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Design, analysis and performance evaluation of a third order distributed protocol for platooning in the presence of time-varying delays and switching topologies ☆

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ABSTRACT

This paper is concerned with the problem of designing a decentralized consensus protocol for platooning of non-identical vehicles in the presence of heterogeneous time-varying communication delays. The proposed control protocol makes use of a state feedback and to this aim drivetrain dynamics are modeled as third-order linear systems. Necessary and sufficient conditions for convergence and exponential stability, derived by using an appropriate Krasovskii functional, demonstrate the ability of the platoon in reaching the required regime with an exponentially bounded behavior. The proposed LMI-based approach allows to estimate both delay margin and decay rate. Moreover, convergence is proven under switching communication network topologies by means of a Lyapunov-Razumikhin function, and the assessment of a string stable behavior has been also theoretically investigated. High-fidelity simulations with Plexe show the effectiveness of the theoretical results in different driving conditions and in the presence of external disturbances and communication impairment. Different communication channel models are used in the validation stage to further prove robustness of the proposed methodology with respect hard delay and packets losses.

1. Introduction

Platooning is a viable control solution for cooperative driving systems. The goal is to achieve decentralized control of a fleet of vehicles so that they all converge towards some common target motion specified by a leader vehicle. The speed and relative position of each vehicle in the platoon are then regulated by taking into account those of the neighboring vehicles and the reference motion of the leader. The building and managing of platoon requires multiple technologies. Elements essentials for guaranteeing coordination of vehicles are: (i) control algorithm to regulate the relative distance with respect to the vehicle ahead and to coordinate and stabilize the formation during motion and (ii) communication network to exchange information among vehicles. In this scenario each vehicle within the platoon is equipped with on board sensors, to get measurements about its state variables, and hardware for V2V wireless communication, necessary to share information with

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Nomenclature

VANET	Vehicular Ad Hoc Network
MAC	Medium Access Control
CCH	Control Channel
PER	Packet Error Rate
SUMO	Simulation of Urban MObility
MSDU	MAC Service Data Unit
QPSK	Quadrature Phase-Shift Keying
V2V	Vehicle to Vehicle
LMI	Linear Matrix Inequality

neighbors and to receive reference signals (di Bernardo et al., 2016; Kianfar et al., 2012). Indeed, only by sharing information from neighboring, vehicles are able to reach a joint objective (Wang et al., 2014) under the action of decentralized, and distributed, collaborative control strategies (Wang et al., 2016).

Since information is exchanged through wireless network, different time-varying delays are associated to their communication (Jia and Ngoduy, 2016). It has been shown that such time-varying delays can compromise stability of the platoon, and even lead to the loss of the desired common motion for the formation, as well as robustness in the presence of bounded disturbances acting on the leader motion (string stability) (Liu et al., 2001). Typically, research work on platooning mainly focuses on this last aspect and investigate how the variation of the amount of inter-vehicular communication delay, assumed to be constant and equal for each vehicle, affects string stability (e.g., see Liu et al., 2001; Oncu et al., 2014; Lu et al., 2004 and references therein). Less attempts instead concern the design of control algorithms able to counteract the presence of delays. A review of the literature in this field can be found in Dey et al. (2016), where most of the work is proposed under the hypotheses of ideal communication or under the restrictive assumption that communication delays are homogenous (or unique) and often constant, all over the communication network. Note that this is a classical hypothesis currently made also in the generic context of consensus problems in multi-agents systems (e.g. see Wang et al. (2016) and Li et al. (2013) and references therein). Furthermore, the stabilization problem of linear and nonlinear systems with time-varying input and/or state delays is still a cumbersome problem in control theory (Bekiaris-Liberis and Krstic, 2013), where recent research work is devoted to the compensation of delay to avoid catastrophic effects on the closed-loop dynamics (see for example Bekiaris-Liberis and Krstic (2012) and Bekiaris-Liberis and Krstic (2013) and references therein).

Recently, by exploiting the dynamic networks theory, consensus has been proposed as an effective tool to design control algorithms able to deal with both time-varying delays and space constraints in di Bernardo et al. (2015), di Bernardo et al. (2016), and Jia and Ngoduy (2016). Following this approach, the vehicular fleet was modeled as a dynamical network of second-order linear agents that communicate over a wireless network with an arbitrary topology (not necessarily limited to a predecessor-follower structure, or other pre-fixed pairwise interactions, like in the classical Cooperative Adaptive Cruise Control approach Rajamani, 2012). Specifically, in di Bernardo et al. (2015) and Jia and Ngoduy (2016) the analytical derivation has been performed leveraging the ideal assumptions that vehicles are identical (the dynamics are represented as simple double integrators) and that communication impairments can be modeled as an aggregate communication delay at vehicle/node level. The hypothesis of aggregate communication delays has been also recently exploited for control design in Jia and Ngoduy (2016) with the different aim of attenuating car-following traffic leveraging V2V, V2I communication with the road infrastructure, and roadside sensors.

As highlighted in Cao et al. (2013), when treating with communication networks, e.g. based on the IEEE 802.11p protocol, each communication link, that connects a pair of agents, is affected by a different variable time-delay that depends from actual conditions of the communication channel. It follows that in vehicular networks delays have to be considered as time-varying functions depending from the specific communication link under investigation (di Bernardo et al., 2016) (multiple, or heterogenous, time-varying delays).

Under this framework this paper present a further extension of the approach presented in (di Bernardo et al., 2016) whose advantage is threefold. Firstly, vehicles in the network are modeled by non identical, or heterogeneous, third-order drivetrain linear systems, which are well established in the automotive literature (e.g. see Rajamani, 2012), rather than being simply approximated as second-order inertial agents. Usually car-following models rely on third-order dynamics of non-identical vehicles that explicitly consider the acceleration variable to mimic the vehicles driving along a lane (Jia et al., 2014). Moreover, acceleration-based connected cruise control has been recently indicated as a key ingredient to increase roadway traffic mobility, enabling automated vehicle to better respond to traffic conditions, and to avoid any vehicle falling too far behind the vehicle ahead (e.g. see Rajamani, 2012; Jia and Ngoduy, 2016; Jin and Orosz, 2014; Han et al., 2013 and references therein). For these reasons our analytic derivation leverages on third-order dynamics of non-identical vehicles and exploits a full state-feedback control approach. Note that the exploitation of a third-order model has been recently highlighted as a