Proceedings of the SICE Annual Conference 2022
September 6-9, 2022, Kumamoto, Japan

Synchronization of Heterogeneous Vehicle Platoons using Distributed Model Reference Adaptive Control

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Abstract: This paper addresses the problem of heterogenous vehicle platoons, where each follower has a different nominal model and is subjected to uncertainty in the inertial time lag and control effectiveness. Distributed model reference adaptive control (DMRAC) is utilized to achieve synchronization. Each follower vehicle employs a heterogenous reference model and a nominal controller, along with an additional adaptive term to ensure that the follower may track the reference model despite uncertainties. The conditions on the coupling gain and adaptation law for each follower to ensure stability are derived. It is shown that the proposed controller guarantees the stability of the heterogenous vehicle platoon, which implies the synchronization of followers' state to the leader. Numerical simulation validates the efficacy of the proposed controller. Moreover, the performance and characteristics of DMRAC are analyzed and compared to conventional control schemes.

Keywords: directed topology, distributed model reference adaptive control, heterogeneous vehicle platoon.

1. INTRODUCTION

With the advancement of communication, sensor, and artificial intelligence technologies, the future trend of intelligent transportation systems is connected and automated vehicles (CAVs). CAVs have the capability to communicate to everything (V2X), including to other vehicles (V2V), pedestrians, infrastructures, and public facilities in the vicinity [1]. This paper focuses on one possible application of CAVs called the vehicle platoon. A vehicle platoon is a train-like driving formation of vehicles which consists of one leader and *N*-followers, connected via a network of sensors or wireless communication technology. The objective of the platoon is to synchronize all the followers to the leader's state by maintaining the desired inter-vehicular distance.

A vehicle platoon is described by its node dynamics, information flow topology, formation geometry, and distributed controller [2]. Node dynamics represents the vehicular longitudinal dynamics. The information flow topology can be either a directed or undirected topology. Formation geometry explains the spacing policy that is applied to the platoon formation, which is typically based on either constant spacing policy (CSP) or constant time heading (CTH). Lastly, the distributed controller is applied by each follower to achieve the platoon objective.

One important issue in the design of distributed controllers for vehicle platoon applications is the existence of uncertain dynamics. Vehicle dynamics is a complex system composed of many subsystems and parameters that are difficult to accurately model. Therefore, in the modeling process, simplification, approximations, or assumptions are unavoidable and may produce significant modeling error [3]. The uncertainties can also be caused by road conditions and other environmental factors [4]. A controller designed without consideration of these uncertainties may experience a deterioration in performance when the actual vehicle dynamics deviate significantly from the nominal model. In extreme cases, this may lead to system instability [4]. To handle this issue, an augmented model reference adaptive control approach was developed by Harfouch et al. [5] specifically for vehicle platoons with CTH and PF topology. Distributed model reference adaptive control (DMRAC) was later proposed by Prayitno et al. [6] for vehicle platoons with CSP and can be applied to various directed and undirected topologies. However, both [5] and [6] assume a homogenous system where all platoon vehicles share an identical nominal model based on the lead vehicle. This assumption is not realistic in many situations where the actual vehicles in the platoon consist of different types and brands [4,7]. As an example, a vehicle platoon may simultaneously involve passenger cars, buses, vans, and trucks. These vehicles have different dynamics and parameters, especially in terms of the inertial time lag, and can be categorized as a heterogeneous vehicle platoon [4]. Passenger vehicles typically have smaller inertial time lag when compared to heavy duty vehicles [8]. Each individual vehicle may not perform optimally when the controller is designed based on a shared nominal model that differ significantly from the actual model.

Consequently, this paper proposes a method to achieve synchronization of heterogeneous vehicle platoons subjected to uncertain dynamics using DMRAC. Compared to [6], each follower employs a different reference model and nominal controller. The nominal control input is based on cooperative state variable feedback (CSVFB) [9] and is responsible for tracking the leader's state. In addition, an adaptive term is designed to suppress the effect of uncertainties in the inertial time lag and control effectiveness, such that each follower is able

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to track its reference model. The contribution of this paper is to provide meaningful stability analysis of DMRAC for heterogeneous vehicle platoons that may be realistically encountered in intelligent transportation systems.

2. PROBLEM FORMULATION

Consider a heterogeneous vehicle platoon consisting of one leader and *N*-followers. The follower vehicles are subjected to uncertain dynamics and represented in the state-space form as

$$\dot{x}_i = A_i x_i + B_i \Omega_i \left[u_i + \Omega_i^{-1} \eta_i(x_i) \right]. \quad (1)$$

Here, $x_i \in \mathbb{R}^n$, $u_i \in \mathbb{R}^m$, Ω_i, and $\eta_i(x_i)$ are the state vector, control input, control effectiveness and unknown matched uncertainty of the i^{th} vehicle respectively. $A_i \in \mathbb{R}^{n\times n}$ and $B_i \in \mathbb{R}^{n\times m}$ are the nominal i^{th} vehicle system matrices given as

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{bmatrix}, \text{ and } B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau_i} \end{bmatrix}, \quad (2)$$

where τ_i is the follower's inertial time lag of the powertrain.

