Hierarchical Fuzzy Logic-Based Variable Structure Control for Vehicles Platooning

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***Abstract*— This paper proposes a variable structure control approach for vehicles platooning based on a hierarchical fuzzy logic. The leader-follower vehicle dynamics with model uncertainties is discussed from the viewpoint of a consensus problem. A practical two-layer fuzzy control for the platooning is designed by employing two common spacing policies to ensure system robustness in different scenarios. The two policies, i.e., constant distance and constant time headway, utilize the predecessor-successor information flow from the immediate predecessor and follower other than controlled vehicles. The first layer of the fuzzy system combines spacing control with velocity-acceleration control to achieve a rapid tracking for the desired control commands, and the second layer combines the sliding mode control to adaptively compensate for reducing the state errors caused by parameter uncertainties and disturbances. Shift between different controller parameters is based on performance boundaries to guarantee the stability of individual vehicle and platooning for arbitrary initial spacing and velocity errors. These performance boundaries can be determined by using a Lyapunov method with exponential stability. Simulation of a ten-vehicle large platooning with two spacing policies shows that the control performance of the newly proposed method is effective and promising.**

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***Index Terms*— Vehicles platooning, platoon stability, hierarchical fuzzy control, constant distance, constant time headway, adaptive compensation.**

I. Introduction

VEHICLES platooning has always been under large field operational tests, from earlier PATH – a California traffic automation project with seven-vehicle platooning [1], and Smart Cruise 21 DEMO – a Japanese platooning service with five-vehicle platooning [2], to Energy ITS – a Japanese platooning project with four-truck platooning [3], and then to current SARTRE/SCANIA/Daimler – three European truck platooning projects with three or four trucks platooning [4]–[6]. The design of vehicle platooning system mainly requires the integrations of spacing policy, information flow and control scheme. The desired safety spacing that the controlled vehicle is expected to keep from its preceding one is called the spacing policy, which typically chooses the velocity of the controlled vehicle. It also can choose a constant or other variable as the control object [7]. The most common spacing policy uses a constant distance or time headway. When using the constant distance (CD) policy, the distance between the inter and controlled vehicles is independent and applying the single predecessor information may not ensure the string stability [8]. The term "string stability" is a property whereby the velocities/positions of the controlled vehicles will not be impacted by the fluctuations of the velocity/position of the leading vehicle [9], [10]. This property is attained through the information flow of the leading vehicle in the CD policy or constant time headway (CTH) policy, where the inter-vehicle communication is utilized to get accurate velocity/position information [8], [11]. Although the CTH uses the information flow of the leading vehicle to guarantee the string stability, the string stability is only achieved in small or medium platoon [12], [13]. If the predecessor-successor information flow is used, the velocities/positions of both the preceding and following vehicles can be employed to achieve the string stability in large platoon [14]–[16].

A platooning control system is mainly dependent on the control scheme. The popular model-based control scheme combines the nonlinear vehicle model with various control laws such as PID [13], [17], sliding mode [13], [18], adaptive control [19], linear optimal control [20], and H∞ control [21] to provide expected command tracking performance and string stability. However, some problems remain with the model-based scheme. Firstly, its control laws are usually obtained by means of strict linearization of the vehicle models and normalization of their input-output behavior to simplify the platoon complexity [22]. Secondly, in order to make sure the string stability, it is well satisfied that the difference of the transfer functions between the preceding vehicle and controlled one with respect to the H∞/H_2 norm is less than one, but the specific hints or restrictions on the norms for the platooning system are hard to be understood or convinced [7].

Nowadays, the fuzzy logic has been broadly used for control of longitudinal and lateral vehicle dynamics [23], [24]. It has also been used for following and lane-change maneuvers of vehicles [25], [26]. However, it often builds a fuzzy logic system with the help of prior expert knowledge to define the structure and rules of the fuzzy controller and determine the control parameters. Nevertheless, one laborious task for the fuzzy controller is to minimize the fuzzy rules and reduce the computation effort. Lee and Kim [25] presented a longitudinal control strategy for vehicle platooning using a fuzzy sliding mode controller (FSMC). The sliding mode function, instead of the velocity/acceleration errors, was used as the inputs of the FSMC. It does not require exact mathematical models of vehicles to guarantee the string stability of the controller. Yang *et al.* [27] designed a fuzzy PI controller to realize the longitudinal control of following vehicle. Lee and Tomizuka [28] proposed two different traction force controllers, adaptive fuzzy logic control (AFLC) and adaptive sliding-mode control (ASMC), to deal with robust vehicle platooning problems. ASMC was used in the case where an approximate tire/road model is available while AFLC used the information of tire/road surface condition to adjust the fuzzy rule base. Guo *et al.* [29] proposed two adaptive fuzzy control schemes for multiple high-speed trains (HSTs). In the first scheme, the adaptive fuzzy control in the fault-free case was developed to guarantee the string stability of all trains, whereas in the second scheme, an alternative adaptive fuzzy fault-tolerant control was used to consider the actuator faults and simultaneously reduce the number of adaptive parameters. Furthermore, based on the traditional constant time headway (TCTH) and modified constant time headway (MCTH) policies, Guo *et al.* [30] proposed two distributed adaptive integral sliding mode control (ISMC) strategies to guarantee the bounded stability of individual vehicle and string stability of the platoon. Yan *et al.* [31] developed a coupled sliding surface (CSS) method to link two standalone sliding surfaces to control vehicle platoon with uncertain driving resistance. Previous researches demonstrated good performance of Fuzzy controllers in vehicle platooning. However, the string stability for large platoon control is still a challenging issue. The predecessor-successor information flow can be used to enhance the string stability in large platoon [14]–[16], while to our best knowledge, very limited work has been done to apply the predecessor-successor information flow into the Fuzzy controller for vehicle platooning in large platoon.

To address the aforementioned issue, a novel hierarchical fuzzy logic based variable structure control approach is proposed in this paper. Different to a single layer FSMC controller, a two-layer fuzzy logic based variable structure control is developed to improve the large platoon control performance. The contributions of the proposed approach are briefly summarized as follows.

(1) A new hierarchical (i.e., two-layer) Fuzzy structure is proposed for vehicle platooning whereas most of existing approaches adopt single layer Fuzzy controller. The advantage of the hierarchical fuzzy structure is that the fuzzy rule sets can be significantly cut down [32].

(2) The combination of fuzzy logic and sliding mode control has already been applied to vehicle platooning. The advantages of this method lie in two aspects, one is the global approximation ability of fuzzy logic for unknown model parameters or functions, and the other is the robustness of sliding mode control when interfere model disturbances and nonlinearities. In most existing researches [25]–[31] the sliding mode control plays a major role in the combination to deal with the string stability. However, in the vehicle platooning the disturbances and nonlinearities are mainly involved with unknown model parameters or functions. It is suitable to use fuzzy logic as the core of the combination. In the proposed hierarchical fuzzy logic control the fuzzy logic plays a major role in the combination. The correction factors of different fuzzy base functions are tuned by the sliding mode control law to achieve an adaptive compensation to the approximate error.

Although the spacing polices use the leader-predecessor information flow to guarantee the string stability, the string stability is only achieved in small or medium platoon in the mentioned references. The innovation of this research lies in that the predecessor-successor information flow is used to achieve the string stability in large platoon. A Lyapunov method with exponential stability is used to develop performance boundaries for arbitrary initial spacing and velocity errors and to determine the controller parameters instead of H_∞/H_2 norm construction.

The reminders of this paper are organized as follows. Section II describes the mathematical model of a vehicle longitudinal model. The hierarchical fuzzy control approach is presented in Section III. The consensus issues of platoon stability are discussed in Section IV. In Section V, numerical testing results are presented to demonstrate the promising performance of the proposed approach and conclusions thereafter in Section VI.

