Event-Triggered Consensus Control of Agent-Based Full-Vehicle Suspension Systems

Xiang Sun, Zhou Gu, *Member, IEEE*, Xiufeng Mu, Shen Yan, and Ju H. Park, *Senior Member, IEEE*

***Abstract*—This article studies the event-triggered consensus control of agent-based active full-vehicle suspension systems (AFSSs). A novel agent-based AFSS model is put forward, by regarding four quarter-vehicle suspension systems (QVSSs) agents with connections. To better utilize cloud technology and improve control performance, a virtual leader is designed at the center of AFSS. The road information stored in the cloud is used as the virtual leader's input to simulate the optimal driving situation of the actual vehicle. Meanwhile, an event-triggered control method for agent-based AFSSs is presented to save communication resources between agents. By utilizing the Lyapunov-Krasovskill functional approach, sufficient conditions are driven to guarantee satisfactory performance of AFSSs. The performance of AFSSs under road disturbances, such as pitch and roll acceleration, can be improved by implementing a consensus control method under the agent-based AFSS model. Finally, the effectiveness of the proposed approach is validated by a real numerical example of AFSSs.**

***Index Terms*—Agent-based active full-vehicle suspension systems, event-triggered mechanism, leader-following.**

I. Introduction

During the past decades, the control of active suspension systems (SSs) utilizing actuators to generate controllable forces between the sprung and unsprung masses has attracted constant attention for improving ride comfort, road holding, and driving safety [1], [2], [3]. A quarter-vehicle suspension system (QVSS) that reflects the vertical dynamic of SSs is usually studied as a research object to evaluate the suspension performance of the proposed control strategy. For instance, in [4], a novel adaptive fuzzy control approach for active QVSSs considering control input delay was presented to obtain superior suspension performance in both control and transient responses. To guarantee a high vibration isolation performance, a new terminal sliding mode control scheme with an adaptive disturbance observer was put forward for active QVSSs in [5]. an adaptive active disturbance rejection sliding mode control strategy in [6] is proposed to improve the vertical stability of active hydro-pneumatic suspension. In [7], an H_∞ control of uncertain active QVSSs based on the Takagi-Sugeno (T-S) fuzzy model was proposed to satisfy suspension performance with the H_∞ disturbance attenuation index. Moreover, the effectiveness of the proposed method is confirmed by semi-vehicle suspension systems (SVSSs). To solve the uncertain information in the membership function of the T-S fuzzy QVSSs, an interval type-2 fuzzy method was presented in [8]. Compared to models of QVSSs and SVSSs, the AFSS model can be used to evaluate more suspension performance indicators, such as pitch and roll acceleration, when designing a vehicle suspension system [9], [10], [11]. This is one of the motivations for this research.

Recent achievements in wireless communication and digital techniques have promoted the development of networked active SSs, such as cloud-aided SSs [12]. Under the framework of cloud-aided SSs, cloud computing offers potentially unlimited computing power to accelerate the implementation of prediction, optimization, and collaborative control strategies for SSs. The road profile information can be provided to the vehicle from an up-to-date cloud database if necessary, and the vehicle can conveniently obtain real-time road profile information from a wireless sensor network, thereby improving the control performance of networked SSs. In [12], a fault-tolerant finite frequency control approach was proposed to guarantee the normal operation of cloud-aided QVSSs in the event of actuator failure. A distributed H_∞ filter design for cloud-aided SVSSs considering time delay and limited bandwidth was put forward in [13], by which the performance of SVSSs under different road conditions can be ensured. An adaptive backstepping control design of cloud-aided AFSSs is investigated in [10], wherein the control strategy is updated based on the storage information in the distant cloud. In addition, multi-agent technology has provided some novel approaches for networked SSs. For example, the coordination of active SSs and electric power systems by using the multi-agent method can minimize the vehicle attitude

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Xiang Sun is with the College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China, and also with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, South Korea (e-mail: sx032812@163.com).

Zhou Gu is with the College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China, and also with the College of Automation and Electronic Engineering, Qingdao University of Science and Technology, Qingdao, Shandong 266061, China (e-mail: gzh1808@163.com).

Xiufeng Mu and Shen Yan are with the College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China (e-mail: muxf16@163.com; yanshenzdh@gmail.com).

Ju H. Park is with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, South Korea (e-mail: jessie@ynu.ac.kr).

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change induced by steering and road roughness, thereby improving control performance [14]. However, few studies have found that AFSSs are considered multi-agent systems (MASs) with four coupled QVSSs. Furthermore, the performance of vehicle attitude control under various road disturbances, such as pitch and roll acceleration, can be improved via consensus control of agent-based AFSSs, which is another motivation for this study.

For cloud-based AFSSs, the wireless network is a medium of signal transmission. Accordingly, the problem of limited network bandwidth is inevitable. Event-triggered mechanism (ETM) has attracted compelling attention as an efficient way to relieve the network burden [15], [16], [17], [18], [19]. Under this mechanism, the transmission of measurement data packets to the network depends on the event-triggering condition instead of a fixed period release. Therefore, the redundant data can be greatly reduced, and the network bandwidth can be significantly saved [20], [21], [22], [23], [24]. To mention a few, an event-triggered H_∞ controller design for networked control systems with distributed delays was investigated in [25]. To accommodate the variation of the system, an adaptive ETM with a time-varying threshold that can be adjusted with the system state was developed in [26], [27], [28]. Moreover, this method was also adopted in [29] to meet the requirements of networked active QVSSs while economizing more communication resources. For improving the system performance and flexibility, [30], [31], [32] proposed a memory-based ETM that utilizes a series of historical triggering data in the design of event-triggering conditions. In [33], an adaptive memory-based ETM was put forward by combining the above advantages of ETMs. For event-driven multi-agent consensus control, the ETM can be roughly divided into two categories: 1) the centralized ETM, where the control is updated according to all nodes' current states [34]; and 2) the distributed ETM, in which each node and its nearby nodes' status information is used to update the control [35]. In [36], a centralized ETM and a distributed dynamic ETM were designed for the leader-following MASs, respectively. In [37], a distributed event-triggered leader-following control strategy was introduced to save the network bandwidth of the communication channels of MASs and ensure the leader-following consensus of MASs with semi-Markov switching topologies. On this basis, a fault-tolerant control against erroneous transmission and external interference was developed to improve the reliability of MASs in [38].

Inspired by the aforementioned discussion, this article investigates the event-triggered consensus control problem for agent-based AFSSs shown in Fig. 1. The main contributions of this article can be summarized as follows:

1) Different from the existing AFSS in [10] and [11], a novel modeling approach for agent-based AFSSs is put forward, wherein four quarter-vehicle suspension systems (QVSSs) are considered to be agents with connections. The control problem for the AFSS is then converted into the multi-agent consensus control problem.
2) A virtual leader of the QVSS is constructed at the center of AFSSs. The virtual leader system uses the road information stored in the cloud to simulate the optimal driving situation of real vehicles. Therefore, the control performance can be further improved.
3) To save communication resources and ensure the performance of AFSSs, a novel event-triggered leader-following control strategy for agent-based AFSSs is proposed, by which the mis-triggering events can be reduced when the SS tends to be stable.

