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Evaluating the performance of vehicular platoon control under different network topologies of initial states

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HIGHLIGHTS

- A feedback based protocol for platoon control is proposed considering the longitudinal and lateral gaps simultaneously.
- The stability and consensus of the vehicular platoon is analyzed using the Lyapunov technique.
- Effects of different network topologies of initial states on convergence time and robustness of platoon control are investigated.
- Results demonstrate the effectiveness of the proposed protocol with respect to the position and velocity consensus.
- The findings illustrate the convergence time is associated with the initial states, while the robustness is not significantly.

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ABSTRACT

This study proposes a feedback-based platoon control protocol for connected autonomous vehicles (CAVs) under different network topologies of initial states. In particularly, algebraic graph theory is used to describe the network topology. Then, the leader–follower approach is used to model the interactions between CAVs. In addition, feedback-based protocol is designed to control the platoon considering the longitudinal and lateral gaps simultaneously as well as different network topologies. The stability and consensus of the vehicular platoon is analyzed using the Lyapunov technique. Effects of different network topologies of initial states on convergence time and robustness of platoon control are investigated. Results from numerical experiments demonstrate the effectiveness of the proposed protocol with respect to the position and velocity consensus in terms of the convergence time and robustness. Also, the findings of this study illustrate the convergence time of the control protocol is associated with the initial states, while the robustness is not affected by the initial states significantly.

1. Introduction

Over the past few decades, traffic problems such as traffic congestion, traffic management, transportation planning have received much attention. To address these problems, there has been a lot of focus on capturing the complex mechanisms behind the phenomena of vehicular traffic flow from the microscopic and macroscopic viewpoints. Consequently, various traffic flow models such as car-following (CF) models [1–14] and lattice hydrodynamic models [15–18] have been proposed.

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However, these models focus on understanding the characteristics of traffic flow rather than the vehicular formation forming. Especially regarding to the stability analysis of the above traffic flow models, the assumption that the traffic flow is a steady-state platoon with identical space headway and velocity is made first [2–13,15–17]. As we know that platoon-based driving pattern (a special formation) referred to a group of vehicles traveling together with short inter-vehicle headway is regarded as a promising driving manner. Benefits of platoon driving pattern include the road capacity increase, traffic congestion mitigation, and energy consumption and exhaust emissions reduction [19,20].

Recently, autonomous vehicles (AVs), i.e., Google driverless car, have received much attention. Compared to human-driven vehicles, AVs can be operated without direct driver input to control the steering, acceleration, and braking so that the vehicles can travel with higher mobility, less faults, and smarter choices. In this context, AVs equipped with the communication technology (i.e., vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications), connected autonomous vehicles (CAVs), can generate and capture environmentally relevant real-time transportation data and use this data to create actionable information to support and facilitate green transportation choices [21], such as improving the efficiency of intersections [22] and applying to the real-time adaptive signal control [23]. In the context of CAVs, an AV can cooperate with other AVs based on the information of position, speed, and acceleration via the V2V communications. Consequently, it leads to an efficient cooperative task. On the other hand, in many developing countries where multiple vehicles can travel in parallel in a road without lane discipline. And past studies illustrate that the vehicles travel with lateral gaps consume more energy under non-lane-discipline environment [14]. Hence, there is a research need to study the control protocol to facilitate the CAVs to form a platoon considering the longitudinal and lateral gaps simultaneously under the non-lane-discipline environment.

Existing approaches to vehicular formation control can be classified as the leader–follower approach and the virtual leader approach. The leader–follower approach is of significance for the multi-agent control problem, where the leader moves along a predefined trajectory while the others, the followers, maintain a desired distance and orientation to the leader [24]. By applying the local leader–follower control to small fraction of agents, Guan et al. [25] proved that the states of the pinning-controlled multi-agent system can approach the states of the leader in finite time. Ma et al. [26] and Djaidja et al. [27] studied the leader-following consensus control for multi-agent systems under measurement noise. However, the reference leader to track is considered constant. To address this issue, Su et al. [28] and Peng et al. [29] considered the situation that the leader moves with a varying velocity, and then designed the protocol which enables followers to asymptotically track the leader. Although the leader–follower approach depends heavily on the leader for achieving the goal. However, this approach is widely used in the cooperative systems for its simplicity and scalability.

Unlike the leader–follower approach, the virtual leader approach assumes each agent behaves like particles embedded in a rigid virtual structure. Desired trajectories are not assigned to each single agent but to the entire formation as a whole. Lu et al. [30] investigated the tracking control problems with a virtual leader under the conditions of fixed and switching topologies in finite time, respectively. Ren et al. [31] proposed a feedback protocol in order to improve the performance of the system in terms of the robustness. Shi et al. [32] introduced a set of coordination control laws that enables the group to generate the desired stable state, and then studied the coordinated control for multiple agents using the virtual leader approach. Zhang et al. [33] proposed a distributed feedback law related to the virtual leader to address the problem of coordinated path tracking. This approach avoids the problems with disturbance rejection inherent in the leader–follower approach, but at the cost of high communication and computation capabilities needed to synthesize the virtual leader and communicate its position in time to support real-time control of other vehicles. In addition, it may cause unexpected instability for algorithms without considering the communication delay and feedback [34,35].

The literature review heretofore illustrates that the formation control is an important issue in the cooperative systems. However, the above mentioned studies do not consider the effects of different network topologies of initial states. Also, they do not consider the space constraints as well. Hence, motivated by the CAVs context, this study restricts its focus to protocol design to facilitate the CAVs to form a platoon under the non-lane-discipline road. The emphasis is on the effects of different network topologies of initial states on the platoon control performance. Specifically, we firstly transform a general problem into an analytical formation to describe the network topology using the algebraic graph theory. Then, the interactions between CAVs are modeled using the leader–follower approach. In addition, feedback-based protocol is designed to control the platoon considering the longitudinal and lateral gaps simultaneously. The stability and consensus of the platoon is analyzed using the Lyapunov technique. Effects of different network topologies of initial states on convergence time and robustness are investigated. Results from numerical experiments demonstrate the effectiveness of the proposed protocols with respect to the position and velocity consensus in terms of the convergence time and robustness.

The rest of the paper is organized as follows: Section 2 presents the problem formulation and some preliminaries. Section 3 proposes control protocol for CAVs, and analyzes the stability and consensus problems. Section 4 performs numerical experiments under different initial states. Section 5 concludes this study.

2. Problem formulation and preliminaries

As shown in Fig. 1, the vehicular systems include a leading vehicle (noted as the leader), and other following vehicles (noted as followers, vehicle i, $i+1$, $i+2$). Considering the characteristics of AVs, we treat each CAV as an agent using the multi-agent systems theory. The goal of this study is to design control protocol to facilitate CAVs in Fig. 1 to form a platoon as shown in Fig. 2 in the context of V2V communications, which the initial longitudinal and lateral gaps between any vehicles