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Adaptive multi-agents synchronization for collaborative driving of autonomous vehicles with multiple communication delays[☆,☆☆]

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ABSTRACT

The development of automated and coordinated driving systems (platooning) is an hot topic today for vehicles and it represents a challenging scenario that heavily relies on distributed control in the presence of wireless communication network. To actuate platooning in a safe way it is necessary to design controllers able to effectively operate on informations exchanged via Inter-Vehicular Communication (IVC) systems despite the presence of unavoidable communication impairments, such as multiple time-varying delays that affect communication links. To this aim in this paper we propose a novel distributed adaptive collaborative control strategy that exploits information coming from connected vehicles to achieve leader synchronization and we analytically demonstrate its stability with a Lyapunov-Krasovskii approach. The effectiveness of the proposed strategy is shown via numerical simulations in PLEXE, a state of the art IVC and mobility simulator that includes basic building blocks for platooning.

1. Introduction

Nowadays Intelligent Transportation Systems (ITS) lead to positive effects, in terms of pollution and safety. Connected vehicles improve the traffic flow mitigation, and a fundamental aim is to cooperatively drive the road by operating vehicle's platoon that maintain an optimal inter-vehicular spacing policy, tracking at the same time desired speed and acceleration profiles. The natural breakthrough is the improvement of road capacity and traffic congestion mitigation (Claes et al., 2011; Claes and Holvoet, 2014), while preserving at the same time fuel economy and decrease of pollutants emissions (Wan et al., 2016; Farah and Koutsopoulos, 2014; Lioris et al., 2017; Liu et al., 2017b; Maiti et al., 2017).

In this driving paradigm all connected vehicles embed wireless communication hardware in order to share information with neighbors and to receive the reference signal coming from the leading vehicle. To support ITS applications, the IEEE 802.11p communication protocol is the de facto vehicular networking standard (Karlsson et al., 2012). It defines the enhancements necessary to the IEEE 802.11 (the basis of products marketed as Wi-Fi) for allowing data exchange among high-speed vehicles and/or between the vehicles and the roadside infrastructure (Alasmary and Zhuang, 2012). On the basis of information received from vehicles within the platoon, the on-board control algorithm is responsible of the safe tracking of the desired velocity and acceleration profile, *i.e.* vehicles have to track the leader motion while respecting at the same time a pre-determined inter-vehicles spacing policy (Alvarez and Horowitz, 1997; Ayres et al., 2001). The goal is to perform a reference tracking that allows followers to pursue the leader in a safe

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way but guaranteeing at the same time excellent transient dynamics. Transient performance are fundamental during normal operation, when deceleration, or acceleration, maneuvers must be safely executed (*e.g.* in the occurrence of sudden traffic) avoiding that any vehicle in formation falls too far behind the vehicle ahead (Rajamani, 2011; Alvarez and Horowitz, 1999). Tracking ability assume also a great importance during join or emergency braking maneuvers, when all vehicles has to safely brake reaching their required stand-still distance when they finally stop (Milanés et al., 2014; Liu et al., 2015, 2017c).

Although a platoon is a group of lined vehicles, different communication topologies arise, depending from the on board communication facilities, their features (Zheng et al., 2016a; Salvi et al., 2017), and how the information is used by the control algorithm. Furthermore, since vehicles are moving within a non-ideal wireless communication environment, information can be received by each vehicle with a different (multiple, or heterogeneous) time-varying delay, whose current value depends on the network conditions (Cao et al., 2013; Zheng et al., 2014). Note that since communication impairments are unavoidable in practice, the control input, that is computed on the base of the network information, results to be affected by delay in realistic scenarios and packet losses (Richard, 2003).

Typical control schemes for platoon follow a Cooperative Adaptive Cruise Control (CACC) approach which adopts pre-fixed communication patterns during control design, such as, for example, predecessor-follower (Rajamani, 2011; Zhou et al., 2017). The aim is to provide robustness to the platoon that is assumed to be already formed and traveling with a target velocity, so that small perturbation on leading vehicle are de-amplified toward the platoon tail. The analytical control synthesis is usually performed by exploiting linear tools in the frequency domain under the assumption that the inter-vehicle communication is ideal or affected by a unique constant delay. A sensitivity analysis is sometimes added to investigate the effect of delay variation. See Dey et al. (2016a), and references therein, for a recent and wide review of the technical literature.