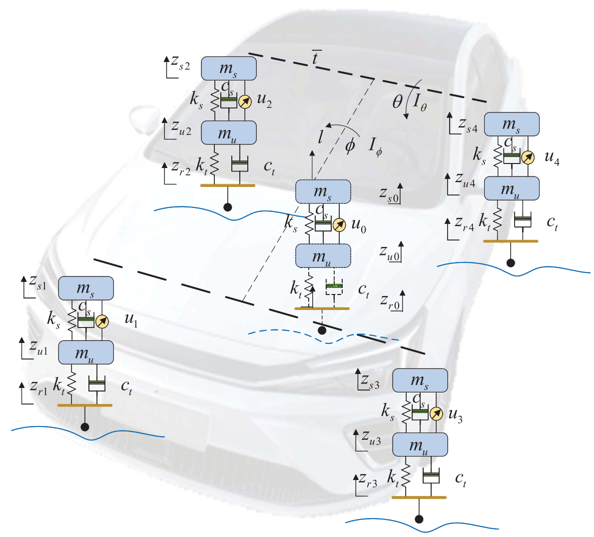

Fig. 1. Model of agent-based AFSSs.

TABLE I
NOTATIONS

Notations	Representations
$\mathbf{He}\{X\}$	$X^T + X$
$\parallel X \parallel_2$	$(X^T X)^{\frac{1}{2}}$
$\mathbb{N}$	The set of real numbers
$\mathbb{N}^n$	n-dimensional Euclidean space
$\mathcal{E}$	The set of directed edges
(v_j, v_i)	The ordered pair of nodes
$N_i = \{j \mid (v_j, v_i) \in \mathcal{E}\}$	The set of neighbors of node i
$\otimes$	The Kronecker product
$L = (l_{ij})_{N\times N}$	$l_{ii} = \sum_{j\in N_i} a_{ij}$ and $l_{ij} = -a_{ij}$, for $i \neq j$

The rest of this article is organized in what follows. We introduce the model of agent-based AFSSs and problem statement in Section II. In Section III, an H_∞ control for agent-based AFSSs is designed. The usefulness of the proposed method is demonstrated by an illustrative example of agent-based AFSSs in Section IV. Section V concludes this article.

In this article, the following notations and graph theory in Table I will be used.

II. Modeling of Agent-Based AFSS With Event-Triggered Mechanism

A. Agent-Based AFSSs

Consider the model of the QVSS in [7], one can achieve the following state-space expression:

$$\dot{x}(t) = Ax(t) + Bu(t) + D\omega(t), \tag{1}$$

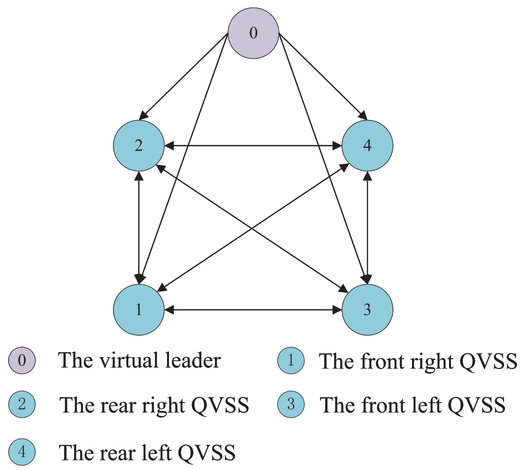

Fig. 2. Diagram topology of the agent-based AFSS.

TABLE II
SYMBOLS OF THE AFSS

Symbol	Quantity
z_{ri}	Road movement input of the i-th QVSS
z_{si}	Sprung masses movements of the i-th QVSS
z_{ui}	Unsprung masses movements of the i-th QVSS
u_i	Actuator force of the i-th QVSS
x_{1i}	Suspension deflection of the i-th QVSS
x_{2i}	Tyre deflection of the i-th QVSS
x_{3i}	Sprung mass velocity of the i-th QVSS
x_{4i}	Unsprung mass velocity of the i-th QVSS
l	Distance between the fore axle and the center of AFSSs
$\bar{t}$	Half of the fore axle

where

$$A = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{k_s}{m_s} & 0 & -\frac{c_s}{m_s} & \frac{c_s}{m_s} \\ \frac{k_s}{m_u} & -\frac{k_t}{m_u} & \frac{c_s}{m_u} & -\frac{c_s+c_t}{m_u} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{m_s} & -\frac{1}{m_u} \end{bmatrix}^T,$$

$$D = \begin{bmatrix} 0 & -1 & 0 & \frac{c_t}{m_u} \end{bmatrix}^T.$$

and the symbols can be found in [7].

As is shown in Fig. 1, the AFSS is modeled as MASs composed of four coupled QVSSs. Agents 1–4 represent the fore right QVSS, the rear right QVSS, the fore left QVSS, and the rear left QVSS, respectively. Then, the problem of the AFSS control turns out to be a multi-agent consensus control problem.

Remark 1: To further study the consensus problem for AFSSs, it is assumed that the leader's information can be transmitted to each agent of QVSS and both agents can interact with each other in this model, therefore, the Laplacian matrix is given by $\hat{L} = L + \hat{A}, \hat{A} = \text{diag}\{a_{10}, a_{20}, \ldots, a_{N0}\}$, where $N = 4$. The diagram topology of the agent-based AFSS is shown in Fig. 2 .

Remark 2: Due to the specialty of the center of AFSSs, a virtual leader is created at the central point, at which the force is hardly affected by the mutual coupling between different subsystems of the AFSS. Moreover, the motion state of the center point can reflect the overall trend of the AFSS, which will further improve the vehicle performance of the AFSS by locating the virtual leader at the center point among AFSSs.

The dynamic equation of the leader at the center of the AFSS can be expressed as

$$\dot{x}_0(t) = (A + BK_0)x_0(t) + D\omega_0(t). \tag{2}$$

Remark 3: K_0 and $\omega_0(t)$ are the known, which can be obtained from the information stored in the cloud.

Due to the mutual coupling between subsystems of the AFSS, the i-th agent of independent SS can be expressed in what follows

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t) + D\omega_i(t) + f_{wi}(t), \tag{3}$$

where $f_{wi}(t) = \sum_{j\in N_i} a_{ij}[g_{wi}(x_i(t)) - g_{wj}(x_j(t))]$ is the function representing the mutual coupling between subsystems of the AFSS and $g_{wi}(x_i(t))i \in \{1, 2, \ldots, N\}$ is a nonlinear function.

