

# Network Scheduling for Distributed Controls of Electric Vehicles Considering Actuator Dynamic Characteristics

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## ABSTRACT

Electric vehicle (EV) has been regarded as not only an effective solution for environmental issues but also a more controllable and responsible device to driving forces with electric motors and precise torque measurement. For electric vehicle equipped with four in-wheel motors, its tire longitudinal forces can be generated independently and individually with fully utilized tire adhesion at each corner. This type of the electric vehicles has a distributed drive system, and often regarded as an over-actuated system since the number of actuators in general exceeds the control variables. Control allocation (CA) is often considered as an effective means for the control of over-actuated systems. The in-vehicle network technology has been one of the major enablers for the distributed drive systems.

The vehicle studied in this research has an electrohydraulic brake system (EHB) on front axle, while an electromechanical brake system (EMB) on rear axle. The focus of this study is on the scheduling of the networked control for the distributed systems. A network control system (NCS) model is first established with a continuous-time based plant model, a discrete controller and a FlexRay communication model, in addition to the electric vehicle model with tire model and driving/braking actuator models.

An integrated vehicle control allocation method based on constraints optimization is then proposed. The dynamic characteristics of each actuator are considered on the control allocation with higher-bandwidth actuators being used for faster control commands. It is also considered for the scheduling optimization of FlexRay which minimizes a cost function and subject to a set of constraints.

Finally, a hardware-in-the-loop (HIL) system is built, which consists of a driving simulator, four in-wheel motors, EHB and EMB brake systems, all connected via FlexRay communication in order to validate the proposed scheduling methods. The experimental results have demonstrated the improved responses of actuators when considering their dynamic characteristics, improved control performance via properly designed control allocation, and reduced bus efficiency via optimized scheduling methods.

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## INTRODUCTION

The development trend of modern automobile industry is powertrain electrification and control system electronization. The NCSs, which the controllers are connected to sensors and actuators through a communication network, are essential to it to reduce hardwiring weight [1]. In recent years, in-vehicle network technologies and x-by-wire concepts have been actively applied to vehicle control systems. As there are increasing electronic control units (ECUs) communication via in-vehicle network, such as CAN bus, the network bandwidth leads to the performance degradation of the NCSs [2].

The increasing researches focus on the alternative powertrain configurations for electrified vehicles including pure electric vehicles and hybrid electric vehicles [3]. The distributed drive electric vehicle which has outstanding advantages, e.g., the better dynamics controllability, the higher efficiency and the better reliability, is quite

different from traditional vehicles [4]. The main advantages in the dynamics control of distributed drive electric vehicles are shown in two aspects: more flexibility degrees of freedom because of four independent continuous controllable actuators fully utilizing the adhesion of each tire; the actuators with faster response and higher accuracy dynamics [5].

A distributed drive electric vehicle is a typical over-actuated system, which consists of many subsystems including in-wheel motors, braking systems and a vehicle control units (VCU). Control allocation (CA) is a critical process in the over-actuated systems [6]. However, the network delays are inevitable due to the bandwidth constraints in powertrain systems [7]. The powertrain system performance has not been fully achieved by the reason of the random delays. In order to reduce performance degradation caused by message delays in networked control systems, message scheduling is a very effectively methods applied to utilized the limited network bandwidth.

The sequence of the communication signal is exclusively dependent on the time processes for time-triggered (TT) communication protocols. The TT architecture is the appropriate choice for the real-time applications, due to its determinacy for the control sequences. For this reason, the periodic control signal communication sequences can be planned at the design stage [8]-[10].

The challenge is optimizing a scheduling that not only ensures communication in an orderly way but also guarantees the NCS performance. The scheduling algorithms in the literature mainly put forward the maximum allowed delay time for communication, such as [11] [12]. These algorithms guarantee the basic performance using the exchanged messages but the dynamic process of the NCS is ignored.

In this paper, a hierarchical NCS architecture is proposed for a distributed drive electric vehicle. In the distributed drive electric vehicle powertrain control system, the sensors, motor control unit (MCU) and VCU are operating under TT mode. In the upper-level controller, a torque allocation algorithm satisfies the dynamic demand from the driving or braking torque of four wheels, fully utilizing the high bandwidth actuators. It is also considered for the scheduling optimization of FlexRay which minimizes a cost function and subject to a set of constraints. The networked control system scheduling is calculated, and the effectiveness of the mentioned state function is verified by the HIL system.

This paper is organized as follows: firstly, NCS models, including the TT communication model, a reference model for vehicle dynamics control, a body model, a tire model and actuator dynamic characteristics are presented. Secondly, the networked control architecture is introduced, including upper-level controller, allocation algorithm and scheduling optimization. Finally, a HIL system is built, in order to validate the proposed scheduling methods. Conclusions are proposed in the last section.

