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Distributed periodic event-triggered terminal sliding mode control for vehicular platoon system

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In recent years, the platooning of vehicular systems has attracted great attention in alleviating severe traffic issues. The cornerstone of a vehicular platoon system is wireless inter-vehicle communication, i.e., VANETs, which allows vehicles to share useful information [1]. However, a large number of vehicles occupying the communication channel can impose a significant burden on the communication system, resulting in undesirable communication issues [2].

To conserve the limited communication resources, the event-triggered mechanism (ETM) has recently been proposed and applied to vehicular platoon systems while ensuring the string stability of the platoon [1]. In [2], the dynamic event-triggered mechanism (DETM) was investigated for vehicular platoons and the triggering threshold was adjusted based on vehicular status. However, both ETM and DETM require continuous measurement of system states to determine triggering instants, which may pose difficulties in deploying them on a time-sliced software platform. As an alternative, the periodic event-triggered mechanism (PETM) periodically monitors the status without continuous measurement and has received extensive attention. To the best of the authors' knowledge, there is little research on PETM for vehicular platoon systems.

In addition to limited communication resources, ETM-based systems are more vulnerable to perturbations due to reduced real-time data communication. Unfortunately, there are few studies on ETM-based vehicular systems that consider the effect of perturbations [1, 2]. Sliding mode control (SMC), as an important robust control method, has attracted considerable research attention [3]. A detailed review is given in Appendix A. This work aims to simultaneously alleviate the communication burden and enhance anti-interference by studying a distributed nonsingular terminal sliding mode control (NTSMC) for vehicular platoon systems based on a periodic event-triggered mechanism without the Zeno phenomenon. To prevent varying traffic density from degrading traffic flow efficiency [4], this work considers traffic flow stability (TFS) and proposes a novel coupled quadratic spacing strategy. Furthermore, a PETM-based finite-time extended state observer (PFESO) is designed to enhance anti-interference performance.

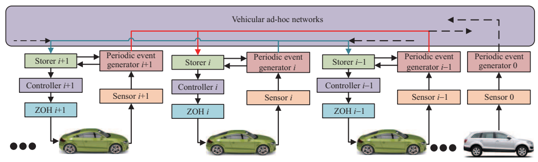

Figure 1 (Color online) Schematic diagram of a vehicular platoon system.

Problem formulation. In this work, a vehicular platoon system consisting of N follower vehicles and a leader vehicle is considered as shown in Figure 1. The leader is assumed to drive under a predefined trajectory governed by

$$\dot{x}_0(t) = v_0(t), \quad \dot{v}_0(t) = a_0(t), \tag{1}$$

where $x_0(t)$ and $v_0(t)$ denote the position and the velocity of the leader, respectively. The dynamics of the ith follower vehicle is described by the following third-order model:

$$\begin{aligned} &\dot{x}_i(t) = v_i(t), \quad \dot{v}_i(t) = a_i(t), \\ &\dot{a}_i(t) = -\frac{1}{\tau_i}\left(a_i(t) + \frac{\nu A_i C_{di}}{2m_i} v_i(t)^2 + \frac{d_{mi}}{m_i}\right) + \frac{u_i(t)}{\tau_i m_i} \\ &\qquad -\frac{\nu A_i C_{di} v_i(t) a_i(t)}{m_i} + \bar{w}_i(t), \end{aligned} \tag{2}$$

where $x_i(t)$, $v_i(t)$, and $a_i(t)$, $i = 1, \ldots, N$ are the position, velocity, and acceleration of the ith vehicle, $u_i(t)$ is the engine/brake input, τ_i is the engine time constant, ν, A_i, C_{di}, d_{mi} are the air density, cross-sectional area, drag coefficient, and mechanical drag of vehicle i and usually unknown in practice, and m_i denotes the mass of ith vehicle, $\bar{w}_i(t)$ is unknown external disturbance. $w_i(t) = -\frac{\nu A_i C_{di}}{2\tau_i m_i} v_i(t)^2 - \frac{d_{mi}}{\tau_i m_i} - \frac{\nu A_i C_{di} v_i(t) a_i(t)}{m_i} + \bar{w}_i(t)$ is considered the lumped disturbance and satisfies the following assumption.