Remark 4: Since the coupling influence between subsystems in the FVSSs is limited, it is assumed that the function $g_{wi}(t)$ should satisfy the following generalized Lipschitz condition:

$$\| g_{wi}(x_i(t)) - g_{wj}(x_j(t)) \|_2 \leq \| T(x_i(t) - x_j(t)) \|_2, \tag{4}$$

where matrix T represents the maximum allowable upper boundary of coupling among different subsystems of AFSSs, which is caused by the hardware connection.

B. Performance Indicators of AFSSs

As discussed in [10], ride comfort, as an important performance evaluation index of AFSSs, is usually quantified by pitch acceleration θ and roll acceleration ϕ.

From Fig. 1, one can obtain the following motion equations:

$$\begin{aligned} I_\theta \ddot{\theta} &= -l\left[\mathcal{F}_1(t) + \mathcal{F}_3(t)\right] + l\left[\mathcal{F}_2(t) + \mathcal{F}_4(t)\right], \\ I_\phi \ddot{\phi} &= \bar{t}\left[\mathcal{F}_1(t) + \mathcal{F}_2(t)\right] + \bar{t}\left[\mathcal{F}_3(t) + \mathcal{F}_4(t)\right]. \end{aligned} \tag{5}$$

where $\mathcal{F}_i(t) = c_s\dot{\mathcal{Z}}_i(t) + k_s\mathcal{Z}_i(t) + u_i(t)$ and $\mathcal{Z}_i(t) = z_{ui}(t) - z_{si}(t)$.

Remark 5: Note that parts of the AFSS are asymmetric. Then the l and $\bar{t}$ in (5) can be further extended as follows:

$$l = \frac{l_f + l_r}{2}, \bar{t} = \frac{t_r + t_f}{2}, \tag{6}$$

where l_f and l_r represent distance between the fore and rear axles and the center of AFSSs, respectively. t_r and t_f are length of left and right axles, respectively.

Define $l_\theta = \frac{l}{I_\theta}, t_\phi = \frac{\bar{t}}{I_\phi}, C_\theta = l_\theta\tilde{C}, D_{1\theta} = l_\theta, \tilde{C} = [-k_s \quad 0 \quad -c_s \quad c_s], C_\phi = t_\phi\tilde{C}, D_{1\phi} = t_\phi$.

From (5), one can obtain

$$\begin{aligned} z(t) &= \begin{bmatrix} z_\theta^T(t) & z_\phi^T(t) \end{bmatrix}^T, \\ z_\theta(t) &= \mathcal{I}_\theta\left[\mathcal{C}_\theta\chi(t) + \tilde{\mathcal{D}}_{1\theta}\chi_u(t)\right], \\ z_\phi(t) &= \mathcal{I}_\phi\left[\mathcal{C}_\phi\chi(t) + \tilde{\mathcal{D}}_{1\phi}\chi_u(t)\right], \end{aligned} \tag{7}$$

where

$$\mathcal{C}_\theta = I_N \otimes C_\theta, \tilde{\mathcal{D}}_{1\theta} = I_N \otimes D_{1\theta},$$

$$\mathcal{C}_\phi = I_N \otimes C_\phi,\ \tilde{\mathcal{D}}_{1\phi} = I_N \otimes D_{1\phi},$$
$$\chi(t) = \begin{bmatrix} x_1^T(t) & x_2^T(t) & x_3^T(t) & x_4^T(t) \end{bmatrix}^T,$$
$$\chi_u(t) = \begin{bmatrix} u_1^T(t) & u_2^T(t) & u_3^T(t) & u_4^T(t) \end{bmatrix}^T,$$
$$\mathcal{I}_\theta = [-1 \quad 1 \quad -1 \quad 1], \mathcal{I}_\phi = [-1 \quad -1 \quad 1 \quad 1].$$

C. A Novel Communication Mechanism

To save the limited network bandwidth between agent-based AFSSs, a novel ETM is put forward as follows

$$\Psi_i(t) = e_i^T(t) W e_i(t) - \sigma_i \xi_i^T(t) W \xi_i(t), \tag{8}$$

where $e_i(t) = x_i(t_k^i h) - x_i(t_k^i h + l^i h), \xi_i(t) = \sum_{j\in N_i} a_{ij}[x_i(t_k^i h) - x_j(t_k^j h)] + a_{i0}[x_i(t_k^i h) - x_0(qh)]$, $qh = t_k^i h + l^i h, q, l^i \in \mathbb{N}$, and σ_i is a predefined parameter. If $\Psi_i(t) > \varsigma_i$, the data-packets at this sampling instant are needed to be transmitted and $\sum_{i=1}^N \varsigma_i = \varsigma$.

Remark 6: The signal of the agent-based vehicle suspension system is sampled with a fixed sampling period h. The sampling sequence can be represented by the set $S_1 = \{0, h, 2h, \ldots, qh\}, q \in \mathbb{N}$. This method of transmitting signals with a fixed sampling period is known as a time-triggered mechanism. However, to save the limited network bandwidth between agent-based AFSSs, the sampling signal of the i-th QVSSs can be transmitted over the wireless network to the controller and other QVSSs only when a transmission event is generated by the proposed ETM. The set of transmitted packets sequence is denoted by $S_2^i = \{t_0^i h, t_1^i h, t_2^i h, \ldots, t_k^i h\}$. It is clear that $S_2^i \subset S_1$.

Remark 7: The virtual leader is assumed to be driven by time triggered mechanism with a sampling period h, and all agents are sampled synchronously. Therefore, one can obtain that $qh = t_k^i h + l^i h$.

Remark 8: From (8), it is clear that the next releasing instant is related to the sampling data of both the neighbor and the leader. If $\Psi_i(t) < \varsigma_i$, it implies that the sampling data of the i th agent is unnecessary to its neighbor agents, thereby significantly relieving the network burden.

Remark 9: Different from the general ETM for MASs, such as in [37] and [38], here $\Psi_i(t) > \varsigma_i$ is used to replace $\Psi_i(t) > 0$ as a judgment condition. In this way, some unexpected triggering events can be avoided when the systems tend to be stable, for example, the triggering events during 10–20 s in [39].

D. Consensus Controller Design

Using the ETM in (8), the consensus control law can be established as follows:

$$u_i(t) = K\xi_i(t) + u_0(t), \tag{9}$$

for $t \in [t_k^i h, t_{k+1}^i h)$, where K is the control gain.

