Research Article

H_∞ Control of Four-Wheel-Independent-Drive Electric Vehicles with Random Time-Varying Delays

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The random time-varying delays would reduce control performance and even deteriorate the EV system. To deal with random time-varying delays and achieve a real-time steady-state response, considering randomness of delay and a rapid response, an H_∞ -based delay-tolerant linear quadratic regulator (LQR) control method based on Taylor series expansion is proposed in this paper. The results of cosimulations with Simulink and CarSim demonstrate the effectiveness of the proposed controller through the control performance of yaw rate, sideslip angle, and the running track. Moreover, the results of comparison with the other controller illustrate the strength of explicitly.

1. Introduction

With the rapid development of EV technology, the stability of EV is concerned by enterprise and research institution [1]. Due to unique technical advantages such as simplified transmission, regenerative braking system of each wheel, and electronic initiative chassis [2], 4WIDEVs have attracted great attention [3].

However, some random time-varying delays of environment interference and network may cause the 4WIDEV system to be unstable. On one hand, since the working environment of 4WIDEV changes tremendously, some interferences increase in the conditions of road [4], the variational parameters of motors, the variational parameters of 4WIDEV [5–7], and electromagnetic interference (EMI) [8], which are random and difficult to measure. On the other hand, 4WIDEV controls are also characterized by fast dynamics, whereas the response time and accuracy of controller may be influenced under the network-induced delays.

There are a few approaches against network delays [9]; for example, an H_∞ controller [10] is proposed to decrease CAN delays. However, environment interference delays are not considered in literature [10]. Meanwhile, longitudinal force and vertical force are ignored in 2-DOF model which is proposed in literature [10]. There are numerous approaches

for the appropriate handling based on polytopic inclusions [11]. In literature [12], a method based on Jordan normal form (JNF) is proposed. However, the polytope of JNF is too large to store in real-time system. Then a method based on elementwise minimization-maximization (EMM) [13] is used to describe random time-varying delays. Though EMM is the same order of magnitude as Taylor series expansion (TA) [14], it is more complex than TA. Therefore, TA is chosen to deal with random time-varying delays in this paper. However, there is no approach against random network delays proposed. There are rare research studies to restrain onboard random time delays of network. Based on the theoretical research on network-induced delays [9], a practical result of the network-induced delay model was adopted for the study of automotive system [10]. Even though there are few approaches against CAN network delays, there is no method which is proposed to deal with network delays and environment interference delays.

The main work is as follows; firstly, the environment delays and network delays are explicitly considered in the vehicle yawing moment control problem. Considering that the random time-varying delays lead to a challenging control problem for the vehicle lateral stability and handling, the delays are described via the polytopic technique, which is different from the conventional control strategy.

FIGURE 1: Electric control system structure.

Furthermore, an H_∞ -based LQR tracking control scheme is designed to make the control performance and the robustness of 4WIDEV against random time-varying delays.

The remaining sections of this paper are organized as follows. In Section 2, the 4WIDEV control system is studied. In Section 3, the H_∞ -based LQR is designed to solve random time-varying delays with LMI theory. In Section 4, the effectiveness of controller is demonstrated via cosimulation with Simulink and CarSim. Section 5 presents some concluding remarks.

2. WIDEV Control System

2.1. Electric Control System Structure. As is shown in Figure 1, a 4WIDEV structure consists of driving intention recognition, 4WIDEV controller, network, in-wheel motors, and transducer and estimate system.

As is described in Figure 1, the transducer system is designed to gather accelerate pedal location, braking pedal location, longitudinal and transverse acceleration, yaw rate, and velocity as inputs. Driving intention recognition determines expected vehicle velocity V_{des} and steering angle δ . 4WIDEV controller picks up expected yaw moment M_Z and expected vehicle driving moment F_{des} . Moreover, on the premise of satisfying proposed M_Z and F_{des} , torque allocation set is in charge of calculating driving moment T_i and steering angle of four wheels δ_f . The control signals are exchanged using control area network (CAN or FlexRay) [10].