II. Vehicle Mathematical Model

Let us assume horizontal road condition in the platooning control of N vehicles. The dynamic model of i^{th} ($i = 1, 2, \ldots, N$) vehicle is described in (1) [33]

$$x_i = f_i(\dot{x}_i, \ddot{x}_i) + g_i(\dot{x}_i)u_i \tag{1}$$

where

$$\begin{cases} f_i(\dot{x}_i, \ddot{x}_i) = -\dfrac{1}{\tau_i(\dot{x}_i)}(\ddot{x}_i + \dfrac{k_{d,i}}{m_i}\dot{x}_i^2 + \dfrac{k_{m,i}}{m_i}) \\ \qquad\qquad\qquad - \dfrac{2k_{d,i}}{m_i}\dot{x}_i\ddot{x}_i + \dfrac{d_1(t)}{m_i} + \dfrac{d_2(t)}{m_i} \\ g_i(\dot{x}_i) = \dfrac{1}{m_i\tau_i(\dot{x}_i)} \end{cases}$$

and the model parameters are listed in Table I.

TABLE I
VEHICLE MODEL PARAMETERS

Parameters	Description
m/kg	total mass
τ/s	engine time constant
k_d/kg·m^{-1}	aerodynamic drag parameter
k_m/N	mechanical drag
x/m	vehicle's position
$\dot{x}$/m·s^{-1}	vehicle's velocity
$\ddot{x}$/m·s^{-2}	vehicle's acceleration
d_1	external disturbance
d_2	engine transmission variations
u	the throttle/brake input

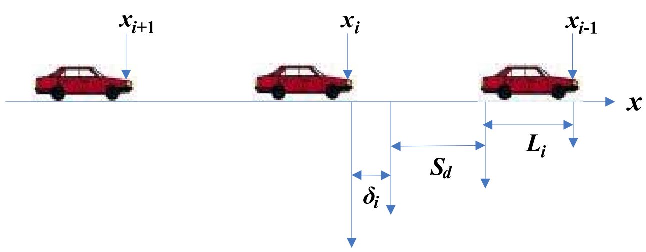

Fig. 1. Platoon configuration.

Let (x_i, x_{i-1}, x_{i+1}), (v_i, v_{i-1}, v_{i+1}) and (a_i, a_{i-1}, a_{i+1}) be respectively the position, velocity and acceleration of the i^{th}, $(i-1)^{\text{th}}$ and $(i+1)^{\text{th}}$ vehicle, as shown in Fig. 1. The spacing error δ_i for i^{th} vehicle is defined as

$$\delta_i = \zeta_i - S_{d,i} \tag{2}$$

where $\zeta_i (= x_{i-1} - x_i - L_i)$ denotes the actual spacing between i^{th} and $(i-1)^{\text{th}}$ vehicles, L_i denotes the $(i-1)^{\text{th}}$ vehicle length, $S_{d,i}$ denotes the desired safety distance,

In this research the predecessor-successor spacing is introduced into the vehicle platooning control. This means, for the ith vehicle, one should consider the relative actual spacing by subtracting the actual spacing between ith vehicle and its leader and follower, i.e., $(\zeta_i - \zeta_{i+1})$.

$$\zeta_{\text{ps},i} = \zeta_i - \zeta_{i+1} = x_{i-1} - 2x_i + x_{i+1} \tag{3-1}$$

The desired safety distance $S_{d,i}$ can be obtained for i^{th} vehicle by [34]

$$S_{d,i} = h_1(v_i^2 - v_{i-1}^2) + h_2 v_i + h_3 \tag{3-2}$$

where h_1, h_2, h_3 denote three positive constants, which can be calculated from the human reaction time, vehicle full acceleration and deceleration, and maximum allowable jerk. When the vehicle platoon performs a steady state maneuver (i.e., v_i is close to v_{i-1}), the desired safety distance can be estimated as

$$S_{d,i} = h_2 v_i + h_3 \tag{4}$$

In (4), the desired safety distance integrates the polices of both constant distance spacing (h_3) and CTH ($h_2 v_i$).

As a result, the two different spacing policies are considered for the platooning control in this paper, and the predecessor-successor spacing error δ_i for i^{th} vehicle is rewritten as

$$\delta_i = \zeta_{\text{ps},i} - S_{d,i} \tag{5}$$

It is first assumed that the immediate preceding and following vehicles contribute different effects on the i^{th} vehicle. Prior information about the desired distance, velocity and acceleration of the i^{th} vehicle can be obtained below.

(1) Desired distance:

$$S_{d,i} = t_{\text{des}} v_i + d_0$$

where t_{des} is a time constant, depending on sensor delays due to sampling, d_0 is a safe distance that ensure the anti-collision between two vehicles under some extreme stop situations.

(2) Desired velocity:

$$v_{\text{des}} = q_1 v_{i-1} + q_2 v_{i+1}$$

where q_1 and q_2 are respectively the designed motion weight factors for $(i\text{-}1)^{\text{th}}$ and $(i+1)^{\text{th}}$ vehicles and they are used for both velocity and acceleration.

(3) Desired acceleration:

$$a_{\text{des}} = q_1 a_{i-1} + q_2 a_{i+1}$$

According to the leader-follower consensus control, in the process of tracking the leader, the state errors for all vehicles within the platoon, caused by parameter uncertainties and external disturbances [29], [30], can be eventually reduced to be zero. Nevertheless, the influence of the initial conditions, the attraction domain and the convergence rate on the convergence behavior of the states must be considered. Here, a Lyapunov method with exponential stability is used to develop performance boundaries for arbitrary initial spacing and velocity errors, and to determine the controller parameters to guarantee the control stability of both individual vehicle and platoon.

It should note that, for the last vehicle which does not have following vehicle, a virtual vehicle is used as its follower. Furthermore, the relative velocity/distance between the last vehicle and its virtual follower are assumed to be zero at any time. The constant speed control with a bounded acceleration is taken for the leading vehicle.

Therefore, the throttle/brake input $u_i(t)$ of the i^{th} vehicle is determined to achieve the following control objectives.

(1) Eliminate the spacing error, i.e.,

$$\lim_{t\to\infty} |\delta_i| = 0.$$

(2) Regulate the relative velocity of the preceding and following vehicles under the constant speed control of the leading vehicle, i.e.,

$$\lim_{t\to\infty} |\dot{x}_{i-1} - \dot{x}_i| = 0, \quad \text{for constant } \dot{x}_i.$$

(3) Control the acceleration of the following vehicle under the constant speed control of the leading vehicle, i.e.,

$$\lim_{t\to\infty} |\ddot{x}_i| = 0, \quad \text{for constant } \dot{x}_i.$$

(4) Ensure the platoon exponential stability, i.e.,

$$|\delta_i(t)| \le |\delta_{i-1}(t)| + \mathrm{e}_t.$$

where e_t is an exponentially vanishing term.