Define $\eta_i(t) = t - t_k^i h - l^i h$, the successful transmitted data $x(t_k^i h)$ can be rewritten as

$$x_i(t_k^i h) = e_i(t) + x_i(t - \eta_i(t)). \tag{10}$$

Define $\delta_i(t) = x_i(t) - x_0(t)$, and combine (9) and (10), one can obtain

$$\begin{aligned} u_i(t) = K \Bigg\{ & \sum_{j\in N_i} a_{ij} [e_i(t) - e_j(t) + \delta_i(t - \eta_i(t)) \\ & - \delta_j(t - \eta_j(t))] + a_{i0}[e_i(t) + \delta_i(t - \eta_i(t))] \Bigg\} \\ & + u_0(t). \end{aligned} \tag{11}$$

For convenience, the following definitions are introduced

$$\begin{aligned} \delta(t) &= \begin{bmatrix} \delta_1^T(t) & \delta_2^T(t) & \ldots & \delta_N^T(t) \end{bmatrix}^T, \\ e(t) &= \begin{bmatrix} e_1^T(t) & e_2^T(t) & \ldots & e_N^T(t) \end{bmatrix}^T, \\ \omega(t) &= \left[\omega_1^T(t) - \omega_0^T(t)\ \omega_2^T(t) - \omega_0^T(t), \right. \\ & \qquad \left. \ldots\ \omega_N^T(t) - \omega_0^T(t)\right]^T, \\ \delta(t - \eta(t)) &= \left[\delta_1^T(t - \eta_1(t))\ \delta_2^T(t - \eta_2(t)) \right. \\ & \qquad \left. \ldots\ \delta_N^T(t - \eta_N(t))\right]^T, \\ f_w(t) &= \begin{bmatrix} f_{w1}^T(t) & f_{w2}^T(t) & \ldots & f_{wN}^T(t) \end{bmatrix}^T. \end{aligned}$$

From (7) and (11), it yields that

$$\begin{aligned} z_\theta(t) &= \mathcal{I}_\theta [\mathcal{C}_\theta \delta(t) + \mathcal{D}_{1\theta}\mathcal{K}\delta(t - \eta(t)) + \mathcal{D}_{1\theta}\mathcal{K}e(t)], \\ z_\phi(t) &= \mathcal{I}_\phi [\mathcal{C}_\phi \delta(t) + \mathcal{D}_{1\phi}\mathcal{K}\delta(t - \eta(t)) + \mathcal{D}_{1\phi}\mathcal{K}e(t)], \end{aligned} \tag{12}$$

where

$$\mathcal{D}_{1\theta} = \hat{L} \otimes D_{1\theta}, \mathcal{D}_{1\phi} = \hat{L} \otimes D_{1\phi}, \mathcal{K} = I_N \otimes K.$$

Defining $\lambda(t) = \begin{bmatrix} \delta^T(t) & \delta^T(t - \eta(t)) & e^T(t) \end{bmatrix}^T$ and combining (2), (3), (11), and (12), one can get the leader-following mulgti-agent AFSS model by Kronecker product as follows:

$$\begin{cases} \dot{\delta}(t) = \hat{\mathcal{A}}\lambda(t) + \mathcal{D}\omega(t) + \mathcal{I}f_w(t), \\ z(t) = \hat{\mathcal{C}}\lambda(t), \end{cases} \tag{13}$$

where

$$\hat{\mathcal{A}} = \begin{bmatrix} \mathcal{A} & \mathcal{BK} & \mathcal{BK} \end{bmatrix}, \hat{\mathcal{C}} = \begin{bmatrix} I_\theta \mathcal{C}_\theta & I_\theta \mathcal{D}_{1\theta}\mathcal{K} & I_\theta \mathcal{D}_{1\theta}\mathcal{K} \\ I_\phi \mathcal{C}_\phi & I_\phi \mathcal{D}_{1\phi}\mathcal{K} & I_\phi \mathcal{D}_{1\phi}\mathcal{K} \end{bmatrix},$$
$$\mathcal{A} = I_N \otimes A, \mathcal{B} = \hat{L} \otimes B, \mathcal{C} = I_N \otimes C, \mathcal{D} = I_N \otimes D,$$
$$\mathcal{I} = I_N \otimes I.$$

The primary purpose of this article aims to develop the consensus controller in (9) such that the systems (13) have a satisfying ride performance with an H_∞ attenuation lever γ based on the ETM in (8).

III. Design of Agent-Based AFSSs

In this section, sufficient conditions are presented to guarantee the stability of event-triggered agent-based AFSSs in Theorem 1, and the criterion of controller design is given in Theorem 2.

Before proceeding further, the following definition is given.

Definition 1: Given a scalar $\varsigma > 0$ and $\mathcal{P} > 0$. The multi-agent AFSS in (13) is uniformly ultimately bounded (UUB) with an H_∞ attenuation level γ if the following hold

1) When $\omega(t)=0$, for the multi-agent AFSS in (13), if exists a compact set $\mathbb{R}\in\mathbb{N}^n$ with $\delta(t_0+\tau)=\delta_{t_0}\in\mathbb{U},\tau\in[-\eta,0],\eta>0$, there exist a ς, a symmetric matrice $\mathcal{P}>0$, and a number $\Im(\varsigma,\delta_{t_0})$ such that $\delta^T(t)\mathcal{P}\delta(t)<\sqrt{\varsigma},\forall t\geq t_0+\Im$;
2) For a positive parameter γ, $J=\int_0^\infty[\parallel z(t)\parallel_2-\gamma\parallel\omega(t)\parallel_2]dt\leq 0$ with $\omega(t)\in\mathcal{L}_2[0,\infty)$ is satisfied under zero-initial condition.

For the sake of description in subsequent analysis, the following definitions are introduced $\zeta(t)=\begin{bmatrix}\zeta_1^T(t) & e^T(t) & \omega^T(t) & f_w^T(t)\end{bmatrix}^T$, where $\zeta_1(t)=\begin{bmatrix}\delta^T(t) & \delta^T(t-\eta(t)) & \delta^T(t-h)\end{bmatrix}^T$.

Theorem 1: For given scalars $\sigma_i\in(0,1)$, $i\in\{1,2,3,4\},\varsigma>0$ and matrices K, the agent-based AFSS in (13) are UUB with an H_∞ attenuation level γ, if there exist symmetric matrices $\mathcal{P}>0,Q>0,R>0,W>0$ such that

$$\Phi=\begin{bmatrix}\Theta_{11} & * \\ \Theta_{21} & \Theta_{22}\end{bmatrix}<0, \tag{14}$$

$$\begin{bmatrix}R & * \\ M & R\end{bmatrix}\geq 0, \tag{15}$$

where

$$\Theta_{11}=\begin{bmatrix}\Xi_{11} & * & * & * & * & * \\ \Xi_{21} & \Xi_{22} & * & * & * & * \\ \Xi_{31} & \Xi_{32} & \Xi_{33} & * & * & * \\ \Xi_{41} & \Xi_{42} & 0 & \Xi_{44} & * & * \\ \Xi_{51} & 0 & 0 & 0 & -\gamma^2 I & * \\ \mathcal{P} & 0 & 0 & 0 & 0 & -\mathcal{P}\end{bmatrix},$$