Assumption 1: The unknown matched uncertainty in (1) is linearly parameterized as [3]

$$\eta_i(x_i) = W_i^T \sigma_i(x_i) \quad (3)$$

where $W_i \in \mathbb{R}^{s\times m}$ is an unknown constant weighting matrix and $\sigma_i(x_i): \mathbb{R}^n \to \mathbb{R}^s$ is a known basis vector function.

The dynamics of the lead vehicle is represented by

$$\dot{x}_0 = A_0 x_0, \quad (4)$$

where $x_0 \in \mathbb{R}^n$ is the leader's state and $A_0 \in \mathbb{R}^{n\times n}$ is the leader's system matrix represented as

$$A_0 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_0} \end{bmatrix}, \quad (5)$$

where τ_0 is the leader's inertial time lag of the powertrain.

The state vector of all vehicles is defined as $x_i = [p_i + i \cdot d_r \quad v_i \quad a_i]^T$, for $i \in \{0,1,\dots,N\}$, where p_i, v_i, and a_i are the position, velocity, and acceleration of the i^{th} vehicle, and d_r is the desired constant spacing distance. Here, $i = 0$ represents the lead vehicle while $i = 1,2,\dots,N$ corresponds to the followers.

Let the reference model for each follower be defined as

$$\dot{x}_{i,r} = A_i x_{i,r} + B_i u_{i,nr}, \quad (6)$$

where $x_{i,r} \in \mathbb{R}^n$ is the follower's reference state and $u_{i,nr} \in \mathbb{R}^m$ is the reference control signal.

A graph is used to model the information exchange between follower vehicles in the vehicle platoon and is denoted as $\mathcal{G}(\mathcal{V},\mathcal{E})$. Here, $\mathcal{V} = \{v_1, v_2, \dots, v_N\}$ is a set of nodes that represents the follower vehicles and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of edges that represents the information exchange between follower vehicles. To include the leader, an augmented graph $\tilde{\mathcal{G}}(\tilde{\mathcal{V}},\tilde{\mathcal{E}})$ is defined such that $\tilde{\mathcal{V}} = \{v_0, v_1, v_2, \dots, v_N\}$ and $\tilde{\mathcal{E}} \subseteq \tilde{\mathcal{V}} \times \tilde{\mathcal{V}}$. A vehicle topology is considered a directed graph (digraph) if all edges are directed from one vehicle to another. It contains a spanning tree if there is a root vehicle, and departing from this root vehicle, all vehicles can be reached by following edge arrows. The exchange of information between vehicles in $\mathcal{G}$ can be represented by an adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$, where $a_{ij} = 1$ means vehicle j send information to vehicle i , otherwise $a_{ij} = 0$. Denote the in-degree matrix as $D = diag\{d_{11}, d_{22}, \dots, d_{NN}\}$, where $d_{ii} = \sum_{j=1}^{N} a_{ij}$. The Laplacian matrix L is defined as $L = D - \mathcal{A} \in \mathbb{R}^{N\times N}$ where $\ell_{ii} = d_{ii}$ and $\ell_{ij} = -a_{ij}$. Direct information flow from the leader to the followers is represented by a pinning gain matrix, $G = diag\{g_{11}, g_{22}, \dots, g_{NN}\}$, where $g_{ii} = 1$ means that follower i receives information directly from the leader, otherwise $g_{ii} = 0$

Assumption 2: The graph $\tilde{\mathcal{G}}$ is directed and contains at least one spanning tree with the leader as a root node [10].

The objective of this paper is to design a distributed controller u_i for the uncertain, heterogeneous follower (1), such that the follower can track the reference model (6) and simultaneously achieve synchronization to the leader's state (4).

3. DISTRIBUTED MODEL REFERENCE ADAPTIVE CONTROLLER

Distributed model reference adaptive controller consists of a reference model and a main control system, as in [6]. This will be modified to consider a heterogeneous vehicle platoon. The reference model for each follower vehicle is represented by (6), with the reference control signal designed as

$$u_{i,nr} = c_i K_i \left\{ \sum_{j=1}^{N} a_{ij} \left(x_{j,r} - x_{i,r} \right) + g_{ii} \left(x_{0,r} - x_{i,r} \right) \right\} , \quad (7)$$

where

$$K_i = R_i^{-1} B_i^T P_i, \quad (8)$$

while c_i and $K_i \in \mathbb{R}^{m\times n}$ are the scalar coupling gain and feedback gain matrix of the i^{th} vehicle respectively. P_i is a solution of the algebraic Riccati equation (ARE)

$$0 = A_i^T P_i + P_i A_i + Q_i - P_i B_i R_i^{-1} B_i^T P_i , \quad (9)$$

where Q_i and R_i are positive definite matrices.