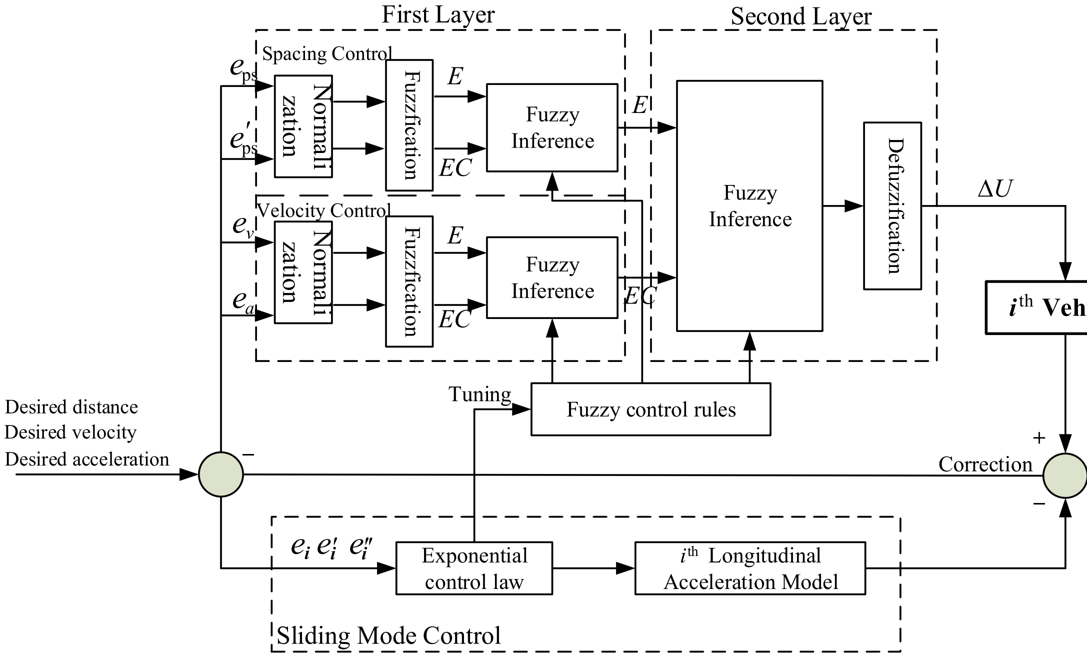

Fig. 2. The flow chart of the proposed hierarchical Fuzzy control system. The two-layer fuzzy controller has 4 inputs and 1 output. The 4 inputs are respectively the predecessor-successor spacing error $e_{\text{ps},i}$, and its changing rate $\dot{e}_{\text{ps},i}$, the velocity error $e_{\upsilon,i}$ and the acceleration error $e_{a,i}$. The output is the incremental value of the acceleration/brake, i.e., Δu. The inputs of the sliding mode control are e_i, $\dot{e}_i$ and $\ddot{e}_i$; e_i $(i = 1, 2, 3)$ respectively denotes the errors between the desired distance, velocity, acceleration and the actual values; $\dot{e}_i$ and $\ddot{e}_i$ are the first-order and its second-order derivative of e_i, respectively.

III. Hierarchical Fuzzy Logic Based Controller

Fig. 2 describes the proposed two-layer fuzzy control structure. The first layer consists of both spacing control and velocity/acceleration control. The spacing control employs the predecessor-successor spacing error $e_{\text{ps},i}$, (i.e., δ_i) and its changing rate $\dot{e}_{\text{ps},i}$ as inputs. The velocity/acceleration control [36], [37] employs the velocity error $e_{\upsilon,i}$ (i.e., difference of the actual and desired velocities) and the acceleration error $e_{a,i}$ (i.e., difference of the actual and desired acceleration) as inputs. Furthermore, the second layer directly uses the outputs of the first layer as its inputs. The correction factors of different fuzzy base functions are tuned by the sliding mode control law to achieve an adaptive compensation for the approximate error. The output of the second layer is the incremental value of u in (1).

In summary, the structure of the hierarchical fuzzy system includes:

Fuzzy sets: {**NB**: negative big, **NM**: negative medium, **NS**: negative small, **ZO**: zero, **PS**: positive small, **PM**: positive medium, **PB**: positive big}

Fuzzy domains of the hierarchical fuzzy logic system: {1, 2, 3, 4, 5, 6, 7}

Fuzzy rules:

$$\text{IF } E \text{ is } A_1 \text{ and } EC \text{ is } A_2, \quad \text{THEN } U \text{ is } B$$

The rule sets of the fuzzy controller in Table II are drawn based on the factors of existing driving experience (refer to [25], [33]) and control objectives. In addition, the rule sets are the same for the two-layer fuzzy controllers.

Traditional fuzzy control systems usually adopt a singleton fuzzifier, Mamdani inference, a center average defuzzification, and Gaussian membership function (GMF). Equation (6) describes the basic mathematical expression of a Fuzzy control system.

TABLE II
FUZZY CONTROL RULES

U		E						
		PB	**PM**	**PS**	**ZO**	**NS**	**NM**	**NB**
EC	**PB**	**PB**	**PB**	**PB**	**PB**	**PM**	**PS**	**ZE**
	PM	**PB**	**PB**	**PM**	**PM**	**PS**	**ZE**	**NS**
	PS	**PB**	**PM**	**PM**	**PS**	**ZE**	**NS**	**NM**
	ZO	**PB**	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
	NS	**PM**	**PS**	**ZE**	**NS**	**NM**	**NM**	**NB**
	NM	**PS**	**ZE**	**NS**	**NM**	**NM**	**NB**	**NB**
	NB	**ZE**	**NS**	**NM**	**NB**	**NB**	**NB**	**NB**

$$u = f(e, ec) = \frac{\sum_{i=1}^{k} \theta_i (\mu_E^i(e)\mu_{EC}^i(ec))}{\sum_{i=1}^{k} \mu_E^i(e)\mu_{EC}^i(ec)} \tag{6}$$

where e and its derivative ec are generic terms, denoting the inputs of the Fuzzy control system; $\mu_E(e)$ and $\mu_{EC}(ec)$ are the GMF describing the fuzzy sets of e and ec, respectively; θ_i is the principal value of i^{th} fuzzy set of u; k is the sequential fuzzy sets, and $k = 1, 2, \ldots, 7$.

Define the fuzzy base functions as

$$\varepsilon_i(e, ec) = \frac{\mu_E^i(e)\mu_{EC}^i(ec)}{\sum_{i=1}^{k} \mu_E^i(e)\mu_{EC}^i(ec)} \tag{7-1}$$

Obviously, we have

$$\sum_{i=1}^{k}\varepsilon_i(e,ec)=1,\quad 0\le\varepsilon_i(e,ec)\le 1 \tag{7-2}$$

Thus, $\varepsilon_i(e, ec)$ could be taken as the weight of the i^{th} Fuzzy rule and (6) can be rewritten as

$$f(e,ec)=\sum_{i=1}^{k}\theta_i\varepsilon_i(e,ec) \tag{8}$$

Note that (e, ec) is a generic expression, it could be the spacing error $(e_{\text{ps},i}, \dot{e}_{\text{ps},i})$ or the velocity error $(e_{\upsilon,i}, e_{a,i})$.

The hierarchical fuzzy control integrates two fuzzy controllers into a two-layer structure. Different to the single layer fuzzy control, in the hierarchical fuzzy structure θ_i is treated as a correction factor of i^{th} fuzzy rule at the first layer. The outputs of the first layer do not need defuzzification and are directly used as inputs for the second layer.

In the present work, the first layer of the proposed hierarchical fuzzy structure implements the spacing and velocity control. Let us take the fuzzy sets {**PB**} as an example to derive the mathematical expression of the second layer. Assume the weight of the spacing control output in the first layer belonging to one of the fuzzy sets {**PB**} is

$$\mu_{\text{ps},i}^{pb}=\sum_{U_{\text{ps},i}\subset\{PB\}}\theta_{\text{ps},i,j}\varepsilon_{\text{ps},i,j} \tag{9-1}$$

Then the output of the spacing Fuzzy controller is

$$u_{\text{ps},i}=\frac{\mu_{\text{ps},i}^{pb}}{PB}+\frac{\mu_{\text{ps},i}^{pm}}{PM}+\frac{\mu_{\text{ps},i}^{ps}}{PS}+\frac{\mu_{\text{ps},i}^{zo}}{ZO}+\frac{\mu_{\text{ps},i}^{ns}}{NS}+\frac{\mu_{\text{ps},i}^{nm}}{NM}+\frac{\mu_{\text{ps},i}^{nb}}{NB} \tag{9-2}$$

Similarly, the weight of the velocity control output belonging to {**PB**} is

$$\mu_{\upsilon,i}^{pb}=\sum_{U_{\upsilon,i}\subset\{PB\}}\theta_{\upsilon,i,j}\varepsilon_{\upsilon,i,j} \tag{9-3}$$

and the output of the velocity Fuzzy controller is

$$u_{\upsilon,i}=\frac{\mu_{\upsilon,i}^{pb}}{PB}+\frac{\mu_{\upsilon,i}^{pm}}{PM}+\frac{\mu_{\upsilon,i}^{ps}}{PS}+\frac{\mu_{\upsilon,i}^{zo}}{ZO}+\frac{\mu_{\upsilon,i}^{ns}}{NS}+\frac{\mu_{\upsilon,i}^{nm}}{NM}+\frac{\mu_{\upsilon,i}^{nb}}{NB} \tag{9-4}$$

Hence, the second fuzzy layer can be described as follows:

$$\begin{cases}u_{fz,i}=\sum_{j=1}^{k}d_{fz,i,j}(\theta_{fz,i,j}\varepsilon_{fz,i,j})\\ \varepsilon_{fz,i,j}=\min\{\mu_{i,j}(\text{ps}),\mu_{i,j}(\upsilon)\}\end{cases} \tag{9-5}$$

where $\theta_{\text{ps},i,j}$, $\theta_{\upsilon,i,j}$ and $\theta_{fz,i,j}$ are the correction factors of j^{th} fuzzy rule for the spacing, velocity and second layer control, respectively; $\varepsilon_{\text{ps},i,j}$, $\varepsilon_{\upsilon,i,j}$ and $\varepsilon_{fz,i,j}$ are the weights of j^{th} fuzzy rule for the spacing, velocity and second layer control, respectively; $d_{fz,i,j}$ is the center value of the output membership function which is depended by the j^{th} fuzzy rule for the i^{th} vehicle; $\mu_{i,j}(\text{ps})$ and $\mu_{i,j}(\upsilon)$ are spacing and velocity values of the input membership functions of the second fuzzy layer.