2.2. Model of 4WIDEV. Without any loss of generality, we can get three assumptions [10].

Assumption 1. 4WIDEV is symmetrical and its moving coordinate origin is center of gravity (CG).

Assumption 2. The steering wheel angle is equal to front wheel angle and same characteristics of each wheel.

Assumption 3. Air resistance is ignored.

In this paper, a 4-DOF model of 4WIDEV is used for controller design, as is shown in Figure 2. Through the stress analysis of 4WIDEV and Newton's second law of motion, we can get 4-DOF vehicle model as follows [10]:

$$\dot{x} = A_c x + B_{\omega c} \omega + B_{uc} F_{\Delta x}, \quad (1)$$

where $x = [\beta \ r \ \phi \ \dot{\phi}]^T$, $\omega = \delta$, $F_{\Delta x} = (F_{xf} - F_{xfl}) + (F_{xrr} - F_{xrl})$

$$A_c = \begin{bmatrix} -\frac{I_{eq} C_0}{I_{xx} \mu u} & -1 - \frac{I_{eq} C_1}{I_{xx} \mu u^2} & \frac{h_{CG}(mg \cdot h_{CG} - k_\phi)}{I_{xx} u} & -\frac{h_{CG} b_\phi}{I_{xx} u} \\ -\frac{C_f}{I_{zz}} & -\frac{C_2}{I_{zz} u} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{h_{CG} C_0}{I_{xx}} & -\frac{h_{CG} C_1}{I_{xx} u} & \frac{mg \cdot h_{CG} - k_\phi}{I_{xx}} & -\frac{b_\phi}{I_{xx}} \end{bmatrix},$$

$$B_{\omega c} = \begin{bmatrix} 0 & \frac{d}{2I_{zz}} & 0 & 0 \end{bmatrix}^T,$$

$$B_{uc} = \begin{bmatrix} \frac{1}{\mu u} \left(\frac{2C_f I_{eq}}{I_{xx}} + F_{xf} \right) & \frac{a}{I_{zz}} (2C_f + F_{xf}) & 0 & \frac{2C_f + h_{CG} F_{xf}}{I_{xx}} \end{bmatrix}^T,$$

$$I_{eq} = I_{xx} + m h_{CG}^2,$$

$$C_0 = 2C_f + 2C_r,$$

$$C_1 = 2aC_f - 2bC_r,$$

$$C_2 = 2a^2 C_f + 2b^2 C_r,$$

(2)

where m is the mass of 4WIDEV, I_z is the inertia of 4WIDEV, I_{zz} is yaw inertia, I_{xx} is roll inertia, l_f is the distance from CG to front axles, l_r is the distances from CG to rear axles, b is the distance from front axle to CG, and a is the distance from rear axle to CG. d is track width, h_{CG} is height of CG, δ is the front wheels steering angle which is inputs, α_f is front tires slip angle, α_r is rear tires slip angle, β is sideslip angle, ϕ is roll angle and $\dot{\phi}$ derivative of roll angle, F_{xf} is longitudinal force of front tire, F_{rf} is rear longitudinal force, F_{yf} is lateral force of front tires, F_{yr} is rear tires lateral force, V is the CG velocity [15] of 4WIDEV, u is longitudinal velocity, v is lateral velocity, r is yaw rate, b_ϕ is roll damping, C_f is cornering stiffness of front tire, C_r is cornering stiffness of rear tire, and k_ϕ is roll angle stiffness. δ is the input of 4WIDEV model, and β , r , ϕ , and $\dot{\phi}$ are four states of 4WIDEV model.