The control input for the i^{th} follower vehicle with the uncertain dynamics described by (1) is designed as

$$u_i = u_{i,n} - u_{i,a}, \quad (10)$$

where $u_{i,n}$ is the nominal control and $u_{i,a}$ is the adaptive term. The nominal control signal is designed as

$$u_{i,n} = c_i K_i\{\sum_{j=1}^{N} a_{ij}(x_j - x_i) + g_{ii}(x_0 - x_i)\}, \quad (11)$$

with K_i is given by (8). The condition on the coupling gain c_i will be derived later.

The adaptive term is derived as in [6] by substituting (10) into (1), then adding and subtracting the term $c_i B_i K_i \varepsilon_i$, finally yielding

$$\dot{x}_i = A_i x_i + c_i B_i K_i\{\sum_{j=1}^{N} a_{ij}(x_j - x_i) + g_{ii}(x_0 - x_i)\} + B_i \Omega_i[\theta_i{}^T \Phi_i(\sigma_i(x_i), u_{i,n}) - u_{i,a}], \quad (12)$$

where $\theta_i{}^T = \begin{bmatrix} \Omega_i{}^{-1} W_i{}^T \\ I - \Omega_i{}^{-1} \end{bmatrix}^T$, and $\Phi_i(\sigma_i(x_i), u_{i,n}) = \begin{bmatrix} \sigma_i(x_i) \\ u_{i,n} \end{bmatrix}$. Since $\theta_i{}^T$ is unknown, the estimated value $\hat{\theta}_i{}^T$ is used instead to construct the following adaptive term

$$u_{i,a} = \hat{\theta}_i{}^T \Phi_i(\sigma_i(x_i), u_{i,n}), \quad (13)$$

which will suppress the effect of uncertainty. Substituting the adaptive term (13) into (12) gives

$$\dot{x}_i = A_i x_i + c_i B_i K_i\{\sum_{j=1}^{N} a_{ij}(x_j - x_i) + g_{ii}(x_0 - x_i)\} - B_i \Omega_i\left[\tilde{\theta}_i{}^T \Phi_i(\sigma_i(x_i), u_{i,n})\right], \quad (14)$$

where $\tilde{\theta}_i = \hat{\theta}_i - \theta_i$ is the parameter estimation error. Here, $\sigma_i(x_i) = x_i$ is used as the known basis function.

Let the tracking error of each follower with respect to the reference model state be defined as $e_i = x_i - x_{i,r}$. In this control scheme, both the actual and reference control loops employ the same neighbor and leader states, ($x_j = x_{j,r}$, $x_0 = x_{0,r}$). Therefore, the effect of these states on the tracking error dynamics will cancel each other. Finally, the tracking error dynamics can be described as

$$\dot{e}_i = A_{i,m} e_i - B_i \Omega_i\left[\tilde{\theta}_i{}^T \Phi_i(\sigma_i(x_i), u_{i,n})\right], \quad (15)$$

with

$$A_{i,m} = A_i - c_i(d_{ii} + g_{ii}) B_i K_i, \quad (16)$$

where d_{ii} and g_{ii} are the i^{th} diagonal elements of the in-degree matrix D and pinning gain matrix G respectively.

The objective of the adaptive term is to suppress the effects of system uncertainties such that the state of each follower vehicle approaches the state of the reference model, $x_i \to x_{i,r}$ as $t \to \infty$, which signifies that the third term of (14) becomes zero. The tracking error dynamics of the vehicle platoon can be formulated by omitting the third term of (14), which can be represented as $\delta_i = x_i - x_0$, where $\delta_i = [\delta_{i,p} \quad \delta_{i,v} \quad \delta_{i,a}]^T$ is the state tracking error to the leader. Inspired by [8], since the leader moves with constant speed ($\dot{v}_0 = 0$), the tracking error to the leader can be defined as

$$\begin{cases} \delta_{i,p} = p_i + i \cdot d_r - p_0 \\ \delta_{i,v} = \dot{p}_i - \dot{p}_0 = v_i - v_0 \\ \delta_{i,a} = \ddot{p}_i - \ddot{p}_0 = a_i \end{cases}. \quad (17)$$

The nominal control (11) can be rewritten as

$$u_i = c_i K_i[\sum_{j=1}^{N} a_{ij}(\delta_j - \delta_i) - g_{ii}\delta_i]. \quad (18)$$

To analyze the stability of the heterogeneous platoon, the tracking error dynamics of each follower w.r.t the leader is represented as

$$\dot{\delta}_{i,p} = \delta_{i,v}$$

$$\dot{\delta}_{i,v} = \delta_{i,a}$$

$$\dot{\delta}_{i,a} = -\frac{1}{\tau_i}\delta_{i,a} + \frac{1}{\tau_i} c_i K_i[\sum_{j=1}^{N} a_{ij}(\delta_j - \delta_i) - g_{ii}\delta_i], \quad (19)$$

where $K_i = [k_{i,p} \quad k_{i,v} \quad k_{i,a}]$.