As the hierarchical fuzzy control approximates the states errors caused by system uncertainties and disturbances, the sliding mode control law can be used to tune the correction factors to achieve an adaptive compensation for the approximation error.

Define a sliding surface as

$$S_i=c_{i,1}e_{\text{ps},i}+c_{i,2}e_{\upsilon,i}+e_{a,i} \tag{10}$$

where $c_{i,1},\ c_{i,2}>0$ and the sliding surface satisfies the following sliding mode control conditions

$$\dot{S}_i=-\lambda S_i,\ \lambda>0 \tag{11}$$

Then we can obtain

$$\dot{e}_{a,i}+(\lambda+c_{i,2})e_{a,i}+(\lambda c_{i,2}+c_{i,1})e_{\upsilon,i}+\lambda c_{i,1}e_{\text{ps},i}=0 \tag{12}$$

According to (1), (10) and (12), an ideal tracking controller can be expressed by

$$u_i^*=\frac{1}{g_i(\dot{x}_i)}\left[-f_i(\dot{x}_i,\ddot{x}_i)+\lambda S_i+(c_{i,1}e_{\upsilon,i}+c_{i,2}e_{a,i})+\dot{a}_{i,\text{des}}\right] \tag{13}$$

where $\dot{a}_{i,\text{des}}$ is the derivative of the desired acceleration a_{des}. Because $f_i(\dot{x}_i,\ddot{x}_i)$ and $g_i(\dot{x}_i)$ are partially or completely unknown, the output of the second layer $u_{fz,i}$ in (9) can be used to estimate the ideal tracking controller in (13), and the following optimal weight vectors are used to meet the desired tracking performance

$$\left\{\theta_{\text{ps},i}^*,\ \theta_{\upsilon,i}^*,\theta_{fz,i}^*\right\}=\arg\min_{\theta_{\text{ps},i}\in\Omega_{\theta_{\text{ps},i}},\theta_{\upsilon,i}\in\Omega_{\theta_{\upsilon,i}},\theta_{fz,i}\in\Omega_{\theta_{fz,i}}}\left[\sup\left|u_i^*-u_{fz,i}\right|\right] \tag{14-1}$$

where $\Omega_{\theta\text{ps},i}, \Omega_{\theta\upsilon,i}, \Omega_{\theta fz,i}$ are the feasible regions of the weight vector $\{\theta_{\text{ps},i},\ \theta_{\upsilon,i},\ \theta_{fz,i}\}$. The approximation error is defined as

$$\omega_i^*=u_{fz,i}^*-u_i^* \tag{14-2}$$

where $u_{fz,i}^*$ is the optimal controller for the hierarchical fuzzy control system. Substituting (14) into (12), it yields

$$\begin{aligned}\dot{e}_{a,i}&=-(\lambda S_i+c_{i,1}e_{\upsilon,i}+c_{i,2}e_{a,i})\\&\quad+g_i(\dot{x}_i)(u_{fz,i}^*-u_{fz,i})+g_i(\dot{x}_i)(u_i^*-u_{fz,i}^*)\\&=-(\lambda S_i+c_{i,1}e_{\upsilon,i}+c_{i,2}e_{a,i})+g_i(\dot{x}_i)\varphi_i-g_i(\dot{x}_i)\omega_i^*\end{aligned} \tag{15}$$

where

$$\varphi_i=u_{fz,i}^*-u_{fz,i}$$

If φ_i and ω_i^* are bounded, the $\dot{e}_{a,i}$ is also bounded.

According to the convergence characteristics of the exponential stability, the parameter correction for the hierarchical fuzzy control should consider not only the initial errors of the vehicle states, but also the convergence speed that reaches to the sliding surface. So, the following adaptive law is introduced to correct the weight vectors.

$$\begin{cases}\tilde{\theta}_{\mathrm{ps},i} = \eta_{\mathrm{ps},i}(\dot{S}_i + \lambda S_i)\varepsilon_{\mathrm{ps},i} \\ \tilde{\theta}_{v,i} = \eta_{v,i}(\dot{S}_i + \lambda S_i)\varepsilon_{v,i} \\ \tilde{\theta}_{fz,i} = \eta_{fz,i}(\dot{S}_i + \lambda S_i)\varepsilon_{fz,i}\end{cases} \quad (16)$$

where $\eta_{\mathrm{ps},i}$, $\eta_{v,i}$, $\eta_{fz,i}$ are adaptive parameters.

Thus, the state errors of the i^{th} vehicle caused by uncertainties and disturbances can be reduced by the following adaptive compensation control law

$$u_i = u_{fz,i} + k_{i,c}(\dot{S}_i + \lambda S_i) \quad (17)$$

where $k_{i,c}$ is the compensation factor.

IV. Platoon Stability

The platoon stability in the platooning control is regarded as string stability. The platooning system should guarantee the string stability to achieve a stable vehicle platooning control. Since the stability of individual vehicles cannot ensure the string stability, it is important to design proper platooning controller to guarantee the string stability.

A. Individual Vehicle Stability

Because the parameters and disturbances in the vehicle mathematical model described in (1) are usually unknown, it is possible to define their boundaries in the platooning controller.

$$\begin{cases} m_i \le M \\ k_{d,i} \le K_D \\ k_{m,i} \le K_M \\ \tau_i(\dot{x}_i) \le \Gamma \\ |d_1(t)| \le D_1, \quad |d_2(t)| \le D_2 \end{cases} \quad (18)$$

where, M, K_D, K_M, Γ, D_1 and D_2 are positive constants.

Assume the following constrains

$$0 < b_1 \le \frac{m_i \tau_i(\dot{x}_i)}{h_2} \le b_2 \quad (19)$$

where, b_1 is an unknown positive constant and b_2 is a known positive constant. If the vehicle's jerk has an upper boundary A, i.e.,

$$\left|\dddot{x}_i\right| \le A \quad (20)$$

Then, the following Lyapunov-like function can be used as the design base for the platooning controller.

$$V_1 = \frac{1}{2}\frac{m_i \tau_i(\dot{x}_i)}{h_2} S_i^2 \quad (21\text{-}1)$$

The derivative of V_1 can be derived by substituting (1) and (10) into (21-1).

$$\dot{V}_1 = \frac{m_i \tau_i(\dot{x}_i)}{h_2} S_i(\dot{a}_{i,\mathrm{des}} - \dddot{x}_i + c_{i,1}\dot{e}_{\mathrm{ps},i} + c_{i,2}\dot{e}_{v,i}) \quad (21\text{-}2)$$

If take the boundaries in (11) and (15) and the control law u_i into accounts, (21-2) can be rewritten as

$$\dot{V}_1 \le -\frac{1}{2}\frac{kM\Gamma}{h_2} S_i^2 \le -k\frac{1}{2}\frac{m_i \tau_i(\dot{x}_i)}{h_2} S_i^2 = -kV_1(t) \quad (21\text{-}3)$$

where

$$k > \max\left\{\frac{2(1+h_2)}{h_2}, k_{i,c}\right\}$$

As a result, an exponential convergence of $S_i(t)$ can be derived by

$$\frac{b_1}{2} S_i^2(t) \le V_1(t) \le V_1(0)\mathrm{e}^{-kt}, \quad \forall t \in [0, \infty) \quad (21\text{-}4)$$

It is concluded from the above analysis that the vehicle stability is achieved based on the obtained exponential convergence.

