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Wireless cars: A cyber-physical approach to vehicle dynamics control

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ABSTRACT

A non-conventional drive-by-wireless technology for guidance and control of a redundantly actuated electric car supported by an on-board wireless network of sensors, actuators and control units is proposed in this article. Several optimization-based distributed feedforward control schemes are developed for such powertrain infrastructures. In view of the limitations of the commercial off-the-shelf wireless communication technologies and the harshness of the in-vehicle environments, a pressing design and implementation aspect, in addition to the robustness against information loss, refers to fulfilling the hard real-time computational requirements. In this work, we address such problems by introducing several distributed event-based control schemes in conjunction with adaptive scheduling at the protocol level. Hereby we obtain a simple tuning mechanism to compromise between the outcome accuracy and computation efficiency (i.e., communication traffic intensity). Using simulative evaluations, we demonstrate the viability of the proposed algorithms and illustrate the impact of external interferences in an IEEE 802.15.4 based wireless communication solution.

1. Introduction

Due to the increasing number of modern technological devices that share computation, information, and communication resources in embedded distributed systems, in recent years a need for so-called cyber-physical control approaches concerning management of computational and communication resources has emerged. Often times lead such approaches to new insights into designing efficient complex systems. In this work, we provide such a reflection in designing non-conventional robust and cost-effective solutions in vehicle dynamics control. The present work is firmly based upon and provides a considerable extension to the author's previous works [see, e.g., 1] on distributed feedforward control schemes for control of all-wheel actuated vehicles. Such powertrains are equipped with independent steering and/or driving/braking actuators. Main inspiring sources of our work in the field of global chassis control have been the initial ideas in [2–4]. While these works focus mainly on centralized control structures, our control schemes essentially distinguish from the latter ones in that we focus our attention on the design of efficient and distributed control schemes. The distributed control approach provides inherent operational robustness benefits stemming from the redundancy of the computation topology. While cost-efficiency is implied by the allocation of sub-tasks (i.e smaller tasks) to parallel processors with lower computational power and memory space requirements, real-time efficient solutions of complex task may become a bottleneck (see below).

The underlying computational control algorithms, leading to advanced control automotive concepts, impose stringent reliability and latency requirements on the communication layer that can be accomplished by the deterministic and fault-tolerant wired-based communication technologies such as TTP [5] and FlexRay. In contrast to a variety of by-wire solutions that have been circulating for quite a while in the automotive and control literature, in this work, we propose a non-conventional in-vehicle drive-by-wireless approach, by introducing wireless transmissions to support the information exchange amongst the electronic computational units (ECUs) for vehicle dynamics control. We believe that in comparison to a more conservative wire-based solution, a wireless one can provide distinctive benefits in terms of design, construction, installation flexibility, maintenance, add-on functionalities and removes the cost, weight and maintenance overheads of additional wiring to the controllers and actuators. But, from the current technological perspective it is also more vulnerable, especially in light of the challenging in-vehicle operating environment characterized by non-line-of-sight links and significant multi-path effects due to reflections from metallic surfaces. Moreover, it turns out that hard real-time requirements represent a difficulty as a considerable amount of time in such embedded distributed systems is spent with information processing at the protocol level. As no commercial off-the-shelf available wireless communication solution is capable of meeting such stringent

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requirements, in this work, we focus on algorithmic scheduling approaches concerning information exchange and a balance between the communication amount and resulting control performance. To this end, we introduce a conjunction of a prediction-based adaptive data transmission scheduling scheme on the basis of time division multiple access (TDMA) and an event-triggered distributed optimization algorithm enhanced by Kalman-filtering. The event-triggered impact is imposed in the dual Lagrange formulation of the underlying optimization problem, while Kalman-filtering is introduced to smoothen the convergence and reduce the errors caused by the event-triggered impact. Adaptive scheduling is needed for time compensation and an effective acceleration of the communication interface. Our approach leads eventually to a cross-layer design at the protocol level providing a prioritization in information exchange implied by a discrimination of the information content into critical and non-critical on the basis of the event-triggered action. In other words, the important data in terms of some control system metrics are given higher priority, while the less important ones are simply not transmitted. This represents the key idea of our event-triggered cross-layer design approach for overcoming the technological bottleneck of the commercially available off-the-shelf wireless solutions in view of the hard real-time specifications. Note that the idea of adaptive flow control has been studied previously in literature with many applications in real world scenarios such as low delay high-capacity applications e.g. [6,7]. As TDMA schemes with periodic fixed pre-determined time slot allocations turn out to be inefficient for our application, adaptive scheduling is indispensable. Such adaptive TDMA schemes have been considered, e.g., in [8], where communicating units announce their transmission schedule in a so-called mini slot allocated to them [9,10].

The remainder of the article is organized as follows. In Section 2 we recall preliminaries referring to vehicle dynamics and distributed optimization. Additionally, we provide the problem formulation. In Section 3 we introduce our event-based optimization algorithms. In Section 4 we apply the proposed algorithms to our original problem formulation. The wireless standards and the basic requirements for the communication layer from the robustness and latency points of view are discussed in Section 5. Finally, in Section 6 we discuss the simulation and experimental results.