Let $\delta_p = col(\delta_{1,p}, \delta_{2,p}, .., \delta_{N,p}) \in \mathbb{R}^N$, $\delta_v = col(\delta_{1,v}, \delta_{2,v}, .., \delta_{N,v}) \in \mathbb{R}^N$, $\delta_a = col(\delta_{1,a}, \delta_{2,a}, .., \delta_{N,a}) \in \mathbb{R}^N$ and $\delta = [\delta_p \quad \delta_v \quad \delta_a]^T$, such that the global tracking error dynamics of the vehicle platoon can be defined as

$$\dot{\delta} = \hat{A}\delta, \quad (20)$$

with

$$\hat{A} = \begin{bmatrix} 0_N & I_N & 0_N \\ 0_N & 0_N & I_N \\ -\beta_p H & -\beta_v H & -\beta_a H - \alpha \end{bmatrix}, \quad (21)$$

where $H = L + G$, $\beta_p = diag(\beta_{1,p}, \beta_{2,p}, .., \beta_{N,p})$, $\beta_v = diag(\beta_{1,v}, \beta_{2,v}, .., \beta_{N,v})$, $\beta_a = diag(\beta_{1,a}, \beta_{2,a}, .., \beta_{N,a})$, $\beta_{i,p} = \frac{1}{\tau_i} c_i k_{i,p}$, $\beta_{i,v} = \frac{1}{\tau_i} c_i k_{i,v}$, $\beta_{i,a} = \frac{1}{\tau_i} c_i k_{i,a}$ and $\alpha = diag\left(\frac{1}{\tau_1}, \frac{1}{\tau_2}, .., \frac{1}{\tau_N}\right)$.

4. MAIN RESULT

Theorem 1. Consider a heterogeneous vehicle platoon with the dynamics expressed by (1) and (4), and the network topology satisfying Assumption 2. The reference model is constructed according to (6) and (7). By applying the distributed controller (10) with feedback gain K_i as in (8) and selecting the coupling gain c_i such that

$$c_i \geq \frac{1}{2(d_{ii} + g_{ii})}, \quad (22)$$

where d_{ii}, g_{ii} are the diagonal elements of matrices D and G respectively, along with the adaptation law

$$\dot{\hat{\theta}}_i = \gamma_i \Phi_i(\sigma_i(x_i), u_{i,n}) e_i{}^T P_i B_i, \quad (23)$$

where $\gamma_i > 0$ is the adaptation rate, then the tracking error w.r.t the reference state satisfies $\lim_{t\to\infty} \|e_i\| = 0$ and the tracking error w.r.t the leader state satisfies $\lim_{t\to\infty} \|\delta_i\| = 0$.

Proof. There are two steps in this stability proof: (i) it will be shown that $e_i \to 0$ as $t \to \infty$ and (ii) it will be shown that $\delta_i \to 0$ as $t \to \infty$.

Proof of $e_i \to 0$ as $t \to \infty$

Consider the following Lyapunov candidate function

$$V_i(e_i, \tilde{\theta}_i) = e_i^T P_i e_i + \gamma^{-1} tr\left(\Omega_i^{1/2} \tilde{\theta}_i^T \tilde{\theta}_i \Omega_i^{1/2}\right). \quad (24)$$

The first derivative of V_i along (15) is

$$\dot{V}_i = e_i^T\left[P_i A_{i,m} + A_{i,m}^T P_i\right] e_i - 2 e_i^T P_i B_i \Omega_i \tilde{\theta}_i^T \Phi_i\left(\sigma_i(x_i), u_{i,n}\right) + 2\gamma^{-1} tr\left(\Omega_i \tilde{\theta}_i^T \dot{\hat{\theta}}_i\right). \quad (25)$$

Using the trace identity $tr(a^T b) = b a^T$, (25) can be simplified as

$$\dot{V}_i = e_i^T\left[P_i A_{i,m} + A_{i,m}^T P_i\right] e_i - 2\gamma^{-1}\left(\Omega_i \tilde{\theta}_i^T\left[\gamma \Phi_i(\sigma_i(x_i), u_{i,n}) e_i^T P_i B_i - \dot{\hat{\theta}}_i\right]\right). \quad (26)$$

By choosing the adaptation law $\dot{\hat{\theta}}_i$ according to (23),

$$\dot{V}_i = e_i^T\left[P_i A_{i,m} + A_{i,m}^T P_i\right] e_i. \quad (27)$$

By substituting (16), $P_i A_{i,m} + A_{i,m}^T P_i$ finally becomes

$$P_i A_{i,m} + A_{i,m}^T P_i = -Q_i - (2c_i(d_{ii} + g_{ii}) - 1) K_i^T R_i K_i. \quad (28)$$

