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An Improved Motion Control With Cyber-Physical Uncertainty Tolerance for Distributed Drive Electric Vehicle

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ABSTRACT A lateral motion control scheme for a distributed drive electric vehicle is presented in this paper, which takes into account both in-car network and movement-parameter uncertainty in a synthetic manner. Distributed drive vehicles have obvious advantages in terms of safety and comfort at high speeds due to the well-known E/E architecture, which includes an in-vehicle network, advanced vehicle motion control, and Advanced Driver Assistance System (ADAS) technologies. This is a fundamentally cyber-physical system. However, on the other hand, the application/insertion of in-vehicle network and the dynamic of wide-range varying speeds introduce additional system uncertainties, such as time-varying network induced delays and inevitable system perturbation, making controller design a difficult problem and even making the system unstable. This paper develops a cyber-physical control scheme and under which a two-process perturbation analysis is proposed to illustrate the system uncertainties. A hierarchical control strategy is also devised, with an upper-level gain-scheduling controller dealing with speed perturbation uncertainties and a lower-level H_∞-LQR controller dealing with in-vehicle network uncertainty. Using real-time hardware in loop testing, the suggested control technique was found to be effective in dealing with both in-vehicle network and system perturbation problems while also ensuring reliable vehicle stability in all three scenarios.

INDEX TERMS Distributed drive electric vehicle, cyber -physical, direct yaw-moment control (DYC), H_∞-based linear quadratic regulator (H_∞-LQR), gain-scheduling, two-process perturbation analysis.

I. INTRODUCTION

Recently, with the rapid development of smart sensors, digital controllers, and in-vehicle network technologies in the automotive sector, smart distributed electric vehicles have gained interest because to their advantages in terms of safety, comfort, and structural flexibility [1]–[10]. For smart distributed drive electric vehicles, advanced lateral motion control considering wide-range vehicle speeds is one of the most important topics. There have been various research studies have focused on lateral motion control considering uncertainty caused by vehicle speed in recent years [6], [8], [11]–[17]. X. Ding et al and B. Leng et al studied the vehicle speed estimation of distributed drive electric vehicles, which is one of the most important issues for studying and designing distributed drive electric vehicles [15], [16]. N. Ding et al pointed that varying vehicle speeds would make a distributed drive electric vehicle a time-varying dynamic system, where the parameters e.g. cornering stiffness and system matrix are time-varying. The lateral motion control should be designed with considering system uncertainties caused by varying vehicle speeds, these uncertainties would make the vehicle control system unstable [18]. H. Jing et al designed a H_∞ dynamic output-feedback controller to improve the robustness of vehicle lateral motion control with considering vehicle longitudinal velocity [13]. H. Zhang et al

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presented gain-scheduling control strategy to enhance the adaptation of the time-varying vehicle lateral motion control system [6], [14]. X. Huang et al employed the weighted gain-scheduling H_∞ to further improve the adaptation and robustness of the time-varying vehicle lateral motion control [14].

For vehicle lateral motion control, new electronic and electrical architecture (EEA) consisting of digital components, in-vehicle network, has been widely employed to achieve integrated motion control [19], [20]. The application of the in-vehicle network bring advantages in term of data exchanging convenience, wire harness reduction and system diagnosis easiness [21], [22]. On the other hand, the insertion of in-vehicle network result in system uncertainties e.g. dynamic parameters perturbation caused by network-induced delay, which will make the controller design a challenge problem and even make the system unstable [7], [23], [24]. There have been some researches focusing on lateral motion control considering uncertainty caused by network-induced delay [7], [23], [25]–[27]. Klehmet et al and Herpel et al proposed a delay analysis method based on network calculus theory for calculating the worst-case response time of each message sent on CAN in automotive applications [26], [27]. With the proposed delay analysis method, Shuai *et al.* [7] pointed that the application of CAN make a distributed drive vehicle a time-delay dynamic system, where the CAN-induced delay would lead to the oscillation problem of lateral motion control of distributed drive vehicle, and proposed a H_∞-based delay-tolerant LQR controller to enhance the robustness of the vehicle control system. Zhu *et al.* [23] proposed a delay analysis based on two Markov chains theory to model the CAN-induced delay in feedback and forward channels, and designed a robust LQR-based H_∞ controller to deal with the oscillation of the time-delay vehicle lateral motion control with less conservation. Liu *et al.* [25] presented a delay analysis on network-induced delays with considering multiple-package transmissions, and designed a hybrid schedule-control framework to deal with the uncertainty caused by time-varying network-induced delays, and ensure the stability of the time-delay vehicle lateral motion control.

However, each of the aforementioned studies focus on a different sort of system uncertainties, e.g. considering dynamic parameters perturbation caused by varying vehicle speeds without considering dynamic parameters perturbation caused by network-induced delay, or vice versa. As shown in Figure 1, a smart distributed drive electric vehicle has already been a cyber-physical system rather than a pure time-varying/time delay dynamic system, where there are uncertainties which caused by not only the cyber system but also the physical system [28]–[32]. The analysis and design with synthetically considering effect of cyber and physical uncertainties for the vehicle lateral motion control have not been addressed yet.

In order to deal with all aforementioned problem, the main contributions of this study are summarized as follows:

- A cyber-physical control scheme with explicitly considering to tolerate both uncertainties of the physical system and the cyber system is adopted for the advanced DYC, where a two-process perturbation analysis is proposed to illustrate the system uncertainties.
- To deal with all of the aforementioned uncertainties, a hierarchical control approach is developed, in which an upper-level gain-scheduling controller is adopted to handle the uncertainty of the speed perturbation (in view of physical system), and a lower-level H_∞-LQR controller is designed to deal with the uncertainty of the in-vehicle network induced delay (in view of cyber system).

The rest of this paper is organized as follows: in section II, a cyber-physical approach to lateral motion control for distributed drive electric vehicle is described. The distributed drive electric lateral dynamic control model is derived. In section III, the uncertainty of the intelligent distributed drive electric vehicle, is analyzed separately from the physical system and the cyber system. A cyber-physical hierarchical scheme is designed in section IV. In section V, hardware-in-loop (HIL) tests are implemented to validate the proposed method in a real CAN environment. Finally, conclusions are summarized in section VI.