2. Preliminaries

For the sake of completeness and self-sufficiency of our work, in this section we recall some basic facts regarding vehicle dynamics and distributed optimization. Thereby, we intend to support understanding of key expositions in Sections 3 and 4. In the former one, we develop general schemes for solving event-triggered distributed optimization convex problems, while the latter section is dedicated to applying these schemes in solving the allocation problem of tire friction forces in a distributed setting.

2.1. Vehicle dynamics

This section reviews the very basics of rigid body dynamics for ground vehicles. For details, the reader is referred to [11,12]. Fig. 1 provides a depiction of the planar motion of a vehicle with m-wheels (i.e., the vertical displacements in the z-direction shall be neglected). Independent torque τ_i and steering angle θ_i inputs are applied to all wheels. (The index i implies always a sequence $i = 1, 2, \dots, m$ referring to the m-wheels of the vehicle. Here, the passenger cars with $m = 4$ are of primary concern.) The resulting planar motion is described by vehicle body states: v_x (longitudinal

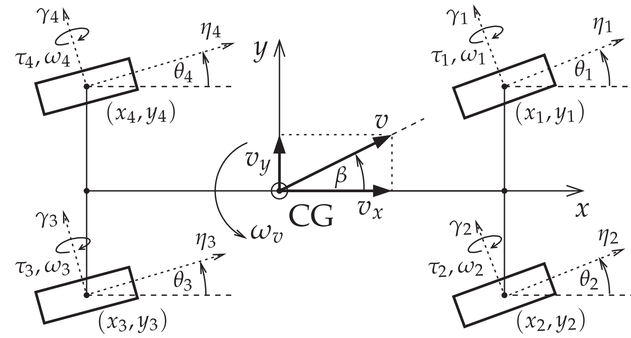

Fig. 1. Variables of a planar vehicle motion.

speed), v_y (lateral speed) and ω_v (yaw rate), while the pitch and roll motion are assumed to be negligible. A chassis reference frame denoted by *xyz* is mounted at the center of gravity (CG) of the vehicle in accordance with the ISO orientation convention (see Fig. 1). This reference frame is used for the description of the evolution of the chassis state variables v_x, v_y and ω_v w.r.t. the ground. In addition, m wheel coordinate systems $\eta_i \gamma_i z$ are attached at the center of each wheel to model the wheel motion and tire friction forces.

The translational and yaw motion of the vehicle in the *xyz* reference frame is modeled as follows:

$$\text{rigid chassis}: \; M\dot{\xi} = g(\xi) + A_\eta(\theta)F_\eta + A_\gamma(\theta)F_\gamma \tag{1}$$

$$\text{four wheels}: \; I_w\dot{\omega}_i = r_w F_{i\eta} + \tau_i \tag{2}$$

$$\text{tire model}: \; F_{i\eta} = f_\eta(\lambda_i, N_i), F_{i\gamma} = f_\gamma(\lambda_i, N_i). \tag{3}$$

We next comment each equation. The first equation concerning force and moment balance is expressed in the chassis *xyz* coordinate frame, with $\xi^T = [v_x, v_y, \omega_v]$. The vector $g(\xi)$ is caused by the yaw motion, and is given by:

$$g(\xi) = m_v[\omega_v v_y, -\omega_v v_x, 0]^T. \tag{4}$$

The force vectors F_η and F_γ include the longitudinal $F_{i\eta}$ and lateral $F_{i\gamma}$ tire friction forces. In (1) these are transformed into the *xyz* frame by means of the matrices $A_\eta(\theta)$ and $A_\gamma(\theta)$, which are determined by the geometrical parameters (wheelbase and track width) of the vehicle, [see, e.g., 11]. The vector θ includes the steering angles θ_i. $M = \text{diag}[m_v, m_v, I_v]$ is the mass matrix, m_v is the vehicle mass, and I_v is the chassis moment of inertia about CG. Eq. (2) stated in the wheel coordinate frame refers to the rotational motion of the wheel i about its own axis γ_i; ω_i stands for its rotational speed. I_w is the wheel moment of inertia, and r_w the effective wheel radius. Eq. (3) describes the general static tire model, where the functions f_η and f_γ depend on the specific tire model. Assuming that the roll and pitch angles of the vehicle remain identically zero, the normal tire forces N_i introduced in (3) are uniquely determined by the planar forces F_η and F_γ. Indeed, it turns out that

$$N = c + P_\eta(\theta)F_\eta + P_\gamma(\theta)F_\gamma, \tag{5}$$

where $N = [N_1, \dots, N_m]^T$, while the constant vector c and matrices P_η, P_γ are again determined by the width, length and height of the vehicle; for details see [11].

2.2. Tire model

Tire models are naturally formulated in the tire wheel coordinate frames $\eta_i \gamma_i z$. In addition to the input angle θ_i, the friction slip variable λ_i in (3) is defined by the chassis (ξ) and wheel (ω_i) state variables. For a given normal force N_i, the static friction forces $F_{i\eta}$ and $F_{i\gamma}$ are uniquely determined by the slip value λ_i. These forces carry out the feedback from the road surface conditions into the