Letter

Distributed Adaptive Asymptotic Tracking of 2-D Vehicular Platoon Systems With Actuator Faults and Spacing Constraints

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Dear Editor,

This letter investigates the adaptive asymptotic tracking sliding-mode control for nonlinear 2-D vehicular platoon systems subject to actuator faults. Firstly, by using the Nussbaum function, the disadvantageous factors brought by the unknown direction actuator faults can be attenuated. Then, a new neural network (NN) asymptotic tracking control method is presented based on the sliding-mode control and bounded estimation approach. By constructing a barrier Lyapunov function, it can be guaranteed that all signals of the corresponding closed-loop systems are bounded, and constraints are not violated. Finally, a numerical simulation is given to verify the obtained results.

In the past few decades, the research on the vehicular platoon systems has received growing interests due to its great anti-interference characteristics and string stability. A plenty of representative control algorithms in this area have been developed in [1]–[4]. Although the aforementioned studies can achieve the string stability, the issue of spacing constraints was not considered. To circumvent this problem, an interesting control scheme was proposed in [5], which can guarantee not only the safe distance but also communication connectivity. Besides, it is desirable for vehicles to guarantee the collision avoidance in some chaotic environments. The distributed tracking control method was proposed for vehicle systems to deal with the problem of obstacle avoidance in [6] by means of the NN. On the basis of existing researches, a vehicle model on a two-dimensional (2-D) plane was first considered in [7], which can simulate the more realistic driving scene. Besides, there were many related results on asymptotic tracking control problem, which provided asymptotic stable tracking error systems with zero errors in [8]–[10].

It is worth noting that, the aforementioned results do not consider the issue of actuator faults, which will lead to deteriorative and instable performance of the system. To ensure the controlled systems' security and dependability, various advanced methods on fault-tolerant control have been reported in [11]–[13]. Recently, the authors have turned the research direction to the fault-tolerant control of the vehicular platoon systems since various types of actuator faults trigger risks to vehicle mechanism. In [14]–[16], the sliding-mode control method and adaptive control technique were used to eliminate the impact of faults for platoon systems. Although lots of significant progress on adaptive fault-tolerant control for vehicular platoon systems have been proposed, the following defects are inevitable in the existing control strategies. 1) The disadvantageous factors brought by the unknown direction actuator faults should be considered, which widely exist in practice and can not be ignored in controller designed. 2) There is no work focusing on the asymptotic tracking control for vehicular platoon systems with unknown direction actuator faults to provide tracking performance with zero-error tracking.

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Motivated by the above considerations, this letter addresses the adaptive asymptotic tracking sliding-mode control problem for nonlinear 2-D vehicular platoon systems subject to actuator faults with unknown directions. The main contributions lie in the following: 1) Different from the traditional control methods [1]–[6], where the proposed control method do not obey principle owing to the existence of unknown direction actuator faults. To solve this problem, we design a Nussbaum function to eliminate disadvantageous factors brought by the unknown direction actuator faults. 2) An asymptotic tracking control for nonlinear 2-D vehicular platoon systems with unknown direction actuator faults is first proposed in this work. Based on the sliding-mode control, we design a novel asymptotic tracking controller to ensure that the practical distance $d_i(t)$ tracks the desired distance d asymptotically.

Problem formulation: Consider a nonlinear ith follower system expressed as the following form:

$$\begin{cases}\dot{x}_i(t) = v_i(t)\cos\psi_i(t), \dot{y}_i(t) = v_i(t)\sin\psi_i(t)\\ \dot{v}_i(t) = a_i(t) = u_i^F(t) + g_i(x_i, y_i, v_i, t) + r_i(t)\\ \dot{\psi}_i(t) = \omega_i(t), \quad \dot{\omega}_i(t) = \epsilon_i(t)\end{cases} \tag{1}$$

where $x_i(t)$, $y_i(t)$ are the vehicle's lengthwise position and horizontal position respectively; $\psi_i(t)$ is the angle between the speed direction and the X-axis direction; $v_i(t)$ and $a_i(t)$, respectively, the vehicle's velocity and acceleration; $u_i^F(t)$ denotes the actuator faults; $g_i(x_i, y_i, v_i, t)$ is uncertainty under nonlinear unmodeled dynamic; $r_i(t)$ represents external disturbance; $\omega_i(t)$ is the angular rate and $\epsilon_i(t)$ is the acceleration of the velocity direction deflection angle.