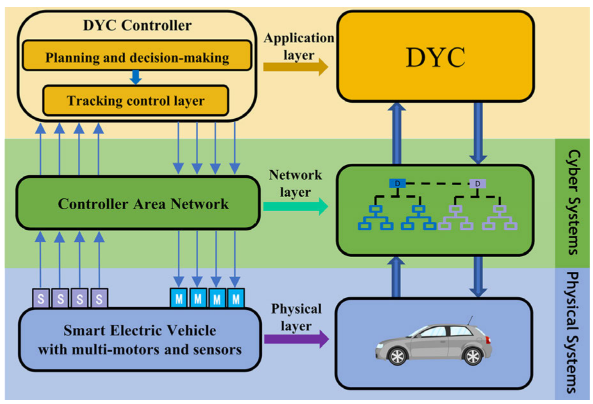


FIGURE 1. DYC architecture based on cyber-physical control scheme.

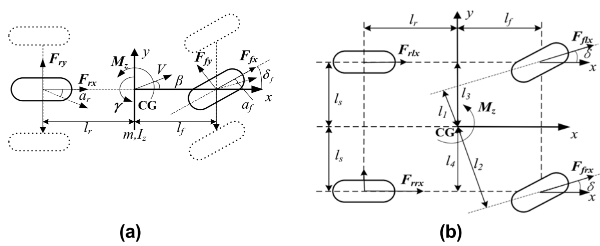


FIGURE 2. Control-oriented vehicle model. (a) 2-DOF lateral dynamics model of a vehicle with DYC. (b) Simplified rigid-body motion model of a vehicle for DYC.

II. SYSTEM DESCRIPTION

As shown in Fig. 1, a smart distributed drive electric vehicle with in-vehicle network and digital components (e.g. smart sensors and motor controllers based on advanced MCU) can be considered as a cyber-physical control system, in which physical information data from/to digital components such as vehicle/wire speed and torque commands are exchanged by in-vehicle network that is actually a cyber channel not a mechanical/physical connection. In this section, basic vehicle dynamics are introduced for the design of the advanced DYC controllers.

A. CONTROL-ORIENTED VEHICLE DYNAMICS MODEL

As shown in the research [17], [26], in this study, a widespread 2-DOF bicycle model of vehicle lateral dynamics, as shown in Fig.2. is adopted for the DYC controller design. In Figure 2, CG is the center of vehicle gravity; m is the vehicle mass; I_Z is the vehicle yaw inertia; M_Z is the yaw moment applied to the vehicle; l_f and l_r denote the distances from the front and rear axles to CG. δ is the steering angle of the front wheels. α_f and α_r respectively represent the slip angle of the front and rear wheels, F_{yf} and F_{yr} separately represent the longitude tire forces of the front and rear wheels. V is the vehicle speed, β is the side slip angle of the CG, and γ is the yaw rate of the vehicle. According to the 2-DOF vehicle model, the lateral dynamics of a vehicle with DYC can be expressed as follows:

$$\dot{x} = Ax + Bu + E\delta_f \tag{1}$$

where

$$x = \begin{bmatrix} \beta & \gamma \end{bmatrix}^T \quad u = M_Z$$
$$A = \begin{bmatrix} \frac{-2(C_f+C_r)}{mV} & \frac{-2(C_f l_f - C_r l_r)}{mV^2} - 1 \\ \frac{-2(C_f l_f - C_r l_r)}{I_z} & \frac{-2\left(C_f l_f^2 + C_r l_r^2\right)}{I_z V} \end{bmatrix}$$
$$B = \begin{bmatrix} 0 & \frac{1}{I_z} \end{bmatrix}^T \quad E = \begin{bmatrix} \frac{2C_f}{mV} & \frac{2C_f l_f}{I_z} \end{bmatrix}^T$$

where C_f and C_r respectively represent the cornering stiffness of the front and rear wheels.

In the DYC, the yaw-moment M_Z is the directly generated, as shown in Fig. 2(b), by the longitudinal tire forces of wheels actuated by motors, which can simply expressed as follows:

$$\begin{aligned} M_Z &= -F_{flx} l_1 + F_{frx} l_2 - F_{rlx} l_3 + F_{rrx} l_4 \\ &= \sum_{i=1}^{4} (-1)^i \frac{T_{mi} i_{redu} l_i}{r} \end{aligned} \tag{2}$$

where

$$\begin{aligned} l_1 &= l_s \cos\delta - l_f \sin\delta \\ l_2 &= l_s \cos\delta + l_f \sin\delta \\ l_3 &= l_4 = l_s \end{aligned}$$

with T_{mi} being the torque measurement of the motor i, i_{redu} being the transmission ratio between the motor and the wheel.

B. REFERENCE STATE MODEL

As shown in the research [25], [33], a typical expression of the reference state model is adopted here as shown in Eq.2, where the desired/reference sideslip angle is set to zero, and the desired/reference yaw rate is usually defined by steering angle, vehicle speed and structural parameters.

The reference state model selects the yaw rate and the side slip angle of the CG:

$$r = \frac{1}{1+\tau_\gamma s} R\delta_f \tag{3}$$

where

$$r = \left[\beta_{ref}\, \gamma_{ref}\right]^T$$
$$R = [0V/\left(l_f + l_r + \frac{mV^2\left(C_r l_r - C_f l_f\right)}{2C_f C_r\left(l_f + l_r\right)}\right)]^T$$

III. SYSTEM UNCERTAINTY ANALYSIS

For the advanced DYC as a typical cyber-physical system, to illustrate the impact of the insertion of the in-vehicle network and the characters of the varying speeds, a two-process perturbation analysis is proposed, where the uncertainties not only in motion control process but also in the data communication process is described in detail in this section. For the uncertainty analysis in lateral motion control process, the impact of the varying speed is mainly considered here in DYC design according to the research [34]. For the uncertainty analysis in data communication process, the effect of the network-induced delay is concentrated on here according to the research [35], [36].