Assumption 1. The disturbance w_i satisfies $|\dot{w}_i| \leqslant w_i^*$ with w_i^* being a positive constant.

Assumption 2 is introduced based on the traffic rules.

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Assumption 2. The velocity $v_i(t)$ and acceleration $a_i(t)$ of vehicle i are bounded time-varying functions, and there exist constants v_m and a_m such that $0 \leqslant v_i(t) \leqslant v_m$ and $-a_m \leqslant a_i(t) \leqslant a_m$.

To guarantee driving safety and TFS, we define the spacing error $e_i = x_{i-1} - x_i - \Delta_i$ and introduce the traditional quadratic spacing policy $\Delta_i = l_i + q_i v_i + \frac{r_i}{2} v_i^2$ [4], where l_i, q_i, and r_i are positive constants. The objective of this study is to design an ETM-based distributed controller u_i such that the vehicular platoon system satisfies (1) practically finite time stable in t_c, i.e., $\lim_{t\to t_c} e_i(t) = \zeta_i$, where ζ_i is a small positive constant, and $\lim_{t\to\infty} v_i(t) = v_0(t)$, (2) strong string stability, i.e., $|e_N(t)| \leqslant |e_{N-1}(t)| \leqslant \cdots \leqslant |e_1(t)|$, and (3) traffic flow stability [4], i.e., $\partial Q_i/\partial \rho_i > 0$, where Q_i and ρ_i denote the gradient of traffic flow rate and traffic density, respectively.

PETM-based finite-time extended state observer. To avoid continuous measurement and frequent inter-vehicle communication, the periodic event-triggered condition for vehicle i is constructed as

$$t_k^{i+1} = \inf_{j\in N^+} \left\{ t = t_k^i + j\lambda_i \mid \|\delta_i(t)\| \geqslant \bar{\delta}_i \right\}, \tag{3}$$

where $\delta_i = \|\xi_i(t) - \xi_i(t_k^i)\|$ denotes the triggered error and the onboard sensors of the ith vehicle measure the state $\xi_i(t) = [e_i(t), v_i(t), a_i(t)]^{\mathrm{T}}$ at a sampling period λ_i, which will be designed latter. In (3), the triggered instant t_k^{i+1} is produced only at the discrete instants $t = t_k^i + j\lambda_i$ and the Zeno behavior can be avoided naturally. $\bar{\delta}_i > 0$ is a given triggering threshold which affects the trigger frequency and control performance. However, a large/small $\bar{\delta}_i$ will lead to less/more communication frequency, but results in less/more accurate control results. Hence the selection of $\bar{\delta}_i$ has to be a reasonable trade-off. A PFESO is designed to deal with external disturbance.

Theorem 1. Under Assumption 1 and the PETM (3), the estimation errors of w_i are finite-time input-to-state stable when the PFESO is designed as follows:

$$\begin{cases} \dot{\hat{x}}_i = \hat{v}_i + k_1^i \varepsilon^2 \left\lceil \dfrac{\hat{x}_i - x_i(t_k^i)}{\varepsilon^3} \right\rfloor^{\alpha_i}, \\ \dot{\hat{v}}_i = \hat{a}_i + k_2^i \varepsilon \left\lceil \dfrac{\hat{x}_i - x_i(t_k^i)}{\varepsilon^3} \right\rfloor^{2\alpha_i - 1}, \\ \dot{\hat{a}}_i = \hat{w}_i + k_3^i \left\lceil \dfrac{\hat{x}_i - x_i(t_k^i)}{\varepsilon^3} \right\rfloor^{3\alpha_i - 2} - \dfrac{a_i(t_k^i)}{\tau_i} + \dfrac{u_i}{m_i \tau_i}, \\ \dot{\hat{w}}_i = \dfrac{k_4^i}{\varepsilon} \left\lceil \dfrac{\hat{x}_i - x_i(t_k^i)}{\varepsilon^3} \right\rfloor^{4\alpha_i - 3}, \end{cases} \tag{4}$$

where $\lceil \cdot \rfloor^{\alpha_i} = \mathrm{sign}(\cdot) \cdot |^{\alpha_i}$. The parameter settings and the proof of Theorem 1 can be found in Appendixes B and C.