The leader system can be defined as

$$\begin{cases}\dot{x}_0(t) = v_0(t)\cos\psi_0, \ \ \dot{y}_0(t) = v_0(t)\sin\psi_0\\ \dot{v}_0(t) = a_0(t).\end{cases} \tag{2}$$

The actuator faults in our research are modeled as follows:

$$u_i^F(t) = \gamma_i(t, t_{\gamma,i})u_i(t) + n_i(t, t_{n,i}) \tag{3}$$

where $\gamma_i(t, t_{\gamma,i})$ denote the fault factors and $n_i(t, t_{n,i})$ are the bias faults. $t_{\gamma,i}$ and $t_{n,i}$ are unknown fault time instants.

Assumption 1: The external disturbances $r_i(t)$ are unknown and bounded satisfying $|r_i(t)| \le \bar{r}_i$, $i = 1, 2, \ldots, n$.

Assumption 2: The unknown parameters $\gamma_i(t, t_{\gamma,i})$ and $n_i(t, t_{n,i})$ referring to (3) satisfy the following conditions: $0 < \underline{\gamma}_i \le |\gamma_i(t, t_{\gamma,i})| \le \overline{\gamma}_i < \infty$ and $|n_i(t, t_{n,i})| \le \bar{n}_i$, $i = 1, 2, \ldots, n$.

Here, two error variables of the vehicles are defined as

$$e_i(t) = d_i(t) - d, \ \ e_{\psi i}(t) = \psi_{i-1}(t) - \psi_i \tag{4}$$

where d is the desired distance with $\Delta_{\min} < d < \Delta_{\max}$. $d_i(t)$ and $\psi_i(t)$ are respectively the distance and the velocity direction deflection angle, which are expressed as

$$d_i(t) = \sqrt{(x_{i-1} - x_i)^2 + (y_{i-1} - y_i)^2} \tag{5}$$

$$\psi_i(t) = \arctan[(y_{i-1} - y_i)/(x_{i-1} - x_i)]. \tag{6}$$

To guarantee collision avoidance and communication maintenance, the spacing restrictions are given as: $0 < \Delta_{\min} < d_i(t) < \Delta_{\max}$, where $\Delta_{\min}$ is the minimum distance to ensure safety, while $\Delta_{\max}$ is the maximum distance to maintain effective communication.

In addition, to guarantee the distance restrictions, the following error constraints should not be violated:

$$k_a < e_i(t) < k_b \tag{7}$$

where $k_a = \Delta_{\min} - d$ and $k_b = \Delta_{\max} - d$.

Choose the following sliding surfaces:

$$s_i(t) = \dot{e}_i(t) + \rho_1 e_i(t) + \rho_2 |e_i(t)|^{\frac{a}{b}} sgn(e_i(t)) \tag{8}$$

$$s_{\psi i}(t) = \rho_3 e_{\psi i}(t) + \dot{e}_{\psi i}(t) \tag{9}$$

where a and b are positive constants satisfying $a > b$, and ρ_1, ρ_2 and ρ_3 are positive constants.