$$\Theta_{21}=\begin{bmatrix}h\mathcal{A} & h\mathcal{BK} & 0 & h\mathcal{BK} & h\mathcal{D} & h\mathcal{I} \\ I_\theta\mathcal{C}_\theta & I_\theta\mathcal{D}_{1\theta}\mathcal{K} & 0 & I_\theta\mathcal{D}_{1\theta}\mathcal{K} & 0 & 0 \\ I_\phi\mathcal{C}_\phi & I_\phi\mathcal{D}_{1\phi}\mathcal{K} & 0 & I_\phi\mathcal{D}_{1\phi}\mathcal{K} & 0 & 0 \\ \mathcal{T} & 0 & 0 & 0 & 0 & 0\end{bmatrix},$$

$$\Theta_{22}=\mathrm{diag}\{-R^{-1},-I,-I,-\mathcal{P}^{-1}\},\ \mathcal{P}=I_N\otimes P,$$

$$\Xi_{11}=\mathrm{He}(\mathcal{PA})+Q-R+\sqrt{\varsigma}\mathcal{P},\mathcal{T}=L\otimes T,$$

$$\Xi_{21}=\mathcal{K}^T\mathcal{B}^T\mathcal{P}+R+M,\Xi_{22}=\mathcal{W}-2R-M-M^T,$$

$$\Xi_{31}=-M,\Xi_{32}=R+M,\Xi_{33}=-Q-R,$$

$$\Xi_{41}=\mathcal{K}^T\mathcal{B}^T\mathcal{P},\Xi_{42}=\mathcal{W},\Xi_{44}=-I_N\otimes W+\mathcal{W},$$

$$\Xi_{51}=\mathcal{D}^T\mathcal{P},\Lambda=\mathrm{diag}\{\sigma_1,\sigma_2,\ldots,\sigma_N\},\mathcal{W}=\left(\hat{L}^T\Lambda\hat{L}\right)\otimes W.$$

Proof: Construct the following Lyapunov function for the AFSS in (13):

$$V(t)=\delta^T(t)\mathcal{P}\delta(t)+\int_{t-h}^t\delta^T(v)Q\delta(v)dv + h\int_{-h}^0\int_{t+s}^t\dot{\delta}^T(v)R\dot{\delta}(v)dvds. \tag{16}$$

By computing the derivation of $V(t)$, one can obtain

$$\dot{V}(t)\leq\delta^T(t)2\mathcal{P}\dot{\delta}(t)+\delta^T(t)Q\delta(t) - \delta^T(t-h)Q\delta(t-h) + h^2\dot{\delta}^T(t)R\dot{\delta}(t)-h\int_{t-h}^t\dot{\delta}^T(v)R\dot{\delta}(v)dv. \tag{17}$$

Using Jessen inequality property [40], one has

$$-h\int_{t-h}^t\dot{\delta}^T(s)R\dot{\delta}(s)ds\leq\zeta_\delta^T(t)\mathcal{M}\zeta_\delta(t), \tag{18}$$

where

$$\mathcal{M}=\begin{bmatrix}-R & * & * \\ R+M & -2R-M-M^T & * \\ -M & R+M & -R\end{bmatrix}.$$

For $\delta^T(t)\mathcal{P}\delta(t)>\sqrt{\varsigma}$, one knows that

$$\delta^T(t)\sqrt{\varsigma}\mathcal{P}\delta(t)-\varsigma>0. \tag{19}$$

Then, it follows from the ETM in (8) and (19) that

$$\begin{aligned}&e^T(t)(I_N\otimes W)e(t)\\ &<[\delta(t-\eta(t))+e(t)]^T\mathcal{W}[\delta(t-\eta(t))+e(t)]\\ &\quad+\delta^T(t)\sqrt{\varsigma}\mathcal{P}\delta(t).\end{aligned} \tag{20}$$

From (4), one has

$$f_w^T(t)\mathcal{P}f_w(t)\leq\delta^T(t)\mathcal{T}^T\mathcal{P}\mathcal{T}\delta(t). \tag{21}$$

Combining (17)–(20) yields that

$$\dot{V}(t)+z^T(t)z(t)-\gamma^2\omega^T(t)\omega(t)\leq\zeta^T(t)\Phi\zeta(t). \tag{22}$$

From Definition 1, one can conclude that the agent-based AFSS in (13) are UUB with an H_∞ attenuation level γ under the proposed consensus controller in (9) and the ETM in (8). This completes the proof. ■

Theorem 2: For given scalars $\sigma_i,i\in\{1,2,3,4\},\sigma_i\in(0,1),\varepsilon,\varsigma$, the agent-based AFSS in (13) is UUB with an H_∞ attenuation level γ, if there exist symmetric matrices $\mathcal{X}>0,\tilde{Q}>0,\tilde{R}>0,\tilde{M}>0,\tilde{W}>0$ such that

$$\tilde{\Phi}=\begin{bmatrix}\tilde{\Theta}_{11} & * \\ \tilde{\Theta}_{21} & \tilde{\Theta}_{22}\end{bmatrix}<0, \tag{23}$$

$$\begin{bmatrix}\tilde{R} & * \\ \tilde{M} & \tilde{R}\end{bmatrix}\geq 0, \tag{24}$$

where

$$\tilde{\Theta}_{11}=\begin{bmatrix}\tilde{\Xi}_{11} & * & * & * & * & * \\ \tilde{\Xi}_{21} & \tilde{\Xi}_{22} & * & * & * & * \\ \tilde{\Xi}_{31} & \tilde{\Xi}_{32} & \tilde{\Xi}_{33} & * & * & * \\ \tilde{\Xi}_{41} & \tilde{\Xi}_{42} & 0 & \tilde{\Xi}_{44} & * & * \\ \tilde{\Xi}_{51} & 0 & 0 & 0 & -\gamma^2 I & * \\ \mathcal{X} & 0 & 0 & 0 & 0 & -\mathcal{X}\end{bmatrix},$$