PETM-based distributed NTSMC. To achieve string stability and TFS simultaneously, the coupled quadratic spacing error is designed as follows:

$$\varepsilon_i = \begin{cases} \gamma_i e_i - e_{i+1}, & i < N, \\ \gamma_i e_i, & i = N, \end{cases} \tag{5}$$

where $0 < \gamma_i \leqslant 1$ is a positive constant. The detailed description of the coupled quadratic spacing error is shown in Appendix D. Due to the outstanding capability in anti-interference, SMC, especially the terminal sliding mode control, has been extensively applied in vehicular platoon systems. This study considers a nonsingular terminal sliding mode surface:

$$s_i = \varepsilon_i + \beta_i \dot{\varepsilon}_i^{p_i}, \tag{6}$$

where β_i, p_i are positive constants, and $p_i = p_i^1/p_i^2 \in (1,2)$, p_i^1, p_i^2 are two assigned odd integers. Then, during a consecutive triggered interval $[t_k^i, t_k^{i+1})$, the terminal sliding mode control law $u_i(t_k^i)$ under the PETM (3) can be represented as

$$\begin{aligned} u_i(t_k^i) = {} & \frac{\tau_i m_i}{\vartheta_i g_i(t_k^i)} (\dot{\varepsilon}_i^{2-p_i}(t_k^i) + k_i \mathrm{sgn}(s_i(t_k^i))) \\ & + \tfrac{\tau_i m_i}{\gamma_i g_i(t_k^i)} \varpi_i(t_k^i) - \tau_i m_i \hat{w}_i(t_k^i), \end{aligned} \tag{7}$$

where $k_i > 0$, $\vartheta_i = \gamma_i \beta_i p_i$, $g_i(t_k^i) = q_i + r_i v_i(t_k^i)$ for concise and $\varpi_i(t_k^i)$ is the latest triggered state of

$$\varpi_i = \begin{cases} \gamma_i (a_{i-1} - a_i - r_i a_i^2 + \tau_i^{-1} g_i a_i) - \ddot{e}_{i+1}, & i < N, \\ \gamma_i (a_{i-1} - a_i - r_i a_i^2 + \tau_i^{-1} g_i a_i), & i = N. \end{cases} \tag{8}$$

Theorem 2. Consider the vehicular platoon systems (1) and (2) under Assumptions 1 and 2, if the sampling period satisfies $\lambda_i \in (0, \frac{1}{L_1^i} \ln(1 + \frac{\sigma_i}{(L_1^i)^{-1}(\bar{h}_i + \bar{w}_m^i) + \bar{\delta}_i}))$ and the switching gain is set as $k_i = \beta_i p_i (q_i + r_i v_m) \cdot (L_2^i (\sum_{j=i-1}^{i+1} \bar{\delta}_j^2)^{\frac{r}{2}} + \gamma_i \bar{w}_m^i + c_i)$, the controller (7) with the PETM (3) assures that the state trajectories of system can reach practical sliding mode in the region $\Omega_i = \{s_i(t) \in R \mid |s_i(t)| \leqslant \gamma_i \bar{\delta}_i + \bar{\delta}_{i+1} + \beta_i L_3^i (\sum_{j=i-1}^{i+1} \bar{\delta}_j^2)^{\frac{1}{2}}\}$ and the coupled quadratic spacing error is ultimately bounded by $\Psi_i = \{\varepsilon_i \in R \mid |\varepsilon_i| < \gamma_i \bar{\delta}_i + \bar{\delta}_{i+1} + \beta_i L_3^i (\sum_{j=i-1}^{i+1} \bar{\delta}_j^2)^{\frac{1}{2}}\}$. Then, the closed-loop system achieves strong string stability and TFS.

The upper bound for δ_i, the selection criterion of the sampling period λ_i, the proof of Theorem 2, and the simulation results can be found in Appendixes E–H.

Conclusion. This work proposes a distributed NTSMC scheme for vehicular platoon systems, which combines a PETM and a novel coupled quadratic spacing strategy. The proposed PETM approach guarantees excellent robust performance without requiring continuous inter-vehicle communication or continuous state measurement. The anti-interference capability can be enhanced by the PFESO, and the proposed coupled quadratic spacing strategy can achieve string stability and TFS simultaneously. Future work includes considering the actuator and communication time delays within the vehicular platoon system.

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Supporting information Appendixes A–H. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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