2.3. Reference State Responses. Generally, the reference sideslip angle which is mainly concerned with the vehicle stability [16] is set as zero to make 4WIDEV stable [17], whereas the reference yaw rate is defined in terms of vehicle parameters, longitudinal speed, and steering input of the driver as [18]

$$r_{ref} = \frac{u}{a + b + (\mu u^2 (C_r b - C_f a) / 2C_f C_r (a + b))} \delta. \quad (3)$$

Applying (3) to (1), the reference state responses can be expressed as follows:

$$y = R\omega, \quad (4)$$

FIGURE 2: Bicycle model of vehicle lateral dynamics.

where

$$y = \begin{bmatrix} \beta_{\text{ref}} \\ r_{\text{ref}} \\ \phi_{\text{ref}} \\ \dot{\phi}_{\text{ref}} \end{bmatrix},$$

$$R = \begin{bmatrix} 0 & \frac{u}{a+b+(mu^2(C_{rb}-C_fa)/2C_fC_r(a+b))} & 0 & 0 \end{bmatrix}^T, \quad (5)$$

where r_{ref} is reference yaw rate, β_{ref} is reference sideslip angle, ϕ_{ref} is reference roll angle, and $\dot{\phi}_{\text{ref}}$ is reference derivative of roll angle.

2.4. Analysis of Random Time-Varying Delays

Assume 1. Random time-varying delays are bounded within an in-vehicle network and EV's working environment [19].

Assume 2. In order to simplify calculation, we suppose that all delays are equivalent to network delays [20]. An explicit expression can be demonstrated as follows:

$$\tau_{l \arg e, j} = \frac{(j+2)l}{R - \sum_{i=0}^{j-1} (l/c_i)}, \quad (6)$$

where $\tau_{l \arg e, j}$ is the upper bound of the delay of the j th message, l is the maximum frame length, R is the rate of communication protocol, and c_i is the cycle length of the i th priority message.

From (6), we can get an integral term as follows:

$$\Gamma(x) = \int_0^x e^{A_c(T_s - \theta)} d\theta; \quad (7)$$

using Taylor series expansion in (7), we can get the following:

$$\Gamma(x) = -\sum_{q=1}^h \frac{(-x)^q}{q!} A_c^{q-1} e^{A_c T_s} + \Theta^h. \quad (8)$$

With a proper selection of the number h , the high-order terms in the remainder can be relatively small. We can neglect the remainder Θ^h and obtain the h -order approximation as is shown in the following:

$$\Gamma^h(x) = -\sum_{q=1}^h \frac{(-x)^q}{q!} A_c^{q-1} e^{A_c T_s}; \quad (9)$$

the random terms can be expressed as a linear combination [11] as follows:

$$\Delta_{i,k} = \sum_{l=1}^{h+1} \mu_{i,l}(k) \bar{\Delta}_{1,l}, \quad i = 0, 1, \dots, Y-1 \frac{dy}{dx}, \quad (10)$$

$$\Delta_{i,k} = \sum_{l=1}^{h+1} u_{i,l}(k) \bar{\Delta}_{0,l}, \quad i = Y,$$

where $\mu_{i,l}(k)$ is a random time-varying coefficient with respect to τ_k and

$$\sum_{l=1}^{h+1} u_{i,l}(k) = 1, \quad u_{i,l}(k) > 0. \quad (11)$$

2.5. Control Model with Random Time-Varying Delays. With the random time-varying delays, (1) is derived as

$$\bar{x}_{k+1} = \bar{A}_d \bar{x}_k + \bar{B}_{wrd} w_k + \bar{B}_{ud} u_k. \quad (12)$$

Considering control delay from the EV controller, we can write the input of the vehicle at time t in the following:

$$u(t) = u_k \quad \forall t \in [kT_s + \tau_k, (k+1)T_s + \tau_{k+1}]. \quad (13)$$

Define the maximum value delay as

$$\tau_{l \arg e} = (r + \nu) T_s, \quad (14)$$

where $Y \in \mathbb{Z}_+$ and $\nu \in R_{[0,1)}$.