A. UNCERTAINTY IN MOTION CONTROL PROCESS

As shown in the studies [5], [23], varying speeds will cause the system uncertainties owing to the nonlinearity relation between system parameter matrices e.g. A, E and vehicle speed V as in Eq.1. The uncertainties in motion control process can be described in the following expressions.

According to robust control system theory, an actual system model is presented as the following:

$$A' = A + \Delta A, \quad E' = E + \Delta E \tag{4}$$

with

$$A' = \begin{bmatrix} \frac{-2(C_f+C_r)}{mV'} & \frac{-2(C_f l_f - C_r l_r)}{mV'^2} - 1 \\ \frac{-2(C_f l_f - C_r l_r)}{I_Z} & \frac{-2(C_f l_f^2 + C_r l_r^2)}{I_Z V'} \end{bmatrix}$$
$$E' = \begin{bmatrix} \frac{2C_f}{mV'} & \frac{2C_f l_f}{I_Z} \end{bmatrix}$$
$$\Delta A = A' - A = \begin{bmatrix} \frac{2(C_f+C_r)\Delta V}{mVV'} & \frac{2(C_f l_f - C_r l_r)\Delta V(V+V')}{mV^2V'^2} \\ 0 & \frac{2(C_f l_f^2 + C_r l_r^2)\Delta V}{I_Z VV'} \end{bmatrix}$$
$$\Delta E = E' - E = \begin{bmatrix} -\frac{2C_f \Delta V}{mVV'} & 0 \end{bmatrix}$$

where A' is the actual system matrix, ΔA is the system matrix perturbation, E' is the input matrix, ΔE is the input matrix perturbation, V' is the actual speed.

B. UNCERTAINTY IN DATA COMMUNICATION PROCESS

As shown in the study [25], the application of in-vehicle network will lead to the new problem, e.g. inevitable network-induced delays as shown in Fig. 3.

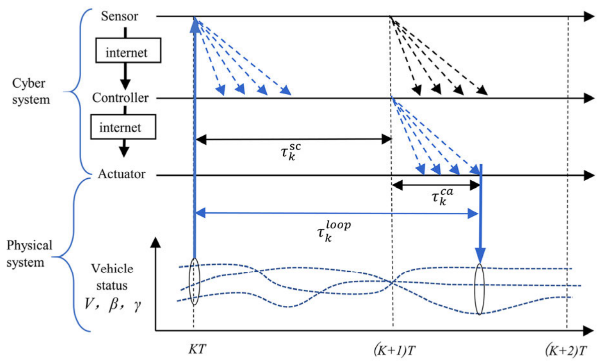


FIGURE 3. Timing diagram of motion control system based on cyber-physical approach.

Where τ_k^{loop} is the delay of the entire control loop, τ_k^{sc} is the delay of the feedback channel from the sensor to the controller, τ_k^{ca} is delay the forward channel from the controller to the actuator. The details of multiple-package transmissions and time-varying network-induced delays are shown in [25].

With assumptions and terms as in [25], the network-induced delays can be expressed as the following:

$$\begin{aligned} &\tau_k^{loop} = \tau_k^{sc} + \tau_k^{ca} \\ &\tau_k^{sc} = T \\ &0 < \tau_k^{ca} \leq T \\ &T < \tau_k^{loop} \leq 2T \end{aligned} \tag{5}$$

Owing to the network-induced delays, the vehicle dynamic control system model can be rewritten as [25]:

$$\begin{aligned} &x_{k+1} \\ &= A_d x_k + B_{ud} u_k + B_{rd} r_k + \Delta_{0,k}(u_{k-1} - u_k) \\ &\quad + \Delta_{1,k}(u_{k-2} - u_{k-1}) + \cdots + \Delta_{\Upsilon,k}(u_{k-\Upsilon-1} - u_{k-\Upsilon}) \end{aligned} \tag{6}$$

where

$$\Delta_{i,k} = \begin{cases} 0, & \tau_{k-i} - iT_s \leq 0 \\ \int_0^{\tau_{k-i}-iT_s} e^{A(T_s-\theta)} d\theta \cdot B_u, & 0 \leq \tau_{k-i} - iT_s \leq T_s \\ \int_0^{T_s} e^{A(T_s-\theta)} d\theta \cdot B_u, & T_s \leq \tau_{k-i} - iT_s \end{cases}$$

Then defining a new vector $\xi(k) = [x_k^T \; u_{k-1}^T \; \ldots \; u_{k-\gamma-1}^T]^T$, an augmented delay system equation can be obtained as

$$\xi_{k+1} = A_{aug}\xi_k + B_{ud,aug} u_k + B_{rd,aug} r_k \tag{7}$$

where

$$A_{aug} = \begin{bmatrix} A_d & \Delta_{0,k} - \Delta_{1,k} & \cdots & \Delta_{\gamma-1,k} - \Delta_{\gamma,k} & \Delta_{\gamma,k} \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & I & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & I & 0 \end{bmatrix}$$

$$B_{ud,aug} = \begin{bmatrix} B_{ud} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad B_{rd,aug} = \begin{bmatrix} B_{ud} - \Delta_{0,k} \\ I \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

where $(\Delta_{0,k}, \Delta_{1,k}, \ldots, \Delta_{\gamma,k})$ are uncertain terms caused by time-induced delay, A_{aug} is the actual system matrix, $B_{ud,aug}$ is the input matrix, $B_{rd,aug}$ is the reference model input matrix.

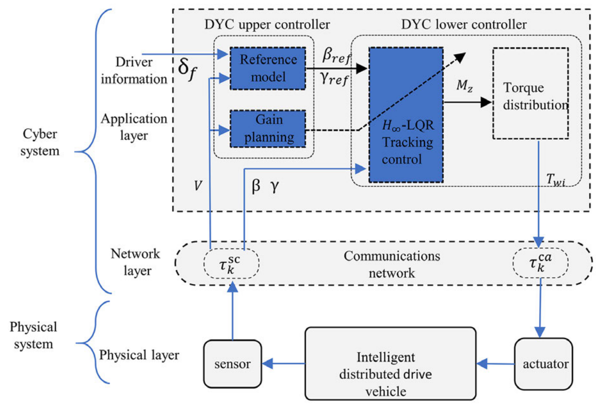


FIGURE 4. The hierarchical approach of the vehicle lateral motion control system based on the cyber-physical control scheme.