Therefore, (27) becomes

$$\dot{V}_i = -e_i^T\left[Q_i + (2c_i(d_{ii} + g_{ii}) - 1) K_i^T R_i K_i\right] e_i. \quad (29)$$

By choosing a coupling gain c_i that satisfies (22),

$$\dot{V}_i \le -\underline{\sigma}(Q_i)\|e_i\|^2 \le 0, \quad (30)$$

where $\underline{\sigma}(\cdot)$ is the minimum singular value. Since $\dot{V}_i \le 0$, this implies that the pair $(e_i, \tilde{\theta}_i) \in \mathcal{L}_\infty$ are bounded. From (30),

$$V_i\left(e_i(t \to \infty), \tilde{\theta}_i(t \to \infty)\right) = V_1\left(e_i(t_0), \tilde{\theta}_i(t_0)\right) - \underline{\sigma}(Q_i)\|e_i\|^2 < \infty, \quad (31)$$

indicating that V_i has a limit as $t \to \infty$. To verify that $\ddot{V}_i$ is bounded, it is necessary to show the boundedness of (15). By virtue of $\dot{V}_i \le 0$, then $e_i \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and $\tilde{\theta}_i \in \mathcal{L}_\infty$. Since θ_i is constant and bounded, this implies that $\hat{\theta}_i \in \mathcal{L}_\infty$. $A_{i,m}$ is Hurwitz by choosing coupling gain c_i as (22) and K_i as (8). Therefore, all terms on the right-hand side of (15) are bounded. This indicates that $\ddot{V}_i$ is bounded and $\dot{V}_i$ is a uniformly continuous function. By Barbalat's lemma, it can be said that $\dot{V}_i \to 0$, and hence $e_i \to 0$ as $t \to \infty$. This implies that the follower vehicle state is guaranteed to track the reference state.

Proof of $\delta_i \to 0$ as $t \to \infty$

Inspired by [8], in order to analyze the stability of the vehicle platoon, the characteristic equation of (20) is formulated as

$$|\lambda I_N - \hat{A}| = \begin{vmatrix} \lambda I_N & -I_N & 0_N \\ 0_N & \lambda I_N & -I_N \\ \beta_p H & \beta_v H & \beta_a H + \alpha \end{vmatrix}$$

$$= \lambda^3 I_N + \lambda^2(\beta_a H + \alpha) + \lambda \beta_v H + \beta_p H. \quad (32)$$

Since β_p, β_v, β_a, α are diagonal matrices and H is a lower triangular matrix, then (32) can be represented as

$$|\lambda I_N - \hat{A}| = \prod_{i=1}^{N} \lambda^3 + \lambda^2\left[\beta_{i,a}(d_{ii} + g_{ii}) + \frac{1}{\tau_i}\right] + \lambda\left[\beta_{i,v}(d_{ii} + g_{ii})\right] + \beta_{i,p}(d_{ii} + g_{ii}). \quad (33)$$

The stability of (20) is equivalent to the stability of N characteristic equations,

$$\lambda^3 + \lambda^2\left[\beta_{i,a}(d_{ii} + g_{ii}) + \frac{1}{\tau_i}\right] + \lambda\left[\beta_{i,v}(d_{ii} + g_{ii})\right] + \beta_{i,p}(d_{ii} + g_{ii}) = 0, \quad i = 1,2,..,N. \quad (34)$$

From (21), by considering that H is a lower triangular matrix, it is seen that $\hat{A}$ is composed of $A_i - c_i(d_{ii} + g_{ii}) B_i K_i$, which is equal to $A_{i,m}$ as in (16). From (28), it is shown that $A_{i,m}$ is Hurwitz for all i. Therefore, all the eigenvalues of (34) have negative real parts and guarantee the stability of the vehicle platoon. Since the leader moves with a constant velocity, and spacing information can be obtained according to [8], the followers can track the leader, which implies that $\delta_i \to 0$ as $t \to \infty$. This completes the proof. ■