Then, the controller $u_i(t)$ is established as

$$u_i(t) = -(D_i(t)+G_i(t)+H_i(t)+ls_i(t))N(\xi_i(t))$$
$$\epsilon_i(t) = \rho_3\dot{e}_{\psi i}(t)+\epsilon_{i-1}(t)+ls_{\psi i}(t) \tag{10}$$

where $D_i(t) = \rho_1\dot{e}_i(t)+\rho_2\frac{a}{b}|e_i(t)|^{\frac{a}{b}-1}\dot{e}_i(t)+\frac{C_i(t)-\dot{e}_i^2(t)}{d_i(t)}$, $G_i(t) = s_i(t)\times(\frac{\hat{\theta}_i\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)}{\sqrt{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)+\sigma_i^2}}+\frac{\hat{\varphi}_i\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)}{\sqrt{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)+\sigma_i^2}}+\frac{\eta_i}{\sqrt{s_i^2+\sigma_i^2}})$, $H_i(t) = \frac{1-\text{sgn}(e_i(t))}{\nu_i}\times\frac{e_i(t)}{{k_a}^2-e_i^2(t)}+\frac{1+\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_b}^2-e_i^2(t)}$ and the adaptive update laws are proposed as

$$\dot{\hat{\theta}}_i(t) = \alpha_i\Big(\frac{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)}{\sqrt{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)+\sigma_i^2}}-\sigma_i(t)\hat{\theta}_i(t)\Big)$$
$$\dot{\hat{\varphi}}_i(t) = \beta_i\Big(\frac{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)}{\sqrt{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)+\sigma_i^2}}-\sigma_i(t)\hat{\varphi}_i(t)\Big)$$
$$\dot{\xi}(t) = (D_i(t)+G_i(t)+H_i(t)+ls_i(t))s_i(t). \tag{11}$$

Here, α_i, β_i and l are positive parameters. The Nussbaum function can be chosen as [7] to attenuate the disadvantageous factors brought by unknown direction actuator faults. In addition, $\sigma_i(t)$ is any uniform boundedness continuous function expressed as: $\sigma_i(t)>0$, $\lim_{t\to\infty}\int_{t_0}^t\sigma_i(\epsilon)d\epsilon \le \overline{\sigma}_i < +\infty$, with $\overline{\sigma}_i$ being an unknown positive constant.

Theorem 1: Consider the 2-D vehicular platoon systems (1) satisfying Assumptions 1 and 2. The controller (10) and the adaptive laws (11) can ensure that the tracking errors converge to zero asymptotically, and all the signals of closed-loop system are bounded.

Proof: The Lyapunov candidate function is selected as

$$V(t) = \Sigma_{i=1}^N(V_i^s(t)+V_i^b(t))$$
$$V_i^s(t) = \frac{1}{2}s_i^2(t)+\frac{1}{2\alpha_i}\tilde{\theta}_i^2(t)+\frac{1}{2\beta_i}\tilde{\varphi}_i^2(t)$$
$$V_i^b(t) = \frac{1-sgn(e_i(t))}{2\nu_i}ln\frac{{k_a}^2}{{k_a}^2-e_i^2(t)} + \frac{1+sgn(e_i(t))}{2\nu_i}ln\frac{{k_b}^2}{{k_b}^2-e_i^2(t)}. \tag{12}$$

Then, by considering (1), (4) and (8), we can obtain

$$\dot{s}_i(t) = D_i(t)-\gamma_iu_i-n_i(t,t_{n,i})-g_i(x_i,y_i,v_i,t)-r_i(t). \tag{13}$$

From (12) and Lemma in [7], the derivative of $V_i^b(t)$ gives

$$\dot{V}_i^b(t) = \Bigg[\frac{1-\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_a}^2-e_i^2(t)}+\frac{1+\text{sgn}(e_i(t))}{\nu_i}\times\frac{e_i(t)}{{k_b}^2-e_i^2(t)}\Bigg][s_i(t)-\rho_1s_i(t)-\rho_2|e_i(t)|^{\frac{a}{b}}\text{sgn}(e_i(t))]$$
$$\le -2\rho_1V_i^b(t). \tag{14}$$