IV. CONTROL DESIGN

For the advanced DYC as a typical cyber-physical system, to deal with all aforementioned problems, a hierarchical control scheme is developed in this study, as shown in Fig.4, where an upper-level gain-scheduling controller is adopted to deal with speed perturbation uncertainties, and a lower-level H_∞-LQR controller is designed to deal with the uncertainty of the in-vehicle network for motion control. The proposed hierarchical control scheme is called GS H_∞-LQR.

The upper controller adaptively executes planning and decision-making tasks to produce the desired β_{ref} and γ_{ref}, and to adjust the system parameters e.g. system matrix A or A' according to the actual varying speeds, to deal with the system uncertainties caused by the speed perturbation.

The lower controller ensures the actual motion parameters β and γ following the desired motion parameters β_{ref} and γ_{ref}, and improving the robustness against to time-varying network induced delay with H_∞-LQR approach.

A. UPPER CONTROLLER

The upper controller is the decision-making layer, which adopts adaptive gain-scheduling control, to extend the linear control method to adapt it to the time-varying system [6]. The basic idea of the algorithm is to obtain some key parameters related to vehicle stability control through online estimation, such as vehicle speed, tire cornering stiffness, etc. The controller parameters e.g. gain $k(V)$ are updated in real time according to the estimated parameters e.g. V, so that the controller can adapt to the parameter uncertainty of the model.

In order to reduce the calculation amount of the controller and avoid a large number of online calculations from affecting the real-time performance of the controller, the controller is designed offline to calculate the change trend of the controller gain $k(V)$ corresponding to different vehicle speeds V, generate a lookup table $K(V)$ and download it to the electronic control unit; during operation, the controller calculates the control rate $u_k = K(V)\xi_k$ online based on the lookup table of the current state. The gain-scheduling control block diagram is as shown in Figure 5.

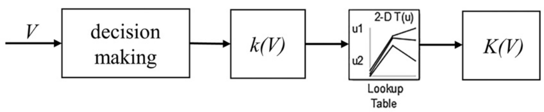


FIGURE 5. Gain-scheduling control block diagram.

B. LOWER CONTROLLER

The lower controller is the tracking control layer, which is used to obtain the torque control commands to maintain the actual vehicle state e.g. β_{ref} and γ_{ref} to follow the target. This layer also takes into account the uncertainty of the cyber system. Considering that the network induced delay time-varying and bounded, the lower controller is designed based on H_∞-LQR control method to ensure the robustness of the system.

The time-varying loop delay brings uncertainty to the control system, e.g. the uncertain term $\Gamma_1(\tau_k)$ in A_{aug} and B_{aug}. The uncertain term $\Gamma_1(\tau_k)$ can be linearized using Taylor expansion [25], and then expressed as a multicellular model.

The Taylor expansion of the uncertainty term $\Gamma_1(\tau_k)$ can be expressed as

$$\Gamma_1(\tau_k) = \int_{T-\tau_k}^{T} e^{As} ds B = -\sum_{q=1}^{\infty} (-\tau_k)^q \frac{A^{q-1}}{q!} e^{AT} B$$
$$\Gamma_1(\tau_k) = -\sum_{q=1}^{h} (-\tau_k)^q \frac{A^{q-1}}{q!} e^{AT} B + \Theta^h \tag{8}$$

Ignoring the h-order infinitesimal, it is approximately as follows:

$$\Gamma_1(\tau_k) = -\sum_{q=1}^{h} (-\tau_k)^q \frac{A^{q-1}}{q!} e^{AT} B \tag{9}$$

definition:

$$G_q = (-1)^{q+1} \frac{A^{q-1}}{q!} e^{AT} B$$

$$\begin{aligned} \varphi_1 &= \left[\, \underline{\rho}^h I \ \underline{\rho}^{h-1} I \ \cdots \ \underline{\rho}^2 I \ \underline{\rho} I \,\right]^T \\ \varphi_2 &= \left[\, \underline{\rho}^h I \ \underline{\rho}^{h-1} I \ \cdots \ \underline{\rho}^2 I \ \overline{\rho} I \,\right]^T \\ &\vdots \\ \varphi_{h+1} &= \left[\, \overline{\rho}^h I \ \overline{\rho}^{h-1} I \ \cdots \ \overline{\rho}^2 I \ \overline{\rho} I \,\right]^T \end{aligned} \tag{10}$$

where: $q = 1, 2, \cdots, h$, $\underline{\rho} = \tau_{\min} = 0$, $\overline{\rho} = \tau_{\max} = T/2$, the uncertain term $\Gamma_1(\tau_k)$ can be expressed as:

$$\begin{aligned} &\Gamma_1(\tau_k) = \sum_{i=1}^{h+1} \mu_j(k)\, U_j \\ &\mu_j(k) > 0, \quad \sum_{j=1}^{h+1} \mu_j(k) = 1, \quad \forall j = 1, 2 \ldots h+1, \\ &\forall k \in \mathbb{Z}^+ \end{aligned} \tag{11}$$

The vertices of a convex polyhedron can be expressed as:

$$U_j = \left[\, G_h \ G_{h-1} \ \cdots \ G_2 \ G_1 \,\right] \varphi_j, \quad \forall j = 1, 2 \ldots h+1 \tag{12}$$

In order to solve the uncertainty of the network control system and ensure the stability of the system, this paper further designs a linear quadratic regulator motion controller based on robust H_∞. The performance index function J is designed as a quadratic form of the error e and the control input u, as shown below.

$$J = \sum_{i=0}^{\infty} (e_i^T Q e_i + u_i^T R u_i) \tag{13}$$

Considering the feedback control rate $u_k = -K_i(V)\xi_k$, the performance function J is equal to the 2-norm of the following expression:

$$z_k = F\xi_k + Hu(k) = F\xi_k - HK_i(V)\xi_k = (F - HK_i(V))\,\xi_k \tag{14}$$

where

$$F = \begin{bmatrix} Q^{1/2} & 0 \\ 0 & 0 \end{bmatrix}; \quad H = \begin{bmatrix} 0 \\ R^{1/2} \end{bmatrix}$$

The motion control problem can be transformed into the optimal control problem of the following closed-loop control system:

$$\begin{aligned} \xi(k+1) &= \left(A_{aug,i}(V) - B_{aug,i}(V)K_i(V)\right)\xi(k) \\ &\quad + G_{aug,i}(V)\delta_f{}'(k) \\ z_k &= (F - HK_i(V))\,\xi_k \end{aligned} \tag{15}$$

where, $A_{aug,i}(V), B_{aug,i}(V), G_{aug,i}(V)$ respectively are the system matrix corresponding to the vehicle speed V, $K_i(V)$ is the controller gain corresponding to the vehicle speed V.

