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Event-triggered platoon control of vehicles with time-varying delay and probabilistic faults

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ABSTRACT

This paper investigates event-triggered platoon control of vehicles with probabilistic faults (i.e., sensor and actuator) and time-varying communication delay. A novel platoon model is established, in which the effect of time-varying delay, event-triggered scheme and probabilistic faults are involved. Based on the new model, criteria for the exponential stability and criteria for co-designing both the output feedback and the trigger parameters are derived by using Lyapunov functional. The obtained controller is complemented by additional conditions established for guaranteeing string stability and zero steady state velocity errors, yielding a useful string stable platoon control method. The effectiveness and advantage of the presented methodology are demonstrated by both numerical simulations and experiments with laboratory scale Arduino cars.

1. Introduction

Over the past decade, a considerable attention has been paid to the research theme of automated vehicles in intelligent vehicle highway systems [1,2]. There are so many advantages of moving vehicle based on the notion of platoons, such as driving safety and comfort, reducing fuel consumption and air pollution, and improving the throughput in the highway [3,4]. Due to this, a lot of research works on platoon control have been extensively studied in [5–7].

The control architectures of platoon investigated in the literature can be classified into three broad categories: *predecessor-following, nearest neighbor following and predecessor and leader following*. The architecture is called *predecessor following* if the control action on a particular vehicle depends on the information with the predecessor, i.e., the vehicle in front of it. This scheme is decentralized, since the control action on each following vehicle is computed based upon measurements obtained by on-board sensors (such as radar/lidar). It was shown that this architecture suffers from a drawback known as string instability [7]. That is, the response of a disturbance on an individual vehicle will be amplified along the string of vehicles. “Time headway” was introduced in [1,8] to overcome this difficulty, and in which the inter-vehicle distances are dependent on vehicle velocities. However, this only helps when the control bandwidths are allowed to diverge as the number of vehicles grows [9]. Alternatively, in [10] shown that string stability can be achieved if the *nearest neighbor following* scheme is adopted, where the control action on a particular vehicle is based on the relative distance and velocity information from its predecessor and follower vehicles. This scheme is also decentralized, since the control information can be obtained by on-board sensors alone. Still, the *nearest neighbor following* control suffers from the high sensitivity to the length of the vehicular platoon and lower performance [11]. In [6], the authors investigate optimal control strategies for the *nearest neighbor following* with an increasing number of vehicles and show that some related LQR

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problems are ill-posed. A mistuning control method is designed in [12] to improve the stability margin of platoon system. In order to enhance the coherence of the *nearest neighbor following control* scheme, an optimal controller was designed in [13].

Another control architecture investigated in the literature, and on which we focus in this research is centralized *predecessor and leader following* platoon control structure. This control scheme is advantageous because, apart from its simplicity in achieving string stability, it utilizes the wireless communication technology to increase the performance of the platoon. However, use of the wireless communication immediately causes some questions on the effect of communication constraints. Under this framework, these works presents in [14,15] studied the effects of communication delays on string stability; longitudinal platoon control and state estimation via communication channels with packed-dropout are addressed in [16,17]; a decentralized communication and control strategy is presented in [18,19] for automated driving assistance to a platoon of vehicles in heavy traffic and scarce visibility.

It is worth noting that most existing results on *the predecessor and leader following* control are limited in at least the following three aspects. Firstly, ignoring the frequently operating on the controller, which can increase fuel consumption and bring uncomfortable to the passengers. In [20], the authors explore how the frequent operation affects the fuel consumption. In [21], a model predictive control method was discussed, which can minimize the frequent operation on the brake or the throttle. Nevertheless, this control method suggested is not applicable to the *predecessor and leader following* platoon system. Secondly, without considering the contingent faults might happen to sensors in practical cars for reasons such as poor visibility due to rain or sandstorm, low battery power, and interference of radar signals (see, e.g., [22]). Different factors may cause different faults properties. For example, when a car is running in the rain, the signal-to-noise ratio of a radar sensor may noticeably decay with the rainfall intensity, and the fault rate may increase with the rain level until momentary freezing or complete fault happens [23]. The vulnerability of automobile radar/lidar sensors to weather phenomena such as rain and snow (which is due to the scattering of radio waves from particulate matters such as raindrops or snowflakes) was studied by many researchers in [22,23]. The combined actuator fault is the third aspect that may add to the limitations since the actuator faults will cause a mistake operate on speed growing or decreasing. Previous work on actuator fault detection and fault tolerant control related to platoon system control have been carried out by Douglas et al. [24], Rajamani and Howell [25] and Jingang and Lionel ([26,27]). However, the detection technology suggested is not applicable to the fully automated platoon control system that we are interested in here. How would probabilistic sensor and actuator faults affect the string of vehicles still remains an open and challenging problem, and this is the intention of this paper.

The aim of this paper is to set up an autonomous platoon control framework that takes full consideration of the probabilistic sensor and actuator faults and time-varying communication delay. We first model the platoon system in the context of an event-triggered scheme, sufficient conditions for the existence of output feedback controllers are derived based on the Lyapunov method, which ensures the exponential stability of the platoon system. With these conditions, not only the individual vehicle stability and string stability can be guaranteed with a desired exponential decay rate, but also zero steady-state velocity errors can be achieved. As will be shown later in both numerical simulations and experiments with Arduino cars, the presented method can serve as an effective algorithm for practical use.

The organization of this paper is as follows. In Section 2, after a brief description of the dynamics of the vehicle model, an event-triggered autonomous platoon model is established with sensor and actuator faults and time-varying delay taken into consideration. In Section 3, an event-triggered controller design procedure is proposed for dealing with sensor and actuator faults and time-varying delay. In Section 4, sufficient conditions for the controller to achieve string stability and zero steady-state velocity errors are presented to complement the event-triggered controller, leading to a string stable algorithm. Simulations and experiments are presented in Section V, showing the usefulness and advantage of the proposed methods. The conclusions are given in Section 5.

Notation: The notation used throughout the paper is fairly standard. The superscript "T" stands for matrix transposition; R^ndenotes the $n-$ dimensional Euclidean space (R stands for R^1) and the notation $P>0$ (≥ 0) means that P is real symmetric and positive definite (semi-definite). In symmetric block matrices, we use an asterisk ($*$) to represent a term that is induced by symmetry and $diag\{\cdots\}$ stands for a block-diagonal matrix. When x is a stochastic variable, $E[x]$ stands for the expectation of x. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. Problem formulations

Consider a platoon system consisting of n vehicles (see Fig. 1) running in a horizontal environment. Denote by z_i, v_i and a_i the ith (i=0,…,n-1) vehicle's position, velocity and acceleration, with i=0 standing for the lead vehicle and the others being followers. Each follower vehicle periodically broadcasts its position, velocity and acceleration to the following vehicle in the platoon one by one. The lead vehicle periodically broadcasts its position, velocity and acceleration to all the follower vehicles in the platoon.

In what follows, we will describe the platoon system model, the time-varying delay, the event-triggered scheme, sensor and actuator faults and our control objective in detail one by one.

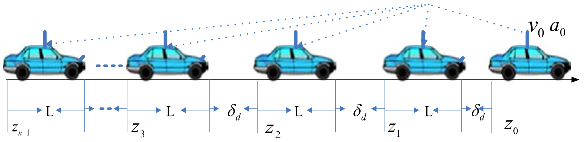

Fig. 1. Platoon of vehicles.