Applying (13) to (12), we obtain

$$\begin{aligned} \bar{x}_{k+1} = & \bar{A}_d \bar{x}_k + \bar{B}_{wrd} w_k + \bar{B}_{ud} u_k + \Delta_{0,k} (u_{k-1} - u_k) \\ & + \Delta_{1,k} (u_{k-2} - u_{k-1}) + \dots + \Delta_{Y,k} (u_{k-Y-1} - u_{k-Y}), \end{aligned} \quad (15)$$

where

$$\Delta_{i,k} = \begin{cases} 0, & \tau_{k-i} - iT_s \leq 0 \\ \int_0^{\tau_{k-i} - iT_s} e^{\bar{A}(T_s - \theta)} d\theta \cdot \bar{B}_u, & 0 \leq \tau_{k-i} - iT_s \leq T_s \\ \int_0^{T_s} e^{\bar{A}(T_s - \theta)} d\theta \cdot \bar{B}_u, & T_s \leq \tau_{k-i} - iT_s. \end{cases} \quad (16)$$

Defining a new state vector $\xi_k = [\bar{x}_k^T u_{k-1}^T \cdots u_{k-Y-1}^T]^T$, from (15), we can get

$$\xi_{k+1} = A_{\text{aug}} \xi_k + B_{wr,\text{aug}} w_k + B_{u,\text{aug}} u_k, \quad (17)$$

where

$$A_{\text{aug}} = \begin{bmatrix} \bar{A}_d & \Delta_{0,k} - \Delta_{1,k} & \cdots & \Delta_{Y-1,k} - \Delta_{Y,k} & \Delta_{Y,k} \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & I & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & I & 0 \end{bmatrix}, \quad (18)$$

$$B_{wr,\text{aug}} = \begin{bmatrix} \bar{B}_{wr,d} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad B_{u,\text{aug}} = \begin{bmatrix} \bar{B}_{ud} - \Delta_{0,k} \\ I \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

In (17), ξ_k is a state vector, u_k is control variables vector, and w_k is random time-varying delays vector. Thus, a discrete-time control model with random time-varying delays is proposed.

3. H_∞ Controller Design

With the system in (17), the control objective is to minimize the tracking error and the control input signals. A performance index is formulated as a combination of the tracking error and the control signals. In this paper, we select a quadratic form of the tracking error and the control signals as follows:

$$J = \sum_{i=0}^{\infty} (e_i^T Q e_i + u_i^T R u_i), \quad (19)$$

where Q and R are two positive definite weighting matrices to regulate the weight of steering angle correction and direct yaw moment. In this paper, Q and R are selected as constants for controller design.

The H_∞ -based LQR tracking controller is obtained by finding the optimized state-feedback gain $K(u_k = K\xi_k)$ to minimize index J , which is also equal to the 2-norm of the following constructed signal:

$$z_k = E\xi_k + Fu_k, \quad (20)$$

where

$$E = \begin{bmatrix} 0 & Q^{1/2} & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}, \quad F = \begin{bmatrix} 0 \\ R^{1/2} \end{bmatrix}. \quad (21)$$

Considering $w = \delta_f$ is bounded in l_2 space [11], we introduce an H_∞ performance index η such that $J < \eta^2 \|w\|^2$. Then, the optimization problem instead that an optimal H_∞ control problem for the following system:

$$\begin{aligned} \xi_{k+1} &= A_{\text{aug}} \xi_k + B_{wr,\text{aug}} w_k + B_{u,\text{aug}} u_k, \\ z_k &= E\xi_k + Fu_k. \end{aligned} \quad (22)$$