Theorem: assuming a given controller, if there is a positive definite matrix Ω, matrix Y, M satisfy: (16), as shown at the bottom of the next page, where: $Y_i = K_i(V)M_i$, then the control system is stable.

Therefore, the controller design based on H_∞ can be expressed as (17), as shown at the bottom of the next page.

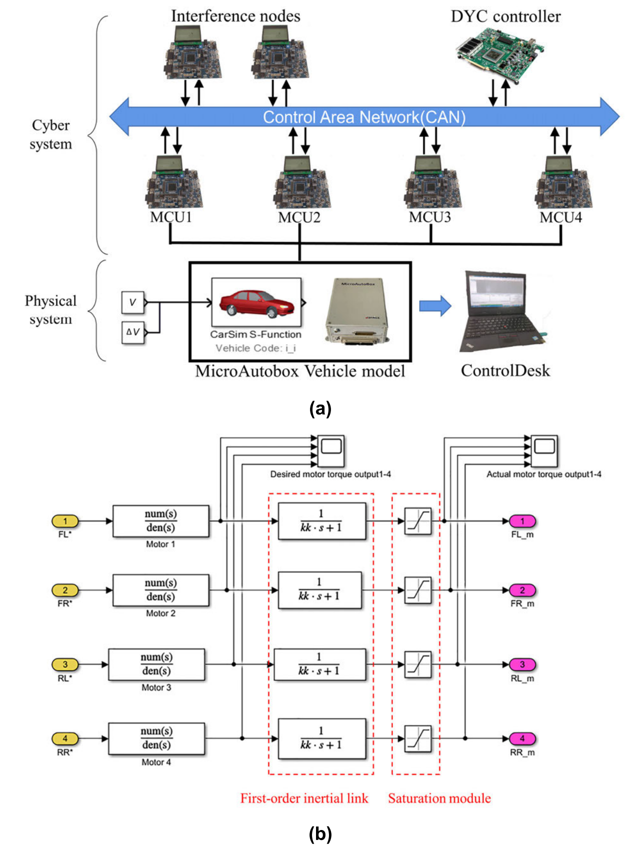


FIGURE 6. HIL test bench. (a) Schematic diagram of HIL simulation platform. (b) Four-wheel motor characteristic model.

This problem can be solved using the LMI toolbox in MATLAB. Controller gain $K_i(V) = Y_i M_i^{-1}$.

V. RESULTS AND DISCUSSIONS

To evaluate the proposed scheme, a real-time hardware-in-the-loop (HIL) test bench using dSPACE AutoBox-based high-fidelity vehicle simulator, a real prototype CAN system and a four-motor control unit (MCU) was constructed using S12X chips, as detailed in [25]. Fig. 6 shows the schematic diagram of hardware-in-the-loop simulation platform.

TABLE 1. Main system parameters.

Symbol	Description	Value/Unit
m	Vehicle mass	1050kg
I_z	Vehicle yaw inertia	1875kg·m²
l_f	Distance from CG to the front axle	1.000m
l_r	Distance from CG to the rear axle	1.471m
c_f	Equivalent cornering stiffness of front tire	30000N/rad
c_r	Equivalent cornering stiffness of rear tire	30000N/rad
i_g	Steer gear ratio	8
f_{band}	Band rate of CAN network	250/Kbits
d_j	Data size in the jth message packet	8/bytes
T_{max}	Motor peak torque	90N·m
P_{max}	Motor peak power	18.8kW
n_r	Motor rated rotating speed	2000rpm
kk	Motor time constant	20ms

The main parameters of the high-fidelity full-vehicle simulator used in the real-time HIL test bench were acquired from a prototype EV by Beijing Electric Vehicle Co., Ltd. and provided in Table 1. The specifications of the four-in-wheel motors in the prototype EV are also described in detail as in [25]. Especially, the models of the four motors (as actuators in this study) are built with considering the torque saturation of the motor (which is the input saturation of the vehicle) as in [18] and the actuator delay (which is described by the first-order inertial link with the time constant $kk = 20$ms here) as shown in Fig. 6(b).

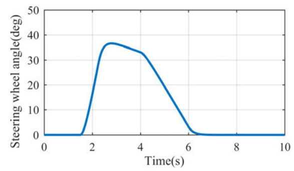
$$T_{\max}(n) = \begin{cases} 90(Nm) & n < 2000(rpm) \\ 9550 \times 18.8(kW)/n(Nm) & n >= 2000(rpm) \end{cases} \tag{18}$$

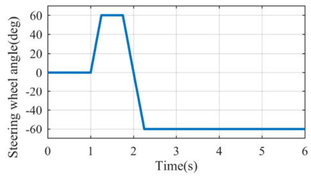
where $90Nm$ is the motor peak torque in the constant torque state, $18.8kW$ is the motor power, $2000rpm$ is the rated rotating speed of the motor, n denotes the motor speed, $T_{max}(n)$ denotes the motor maximum torque.

