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Lateral motion control for four-wheel-independent-drive electric vehicles using optimal torque allocation and dynamic message priority scheduling

Zhibin Shuai [a,b], Hui Zhang [a], Junmin Wang [a,*], Jianqiu Li [b], Minggao Ouyang [b]

[a] Department of Mechanical and Aerospace Engineering, The Ohio State University, Columbus, OH 43210, USA
[b] Department of Automotive Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

In this paper, the vehicle lateral motion control of four-wheel-independent-drive electric vehicles (4WID-EVs) with combined active front steering (AFS) and direct yaw moment control (DYC) through in-vehicle networks is studied. As a typical over-actuated system, a 4WID-EV requires a control allocation algorithm to achieve the generalized control efforts. In this paper, a quadratic programming (QP) based torque allocation algorithm is proposed with the advantage of equally and reasonably utilizing the tire-road friction of each wheel. It is also well known that the in-vehicle network and x-by-wire technologies have considerable advantages over the traditional point-to-point communications, and bring great strengths to complex control systems such as 4WID-EVs. However, there are also bandwidth limitations which would lead to message time-delays in in-vehicle network communications and degradation of control performance. The paper also proposes a mechanism to effectively utilize the limited network bandwidth resources and attenuate the adverse impact of in-vehicle network-induced time-delays, based on the idea of dynamic message priority scheduling. Simulation results from a high-fidelity vehicle model show that the proposed control architecture with the torque allocation algorithm and message dynamic-priority scheduling procedure can effectively improve the vehicle lateral motion control performance, and significantly reduce the adverse impact of the in-vehicle network message time-delays in the simulated maneuvers.

1. Introduction

As in-wheel motor technologies and control methodologies have been actively developed and applied in automotive industry, the four-wheel-independent-drive electric vehicle (4WID-EV), as an emerging configuration of electric vehicles, has attracted increasing research efforts because of its considerable advantages in terms of vehicle motion control, energy optimization, and vehicle structural arrangement (Chen & Wang, 2012; Hori, 2004; Wang, Chen, Feng, Huang, & Wang, 2011; Chen & Wang, in press). For vehicle handling control, active front steering (AFS) and direct yaw moment control (DYC) are two effective strategies, and there have been various studies on their combinations (Mokhiamar & Abe, 2002; Nagai, Shino, & Gao, 2002; Yang, Wang, & Peng, 2009). In a 4WID-EV, each in-wheel motor can individually generate not only braking torque but also driving torque, which greatly increases the flexibility and possibility of fully utilizing the adhesion of each tire. Thus, there have been also studies focusing on the combination of AFS and DYC in 4WID-EVs (Li, Hong, & Liang, 2012; Shuai, Zhang, Wang, Li, & Ouyang, in press).

With the front wheel steering angle and four wheels' driving/braking torque as the control inputs, a 4WID-EV with AFS is a typical over-actuated system. In the control of over-actuated systems, control allocation (CA) is a key process. CA was first developed for the aircrafts and spacecrafts whose numbers of control surfaces are more than the degrees of freedom (Durham, 1993), and then gradually applied in the control of marine vessels and ground vehicles. There have been several different control allocation methods, such as pseudo-inverse, daisy-chaining, linear programming, nonlinear programming, mixed-integer programming, and fixed-point methods (Bodson, 2002; Johansen & Fossen, 2013). For a particular class of control allocation problems, optimal control design can be adopted as a solution (Härkegard & Glad, 2005). Among all these allocation methods, constrained quadratic programming (QP) proves to be a popular method for its flexibility in problem formulation and capability of dealing with constraints (Härkegård, 2004; Petersen & Bodson, 2006). However, in real-time implementations, the conventional QP method has the drawback of high computational requirements. Therefore, some low-computing-cost methods have been developed, such as the adaptive control allocation which could asymptotically achieve

* Correspondence to: E307 Scott Lab, 201 W. 19th Avenue, Columbus, OH 43210, USA. Tel.: +1 614 247 7275.
E-mail address: wang.1381@osu.edu (J. Wang).

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Nomenclature

Abbreviations

2-DOF	two-degree-of-freedom
4WID-EV	four-wheel-independent-drive electric vehicle
AFS	active front steering
CAN	controller area network
CG	center of gravity
DYC	direct yaw moment control
ECU	electronic control unit
ED	earliest-deadline
ID	identifier
LQR	linear quadratic regulator
MFTM	Magic Formula tire model
MTS	mixed traffic scheduling
PI	proportional–integral
QP	quadratic programming