With the state-feedback control, the closed-loop system is

$$\begin{aligned} \xi_{k+1} &= (A_{\text{aug}} + B_{u,\text{aug}} K) \xi_k + B_{wr,\text{aug}} w_k, \\ z_k &= (E + FK) \xi_k, \end{aligned} \quad (23)$$

and inequality is as follows:

$$\|z\|_2 < \eta \|w\|_2. \quad (24)$$

From (24), we can get an optimized control gain K , and the following is achievable:

$$\begin{bmatrix} -\Omega & 0 & (A_{\text{aug},i} + B_{u,\text{aug},i} K) M & B_{wr,\text{aug}} \\ * & -I & (E + FK) M & 0 \\ * & * & \Omega - M - M^T & 0 \\ * & * & * & -\eta^2 I \end{bmatrix} < 0. \quad (25)$$

For Q and R , when η is small, the controlled output is small, and vice versa. Therefore, the controller design can be finally expressed as

$$\begin{aligned} & \min_{\Omega, M, Y, \eta} m \eta^2 \\ \text{s.t.} \quad & \begin{bmatrix} -\Omega & 0 & A_{\text{aug},i} M + B_{u,\text{aug},i} Y & B_{wr,\text{aug}} \\ * & -I & EM + FY & 0 \\ * & * & \Omega - M - M^T & 0 \\ * & * & * & -\eta^2 I \end{bmatrix} < 0 \\ & \forall i = 1, 2, \dots, (h+1)^{Y+1}. \end{aligned} \quad (26)$$

Equation (26) is a typical minimization problem of a linear objective function with constraints of LMIs and can be solved with the LMI Toolbox in MATLAB. Therefore, the minimization under constraints is solved, and a controller against random time-varying delays is proposed. Then the controller is obtained by $K = YM^{-1}$, where K is a fixed gain matrix which can be calculated offline. The PID controller requires the integral and derivative of the error signal.

4. Simulation and Interpretation of Results

The vehicle model parameter values are listed in Table 1.

As is shown in Figure 3, take a PID controller for an example for comparison. Sample time T_s is 10 ms which is the sample period of the closed-loop system. In the simulations, choose the longitudinal vehicle velocity as 80 km/h and the tire-road friction coefficient as 0.85 in all the maneuvers.

FIGURE 3: Simulation diagram constructed by CarSim.

TABLE 1: Main simulation parameters of vehicle.

Vehicle quality m	1296 (unit)
Distance of centroid and front axle l_f	1.25
Distance of centroid and rear axle l_r	1.32
Distance between two front wheels B_f	1.405
Distance between two rear wheels B_r	1.399
Vertical height of vehicle centroid to ground h_e	0.415
Tire radius r	0.1651
Rotational inertia of vehicle spin on Z axle I_z	1750

FIGURE 4: Random time-varying delays series.

4.1. Straight Maneuver. Random time-varying delays are shown in Figure 4. The max delay is 5 ms, and the min delay is 0 ms. It means the delay time of each message.

As is shown in Figure 5, reference velocity of 4WIDEV is 80 km/h. Under the condition without delays, the response time of the PID controller and the H_∞ controller is about 1 second. The overshoot of system is zero. Both controllers have good control performance.

FIGURE 5: Velocity of 4WIDEV without delays in straight maneuver.

FIGURE 6: Velocity of 4WIDEV with random time-varying delays in straight maneuver.

FIGURE 7: Vehicle yaw rate response in curve steering maneuver.

FIGURE 8: Vehicle CG trajectory in curve steering maneuver.

As is shown in Figure 6, reference velocity of 4WIDEV is 80 km/h. Under the condition with random time-varying delays, the PID controller significantly oscillates, whereas the proposed controller demonstrates good robustness. The response time of the proposed controller is about 2 seconds.

Figure 7 shows the simulation results of vehicle yaw rate response in the curve steering maneuver. Without time delays, both the PID controller and the proposed controller give satisfactory results, and the proposed controller performs better without a steady-state tracking error. However, with the random time-varying delays, the PID controller yields oscillations in the transient process and error in steady state, whereas the proposed controller can still track the desired yaw rate, as well as what it does under the ideal network condition.

In addition, the effect of the delays is hence significant enough to influence the vehicle global trajectory with the PID controller. Comparatively, for the proposed controller, the trajectory is just as the driver's expectation, which is displayed in Figure 8.