In order to verify the effectiveness of the proposed method, two typical steering wheel angle inputs are considered in this study, including the J_turn test and the Fishhook test. The

$$\begin{bmatrix} -\Omega_i & 0 & A_{aug,i,j}M - B_{aug,i,j}Y & G_{aug,i} \\ 0 & -I & FM_i - HY_i & 0 \\ M_i^T A_{aug,i,j}^T - Y^T B_{aug,i,j}^T & M_i^T F^T - Y_i^T H^T & -\Omega_i - M_i - M_i^T & 0 \\ G_{aug,i}^T & 0 & 0 & -\eta^2 I \end{bmatrix} < 0$$
$$\forall j = 1, 2, \ldots, (h+1). \tag{16}$$

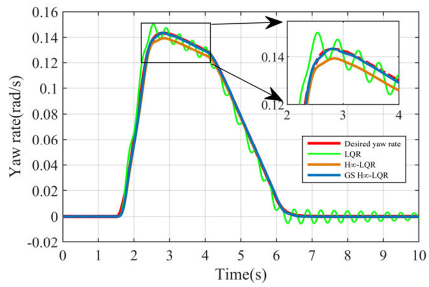
$$\min_{\Omega, M, Y, \eta} \ \eta^2$$
$$\text{subject to} \begin{bmatrix} -\Omega & 0 & A_{aug,i,j}M - B_{aug,i,j}Y_i & G_{aug,i} \\ 0 & -I & FM_i - HY_i & 0 \\ M_i^T A_{aug,i,j}^T - Y_i^T B_{aug,i,j}^T & M_i^T F^T - Y_i^T H^T & -\Omega - M_i - M_i^T & 0 \\ G_{aug,i}^T & 0 & 0 & -\eta^2 I \end{bmatrix} < 0$$
$$\forall j = 1, 2, \ldots, (h+1). \tag{17}$$



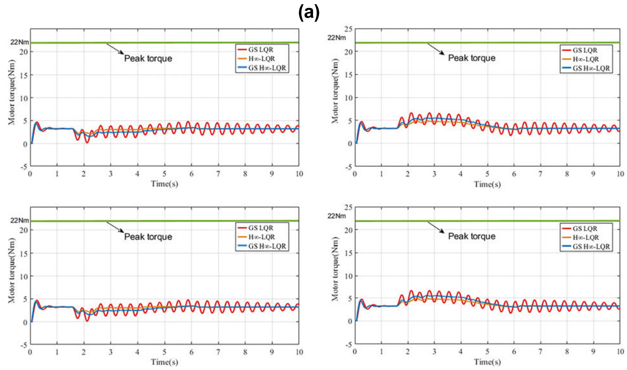


a. steering wheel angle with j_turn **b. steering wheel angle with Fishhook test**

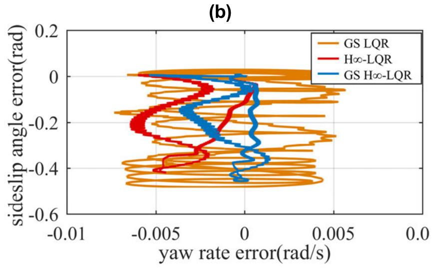
FIGURE 7. Two test cases.



(a)



(b)



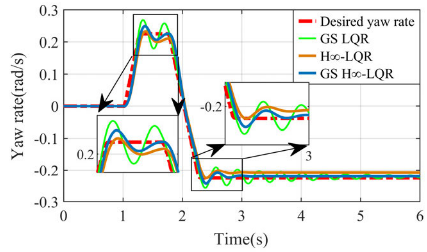
(c)

FIGURE 8. Results of J_turn test. (a)Yaw rate. (b)Torques of four-wheel motors. (c) The $\beta - \gamma$ phase trajectory error.

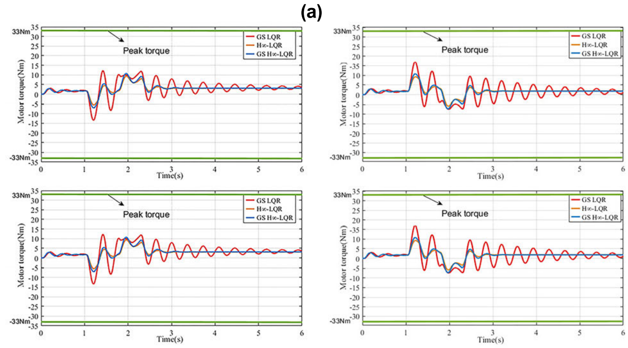
respective steering wheel angle signals are shown in the figure below.

For comparative analysis, two traditional controllers are also designed: the first controller is a gain-scheduling linear quadratic regulator (GS LQR), whose gains are variable with the speeds of the vehicle without considering the affect of network-induced delay. The second controller is H_∞-based linear quadratic regulators (H_∞-LQR) to deal with the affect of network-induced delay, without considering the affect of varying vehicle speeds. The proposed method is presented as GS H_∞-LQR in the legends of Fig. 7 and Fig. 8.

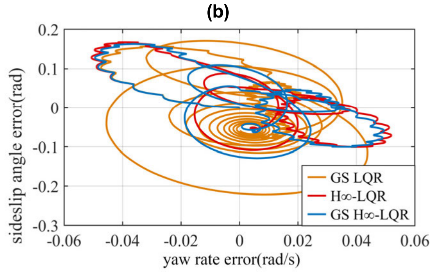
In three control cases, the same parameter values are setting as follows: the system sampling period of the vehicle motion control system is set to T = 0.02s, and the solver



(a)



(b)



(c)

FIGURE 9. Results of Fishhook test. (a) Yaw rate. (b) Torques of four-wheel motors. (c) The $\beta - \gamma$ phase trajectory error.

in the simulator chooses a fixed step size of 0.001 seconds. The selection of the weighting matrix in the performance indicators of the linear quadratic regulator is as follows:

$$Q = \begin{bmatrix} 20000 & 0 \\ 0 & 10000 \end{bmatrix}, R = 0.00005$$

For GS LQR control, gains are:

$$K(15) = \begin{bmatrix} 13427 \ 26434 \end{bmatrix}$$
$$K(20) = \begin{bmatrix} 14188 \ 28417 \end{bmatrix}$$
$$K(30) = \begin{bmatrix} 13870 \ 30609 \end{bmatrix}$$