5. NUMERICAL SIMULATION

Simulation analysis is conducted based on a heterogeneous vehicle platoon consisting of one leader and 5-followers subjected to uncertain dynamics. The information flow between vehicles is realized using predecessor following (PF) topology, as shown in Fig.1, with the Laplacian matrix L and pinning gain matrix G represented by L = [0 0 0 0 0; -1 1 0 0 0; 0 -1 1 0 0; 0 0 -1 1 0; 0 0 0 -1 1] and G = [1 0 0 0 0; 0 0 0 0 0; 0 0 0 0 0; 0 0 0 0 0; 0 0 0 0 0] respectively. The vehicle platoon is formed based on a constant spacing policy with $d_r = 5$ m. The nominal values of the inertial time lag for each vehicle are $\tau_0 = 0.6$, $\tau_1 = 0.25$, $\tau_2 = 0.27$, $\tau_3 = 0.3$, $\tau_4 = 0.5$ and $\tau_5 = 0.7$. The control effectiveness for each vehicle are $\Omega_0 = 1$, $\Omega_1 = 0.5$, $\Omega_2 = 0.6$, $\Omega_3 = 0.6$, $\Omega_4 = 0.7$ and $\Omega_5 = 0.6$. It is assumed that each follower is subjected to uncertainties that can be represented by the following constant weighting matrices: $W_1^T = [0 \;\; 0 \;\; 0.286]$, $W_2^T = [0 \;\; 0 \;\; 0.27]$, W_3^T =[0 0 0.925], W_4^T =[0 0 0.286] and W_5^T =[0 0 0.125]. The initial states of each vehicle are as follows: $x_0(0) = [60,20,0]^T$, $x_1(0) = [40,18,0]^T$, $x_2(0) = [25,19,0]^T$, $x_3(0) = [17,22,0]^T$, $x_4(0) = [10,21,0]^T$ and $x_5(0) = [0,17,0]^T$.

The nominal and reference controllers are designed using LQR with $Q_1 = Q_2 = Q_3 = Q_4 = Q_5 = I_{3\times3}$ and $R_1 = R_2 = R_3 = R_4 = R_5 = 0.1$, resulting in matrices P_i as follows,

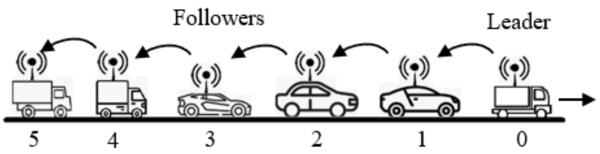

Fig.1 A heterogeneous vehicle platoon with PF topology

$$P_1 = \begin{bmatrix} 1.8324 & 1.1789 & 0.0791 \\ 1.1789 & 2.0811 & 0.1449 \\ 0.0791 & 0.1449 & 0.0682 \end{bmatrix}, \quad (35)$$

$$P_2 = \begin{bmatrix} 1.8380 & 1.1891 & 0.0854 \\ 1.1891 & 2.1001 & 0.1569 \\ 0.0854 & 0.1569 & 0.0745 \end{bmatrix}, \quad (36)$$

$$P_3 = \begin{bmatrix} 1.8462 & 1.2043 & 0.0949 \\ 1.2043 & 2.1285 & 0.1751 \\ 0.0949 & 0.1751 & 0.0842 \end{bmatrix}, \quad (37)$$

$$P_4 = \begin{bmatrix} 1.8995 & 1.3041 & 0.1581 \\ 1.3041 & 2.3191 & 0.3003 \\ 0.1581 & 0.3003 & 0.1562 \end{bmatrix}, \quad (38)$$

$$P_5 = \begin{bmatrix} 1.9500 & 1.4012 & 0.2214 \\ 1.4012 & 2.5109 & 0.4316 \\ 0.2214 & 0.4316 & 0.2402 \end{bmatrix}, \quad (39)$$

and feedback gain matrices $K_1 = [3.1623,\ 5.7946,\ 2.7279]$, $K_2 = [3.1623,\ 5.812,\ 2.7601]$, $K_3 = [3.1623,\ 5.8383,\ 2.8083]$, $K_4 = [3.1623,\ 6.0068,\ 3.1239]$ and $K_5 = [3.1623, 6.1663,\ 3.4309]$. The coupling gains c_i that satisfy (22) are selected as $c_1 = c_2 = c_3 = c_4 = c_5 = 1$ and the adaptation rates are $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0.1$. The selection of Q_i, R_i and c_i represents a trade-off between tracking performance and a reasonable control input signal. The greater the value of c_i or Q_i, the better the tracking performance but requires a large initial control effort. The value of R_i exhibits the opposite effects as Q_i.

The tracking errors e_i and δ_i, shown in Fig. 2 and Fig. 3, illustrate that the follower vehicles are able to track the reference model and simultaneously synchronize to the leader state. To further analyze the performance of the proposed controller, the results are compared to homogeneous DMRAC [6] and CSVFB [9] schemes, which are applied to the heterogeneous platoon. The homogeneous DMRAC in [6] can be utilized for heterogeneous platoons by using an identical nominal model for all vehicles and treating the heterogeneities as uncertainties, whereas CSVFB is applied with heterogeneous nominal control based on the nominal model of each follower. The inter-vehicular tracking error of each follower is shown in Fig. 4. It can be seen that the proposed controller outperforms homogeneous DMRAC and CSVFB, with the corresponding mean squared error (MSE) given in Table.1. By utilizing different nominal controllers designed according to the nominal models of each vehicle, the individual performance of the followers is improved. Moreover, the proposed controller demonstrates faster response in velocity and acceleration tracking as shown in Fig. 5 and Fig. 6. However, one observable drawback is a significant oscillation of the control inputs, as shown in Fig. 7, which may cause vehicle jerk and energy inefficiency. This oscillation is related to the adaptation gain that is selected. A fast adaptation rate improves the transient response of the system but may generate high frequency oscillations in the control signal.