Formation control of autonomous vehicles is one of the typical problems addressed in the context of multi-agent systems (MAS) (e.g. for the flight formation of autonomous aerial vehicles (Bartels and Werner, 2014)). It follows that a multi-agent system has been naturally proposed as an alternative modeling approach to easily handle the coordination of ground vehicles (cars) and to manage platoon tasks (e.g. see (Ren and Beard, 2008; Fernandes and Nunes, 2015; Santini et al., 2017; Seyboth et al., 2016; Salvi et al., 2017; Letter and Elefteriadou, 2017; Petrillo et al., 2017a; Fiengo et al., 2016; Hult et al., 2017) and references therein). By leveraging this paradigm, a platoon composed by multiple connected and automated vehicles is represented as one-dimensional network of dynamical agents, in which each agent only uses its neighboring information to locally control its motion, while it aims to achieve certain global coordination with all other agents. This framework is schematically represented in Fig. 1 as the composition of the following main interrelated components: (a) agent dynamics, that model the longitudinal dynamics of each vehicle; (b) communication topology, which indicates how and if an agent obtains information about other agents depending on the active communication links (see also Fig. 2 where some exemplar platoon topologies are depicted); (c) formation geometry, which defines the desired spacing between adjacent vehicles in a platoon; (d) distributed collaborative control that is implemented at the single-vehicle level and depends on both the state variables of the vehicle itself (measured on board) and information received from neighboring vehicles through the communication topology.

Within the context of multi-agent systems, the consensus-based approaches have been recently proposed in (Santini et al., 2017; Jia and Ngoduy, 2016; Salvi et al., 2017) to deal with both topology variety and heterogeneity in the time-varying communication delays, but the theoretical analysis disregards leader tracking maneuvers (when the leader dynamically changes its velocity profile) and focus on the so called leader-law (Alvarez and Horowitz, 1999), where the platoon first forms itself and then travels with a common constant velocity.

In particular in (Jia and Ngoduy, 2016; Santini et al., 2017 and Salvi et al., 2017) the problem of communication losses has been theoretically investigated by exploiting stability tools for delayed networks, but neglecting acceleration profiles. An alternative approach, based on a sliding mode control, has been also recently designed in (Fernandes and Nunes, 2015) in the presence of an actuation lag, but under the restrictive assumption of perfect communication among agents.

More recently, consensus has been also exploited to achieve leader-tracking by describing the drivetrain but in absence of

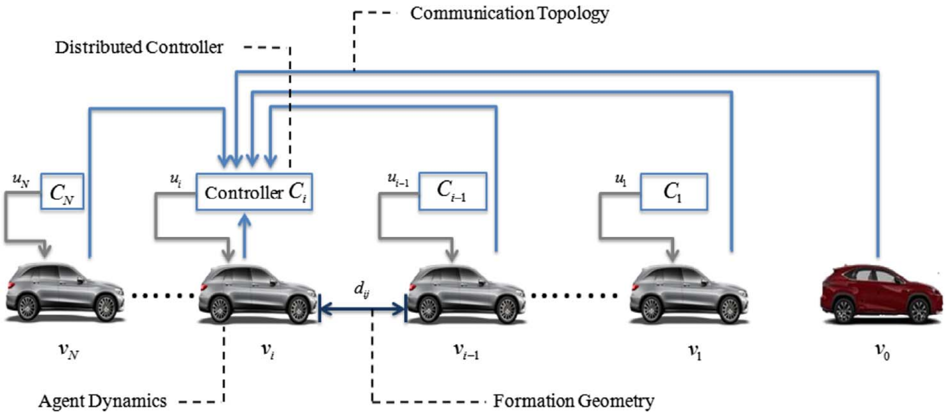

Fig. 1. Schematic representation of a platoon as a multi-agent system (Wu et al., 2016).