Variables

B, C, D, E	coefficients in Magic Formula tire model
C_f, C_r	total cornering stiffness of the two front/rear tires
C_{xi}, C_{yi}	coefficients in friction ellipse concept
F_{xf}, F_{xr}	total longitudinal force of two front/rear wheels
F_{xi}	longitudinal force of wheel i
F_{yf}, F_{yr}	total lateral force of two front/rear wheels
F_{yi}	lateral force of wheel i
F_{zi}	normal force of wheel i
g	the gravitational constant
h_g	height of the vehicle CG
h_r	height of the vehicle roll center
I_z	vehicle moment of inertia about the yaw axis
l_f, l_r	distances from the vehicle CG to the front/rear axle
l_i	distance from the vehicle CG to the wheel plane of wheel i
l_s	half of the vehicle wheel base
m	vehicle mass
p_i	priority class of message i
r_{eff}	wheel effective radius
$r_{\max}, r_{\min}$	torque rate limits of in-wheel motors
T_i	driving/braking force of wheel i
$T_{\max}, T_{\min}$	torque limits of in-wheel motors
T_s	control cycle period
V_x	vehicle longitudinal velocity
V_y	vehicle lateral velocity
α	tire slip angle
β	vehicle sideslip angle
β_{des}	desired vehicle sideslip angle
γ	vehicle yaw rate
γ_{des}	desired vehicle yaw rate
ΔM_z	total yaw moment achieved by DYC
$\Delta\delta_f$	front wheel steering angle controlled by AFS
δ	actual steering angle of front wheels
δ_f	front wheel steering angle manipulated by the driver
κ_f, κ_r	roll stiffness factor of the front/rear suspension
μ	tire-road friction coefficient
$\tau_i(k)$	time delay of message i in the kth control cycle

optimal allocation using update laws (Tjønnås & Johansen, 2008). Interested readers can refer to Bodson (2002) and Johansen and Fossen (2013) for detailed information and reviews of control allocation methods.

For the motion control of 4WID vehicles, several approaches have been developed (Fredriksson, Andreasson, & Laine, 2004; Mokhiamar & Abe, 2004, 2005; Plumlee, Bevly, & Hodel, 2004; Sakai, Sado, & Hori, 2002; Tjønnås & Johansen, 2010; Wang & Longoria, 2006, 2009; Wang, Solis, & Longoria, 2007). With the total longitudinal/lateral forces and total yaw moment being chosen as the generalized control demands by most researchers, there are a variety of selections on the control allocation variables: tire longitudinal forces (Plumlee et al., 2004; Sakai et al., 2002), both tire longitudinal and lateral forces (Fredriksson et al., 2004; Mokhiamar & Abe, 2004, 2005), and tire slip ratios and slip angles (Tjønnås & Johansen 2010; Wang & Longoria, 2006, 2009; Wang et al., 2007). Theoretically, four-wheel-independent-steering system is necessary when including tire lateral forces or tire slip angles as allocation variables. However, it is more practical to use the front-wheel-steering system, though the allocation strategy may be less flexible. Similarly, the tire slip ratio is a better choice than the wheel torque as a control variable for its direct relationship with the actual tire longitudinal force. However, selecting tire slip ratio as a control variable requires slip ratio tracking control module at the low-level and is more difficult to realize in practical applications. Different from the aircrafts and marine vessels, ground vehicles have control allocation variables coupled by nonlinear constraints due to the tire-road friction ellipse (Wang, 2007), which makes QP a competitive candidate of allocation method for its strength in dealing with complex constraints. Various QP-based cost function formations and constraints have been constructed for optimal control allocation.

In the past decade, in-vehicle network and x-by-wire technologies have brought considerable advantages to vehicle control systems, such as making system topology more flexible, decreasing weight of wires, promoting modularization, etc. While on the other hand, as there are more and more electronic control units (ECUs) exchanging messages via in-vehicle network, the network bandwidth is becoming increasingly scarcer. For example, there are around 45 ECUs connected by CAN in a Volkswagen Passat, and in a BMW 7 Series there are 6–10 ECUs in the chassis control system, among which about 180 messages are exchanged via CAN (Davis, Burns, Bril, & Lukkien, 2007). Bandwidth limit of in-vehicle network would induce time-delays to message transmissions, which may lead to performance degradation of the x-by-wire systems (Caruntu, Lazar, Gielen, van den Bosch, & Cairano, 2013). With so many actuators/subsystems (active front-wheel steering system, in-wheel motors, mechanical braking system, etc) coordinated and supervised by a vehicle control unit (VCU), 4WID-EV also confronts the time-delay problem caused by in-vehicle network bandwidth limit.

To reduce the adverse impact of message time-delays in networked control systems, varieties of methods have been developed to maximally utilize the limited network bandwidth, and message scheduling is a very important one. As the most dominant in-vehicle network nowadays, the CAN bus is based on priority arbitration mechanism (Hong & Kim, 2000). Messages with higher priorities have more opportunities to access the bandwidth resources, which would cause less transmission time-delays. Fixed-priority scheduling is most commonly used by setting each message's ID according to its unique priority (Tindell, Burns, & Wellings, 1995; Tindell, Hansson, & Wellings, 1994), which means that certain messages always have more bandwidth resources, and therefore, less time delays than others. However, the importance of information in a particular message possibly changes with system operating conditions and states, and fixed priority for each message may not be the optimal solution. To