)+\eta(t)\right]\\ -\gamma H\otimes I_m\left[e^{\xi}(t)+\xi(t)\right]\end{pmatrix}\\ &=-\gamma\xi^T\left(H\otimes I_m\right)\xi+(1-\beta)\eta^T\eta\\ &\quad-\left(\xi^T+\eta^T\right)\left(\gamma H\otimes I_m e^{\xi}+\beta e^{\eta}\right)\\ &\le-\gamma\lambda_{\min}(H)\|\xi\|^2+(1-\beta)\|\eta\|^2\\ &\quad-\left(\xi^T+\eta^T\right)\left(\gamma H\otimes I_m e^{\xi}+\beta e^{\eta}\right)\\ &=-\gamma\lambda_{\min}(H)\sum_{i=1}^{N}\|\xi_i\|^2+(1-\beta)\sum_{i=1}^{N}\|\eta_i\|^2\\ &\quad-\left(\xi^T+\eta^T\right)\left(\gamma H\otimes I_m e^{\xi}+\beta e^{\eta}\right)\\ &=-\gamma\lambda_{\min}(H)\sum_{i=1}^{N}\|\xi_i\|^2+(1-\beta)\sum_{i=1}^{N}\|\eta_i\|^2+B.\end{aligned} \tag{79}$$

Since the proof later turns out to be the same as in the previous section, there is no proof here. Finally we can prove that $\dot{V} < 0$. To sum up, Theorem 3 is proved.

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