Direct Yaw-moment Control with a F-TDMA Scheduler for Electric Vehicle

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Abstract. This paper proposed a new scheduling approach for direct yaw-moment control (DYC) of distributed-driven electric vehicles (EVs) over a controller area network (CAN). The insertion of the communication network makes the system a distributed control system, which leads to clock asynchrony among control system components and asynchrony-induced delays. This paper employs a flexible Time Division Multiple Access (F-TDMA) scheduler to manage the communication flows. And the stability of the close-loop system is guaranteed by using the pole placement method. The results of the simulation illustrate that the proposed method can effectively deal with the clock asynchrony problems and guarantee the stability of the system.

Keywords: Direct yaw-moment control (DYC); Clock asynchrony; Pole assignment; Flexible time division multiple access (F-TDMA).

1. Introduction

Recently, the transportation electrification is drawing a worldwide interest [1, 2], and advanced distributed-driven electric vehicles (DDEVs) have been rapidly developed, gradually becoming promising candidates for future transportation as their advantages in terms of fast response speed and independent torque control [3-6]. In modern DDEVs, the Controller Area Network (CAN) is normally used, owing to easy integration, low system maintenance, reducing wiring and increasing system agility [7]. However, on the other hand, inserting the communication network into the close-loop may lead to the unexpected network’s effects such as the asynchronous behaviors among plants and asynchrony-induced delays [7]. Direct yaw-moment control (DYC) is one of the key issues in lateral motion control of DDEVs, which can improve the vehicle handling stability. Several recent literature [8-11] have studied the issue on the stabilization of EVs with four in-wheel motors using the networked motion control systems. However, most control methods were designed based on the ideal assumptions that the distributed system are synchronous. In actual networked control systems with distributed elements in different sub-systems, the clock of them may not be synchronous [7, 9], which may lead to complex uncertainties and further degrade the control performance.

This paper proposed a new scheduling approach for DYC of DDEVs, to deal with the effects of the asynchronous behaviors and asynchrony-induced delays, where a flexible Time Division Multiple Access (F-TDMA) approach is introduced to manage the communication information flows.
2. Problem Formulation

2.1. Control-oriented Model for DYC

As shown in Figure 1, to design the motion control strategy based on DYC, a simplified two-degree-of-freedom (2-DOF) vehicle model [9] is adopted in this study. CG denotes the center of vehicle gravity. $l_f$ and $l_r$ are the distances from CG to the front and rear axles, respectively. $m$ and $I_z$ are the vehicle mass and the vehicle yaw inertia, respectively. $F_{Fx}$ and $F_{Fy}$ denote the longitude tire forces and lateral tire forces of front wheels, respectively. $F_{Rx}$ and $F_{Ry}$ denote the longitude tire forces and lateral tire forces of rear wheels, respectively. $M_z$ is the yaw-moment imposed to the vehicle. $\delta_f$ is the steering angle of front wheel. $\beta$ represents the sideslip angle. $\alpha_f$ and $\alpha_r$ are slip angles of front and rear wheels, respectively. $\gamma$ is the yaw rate. $V$ is the vehicle speed.

Figure 1. A simplified 2-DOF lateral dynamics model of a vehicle.

The control-oriented model for the vehicle lateral dynamics can be expressed [11] as follows

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

(1)

where $A$, $B$ and $E$ are the coefficient matrices according to vehicle parameters. The yaw rate and sideslip angle, which reflect the handing performance and the vehicle stability respectively, are often considered in vehicle lateral motion control. The model of the desired yaw rate and sideslip angle can be expressed [11] as follows

$$x_{ref} = R\delta_f$$

(2)

The equality constraint with the yaw-moment $M_z$ is for the DYC application. The expressions for torque distribution principle [9] are as follows

$$-F_{w1}l_1 + F_{w2}l_2 - F_{w3}l_3 + F_{w4}l_4 = M_z = \sum_{i=1}^{4} (-1)^{i+1} \frac{T_{m,i}i_{veh,l_i}}{r},$$

(3)

2.2. Analysis of the Network’s Effects

Generally, in a control system over CAN, it is reasonable to assume that all nodes work in time-driven mode. However, the clock asynchrony among control system components exists in the close-loop. There have been various theoretical studies on calculating the maximum time delay in the close-loop [9, 11, 12]. The time delays can be assumed to be distributed in the interval $[0, T]$, and $T$ is the sampling period, the detailed description of this part can be found in [10]. Moreover, due to the clock asynchrony, multiple sensors may sample at different times and multiple actuators may execute the control command at different times, which may lead to complex uncertainties and bring new challenges to the design of the controller.

3. F-TDMA Based Controller Design with Pole Assignment

To improve the motion performance of the vehicle, a controller with a F-TDMA scheduler unit is developed in this section. The stability of the system is analyzed and guaranteed through purposeful pole assignment.

The controller includes a control unit that generates the desired reference driving force commands and a scheduling unit that manages the communication information flows.
Since the control unit is not the focus of this paper, a discrete linear-quadratic-regulator tracking controller as in [9] is adopted directly in this study.