TABLE III
THE PARAMETER VALUES OF THE AFSSs

Parameter	Value	Unit	Parameter	Value	Unit
m_{sf}	1400	kg	m_s	350	kg
c_s	1200	Ns/m	m_u	100	kg
k_s	30000	N/m	I_θ	2100	kgm^2
k_t	200000	N/m	I_ϕ	460	kgm^2
l	0.70	m	$\bar{t}$	0.71	m

$$\tilde{\Theta}_{21} = \begin{bmatrix} h\mathcal{A}\mathcal{X} & h\mathcal{B}Y & 0 & h\mathcal{B}Y & h\mathcal{D} & h\mathcal{X} \\ I_\theta \mathcal{C}_\theta \mathcal{X} & I_\theta \mathcal{D}_{1\theta} Y & 0 & I_\theta \mathcal{D}_{1\theta} Y & 0 & 0 \\ I_\phi \mathcal{C}_\phi \mathcal{X} & I_\phi \mathcal{D}_{1\phi} Y & 0 & I_\phi \mathcal{D}_{1\phi} Y & 0 & 0 \\ \mathcal{T}\mathcal{X} & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\tilde{\Theta}_{22} = \mathrm{diag}\{-2\varepsilon\mathcal{X} + \varepsilon\tilde{R}^2, -I, -I, -\mathcal{X}\},$$

$$\tilde{\Xi}_{11} = \mathrm{He}(\mathcal{A}\mathcal{X}) + \tilde{Q} - \tilde{R} + \sqrt{\varsigma}\mathcal{X}, \tilde{\Xi}_{21} = Y^T\mathcal{B}^T + \tilde{R} + \tilde{M},$$

$$\tilde{\Xi}_{22} = \tilde{\mathcal{W}} - 2\tilde{R} - \tilde{M} - \tilde{M}^T, \tilde{\Xi}_{31} = -\tilde{M}, \tilde{\Xi}_{32} = \tilde{R} + \tilde{M},$$

$$\tilde{\Xi}_{33} = -\tilde{Q} - \tilde{R}, \tilde{\Xi}_{41} = Y^T\mathcal{B}^T, \tilde{\Xi}_{42} = \tilde{\mathcal{W}},$$

$$\tilde{\Xi}_{44} = -I_N \otimes \tilde{W} + \tilde{\mathcal{W}}, \tilde{\mathcal{W}} = (\hat{L}^T\Lambda\hat{L}) \otimes \tilde{W}, \tilde{\Xi}_{51} = \mathcal{D}^T.$$

In addition, one can calculate consensus controller feedback gain and the triggering matrix by $\mathcal{K} = Y\mathcal{X}^{-1}$ and $W = \mathcal{X}^{-1}\tilde{\mathcal{W}}\mathcal{X}^{-1}$, respectively.

Proof: Define $X = P^{-1}, \mathcal{X} = I_N \otimes X$, $\mathcal{X}_1 = \mathrm{diag}\{\mathcal{X}, \mathcal{X}, \mathcal{X}, \mathcal{X}, I_N, \mathcal{X}, \mathcal{X}, I_N, I_N, \mathcal{X}\}$, and then introduce matrix variables: $Y = \mathcal{K}\mathcal{X}, \tilde{R} = \mathcal{X}R\mathcal{X}, \tilde{M} = \mathcal{X}M\mathcal{X}, \tilde{Q} = \mathcal{X}Q\mathcal{X}$.

Notice that $(\varepsilon R - \mathcal{P})R^{-1}(\varepsilon R - \mathcal{P}) \geq 0$, it yields that

$$-\mathcal{P}R^{-1}\mathcal{P} \leq -2\varepsilon\mathcal{P} + \varepsilon^2 R. \quad (25)$$

Then, one can know that the inequality (23) guarantees the inequality (14) holds. Similarly, (24) holds from (14). This completes the proof. ■

IV. NUMERICAL SIMULATION

In this section, a full-vehicle suspension model is applied to manifest the advantages of our proposed method. The parameter values of the AFSS are listed in Table III.

Similar to [7], the following bump road profiles are selected:

$$z_{r1}(t) = \begin{cases} z^*(l_v t), & 0 \leq t \leq \frac{l}{V_0} \\ 0, & t > \frac{l}{V_0} \end{cases},$$

$$z_{r2}(t) = \begin{cases} 0, & 0 \leq t < \tau_l \\ z^*(l_v(t - \tau_l)), & \tau_l \leq t \leq \bar{\tau}_l \\ 0, & t > \bar{\tau}_l \end{cases},$$

$$z_{r3}(t) = \begin{cases} 0.3z^*(l_v t), & 0 \leq t \leq \frac{l}{V_0} \\ 0, & t > \frac{l}{V_0} \end{cases},$$

$$z_{r4}(t) = 0, t > 0, \quad (26)$$

where $z^*(v) = \frac{a}{2}(1 - \cos(v))$ with $a = 0.1\,m, l_a = 5\,m, V_0 =$ 45 km/h, $\bar{\tau}_l = \frac{l_a}{V_0} + \tau_l$ with $\tau_l = \frac{2\,l}{V_0}$ and $l_v = \frac{2\pi V_0}{l_a}$.

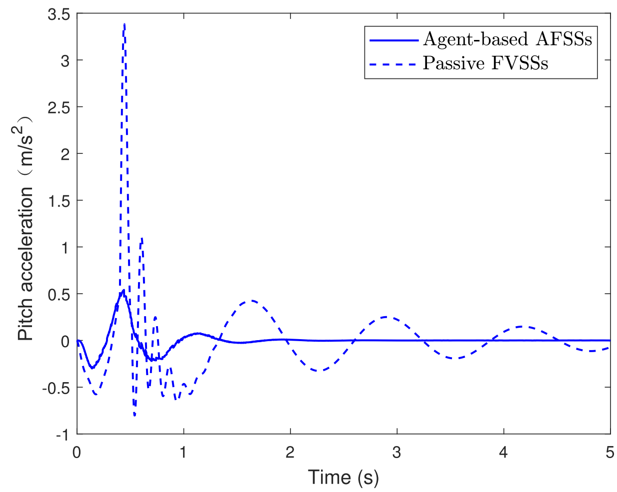

Fig. 3. Pitch acceleration.

The road input of leader system is given as

$$z_{r0}(t) = \frac{1}{4}(z_{r1}(t) + z_{r2}(t) + z_{r3}(t) + z_{r4}(t)) \quad (27)$$

Select $h = 0.01\,s$, $\gamma = 65$, $\sigma_1 = 0.005$, $\sigma_2 = 0.012$, $\sigma_3 = 0.010$, $\sigma_4 = 0.005$, $\varepsilon = 0.4$, $T = \mathrm{diag}\{0.1, 0.1, 0.1, 0.1\}$, $\varsigma = 0.004$, $g_{wi}(x_i(t)) = \sin(Tx_i(t))$, and leader's controller gain $K_0 = 10^3 \times [-0.3807 \quad 0.2160 \quad 0.1512 \quad -0.8648]$.

Considering the topology graph in Fig. 2, one can obtain L and $\hat{A}$, which is given by

$$L = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix},$$

$$\hat{A} = \mathrm{diag}\{1, 1, 1, 1\}.$$

Remark 10: The feedback gain K_0 of the leader is selected through cloud computing, which is suitable for the current situation. In this article, K_0 is selected from [29].