B. String Stability of Platooning Control

The string stability of platooning control is analyzed in this Section. The L_2 sense [15]–[18] is widely used in literature to evaluate the string stability by eliminating the disturbances that transfer from the leading vehicle to its followers. Equation (22-1) depicts the evaluation basis.

$$\|\tilde{y}\|_2 \le \|G\|_\infty \|\tilde{u}\|_2 \quad (22\text{-}1)$$

where $\tilde{u}$ and $\tilde{y}$ denote the input and output of a control system G.

In the platooning control, the relationship of the spacing errors of i^{th} and $(i\text{-}1)^{\mathrm{th}}$ vehicles can be described as

$$\delta_i = F\delta_{i-1} \quad (22\text{-}2)$$

where F is a linear operator. If $\|F\|_\infty \le 1$ or $|F(j\omega)| \le 1$, $\forall\omega > 0$, then $\|\delta_i\|_2 \le \|\delta_{i-1}\|_2$, which means that the disturbances propagated upstream along the platoon are not magnified in L_2 sense if the spacing error of i^{th} vehicle is less than or equal to that of $(i\text{-}1)^{\mathrm{th}}$ vehicle. However, under this circumstance, we can only obtain

$$\int_0^\infty |\delta_i|^2 \mathrm{d}t \le \int_0^\infty |\delta_{i-1}|^2 \mathrm{d}t \quad (22\text{-}3)$$

It will be much appreciated if the spacing error of i^{th} vehicle is less than that of $(i\text{-}1)^{\mathrm{th}}$ vehicle at any time. In other word, in order to guarantee the string stability in the presence of parameter uncertainties and unknown disturbances whose bounds are known, the following inequality should be satisfied.

$$|\delta_i(t)| \le |\delta_{i-1}(t)| + \mathrm{e}_t \quad (23)$$

where e_t is a vanishing term caused by non-zero initial conditions.

Theorem 1: Considering system (1) and predecessor-successor spacing (2), if choose appropriate parameters for the hierarchical fuzzy control law (9) and the adaptive compensation control law (17), the spacing errors (5) will converge to a small neighbourhood around origin. In addition, the string stability (23) can also be guaranteed.

Proof of Theorem 1: First, let us define another sliding surface as

$$S_i = c\delta_i + \dot{\delta}_i \quad (24\text{-}1)$$

where $c > 0$, satisfying

$$c = \frac{1+h_2}{h_2} + \frac{1}{2k_{i,c}}$$

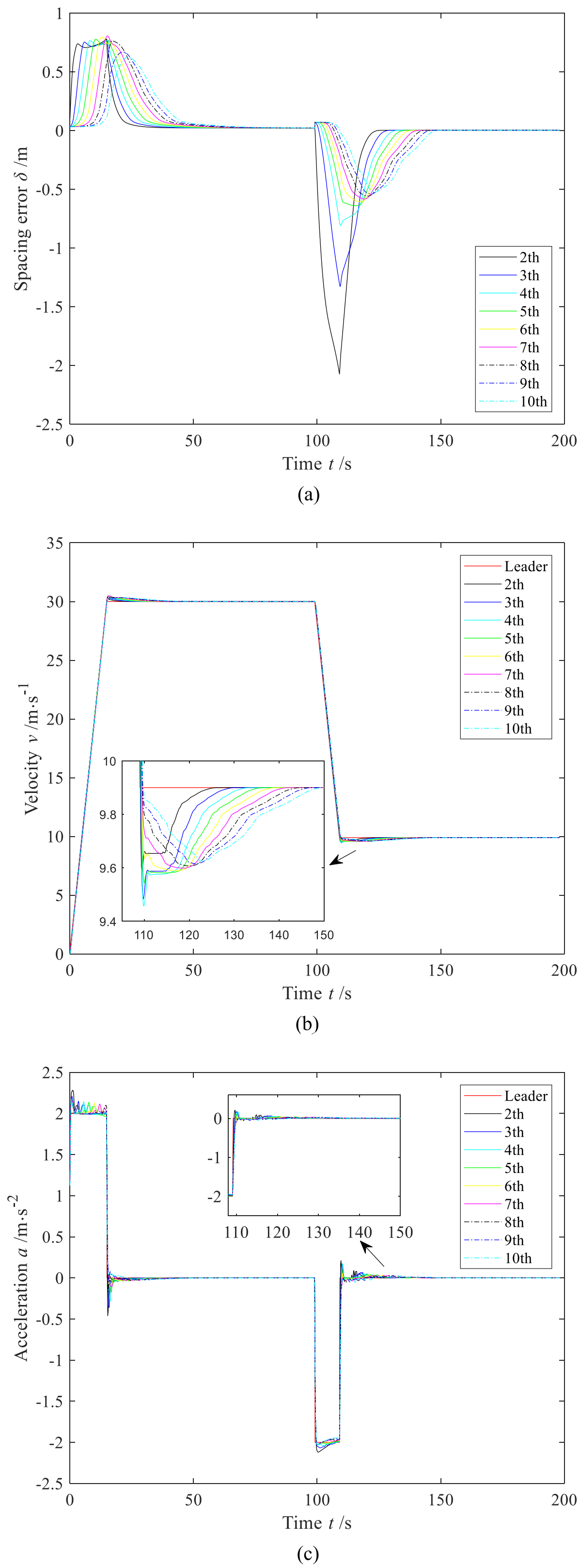

Fig. 3. A ten-vehicle platooning simulation based on FSMC. (a) Spacing error profiles. (b) Velocity profiles. (c) Acceleration profiles.

Since

$$\dot{\delta}_{i-1} = -c\delta_{i-1} + S_{i-1}$$
$$\dot{\delta}_i = -c\delta_i + S_i$$

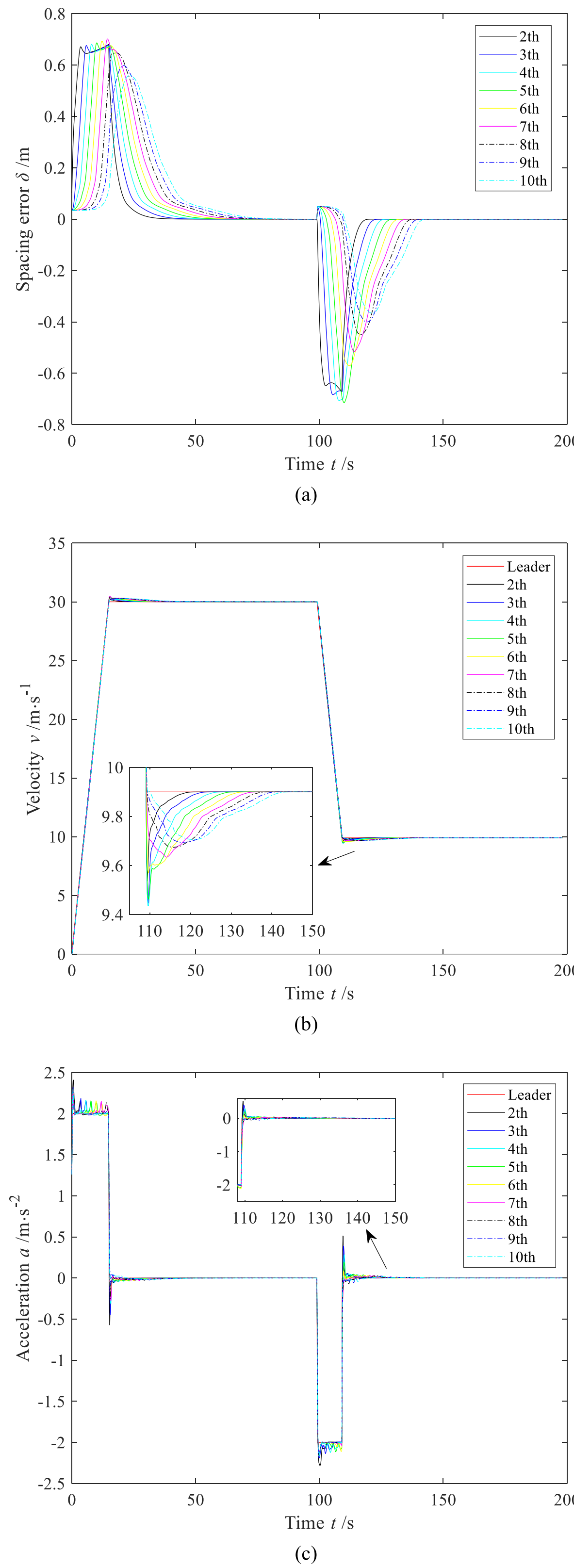

Fig. 4. A ten-vehicle platooning simulation based on the proposed approach.