By utilizing (12)–(14), we have

$$\dot{V}(t) = s_i(D_i-\gamma_iu_i+g_i(x_i,y_i,v_i,t)+n_i(t,t_{n,i})-r_i(t) + \frac{1-\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_a}^2-e_i^2(t)}+\frac{1+\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_b}^2-e_i^2(t)}) -2\rho_1V_i^b(t)-\frac{1}{\alpha_i}\tilde{\theta}_i\dot{\hat{\theta}}_i-\frac{1}{\beta_i}\tilde{\varphi}_i\dot{\hat{\varphi}}_i \tag{15}$$

where $\hat{\theta}_i(t)$ and $\hat{\varphi}_i(t)$ represent the estimation of θ_i^* and φ_i^*. Define $\tilde{\theta}_i(t)=\theta_i^*-\hat{\theta}_i(t)$ and $\tilde{\varphi}_i(t)=\varphi_i^*-\hat{\varphi}_i(t)$.

Referring to [12], the NN $W_{j,i}^{*T}\zeta_{j,i}(X_i)$, $j=1,2$, are employed to approximate the uncertainty of the system such that

$$g_i(x_i,y_i,v_i,t) = W_{1,i}^{*T}\zeta_{1,i}(X_i)+\varepsilon_{1,i}(t)$$
$$n_i(t,t_{n,i}) = W_{2,i}^{*T}\zeta_{2,i}(X_i)+\varepsilon_{2,i}(t) \tag{16}$$

where $\varepsilon_{1,i}(t)$ and $\varepsilon_{2,i}(t)$ are approximate errors and satisfy $|\varepsilon_{1,i}(t)|\le\overline{\varepsilon}_{1,i}$ and $|\varepsilon_{2,i}(t)|\le\overline{\varepsilon}_{2,i}$, $W_{1,i}^*$ and $W_{2,i}^*$ are the given optimal weight vectors.

Then, it gives

$$\dot{V}(t) \le s_i\Big(D_i-\gamma_iu_i+\frac{\hat{\theta}_is_i\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)}{\sqrt{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)+\sigma_i^2}}+\frac{s_i\eta_i}{\sqrt{s_i^2+\sigma_i^2}} + \frac{\hat{\varphi}_is_i\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)}{\sqrt{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)+\sigma_i^2}}+\frac{1-\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_a}^2-e_i^2(t)} + \frac{1+\text{sgn}(e_i(t))}{\nu_i}\frac{e_i(t)}{{k_b}^2-e_i^2(t)}\Big)+\theta_i^*\sigma_i+\varphi_i^*\sigma_i-\eta_i\sigma_i + \tilde{\theta}_i\Big(\frac{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)}{\sqrt{s_i^2\zeta_{1,i}^T(X_i)\zeta_{1,i}(X_i)+\sigma_i^2}}-\frac{1}{\alpha_i}\dot{\hat{\theta}}_i\Big)-2\rho_1V_i^b(t) + \tilde{\varphi}_i\Big(\frac{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)}{\sqrt{s_i^2\zeta_{2,i}^T(X_i)\zeta_{2,i}(X_i)+\sigma_i^2}}-\frac{1}{\beta_i}\dot{\hat{\varphi}}_i\Big). \tag{17}$$

Considering (11) and the estimation errors, it follows that:

$$\dot{V}(t) \le \sum_{i=1}^N[(\varsigma N+1)\dot{\xi}_i-ls_i^2-2\rho_1V_i^b(t)]+\sum_{i=1}^N\sigma_i\mu. \tag{18}$$

where $\mu=\frac{1}{4}\theta_i^{*2}+\frac{1}{4}\varphi_i^{*2}+\theta_i^*+\varphi_i^*+\eta_i$.

Integrating both sides of the above inequality yields

$$V(t) \le V(0)+\sum_{i=1}^N\int_0^t[(\varsigma N+1)\dot{\xi}_i]d\tau-\sum_{i=1}^N l\int_0^t s_i(\tau)^2d\tau - \sum_{i=1}^N\int_0^t\rho_1V_i^b(\tau)d\tau+\sum_{i=1}^N\mu\int_0^t\sigma_id\tau$$
$$\le \sum_{i=1}^N\int_0^t[(\varsigma N+1)\dot{\xi}_i]d\tau+\triangle_0 \tag{19}$$

with $\triangle_0 = V(0)+\mu\overline{\sigma}_i$.

