Resource-aware Cooperative Driving

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1. INTRODUCTION

Intelligent Transport Systems (ITS) based on wireless communication have the potential to improve road safety, traffic throughput and fuel consumption. For example, Cooperative Adaptive Cruise Control (CACC) is a promising ITS technology, which exploits vehicle-to-vehicle (V2V) communication to enable the formation of vehicle platoons with small inter-vehicle distances while avoiding amplifications of disturbances (causing ghost traffic jams) along the vehicle string. The control design for such a safety-critical cyber-physical system is, however, challenging. Firstly, the introduction of wireless communication involves inevitable network imperfections, such as a limited communication bandwidth and time-varying transmission delays. Secondly, it is shown that excessive utilization of communication resources jeopardizes the reliability of the communication channel. Especially the latter might restrict the minimum time gap that can be realized safely. As such, to be able to harvest all the benefits of CACC, it is of interest to design resource-aware controller such that only the information, which is actually needed to establish a (string-)stable platoon, is transmitted over the wireless network.

2. CONTROL SETUP

Consider a vehicle platoon consisting of N identical vehicles equipped with CACC as illustrated in Fig. 2. A CACC system has two objectives, vehicle following and attenuation of disturbances along the vehicle string. The main objective of each vehicle in the platoon is to maintain a desired distance with respect to its predecessor. In case a constant time gap policy is employed, the desired distance of a vehicle i, $i \in \{1, 2, \ldots, N\}$ at time $t \in \mathbb{R}_{\geqslant 0}$ is given by

$$d_{r,i}(t) = r + hv_i(t), \tag{1}$$

where $v_i(t)$ denotes the velocity of vehicle i at time t, r the standstill distance and where $h \in \mathbb{R}_{>0}$ represents the desired constant *time gap*. The first vehicle in the platoon (corresponding to $i = 1$) is assumed to follow a *virtual reference vehicle*. As such, $d_{r,1}$ represents the desired distance between the leading vehicle and the virtual reference vehicle.

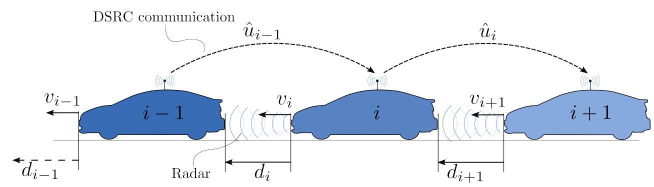

Figure 1: The time-response of the velocity and desired acceleration of the two vehicles and the inter-event times generated by the event-triggering mechanism.

Let $d_i(t)$ represent the actual distance between vehicle i and its preceding vehicle (vehicle $i-1$) at time $t \in \mathbb{R}_{\geqslant 0}$, then we define the spacing error $e_i(t)$, $i \in \{1, 2 \ldots, N\}$, at time $t \in \mathbb{R}_{\geqslant 0}$ as

$$e_i(t) := d_i(t) - d_{r,i}(t). \tag{2}$$

Hence, one of the main objective of CACC systems is to regulate the spacing error as given in (2) towards zero.

Typically, a CACC scheme consists of a feedback controller that depends on the spacing error and a feedforward component being the direct feedthrough of the desired acceleration of the preceding vehicle obtained via V2V communication. To be more concrete, the control law of the i-th vehicle in the platoon has the form

$$\xi_i(t) = \underbrace{k_p e_i(t) + k_d \dot{e}_i(t)}_{\text{feedback}} + \underbrace{\hat{u}_{i-1}(t)}_{\text{feedforward}}, \tag{3}$$

where k_p and k_d are controller gains. See [2] for more details. We employ the notation $\hat{u}_{i-1}$ to denote the most recently received information regarding u_{i-1} by vehicle i.

As mentioned before, a second objective of a CACC system is to avoid disturbance propagation along the vehicle string. In essence, this property, also referred to as string stability, constitutes a $\mathcal{L}_2$-gain property in the sense that the $\mathcal{L}_2$-gain of the platoon systeem with respect to u_{i-1} and u_i, $i \in \{1, 2, \ldots, N\}$ should be less than or equal to one.