Through Theorem 2, one can get

$$W = 10^3 \times \begin{bmatrix} 2.0170 & 0.7843 & -0.1125 & -0.0067 \\ 0.7843 & 9.5998 & -0.5423 & -0.0013 \\ -0.1125 & -0.5423 & 0.3101 & 0.0164 \\ -0.0067 & -0.0013 & 0.0164 & 0.0048 \end{bmatrix},$$

$$K = [142.0792 \quad 505.3714 \quad -245.4348 \quad -13.5178].$$

Simulation results for the agent-based AFSS under the proposed ETM are presented in Figs. 3–9. In Figs. 3 and 4, the blue solid and blue dotted lines represent the pitch and roll acceleration responses of the agent-based active AFSS under consensus controller and passive full-vehicle suspension systems (FVSSs), respectively. From these figures, it can be concluded that ride comfort indexes can be guaranteed under the selected pavement input by the proposed method compared to passive FVSSs using general modeling. The agent-based AFSS' trajectories, including suspension deflection and tyre deflection, are depicted

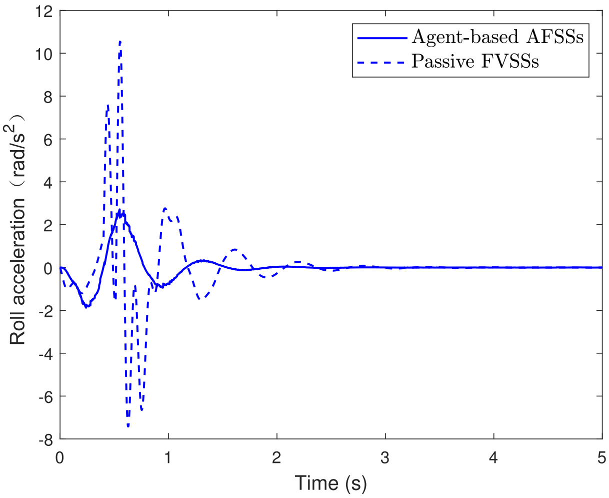

Fig. 4. Roll acceleration.

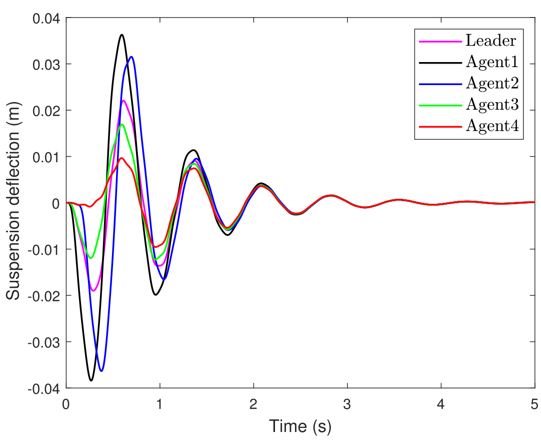

Fig. 5. Suspension deflection of agents and leader.

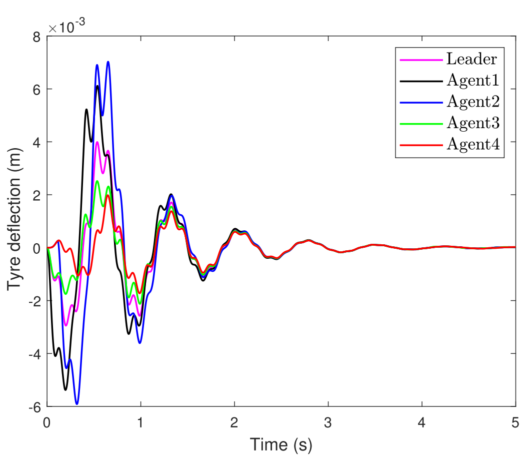

Fig. 6. Tyre deflection of agents and leader.

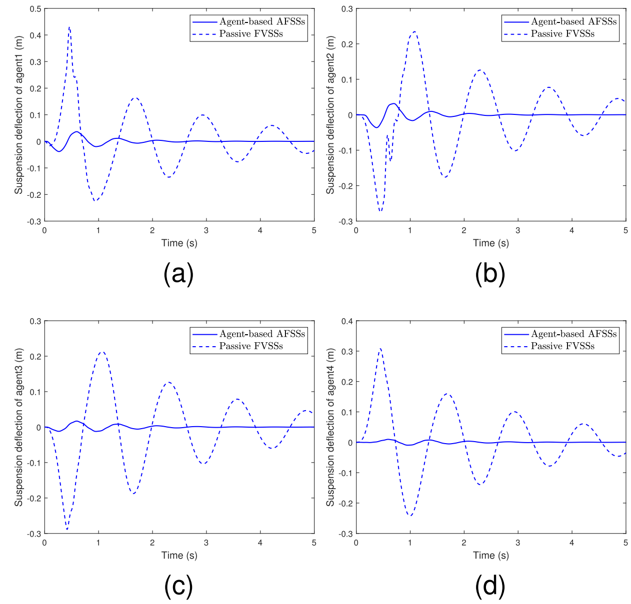

Fig. 7. Suspension deflection of agents and passive FVSSs. (a) Agent 1. (b) Agent 2. (c) Agent 3. (d) Agent 4.

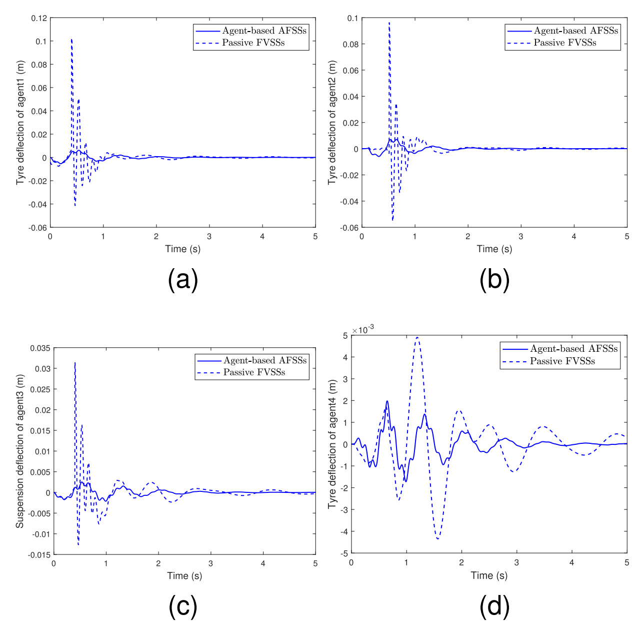

Fig. 8. Tyre deflection of agents and passive FVSSs. (a) Agent 1. (b) Agent 2. (c) Agent 3. (d) Agent 4.

in Figs. 5 and 6, which imply that the error between followers and leader vanishes rapidly under the proposed approach. The results in Figs. 7 and 8 verify the effectiveness of the consensus controller of AFSSs, where blue lines and blue dotted lines are trajectories of suspension deflection and tyre deflection of the agent-based AFSS and passive FVSSs under the bump road profile, respectively. The above results show that the proposed consensus controller of the AFSS has better control performance in suspension deflection and tyre deflection.