Define

$$z = \delta_i - \delta_{i-1} \tag{24-2}$$

Its derivative can be derived by

$$\dot{z} = -cz + S_i - S_{i-1} \tag{24-3}$$

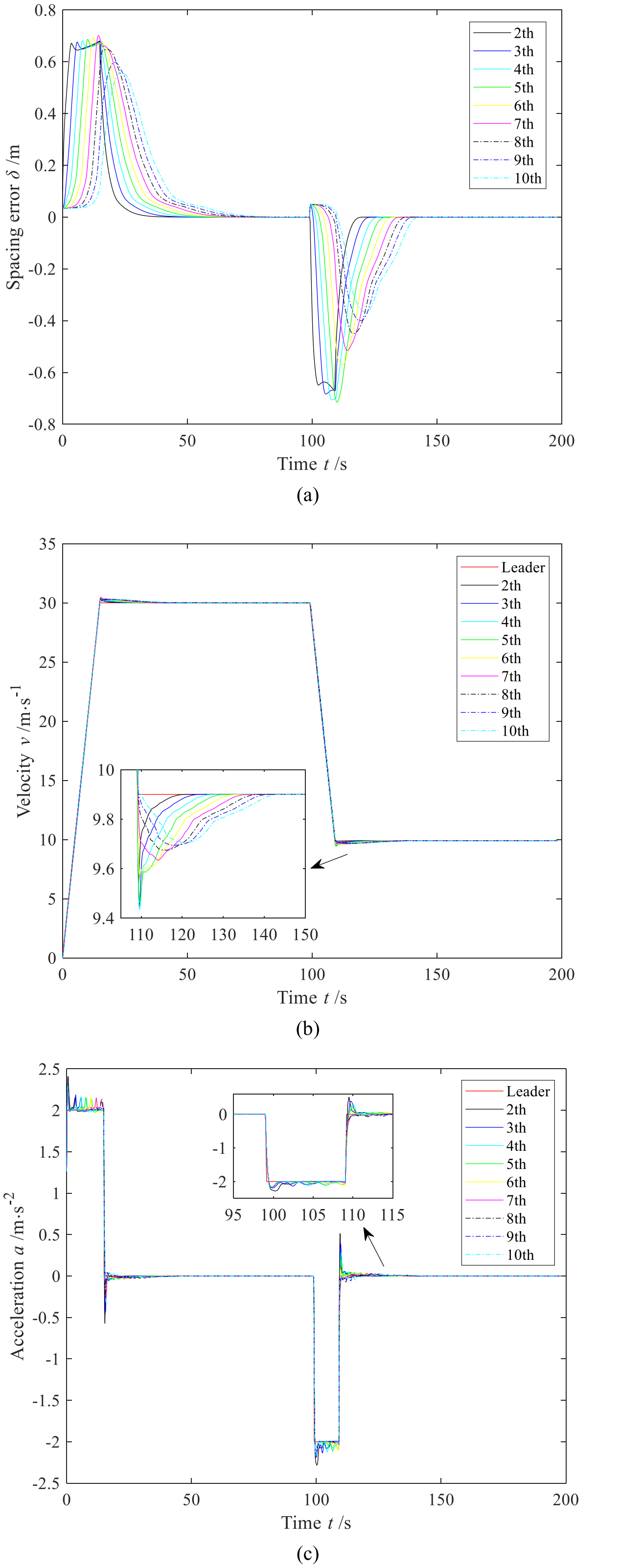

Fig. 5. A ten-vehicle platooning simulation based on CD policy. (a) Spacing error profiles. (b) Velocity profiles. (c) Acceleration profiles.

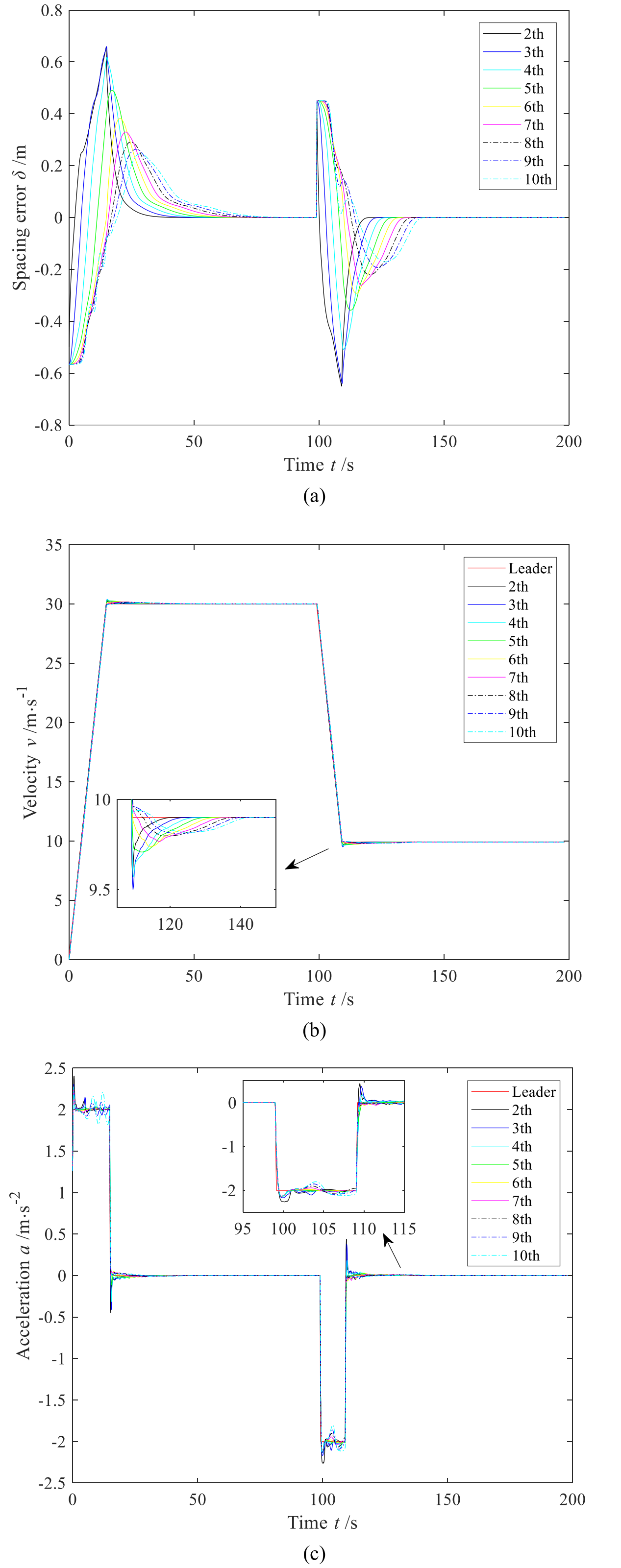

Fig. 6. A ten-vehicle platooning simulation based on CTH policy. (a) Spacing error profiles. (b) Velocity profiles. (c) Acceleration profiles.