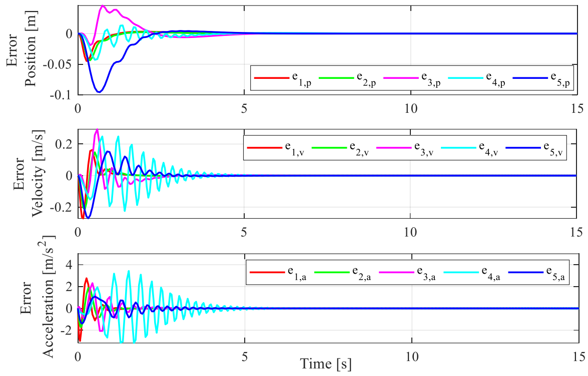

Fig.2 Tracking error (e_i) w.r.t the reference model

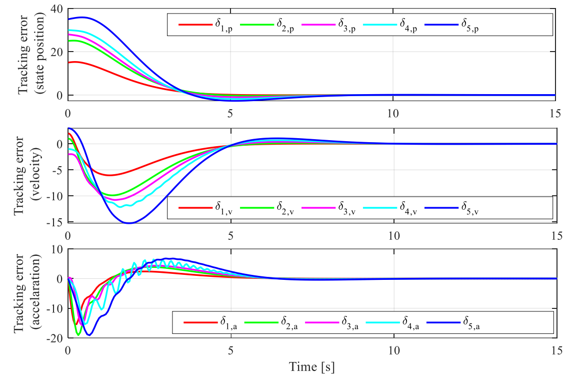

Fig.3 Tracking error (δ_i) w.r.t the leader

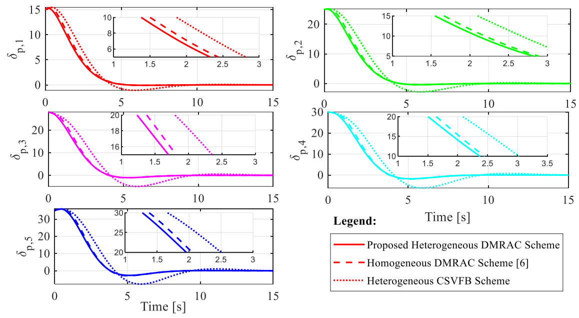

Fig.4 Performance comparison between proposed heterogeneous DMRAC, homogeneous DMRAC and CSVFB in terms of inter-vehicular distance error

Table 1 Mean squared error (MSE) of the inter-vehicular distance in each follower.

Control Schemes	MSE of the inter-vehicular distance (i)				
	1	2	3	4	5
Hetero. DMRAC	19.8	54.1	66.0	81.1	126.3
Homo. DMRAC [6]	20.2	54.9	67.0	81.7	123.9
Hetero. CSVFB	23.3	64.8	81.8	99.7	149.5

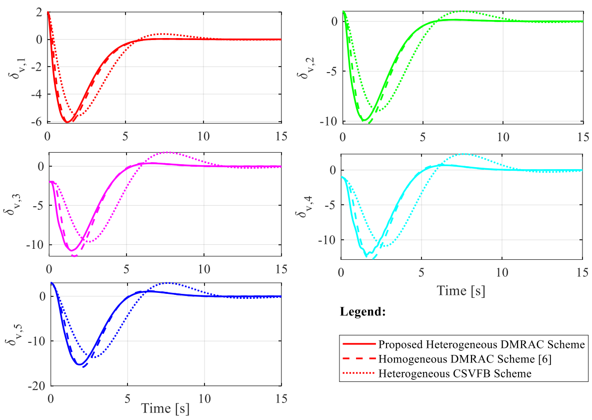

Fig.5 Performance comparison between proposed heterogeneous DMRAC, homogeneous DMRAC and CSVFB in terms of velocity tracking error

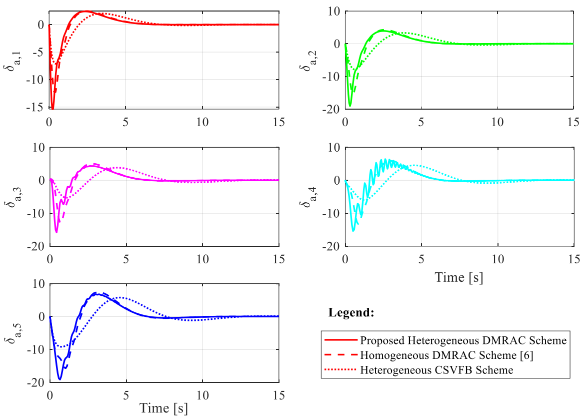

Fig.6 Performance comparison between proposed heterogeneous DMRAC, homogeneous DMRAC and CSVFB in terms of acceleration tracking error