## NETWORKED CONTROL SYSTEM FORMULATION

The networked control system architecture for a distributed drive electric vehicle consists of a VCU, four in-wheel MCUs, and a composite Brake System (CBS) communicated via a FlexRay bus, as shown in Figure 1. The messages are calculated from the demands and sensors which are inputs of the VCU, transmitting to the corresponding actuator controller via the in-vehicle bus. Vehicle states messages are feedback to VCU by other controller or sensors directly.

The vehicle reference model, upper-level controller and torque control allocation algorithm are presented in the VCU. The desired yaw rate, sideslip angle and vehicle speed are calculated by the reference vehicle model. The four wheel torques are distributed by the torque control allocation algorithm which the total yaw moment are calculated by the upper-level controller. A two degree of freedom (2-DOF) vehicle model is adopted in the upper-level controller, which the state variables are the yaw rate and the sideslip angle and the inputs are front wheel steering angle and total yaw moment. Moreover, a four wheel torque

allocation model, in-wheel motor powertrain model, tire model and NCS augmentation model are considered in control allocation procedure, shown in the following sections.

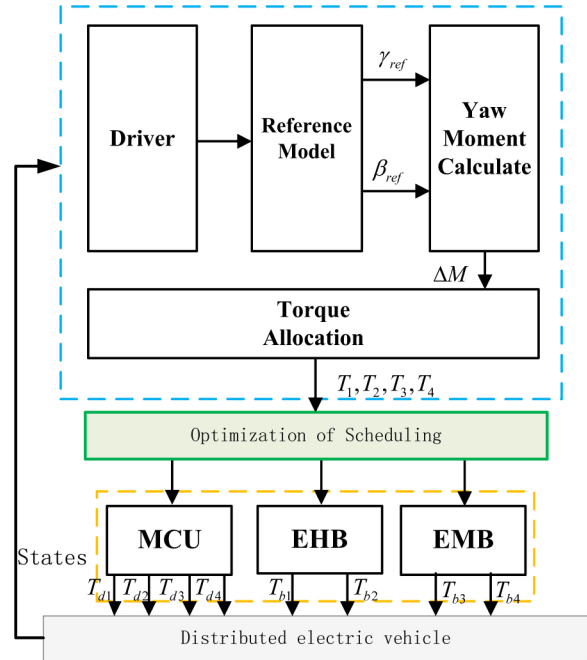


Figure 1. Networked control architecture of the distributed electric vehicle.

### Reference Model

In Figure 2, the 2-DOF vehicle model is adopted [13]. The 2-DOF model can be described as follows:

$$\dot{x} = Ax + Bu \quad (1)$$

where  $x = [\beta \ \gamma]^T$ ,  $u = [\delta \ \Delta M_z]^T$ ,

$$A = \begin{bmatrix} -\frac{C_f + C_r}{mV_x} & -\frac{C_f l_a - C_r l_b}{mV_x^2} - 1 \\ -\frac{C_f l_a - C_r l_b}{I_z} & -\frac{C_f l_a^2 + C_r l_b^2}{I_z V_x} \end{bmatrix},$$

$$B = \begin{bmatrix} \frac{C_f}{mV_x} & 0 \\ \frac{C_f l_a}{I_z} & \frac{1}{I_z} \end{bmatrix}$$

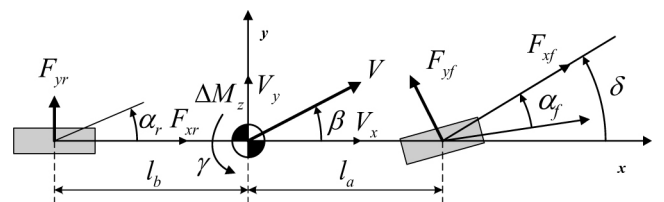


Figure 2. Diagram of a vehicle lateral dynamics model.

Here,  $\beta$  is the vehicle sideslip angle and  $\gamma$  is the vehicle yaw rate as the state variables.  $\delta$  is the front wheel steering angle by the demand.  $C_f$  and  $C_r$  are cornering stiffness of the front tire and the rear tire, respectively.  $V_x$  is the vehicle longitudinal speed.  $\Delta M_z$  is the total yaw moment calculated by the four wheel tire longitudinal forces.

### Torque Allocation Model

A four wheel torque allocation model of a distributed drive electric vehicle is shown in Figure 3.  $l_c$  is half of the vehicle track.  $F_{xi}$  ( $i=1, 2, 3, 4$ ) stands for the longitudinal force of each tire.