This together with Lemma in [17], it can be shown that $V(0)$ and $\sum_{i=1}^N\int_0^t[(\varsigma N+1)\dot{\xi}_i]d\tau$ are bounded on $[0,+\infty)$. In view of the definition of $V(t)$, the boundedness of e_i, $\tilde{\theta}_i$, $\tilde{\varphi}_i$ can be achieved. Besides, we can obtain that $\hat{\theta}_i$ and $\hat{\varphi}$ are bounded. Therefore, we can conclude that all the signals of the controlled system are bounded on $[0,+\infty)$.

Next, we prove the asymptotic tracking performance of the sliding surfaces. By using Barbalat's Lemma [18], one has

$$\lim_{t\to\infty}\sum_{i=1}^N k\int_0^t s_i(\tau)^2d\tau \le \sum_{i=1}^N\int_0^t[(\gamma N+1)\dot{\xi}_i]d\tau+\triangle_0<+\infty.$$

From that, we know $\lim_{t\to\infty}s_i(t)=0$. Together with (8), we can get $\lim_{t\to\infty}e_i(t)=0$. Therefore, the asymptotic convergence is achieved. In addition, to prove the stability of sliding surfaces, the Lyapunov function can be selected as following form:

$$V^\psi(t) = \sum_{i=1}^N(V_i^\psi(t)),\ \ V_i^\psi(t)=\frac{1}{2}s_{\psi i}^2(t). \tag{20}$$

Then, the derivative of (28) can be gained

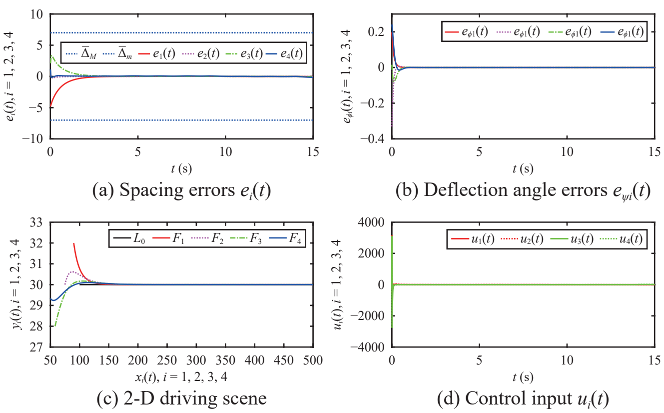
$$\dot{V}_i^\psi(t) = s_{\psi i}(t)\dot{s}_{\psi i}(t) = -ks_{\psi i}^2(t)$$
$$\dot{V}^\psi(t) = \sum_{i=1}^N(-ks_{\psi i}^2(t)) = -2kV^\psi(t) \tag{21}$$

where $\dot{V}^\psi(t)<0$. Hence, $\dot{V}^\psi(t)=0$ if and only if $s_{\psi i}(t)=0$, or else $\dot{V}^\psi(t)<0$, which implies that the object of this letter is ensured that sliding surfaces are asymptotically stable.

Numerical example: A platoon of vehicles with 1 leader vehicle and 4 follower vehicles are taken into account. The desired vehicle distances are set as $d=15$ m, and $\Delta_{\min}=7$ m, $\Delta_{\max}=22$ m. The expected acceleration of leader is $a_0(t)=0.6t$ m/s^2, 2.3 m/s^2,−5 m/s^2 while 0 s $\le t<5$ s, 5 s $\le t<9$ s, 14 s $\le t<15$ s, respectively.