4.2. Curve Steering Maneuver. As is shown in Figure 9, reference velocity of 4WIDEV is 80 km/h. Under the condition without delays, the response time of the PID controller and the H_∞ controller is about 1.5 seconds. The maximum overshoot of system is less than 2%. Both controllers have good control performance.

As is shown in Figure 10, reference velocity of 4WIDEV is 80 km/h. Under the condition with random time-varying delays, the PID controller significantly oscillates, whereas

FIGURE 9: Velocity of 4WIDEV without delays in curve steering maneuver.

FIGURE 10: Velocity of 4WIDEV with random time-varying delays in curve steering maneuver.

the proposed controller demonstrates good robustness. The response time of the proposed controller is about 2 seconds.

Figure 11 shows the simulation results of vehicle yaw rate response in the curve steering maneuver. Without time delays, both the PID controller and the proposed controller give satisfactory results, and the proposed controller performs better without a steady-state tracking error. However, with the random time-varying delays, the PID controller yields oscillations in the transient process and error in steady state, whereas the proposed controller can still track the desired yaw rate, as well as what it does under the ideal network condition.

In addition, the effect of the delays is hence significant enough to influence the vehicle global trajectory with the PID controller. Comparatively, for the proposed controller,

(a) Without delay

(b) With random time-varying delays

FIGURE 11: Vehicle yaw rate response in curve steering maneuver.

the trajectory is just as the driver's expectation, which is displayed in Figure 12.

4.3. Lane-Changing Maneuver. Figure 13 shows the simulation results of vehicle speed response in single lane-changing maneuver. Under the condition without delays, the response time of the PID controller and the proposed controller is about 1.5 seconds. The maximum overshoot of system is less than 3.5%. Both controllers have good control performance. There are some drops in the response curve, which is because of deceleration of the vehicle when it turns a corner.

As is shown in Figure 14, reference velocity of 4WIDEV is 80 km/h. Under the condition with random time-varying delays, the PID controller significantly oscillates, whereas the proposed controller demonstrates good robustness.

Figure 15 shows the simulation results of the vehicle yaw rate under lane-changing maneuver. Under the ideal

FIGURE 12: Vehicle CG trajectory in curve steering maneuver.

FIGURE 13: Velocity of 4WIDEV without delays in lane-changing maneuver.

FIGURE 14: Velocity of 4WIDEV with delays in lane-changing maneuver.

network condition without delays, both the PID controller and the proposed controller can track the desired yaw rate well. Nevertheless, with the random time-varying delays, there are significant oscillations in the vehicle yaw rate with the PID controller, and the oscillations still exist when the steering wheel angle returns to zero in the last 1 s, which indicates that the vehicle system is almost at the criticality of instability, while, for the proposed controller, there is almost no negative influence on the tracking performance even when the random network delays are introduced.

In addition, the effect of the delays is hence significant enough to influence the vehicle global trajectory with the PID controller. Comparatively, for the proposed controller, the trajectory is just as the driver's expectation, which is displayed in Figure 16.

5. Conclusion

In this paper, a yawing moment control method of 4WIDEVs to restrain random time-varying delays is proposed. An H_∞ -based LQR tracking controller is introduced and adopted in the control system against random time-varying delays effectively. Meanwhile, the original system with the terms is induced by random time-varying delays and then describes the randomness as polynomial. Two simulation maneuvers are carried out on an EV model constructed by CarSim to verify the performance of the proposed controller. Simulation results show that the H_∞ controller not only achieves a good control effect under the network condition without delays but also guarantees enough robustness and performance when there are network-induced random time-varying delays in

FIGURE 15: Vehicle yaw rate response in lane-changing maneuver.

FIGURE 16: Vehicle CG trajectory in lane-changing maneuver.

the closed-control loop as well. Comparisons with a PID controller without delays further evidenced the effectiveness of the proposed controller.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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