For H_∞-LQR control, gains are:

$$K = \begin{bmatrix} 5372 \ 10255 \end{bmatrix}$$

For proposed control, gains are:

$$K(15) = \begin{bmatrix} 5372 \ 10255 \end{bmatrix}$$
$$K(20) = \begin{bmatrix} 8593 \ 12520 \end{bmatrix}$$
$$K(30) = \begin{bmatrix} 15223 \ 15214 \end{bmatrix}$$

A. J_TURN TEST

In this test, the longitudinal speed of the vehicle is set to 108 km/h, and the tire-road friction coefficient is 0.8. The Fig. 8 shows the real-time HIL test results of the three control cases in the J_turn test. As shown in Fig. 8(a), only the proposed method can keep the actual yaw rate tracking the desired yaw rate well. The traditional GS LQR leads to significant oscillation in motion control process. The traditional H_∞-LQR make tracking error. As shown in Fig. 8(b), the traditional GS LQR method leads to oscillations in the torque outputs of four driving motors. It means serious damage and extra energy consumption for the driving motors, and ride comfort of the vehicles with the traditional method. Whereas, with the proposed method, the vehicle yaw motion can be adjusted smoother and faster, which means that the vehicle is safer and more comfortable for drivers and passengers in the ramp steering. Fig. 8(c) shows that the traditional H_∞-LQR lead to obvious yaw rate error, it means that inaccurate lateral motion control. The proposed method makes little yaw rate error, which means an accurate lateral motion control.

B. FISHHOOD TEST

In this test, the longitudinal speed of the vehicle is set to 72km/h, and the coefficient of friction between the tire and the road surface is 0.8. The results with three control schemes are shown in Fig. 9 in the fishhood test.

Similarly, only the proposed method can keep the actual yaw rate tracking the desired yaw rate well. While the traditional GS LQR leads to significant oscillation in motion control process and the traditional H_∞-LQR make tracking error. It means that the proposed method is more effective than traditional methods in the fishhood test.

VI. CONCLUSION

The lateral motion control of the smart distributed drive vehicle has been a typical cyber-physical system. This paper proposes a cyber-physical control scheme to analyze the system uncertainties caused by varying vehicle speed and network-induced delay, by introducing a two-process perturbation analysis. Then a hierarchical approach is developed to deal with all the system uncertainties. The real-time HIL test bench test results show that the proposed approach can effectively improve the vehicle motion control performance and ensure the robustness of the networked system. Nowadays, with the new networked electronic and electrical architecture (N-EEA), smarter vehicles with growing ADAS are being developed rapidly. The proposed cyber-physical control scheme and two-process perturbation analysis can be potentially used in ADAS areas such as ACC, which may be also worth of investigating in the future. It is also necessary to further consider and study the vehicle-road collaboration with considering more road condition.

REFERENCES

[1] J. Liang, Y. Lu, G. Yin, Z. Fang, W. Zhuang, Y. Ren, L. Xu, and Y. Li, "A distributed integrated control architecture of AFS and DYC based on MAS for distributed drive electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 5565–5577, Jun. 2021.

[2] T. Shen, G. Yin, Y. Ren, J. Wang, J. Liang, and W. Sha, "Acceleration comfort guaranteed ASR for distributed driving electric vehicle via gain-scheduled robust pole-placement," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2020, pp. 1008–1013.

[3] S. E. Li, F. Gao, K. Li, L. Y. Wang, K. You, and D. Cao, "Robust longitudinal control of multi-vehicle systems—A distributed H-infinity method," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 9, pp. 2779–2788, Sep. 2017.

[4] J. Li, H. Wang, H. He, Z. Wei, Q. Yang, and P. Igic, "Battery optimal sizing under a synergistic framework with DQN based power managements for the fuel cell hybrid powertrain," *IEEE Trans. Transport. Electrific.*, early access, Apr. 21, 2021, doi: 10.1109/TTE.2021.3074792.

[5] W. Cao, Y. Wu, E. Zhou, J. Li, and J. Liu, "Reliable integrated ASC and DYC control of all-wheel-independent-drive electric vehicles over CAN using a co-design methodology," *IEEE Access*, vol. 7, pp. 6047–6059, 2019.

[6] H. Zhang and J. Wang, "Vehicle lateral dynamics control through AFS/DYC and robust gain-scheduling approach," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 489–494, Jan. 2016.

[7] Z. Shuai, H. Zhang, J. Wang, J. Li, and M. Ouyang, "Combined AFS and DYC control of four-wheel-independent-drive electric vehicles over CAN network with time-varying delays," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 591–602, Feb. 2014.

[8] C. Wang, Z. Wang, L. Zhang, D. Cao, and D. G. Dorrell, "A vehicle rollover evaluation system based on enabling state and parameter estimation," *IEEE Trans. Ind. Informat.*, vol. 17, no. 6, pp. 4003–4013, Jun. 2021.

[9] C. Zhai, X. Chen, C. Yan, Y. Liu, and H. Li, "Ecological cooperative adaptive cruise control for a heterogeneous platoon of heavy-duty vehicles with time delays," *IEEE Access*, vol. 8, pp. 146208–146219, 2020.

[10] C. Zhai, F. Luo, and Y. Liu, "Cooperative power split optimization for a group of intelligent electric vehicles travelling on a highway with varying slopes," *IEEE Trans. Intell. Transp. Syst.*, early access, Dec. 29, 2021, doi: 10.1109/TITS.2020.3045264.

[11] G. Rigatos, P. Siano, A. Melkikh, and N. Zervos, "A nonlinear H-Infinity control approach to stabilization of distributed synchronous generators," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2654–2663, Sep. 2018.

[12] Q. Yang, J. Li, W. Cao, S. Li, J. Lin, D. Huo, and H. He, "An improved vehicle to the grid method with battery longevity management in a microgrid application," *Energy*, vol. 198, May 2020, Art. no. 117374.

[13] H. Jing, R. Wang, J. Wang, and N. Chen, "Robust H_∞ dynamic output-feedback control for four-wheel independently actuated electric ground vehicles through integrated AFS/DYC," *J. Franklin Inst.*, vol. 355, no. 18, pp. 9321–9350, 2018.