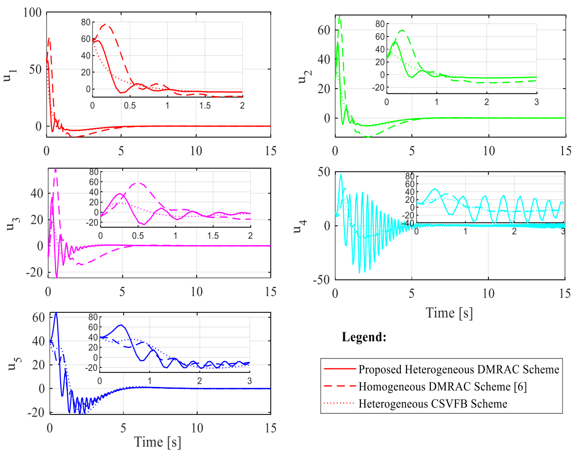

Fig.7 Control input comparison between proposed heterogeneous DMRAC, homogeneous DMRAC and CSVFB.

6. CONCLUSION

The synchronization of a heterogeneous vehicle platoon using distributed model reference adaptive control is presented, where each follower is subjected to uncertainties in control effectiveness and inertial time lag. The proposed control scheme utilized heterogeneous reference models and nominal control for each follower to track the leader state and an adaptive term to attenuate the effect of uncertainties. The efficacy is verified by numerical simulations that show how the uncertain vehicles can track the reference model and achieve synchronization to the leader state. Comparison results with existing controllers demonstrated that the proposed controller is able to improve the overall performance of individual vehicles but may produce an oscillating control input.

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This paper addresses the problem of heterogenous vehicle platoons, where each follower has a different nominal model and is subjected to uncertainty in the inertial time lag and control effectiveness. Distributed model reference adaptive control (DMRAC) is utilized to achieve synchronization. Each follower vehicle employs a heterogenous reference model and a nominal controller, along with an additional adaptive term to ensure that the follower may track the reference model despite uncertainties. The conditions on the coupling gain and adaptation law for each follower to ensure stability are derived. It is shown that the proposed controller guarantees the stability of the heterogenous vehicle platoon, which implies the synchronization of followers' state to the leader. Numerical simulation validates the efficacy of the proposed controller. Moreover, the performance and characteristics of DMRAC are analyzed and compared to conventional control schemes.

Published in: 2022 61st Annual Conference of the Society of Instrument and Control Engineers (SICE)

Date of Conference: 06-09 September 2022

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Date Added to IEEE *Xplore*: 06 October 2022

DOI: 10.23919/SICE56594.2022.9905763

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1. INTRODUCTION

With the advancement of communication, sensor, and artificial intelligence technologies, the future trend of intelligent transportation systems is connected and automated vehicles (CAVs). CAVs have the capability to communicate to everything (V2X), including to other vehicles (V2V), pedestrians, infrastructures, and public facilities in the vicinity [1]. This paper focuses on one possible application of CAVs called the vehicle platoon. A vehicle platoon is a train-like driving formation of vehicles which consists of one leader and N-followers, connected via a network of sensors or wireless communication technology. The objective of the platoon is to synchronize all the followers to the leader's state by maintaining the desired inter-vehicular distance.

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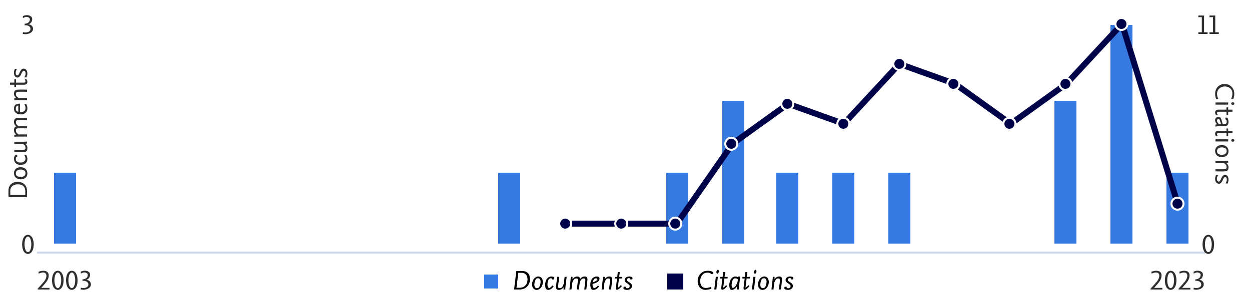

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