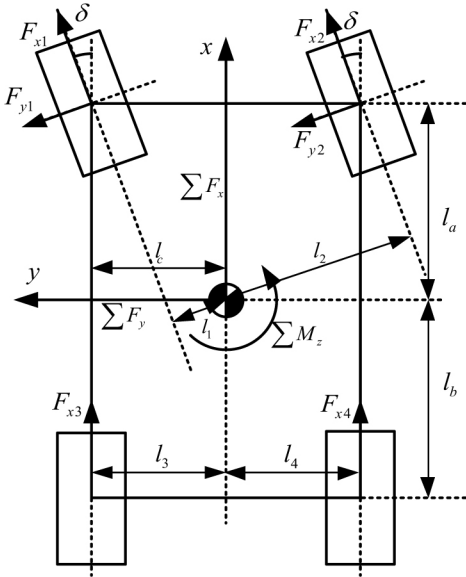


Figure 3. Diagram of a torque allocation vehicle model.

$\Delta M_z$  can be described as follows:

$$\Delta M_z = -F_{x1}l_1 + F_{x2}l_2 - F_{x3}l_3 + F_{x4}l_4 \quad (2)$$

where  $l_1 = l_c \cos \delta - l_a \sin \delta$ ,  $l_2 = l_c \cos \delta + l_a \sin \delta$ ,  $l_3 = l_4 = l_c$ .

The control input vector  $u$  can be distributed into actuator control input vectors:

$$u = \begin{pmatrix} \Delta \delta \\ \Delta M_z \end{pmatrix} = u_0 + u_1 + u_2 + u_3 + u_4 \quad (3)$$

where

$$u_0 = \begin{pmatrix} \Delta \delta \\ 0 \end{pmatrix}, u_1 = \begin{pmatrix} 0 \\ -F_{x1}l_1 \end{pmatrix}, u_2 = \begin{pmatrix} 0 \\ F_{x2}l_2 \end{pmatrix},$$

$$u_3 = \begin{pmatrix} 0 \\ -F_{x3}l_3 \end{pmatrix}, \text{ and } u_4 = \begin{pmatrix} 0 \\ F_{x4}l_4 \end{pmatrix}.$$

The load of each tire is calculated based on the longitudinal acceleration  $a_x$  and lateral acceleration  $a_y$  [14]. Slip angle of each tire can be expressed in [15].  $V_x$  and  $V_y$  are the vehicle longitudinal velocity and lateral velocity, respectively. They can be estimated by observers [16].

### In-Wheel Motor Powertrain Systems Model

The in-wheel motor powertrain system can be written as follows:

$$J_i \dot{\omega}_i = T_{di} - T_{bi} - T_{loadi} \quad (4)$$

where  $J_i$  is the inertia of the  $i$ -th wheel,  $\dot{\omega}_i$  is the  $i$ -th wheel rotation speed,  $T_{di}$  is the  $i$ -th motor drive torque,  $T_{bi}$  is the  $i$ -th wheel frictional brake torque,  $T_{loadi}$  is the external load torque of the  $i$ -th wheel [17].

The  $T_{di}$  can be expressed as follows:  $T_{di} = F_{xi} \cdot R_e$ , where  $R_e$  is the effective radius of each wheel.

### Tire Model

There is a constraint that the tire forces do not exceed the adhesive force limitations. The maximum tire longitudinal force and lateral force are coupled, as shown in [18]. So, the constraint is presented as follows:

$$\left( \frac{F_{xi}}{C_{xi}} \right)^2 + \left( \frac{F_{yi}}{C_{yi}} \right)^2 \leq (\mu F_{zi})^2 \quad (5)$$

where  $C_{xi}$  and  $C_{yi}$  are the tire longitudinal coefficients and lateral coefficients, respectively.

Due to motor torque is achieved by the maximum tire longitudinal force, it is necessary to estimate the tire lateral force. Therefore, the Magic Formula tire model is expressed [19]:

$$F_y = D \sin \left\{ C \arctan \left[ B\alpha - E(B\alpha - \arctan B\alpha) \right] \right\} \quad (6)$$

where  $\alpha$  is the tire slip angle,  $B$  is the stiffness factor,  $C$  is the shape factor,  $D$  is the peak factor, and  $E$  is the curvature factor.

### NCS Augmentation Model

The NCS is described in Figure 4, including the continuous-time plant, the communication model and the discrete controller. The plant  $M^c$  is:

$$M^c : \begin{bmatrix} \dot{\tilde{x}}(t) \\ \tilde{z}(t) \\ \tilde{y}(t) \end{bmatrix} = \begin{bmatrix} A^c & B_1^c & B_2^c \\ C_1^c & D_{11}^c & D_{12}^c \\ C_2^c & 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{x}(t) \\ \tilde{w}(t) \\ \tilde{u}(t) \end{bmatrix}$$