Thus, (24) demonstrates the stable dynamics with input term of $(S_i - S_{i-1})$, whose boundary will eventurelly converge to zero. In order to determine the boundary of z, we define the following positive definite function:

$$V_2 = \frac{1}{2}z^2 + \frac{1}{2}\frac{V_i(0)}{b_1}e^{-k_i t} + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}e^{-k_{i-1} t} \quad (25\text{-}1)$$

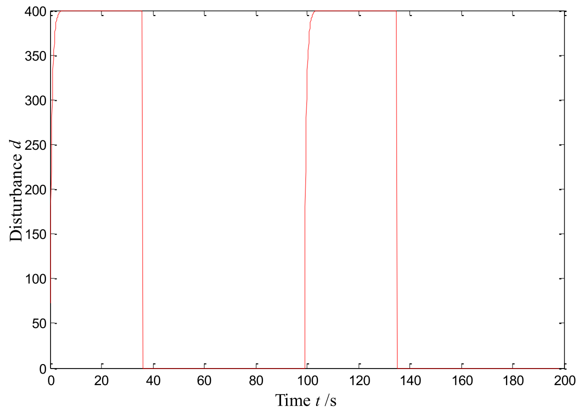

Fig. 7. Profile of the external disturbances.

where

$$V_i(t) = \frac{1}{2}\frac{m_i \tau_i(\dot{x}_i)}{h_2} S_i^2(t)$$
$$V_{i-1}(t) = \frac{1}{2}\frac{m_{i-1} \tau_{i-1}(\dot{x}_{i-1})}{h_2} S_{i-1}^2(t)$$

The derivative of V_2 is calculated by

$$\begin{aligned}\dot{V}_2 &= z[-cz + S_i(t) - S_{i-1}(t)] \\ &\quad - \frac{k_i}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - \frac{k_{i-1}}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} \\ &\le -cz^2 + \frac{1}{2}z^2 + S_i^2(t) + \frac{1}{2}z^2 + S_{i-1}^2(t) \\ &\quad - \frac{k_i}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - \frac{k_{i-1}}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} \\ &= (-c+1)z^2 + \frac{1}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - \frac{k_i}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} \\ &\quad + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} - \frac{k_{i-1}}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} \qquad (25\text{-}2)\end{aligned}$$

where if denote

$$1 - k_i = -k_{i,1} \quad k_{i,1} > 0$$
$$1 - k_{i-1} = -k_{(i-1),i} \quad k_{(i-1),1} > 0$$

then,

$$\begin{aligned}\dot{V}_2 &\le (1-c)z^2 - k_{i,1}\frac{1}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - k_{(i-1),1}\frac{1}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} \\ &= -lV_2(t) \qquad (25\text{-}3)\end{aligned}$$

Since $c = (1 + h_2)\ /h_2 + 1/2k_{i,c}$, $c-\ 1 > 0$, we have

$$\dot{V}_2 = -lV_2(t)$$

where $l = \min\{2(1\ -c),\ k_{i,1},\ k_{(i-1),1}\}$, implying

$$V_2 \le V_2(0)\mathrm{e}^{-lt} \qquad (25\text{-}4)$$

or

$$\begin{aligned}&\frac{1}{2}z^2(t) + \frac{1}{2}\frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t} \\ &\qquad \le [\frac{1}{2}z^2(0) + \frac{1}{2}\frac{V_i(0)}{b_1} + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}]\mathrm{e}^{-lt} \qquad (25\text{-}5)\end{aligned}$$

TABLE III
VEHICLE AND CONTROL PARAMETERS

parameters	value	parameters	value
m	1500	q_2	0.2
k_d	0.3	λ	0.6
k_m	140	c_1	2
τ	0.2	c_2	3
t_{des}	0.02	η_{ps}	0.8
L	5	η_v	0.3
d_0	6.4	η_{fz}	0.1
q_1	0.8	k_c	0.1

Therefore, we can obtain

$$\begin{aligned}&|\delta_i(t) - \delta_{i-1}(t)| \\ &\le \left\{\left[\frac{1}{2}(\delta_i(0) - \delta_{i-1}(0))^2 + \frac{1}{2}\frac{V_i(0)}{b_1} + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}\right]\mathrm{e}^{-lt}\right. \\ &\qquad \left. - \frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - \frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t}\right\}^{1/2} \qquad (26\text{-}1)\end{aligned}$$

As a result, an exponential stability can be obtained from (26) to satisfy (23) by

$$\begin{aligned}&|\delta_i(t)| \le |\delta_{i-1}(t)| \\ &\quad + \left\{\left[\frac{1}{2}(\delta_i(0) - \delta_{i-1}(0))^2 + \frac{1}{2}\frac{V_i(0)}{b_1} + \frac{1}{2}\frac{V_{i-1}(0)}{b_1}\right]\mathrm{e}^{-lt}\right. \\ &\qquad \left. - \frac{V_i(0)}{b_1}\mathrm{e}^{-k_i t} - \frac{V_{i-1}(0)}{b_1}\mathrm{e}^{-k_{i-1} t}\right\}^{1/2} \qquad (26\text{-}2)\end{aligned}$$

and hence, the string stability is automatically satisfied if the exponential stability of the controller design is achieved. This completes the proof.

V. SIMULATION RESULTS

Numerical simulations have been carried out to evaluate the performance of the proposed hierarchical fuzzy control method in a platoon of 10 vehicles. Table III lists the parameters in the simulations. The initial positions of each vehicle in the platoon are 120 108 96 84 72 60 48 36 24 and 12 m, respectively. The desired safety distance $S_{d,i}$ in (4) employs both CD and CTH polices, and the predecessor-successor information flow from the immediate predecessor and follower is used. The simulation parameters are listed in Table III. Each vehicle in the platoon is identical. As can be seen, the initial spacing errors of the platoon are none zero [i.e., 12 - 5 - 6.4 = 0.6 m, calculated using (2)]. Besides, the bounded vehicle's jerk A in (20) is set to 0.5 m/s^2.

In the first simulation, a comparison of the proposed control method with the traditional FSMC [25] is conducted in the platooning control under CD policy. The disturbances are ignored here. The platoon leader firstly accelerates from 0 to 30 m/s at 2 m/s^2. After the velocity reaches 30 m/s, the leader begins to decelerate to 10 m/s at -2 m/s^2. Figs. 3 and 4 describe the comparison results in this scenario.

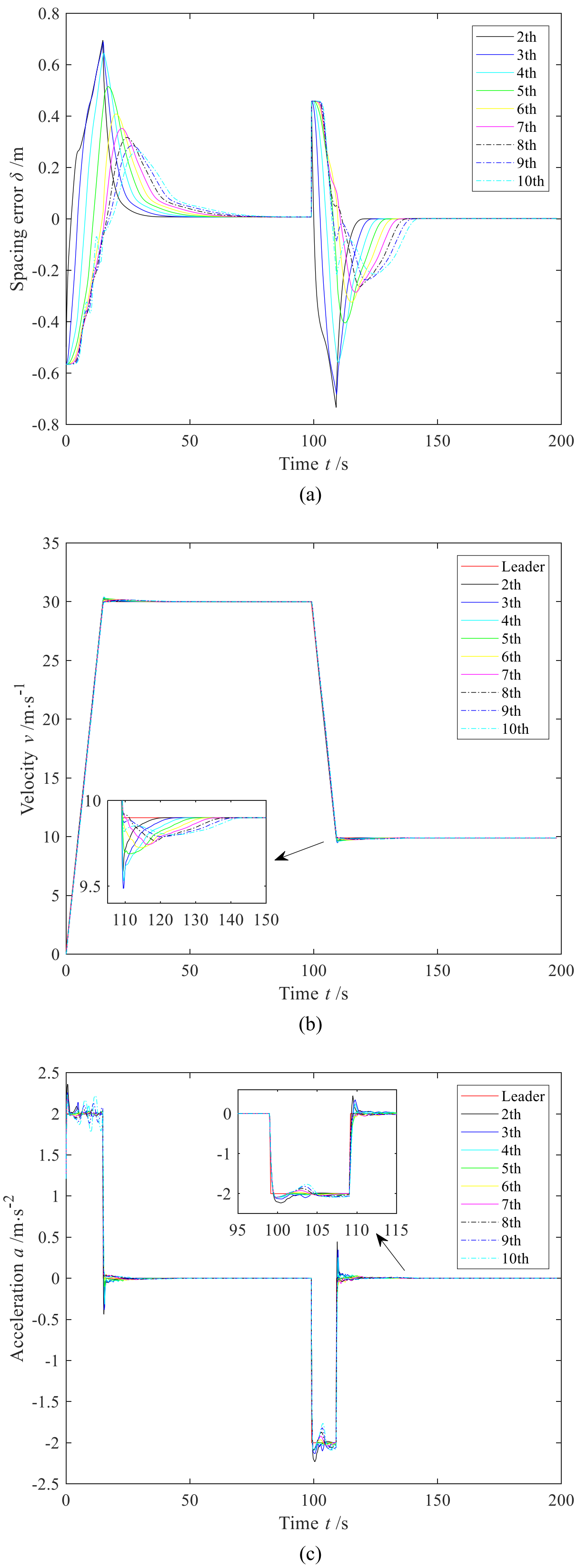

Fig. 8. A ten-vehicle platooning simulation with CTH under the external disturbances. (a) Spacing error profiles. (b) Velocity profiles. (c) Acceleration profiles.