To verify the above results, the system parameters used for simulations are given as: $\alpha_i = 10$, $\beta_i = 0.0009$, $\sigma_i = 10e^{-5t}$, $\hat{\theta}_i(t) = 1$, $\hat{\varphi}_i(t) = 1$, $\rho_1 = 1.5$, $\rho_2 = 0.3$, $\rho_3 = 6$, $a = 6$, $b = 4$, $l = 170$. In the simulation, $g_i(x_i, y_i, v_i, t) = -a_{0,i} - a_{1,i}v_i(t) - a_{2,i}v_i^2(t)$ is used with $a_{0,i} = 0.01176$, $a_{1,i} = 0.00077616$, $a_{2,i} = 0.000016$. In addition, the disturbance $n_i(t, t_{n,i}) = \sin(it + i\pi)$ enters into the system at the beginning. Consider the fault efficiency factors $\gamma_i(t, t_{\gamma,i})$ and bias fault $n_i(t, t_{n,i})$ as: $\gamma_1(t, t_{\gamma,1}) = 1.2 - 0.2\cos(t)$, $\gamma_2(t, t_{\gamma,2}) = 0.5 - 0.2\cos(t)$, $\gamma_3(t, t_{\gamma,3}) = -0.9 - 0.2\cos(t)$, $\gamma_4(t, t_{\gamma,4}) = -0.4 + 0.2\sin(0.01t)$, $n_i(t, t_{n,i}) = 0.3 + 0.2\cos(t)$. For the Nussbaum function, we select $m = 3$, $n = 0.001$.

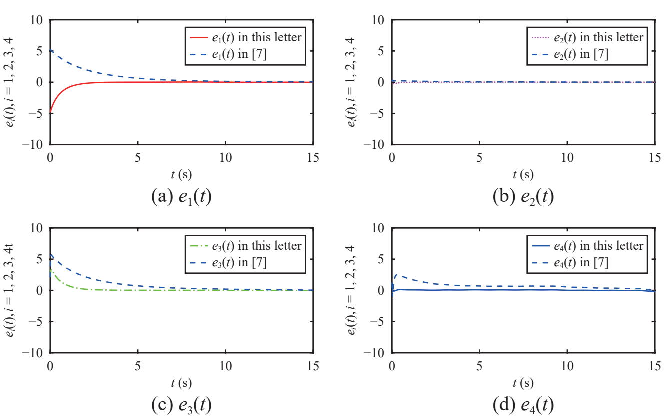
Simulation results under the proposed scheme are depicted in Figs. 1(a)−1(d), Figs. 1(a) and 1(b) show the performance of output variable $d_i(t)$ and $\psi_{i-1}(t)$ and the desired reference d and ψ_i, respectively. It can be observed from these two figures that the tracking errors converge to zero asymptotically despite of unknown direction faults occurring on the actuators, which means that the proposed control scheme can completely compensate for the influence by the fault to the system. Fig. 1(c) shows the practical positions of four vehicles, which can be seen that all followers move to the line, and 2-D driving scene is achieved. Fig. 1(d) shows the curve of control input u_i. Generally, according to the simulation results, it is obvious that the tracking errors converge to zero asymptotically while the whole signals of closed-loop systems are bounded.



(a) Spacing errors $e_i(t)$ (b) Deflection angle errors $e_{\psi i}(t)$ (c) 2-D driving scene (d) Control input $u_i(t)$

Fig. 1. Simulation results of this letter.

To better exhibit the effectiveness of the presented scheme, we make a comparison on convergence results between the presented scheme in this letter and existing control scheme in [7]. From the comparison in Fig. 2, it is very clear that the tracking errors in this letter are much more satisfactory than those in [7].



(a) $e_1(t)$ (b) $e_2(t)$ (c) $e_3(t)$ (d) $e_4(t)$

Fig. 2. Comparison results of $e_i(t)$.

Conclusion: In this letter, 2-D vehicular platoon asymptotic tracking sliding-mode control under unknown directions actuator faults has been investigated. By using the Nussbaum function, the disadvantageous factors brought by the unknown direction actuator faults can be attenuated effectively. Based on the sliding-mode control and bounded estimation approach, a new asymptotic tracking control method is presented to realize the asymptotic convergence of tracking errors. Simulations verify the performance of the proposed approach.

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