To deal with the aforementioned network’s effects, a F-TDMA scheduler unit is developed. As shown in figure 2, one sampling period is divided into several windows. In order to ensure the real-time performance of message transmissions, different types of messages are transmitted in different windows to reduce conflicts. In the meanwhile, in order to keep flexibility, the messages of the same type are transmitted in the same window instead of transmitting each message at a certain time.

| CAN bus | TM | Feedback window | Control window | RM | Reserved window | TM | • • |
|---------|----|-----------------|----------------|----|-----------------|----|-----|
|         | Trigger Message | Reference Message |

**Figure 2.** F-TDMA scheduling method.

The Vehicle Control Unit (VCU) works on Time-triggered mode and broadcasts a trigger message (TM) with the highest priority at the beginning of each Sampling period. All sensors are triggered by the TM to guarantee the synchronized sampling behaviors and transmit feedback signals in the feedback window. Then, the VCU transmits control signals in the control window and broadcasts a reference message (RM) after all control signals have been successfully transmitted. All actuators are triggered by the RM to guarantee the synchronized execution behaviors.

Specially, the size of designed feedback window and control window has to meet the bandwidth constraints to ensure that all messages can be successfully transmitted. To simplify the design, the size of feedback window and control window are both defined as 1/4T in this study, thus the max time delay is T/2, where T is the sampling period of the system.

To guarantee satisfactory control performance, e.g., the stability, the fast performance, pole assignment approach is used to improve the designed close-loop system in this section.

Firstly, considering the network’s effects, with the F-TDMA scheme, the control input can be expressed as a piecewise function as following

\[
 u(t) = \begin{cases} 
 -K\beta(k-1), t \in [kT, kT + \tau_k] \\
 -K\gamma(k), t \in [kT + \tau_k, (k+1)T] 
\end{cases} 
\]

\[
 k = 0, 1, 2... 
\]

(4)

The \( \beta \) and \( \gamma \) are defined as the deviation between the actual motion states \( \beta \) and \( \gamma \) and the targeting reference states, therefore, a new vector \( e \) is obtained as following

\[
 e = x - x_{ref} = [d\beta \ d\gamma]^T 
\]

(5)

Substituting (4) into (5) and discretization, the discrete-time model can be obtained as follows

\[
 e(k+1) = \phi e(k) + \Gamma_1(\tau_k)K\beta(k) + \Gamma_2(\tau_k)K\gamma(k-1) + \tilde{G}_d\delta_f
\]

(6)

Where

\[
 \phi = e^{\Gamma T}, \Gamma_1(\tau_k) = -\int_0^{\tau_k} e^{\Gamma s}dB, \Gamma_2(\tau_k) = -\int_0^{\tau_k} e^{\Gamma s}dB
\]

A new extended vector is defined as \( z(k) = [e'(k) \ e'(k-1)]^T \), thus an augmented delay system equations can be described as follows

\[
 z(k+1) = \tilde{\phi}(\tau_k)z(k) + \tilde{\Theta}\delta_f(k)
\]

(7)

where
\[
\bar{\phi}(\tau_k) = \begin{bmatrix} e^{\tau_k} & \Gamma_1(\tau_k)K & \Gamma_2(\tau_k)K \\ 0 & I \end{bmatrix}, \quad \Theta = \begin{bmatrix} \bar{G}_d \\ 0 \end{bmatrix}
\]

Then, with the augmented delay system equations, if the delay \( \tau \) is known, the poles of the system are known. For a discrete-time system, the control performance is determined by the poles.

The pole assignment approach is very effective for the design of discrete-time systems. Figure 3 (a) shows the influence of pole distribution on the system stability for a discrete-time system. With the proposed scheduling strategy, the worst delay in the close-loop is \( T/2 \), while that is \( 2T \) without scheduling. Figure 3 (b) and (c) show the poles of the system \( (7) \) when the worst delay in the close-loop is \( 2T \) and \( T/2 \), respectively.

(a) Influence of pole distribution on system stability
(b) Pole map of matrix \( \bar{\phi} \) without scheduling
(c) Pole map of matrix \( \bar{\phi} \) with the proposed scheduling strategy

Figure 3. Pole distribution map.

As is shown in figure 3 (b), some poles of the system don’t locate on the right half real axis in the unit circle when the time delay is \( 2T \), which means that more oscillations will occur, and even the system may be unstable.

As is shown in figure 3 (c), when the time delay is short enough, e.g., \( \tau_{\text{max}} = T/2 \) in this study, the poles of the system \( (7) \) will locate on the right half real axis in the unit circle, that is the system will be stable and have satisfactory transient response without oscillations, which is beneficial for the vehicle yaw motion control.

4. Results and Discussion

To evaluate the effectiveness of the proposed control, co-simulations are performed on the CarSim-Simulink platform. The network is simulated by utilizing the TrueTime toolbox, which is recognized by applied in automotive industry [12]. The proposed method is compared with the traditional method without the scheduler, e.g., general periodical time-driven mode. In the simulation, vehicle parameters used in this study are obtained from a prototype of DDEV [11]. The vehicle speed is set as 100km/h, and the tire-road friction coefficient is set as 0.8. The driver model outputs steering wheel angle.

A typical maneuver is considered in this study: single-lane-changing maneuver. Figure 4 (a) shows the steering wheel angle input in the single-lane-changing maneuver. As shown in figure 4 (b) and (c), the proposed method produces satisfactory results of the yaw rate tracking response and sideslip angle response, while the traditional method leads to obvious oscillations, which degrades the performance of control system and even may seriously affect the safety of the vehicle. Therefore, the proposed method can effectively deal with the effects of the network and guarantee the stability of the control system.
5. Conclusion
In this paper, an advanced DYC for EVs over the CAN bus is discussed. To deal with the time delays in the close-loop caused by the clock asynchrony and the asynchronous behaviors of the distributed elements, a F-TDMA scheduler is proposed. The stability of the close-loop system is guaranteed by using the pole placement method. The simulation results illustrated the effectiveness of the proposed method.

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