[14] X. Huang, H. Zhang, G. Zhang, and J. Wang, "Robust weighted gain-scheduling H_∞ vehicle lateral motion control with considerations of steering system backlash-type hysteresis," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 5, pp. 1740–1753, Sep. 2014.

[15] X. Ding, Z. Wang, L. Zhang, and C. Wang, "Longitudinal vehicle speed estimation for four-wheel-independently-actuated electric vehicles based on multi-sensor fusion," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 12797–12806, Nov. 2020.

[16] B. Leng, L. Xiong, Z. Yu, K. Sun, and M. Liu, "Robust variable structure anti-slip control method of a distributed drive electric vehicle," *IEEE Access*, vol. 8, pp. 162196–162208, 2020.

[17] X. Ding, Z. Wang, and L. Zhang, "Hybrid control-based acceleration slip regulation for four-wheel-independently-actuated electric vehicles," *IEEE Trans. Transport. Electrific.*, vol. 7, no. 3, pp. 1976–1989, Sep. 2020.

[18] N. Ding and S. Taheri, "An adaptive integrated algorithm for active front steering and direct yaw moment control based on direct Lyapunov method," *Veh. Syst. Dyn.*, vol. 48, no. 10, pp. 1193–1213, 2010.

[19] J. Wang, D. Yang, and X. Lian, "Research on electrical/electronic architecture for connected vehicles," in *Proc. IET Conf.*, 2016, p. 13. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/cp.2016.1165, doi: 10.1049/cp.2016.1165.

[20] R. Letor and R. Crisafulli, "Smart power devices and new electronic fuses compliant with new E/E architecture for autonomous driving," in *Proc. AEIT Int. Conf. Electr. Electron. Technol. Automot.*, Jul. 2019, pp. 1–6.

[21] Y. Feng, B. Hu, H. Hao, Y. Gao, Z. Li, and J. Tan, "Design of distributed cyber–physical systems for connected and automated vehicles with implementing methodologies," *IEEE Trans. Ind. Informat.*, vol. 14, no. 9, pp. 4200–4211, Sep. 2018.

[22] W. Zeng, M. Khalid, and S. Chowdhury, "In-vehicle networks outlook: Achievements and challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1552–1571, 3rd Quart., 2017.

[23] X. Zhu, H. Zhang, J. Wang, and Z. Fang, "Robust lateral motion control of electric ground vehicles with random network-induced delays," *IEEE Trans. Veh. Technol.*, vol. 64, no. 11, pp. 4985–4995, Nov. 2015.

[24] W. Cao, Z. Liu, Y. Chang, and A. Szumanowski, "Direct yaw-moment control of all-wheel-independent-drive electric vehicles with network-induced delays through parameter-dependent fuzzy SMC approach," *Math. Problems Eng.*, vol. 2017, pp. 1–15, May 2017.

[25] W. Cao, J. Liu, J. Li, Q. Yang, and H. He, "Networked motion control for smart EV with multiple-package transmissions and time-varying network-induced delays," *IEEE Trans. Ind. Electron.*, early access, Apr. 4, 2021, doi: 10.1109/TIE.2021.3070499.

[26] U. Klehmet, T. Herpel, K. Hielscher, and R. German, "Delay bounds for can communication in automotive applications," in *Proc. Meas., Modelling Eval. Comput. Commun. Syst.*, Mar. 2008, pp. 1–15.

[27] T. Herpel, K.-S. Hielscher, U. Klehmet, and R. German, "Stochastic and deterministic performance evaluation of automotive CAN communication," *Comput. Netw.*, vol. 53, no. 8, pp. 1171–1185, Jun. 2009.

[28] T. Zhang, Y. Zou, X. Zhang, N. Guo, and W. Wang, "Data-driven based cruise control of connected and automated vehicles under cyber-physical system framework," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 10, pp. 6307–6319, Oct. 2021.

[29] G. Xiao, "Research on key technologies of remote monitoring system for vehicle network based on CPS," in *Proc. IEEE 3rd Int. Conf. Inf. Syst. Comput. Aided Educ. (ICISCAE)*, Sep. 2020, pp. 413–418.

[30] L. Guo, B. Yang, J. Ye, H. Chen, F. Li, W. Song, L. Du, and L. Guan, "Systematic assessment of cyber-physical security of energy management system for connected and automated electric vehicles," *IEEE Trans. Ind. Informat.*, vol. 17, no. 5, pp. 3335–3347, May 2021.

[31] Z. N. I. X. Liu, D. Li, and H. Yu, "Design of an improved Ethernet AVB model for real-time communication in in-vehicle network," in *Proc. Inf. Technol., Netw., Electron. Automat. Control Conf.*, 2019, pp. 1–10.

[32] Y. Jiang and S. Yin, "Recursive total principle component regression based fault detection and its application to vehicular cyber-physical systems," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1415–1423, Apr. 2018.

[33] Z. Shuai, H. Zhang, J. Wang, J. Li, and M. Ouyang, "Lateral motion control for four-wheel-independent-drive electric vehicles using optimal torque allocation and dynamic message priority scheduling," *Control Eng. Pract.*, vol. 24, pp. 55–66, Mar. 2014.

[34] G. K. Allaboyena, M. Yilmaz, N. Vaidya, and J. Guardiola, "Uncertain vehicle lateral speed dynamics modeling and control frameworks," in *Proc. IEEE Int. Conf. Electro/Information Technol. (EIT)*, May 2018, pp. 655–660.

[35] Z. Li, L. Zhang, B. Yu, H. Chen, and Y. Wang, "H_∞ control for a kind of networked control systems with network induced time delay and data packet dropout," in *Proc. Int. Conf. Control, Automat. Inf. Sci. (ICCAIS)*, 2018, pp. 124–127.

[36] H. Jing, R. Wang, C. Hu, J. Wang, F. Yan, and N. Chen, "Vehicle lateral motion control considering network-induced delay and tire force saturation," in *Proc. Amer. Control Conf. (ACC)*, Jul. 2016, pp. 1–5.

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