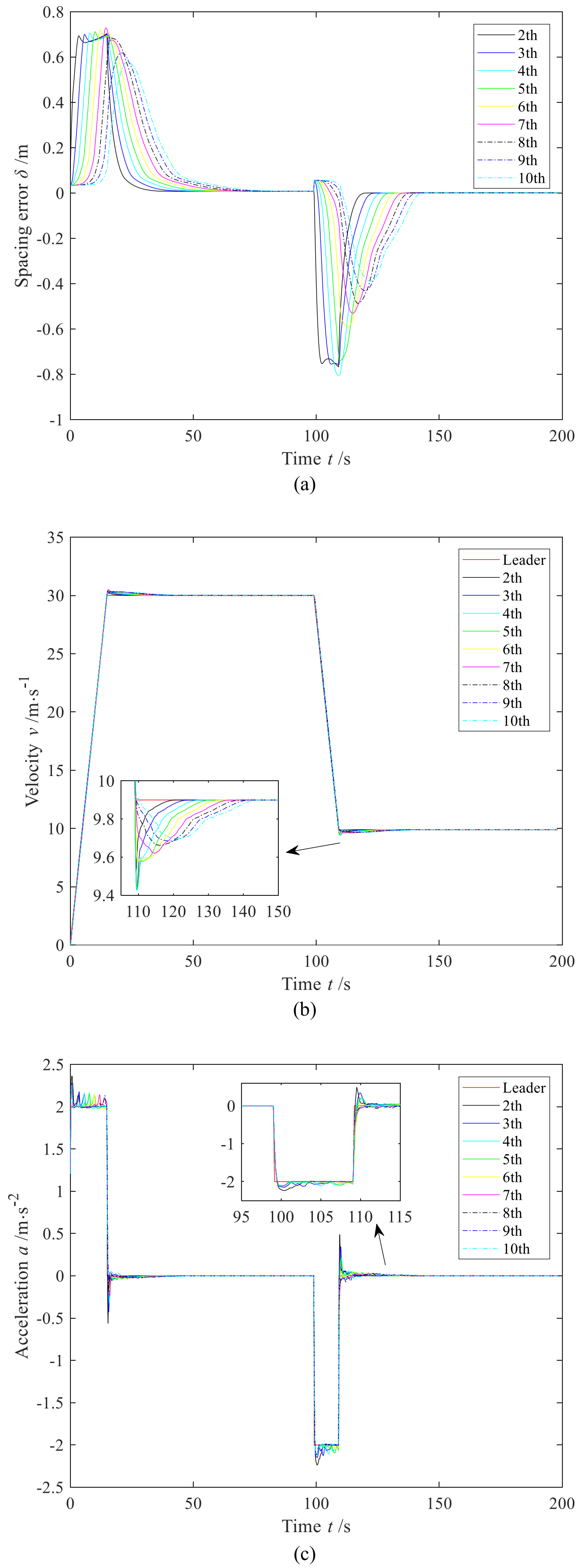

Fig. 9. A ten-vehicle platooning simulation with CD under the external disturbances. (a) Spacing error profiles. (b) Velocity profiles. (c) Acceleration profiles.

Comparing Fig. 3 with Fig. 4 it can be seen that the two methods can track the leader quickly and maintain a small spacing error at the speed-up step; however, when the platoon decelerates, due to uncertainties and disturbance the FSMC method produces a large spacing fluctuation and continuous acceleration chatters, which may result in instability of the

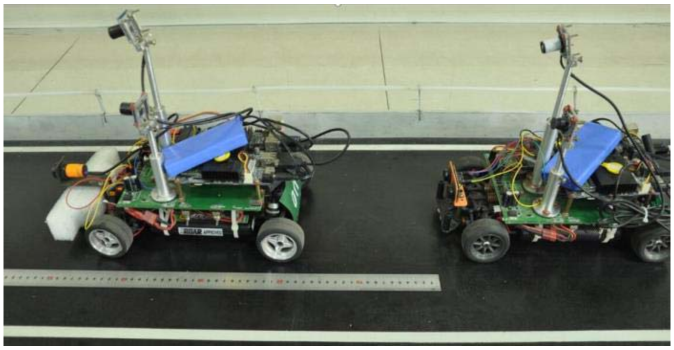

Fig. 10. The scaled intelligent vehicles.

platooning control. In contrast, the proposed method is immune to the system uncertainties and disturbance at the cost of a small overshoot on acceleration to retain the platoon stability.

In the second simulation, the CD and CTH policies are used to evaluate the proposed hierarchical method. In this scenario the platoon has different parameters (m_i, $k_{d,i}$, $k_{m,i}$, τ_i). The disturbances are ignored. Figs. 5 and 6 depict the simulation results.

As can be seen from Figs. 5 and 6 that, satisfactory velocity tracking ability of the proposed method is obtained with both CD and CTH spacing policies. Meanwhile, the platoon string stability can also be hold in the presence of parameters uncertainties.

In the third simulation scenario, the two spacing policies are used again while external disturbances are added by

$$d_1(t) = \begin{cases} 0 & t < 0 \\ 400[1 - \mathrm{e}^{-0.2t}] & 0 \le t \le 36 \\ 0 & 36 \le t \le 99 \\ 400[1 - \mathrm{e}^{-0.2(t-99)}] & 99 \le t \le 135 \\ 0 & t > 135 \end{cases} \quad (27)$$

The profile of the disturbances is shown in Fig. 7. Figs. 8 and 9 provide the simulation results.

It can be seen from Figs. 8 and 9 that the proposed method can still guarantee the platoon string stability when the control system is subject to external disturbances.

Furthermore, experimental tests using four scaled intelligent vehicles (see Fig. 10) is carried out to demonstrate the effectiveness of the proposed hierarchical fuzzy logic-based controller for the platooning control. The scaled vehicle is equipped with a digital-signal-processor (DSP), power supply module, motor drive module that controls the steering motor and the driving motor, and several on-board sensors, including a digital camera for image recognition of the surface, and an optical encoder for vehicle motion acquisition. The experimental video can be found in the supplementary file.

VI. Conclusions and Future Work

A practical hierarchical Fuzzy logic-based controller is presented in this paper. The innovation of the proposed method lies that the predecessor-successor information flow in the platoon is used to ensure the string stability for large platooning control. In addition, both simulation and experimental tests demonstrate that the two-layer based Fuzzy control structure can process system parameters uncertainties and external disturbances. Furthermore, the evaluation results also suggest that the hierarchical Fuzzy control method is effective for both CD and CTH spacing policies by guaranteeing the stability of individual vehicles and the platoon. Because the controller design combines the velocities/positions of both the preceding and following vehicles to maintain the platoon stability for the sake of safety, it is convenient for the field operational tests of vehicles platooning. In the future research we plan to investigate the platoon stability of the hierarchical Fuzzy control in transient state to eventually develop a ready-to-use practical platooning control technique.

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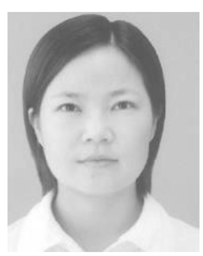

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