3. EVENT-TRIGGERED CONTROL

Since excessive use of the communication network should be avoided, a novel (periodic) event-triggered control (ETC) methodology has been proposed in [1] that aims to reduce the utilization of communication resources while maintaining the desired closed-loop ($\mathcal{L}_2$-gain) performance proper-

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Figure 2: Benchmark platoon consisting of passenger cars equipped with long-range radar and wireless communication.

ties. To be more concrete, in the proposed ETC strategy, the local measurement u_i, $i \in \{1, 2, \ldots, N\}$ is sampled periodically at fixed sample times $s_n^i = nT_s$, $n \in \mathbb{N}$, where $T_s \in \mathbb{R}_{>0}$ is the sample period. At each sample time s_n^i, $n \in \mathbb{N}$, $i \in \{1, 2, \ldots, N\}$, an event-generator decides whether or not the desired acceleration $u_i(s_n^i)$ should be transmitted to the following vehicle instead of transmitting at each sampling instant. Hence, the sequence of event times $\{t_k^i\}_{k\in\mathbb{N}}$ is a subsequence of the sequence of sample times $\{s_n^i\}_{n\in\mathbb{N}}$. The sequence of event/transmission times $\{t_k^i\}_{k\in\mathbb{N}}$ is generated by *dynamic* periodic event-generators of the form

$$t_0^i = 0,\ t_{k+1}^i = \min\{t > t_k^i \mid \zeta_i^\top (N_N - \beta Q)\zeta_i \leqslant 0 \\ \wedge\, \zeta_i^\top(t) Q_i \zeta_i(t) \geqslant 0,\ t = nT_s,\ n \in \mathbb{N}\}, \quad (4)$$

where the dynamic variable η^i evolves according to

$$\dot{\eta}_i(t) = -2\rho\eta_i, \qquad t \in (s_n^i, s_{n+1}^i),\ n \in \mathbb{N}, \quad (5a)$$

$$\eta^i(t^+) = \eta_i + \zeta_i^\top N_T^i \zeta_i, \qquad t \in \{t_k^i\}_{k\in\mathbb{N}}, \quad (5b)$$

$$\eta^i(t^+) = \eta_i + \zeta_i^\top (N_N^i - \beta Q)\zeta_i, \qquad t \in \{s_n^i\}_{n\in\mathbb{N}} \setminus \{t_k^i\}_{k\in\mathbb{N}}, \quad (5c)$$

and where ζ_i denotes the vector $(u_i, \hat{u}_i)$. Moreover, the scalar $\beta, T_s \in \mathbb{R}_{>0}$ and the matrices $Q_i, N_T^i, N_N^i \in \mathbb{R}^{2\times 2}$ can be synthesized by means of LMI conditions the presented in [1].

4. EXPERIMENTAL RESULTS

To validate the proposed resource-aware control design and to demonstrate its technical feasibility, the event-triggered CACC strategy was tested on a platoon of two (almost) identical cars. The Toyota Prius III Executive equipped with long-range radar, GPS and a communication module that uses the IEEE 802.11p-based ETSI ITS G5 standard for communication, is selected as benchmark vehicle. In Fig. 1 and Fig. 2, the experimental results for the ETC proposed in [1] are shown. In particular, the time responses of the spacing errors show that the performance of the ETC implementation is similar to the performance of a conventional time-triggered control scheme. As such, the experimental results illustrate the potential benefits of event-triggered control for relevant cyber-physical systems, namely, having significantly larger inter-event times while realizing similar control performance in comparison with conventional time-triggered control methods.

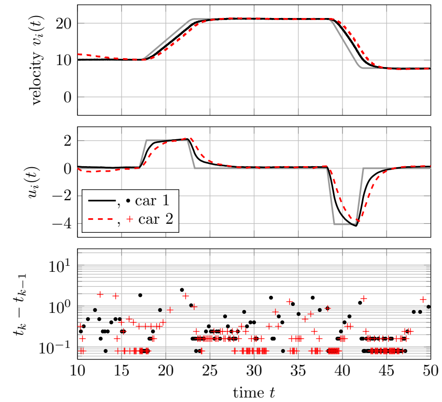

Figure 3: The time-response of the velocity and desired acceleration of the two vehicles and the inter-event times generated by the event-triggering mechanism.

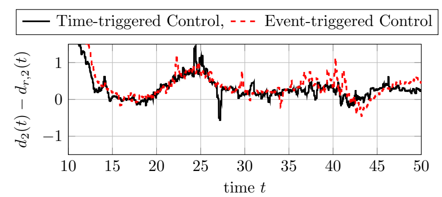

Figure 4: The time-response of the spacing error corresponding to the time-triggered and the event-triggered case.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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