Fig. 9 shows the releasing time intervals of the agent-based AFSS under bump road profiles, from which one can clearly see that many sampled packets of agents are discarded using the proposed ETM. To better demonstrate the effectiveness of the ETM in (8), statistical results on the data releasing rate of the different agents in the simulation duration are listed in Table IV, and the data releasing rate is calculated by $\mathcal{R}_i = \frac{\mathcal{N}_{ri}}{\mathcal{N}_{si}}$, where $\mathcal{R}_i$, $\mathcal{N}_{ri}$, and $\mathcal{N}_{si}$ denote the data releasing rate, the number of data

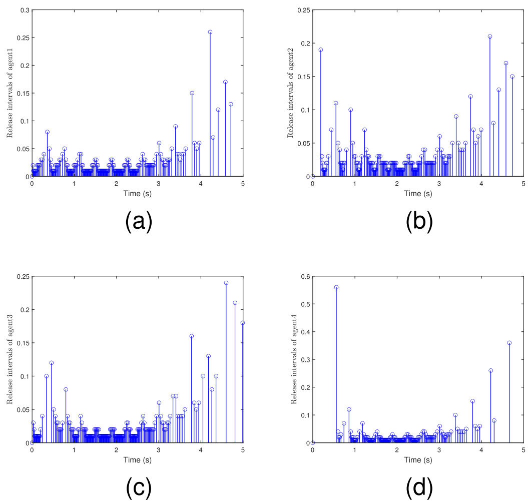

Fig. 9. Release intervals. (a) Agent 1. (b) Agent 2. (c) Agent 3. (d) Agent 4.

TABLE IV
THE DATA RELEASING RATE

	Agent 1	Agent 2	Agent 3	Agent 4
$\mathcal{N}_{si}$	500	500	500	500
$\mathcal{N}_{ri}$	211	163	202	162
$\mathcal{R}_i$	42.2%	32.6%	40.4%	32.4%

releasing, and the number of data sampling of the i-th agent of AFSSs, respectively.

From Fig. 9 and Table IV, one can conclude that the proposed ETM can reduce data packets transmitted between different agents. Compared to the time-triggered transmission scheme, the proposed ETM in (8) can save the network bandwidth of the communication channels between different agents while ensuring the control performance of the active agent-based AFSS.

V. CONCLUSION

The event-triggered consensus control problem for agent-based AFSSs has been investigated in this article. To ensure the vehicle attitude control performance of network communication based AFSSs under road disturbances, a new modeling approach for agent-based AFSSs has been put forward. Based on this model, a virtual QVSS leader has been constructed in the AFSS center, which can utilize the road information stored in the cloud to simulate the optimal driving condition of real vehicles. To save communication resources between agents and guarantee the performance of agent-based AFSSs, an event-triggered consensus controller has been designed for agent-based AFSSs. Finally, an example of real AFSSs has been utilized to illustrate the validity of the proposed method. An extension of the proposed approach for agent-based AFSSs to hardware level will be our future work, besides, how to generalize developed event-triggered consensus control of agent-based AFSSs under more comprehensive situation involving actuator dynamics, dynamic ETM and memory ETM also deserves a deep investigation.

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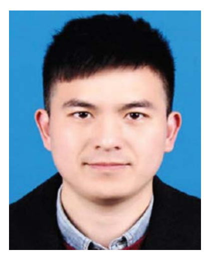
Xiang Sun received the B.S. degree in vehicle engineering from the Jiangsu University of Technology, Changzhou, China, in 2017 and the M.S. degree in control engineering in 2019 from Nanjing Forestry University, Nanjing, China, where he is currently working toward the Ph.D. degree in mechanical engineering. He is a Visiting Ph.D. Student with the Department of Electrical Engineering, Yeungnam University, Gyeongsan, South Korea. His research interests include suspension systems, event-triggered control, and secure control.

Zhou Gu (Senior Member, IEEE) received the B.S. degree from North China Electric Power University, Beijing, China, in 1997, and the M.S. and Ph.D. degrees in control science and engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2007 and 2010, respectively. From 1996 to 2013, he was an Associate Professor with the School of Power Engineering, Nanjing Normal University, Nanjing. He was a Visiting Scholar with Central Queensland University, Rockhampton, QLD, Australia, and The University of Manchester, Manchester, U.K. He is currently a Professor with Nanjing Forestry University, Nanjing. His research interests include networked control systems, time-delay systems, and reliable control and their applications.

Xiufeng Mu received the B.S. degree in 2013 from Nanjing Forestry University, Nanjing, China, where he is currently working toward the Ph.D. degree. His research interests include networked control systems, UAV consensus control, multi-agent systems, and time-delay systems.



Shen Yan received the B.E. and Ph.D. degrees from the College of Electrical Engineering and Control Science of Nanjing Technology University, Nanjing, China, in 2014 and 2019, respectively. From 2017 to 2018, he was a visiting Ph.D. student with the University of Auckland, Auckland, New Zealand. From February 2022 to August 2022, he was a Visiting Scholar with Yeungnam University, Kyongsan, South Korea. He is currently an Associate Professor with the College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing. His research interests include networked control systems, and event-triggered control and their application.

Ju H. Park (Senior Member, IEEE) received the Ph.D. degree in electronics and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1997. From 1997 to 2000, he was a Research Associate with Engineering Research Center-Automation Research Center, POSTECH. In March 2000, he joined Yeungnam University, Kyongsan, Korea, where he is currently the Chuma Chair Professor. He is a Coauthor of the monographs *Recent Advances in Control and Filtering of Dynamic Systems with Constrained Signals* (Springer-Nature, 2018) and *Dynamic Systems With Time Delays: Stability and Control* (Springer-Nature, 2019), and the Editor of an edited volume *Recent Advances in Control Problems of Dynamical Systems and Networks* (Springer-Nature, 2020). He has authored or coauthored a number of articles in the areas of his research interest, which include robust control and filtering, neural/complex networks, fuzzy systems, multiagent systems, and chaotic systems. Prof. Park is a Fellow of the Korean Academy of Science and Technology. In 2015, he was the recipient of the Highly Cited Researchers Award by Clarivate Analytics (formerly, Thomson Reuters) and was listed in three fields, engineering, computer sciences, and mathematics from 2019 to 2022. He is the Editor of the *International Journal of Control, Automation and Systems*. He is also the Subject Editor, Advisory Editor, Associate Editor, and an Editorial Board Member of several international journals, including the*IET Control Theory & Applications, Applied Mathematics and Computation, Journal of The Franklin Institute, Nonlinear Dynamics, Engineering Reports, Cogent Engineering*, IEEE TRANSACTION ON FUZZY SYSTEMS, TRANSACTION ON NEURAL NETWORKS AND LEARNING SYSTEMS, and IEEE TRANSACTION ON CYBERNETICS.