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A control matching model predictive control approach to string stable vehicle platooning

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ABSTRACT

A predictive control strategy for vehicle platoons is presented in this paper, accommodating both string stability and constraints (e.g., physical and safety) satisfaction. In the proposed design procedure, the two objectives are achieved by matching a model predictive controller (MPC), enforcing constraints satisfaction, with a linear controller designed to guarantee string stability. The proposed approach neatly combines the straightforward design of a string stable controller in the frequency domain, where a considerable number of approaches have been proposed in literature, with the capability of an MPC-based controller enforcing state and input constraints.

A controller obtained with the proposed design procedure is validated both in simulations and in the field test, showing how string stability and constraints satisfaction can be simultaneously achieved with a single controller. The operating region that the MPC controller is string stable is characterized by the interior of feasible set of the MPC controller.

1. Introduction

Automated highway, in particular vehicle platooning, is considered as an appealing technology to contribute alleviating traffic flow problem like congestions. A vehicle platoon consists of a chain of automated vehicles following each other led by a specific vehicle, i.e., the leader. The primary objective of a platoon is that vehicles should follow each other by maintaining a desired gap/distance to their preceding vehicles. The idea of platooning dates back to the 1980s when California Partner for Advanced Transportation Technology (PATH) was established to study and develop intelligent vehicle-highway cooperation and communication systems (PATH, 1986; Rajamani, Tan, Law, & Zhang, 2000). Since then, several studies on the potential impact of vehicle platooning on different aspect of transportation and traffic flow have been conducted (Bishop, 2000; Kavathekar & Chen, 2011). Potential benefit of vehicle platooning in reducing the fuel consumption is studied in Alam, Gattami, and Johansson (2010). The impact of vehicle platooning on the traffic flow is studied in, e.g., Shladover, Su, and Lu (2012), Van Arem, van Driel, and Visser (2006) and Arnaout and Bowling (2011). Regardless of the business model, to enable vehicle platooning, controllers must be developed to maintain a desired distance/time gap between vehicles.

In platooning, the longitudinal dynamics are controlled relying on measurements from on board sensors, e.g., radar and camera. However, to enable a short inter-vehicles distance between vehicles and to guarantee the so-called *string stability* property, wireless communication may be required as well (Naus, Vugts, Ploeg, de Molengraft, & Steinbuch, 2010a; Rajamani & Zhu, 2002).

The main challenges in the design of a longitudinal dynamics controller for vehicle platooning applications are (i) satisfying safety and performance requirements within the actuators limitations (hereafter refer to as time domain requirements) and (ii) guaranteeing string stability. As it is shown in previous works, Bu, Tan, and Huang (2010), Li, Li, Rajamani, and Wang (2011), and Kianfar et al. (2012) control specifications and requirements, including safety, performance and actuators limitations can be formulated as inequality constraints in a model predictive control formulation. Alternatively, constraint satisfactions and safety can be verified a posteriori for any linear controller by using the set based approaches as in, e.g., Al Alam, Gattami, Johansson, and Tomlin (2011) and Kianfar, Falcone, and Fredriksson (2013a).

The focus of this paper is the design of a controller accommodating both time domain requirements and string stability. String stability is defined as the ability of a vehicle platoon to attenuate the effect of disturbances introduced by the leader (or any other vehicles) as it propagates down stream in the platoon. However, slightly different definitions for string stability can be found in the literature, e.g., string stability w.r.t. different disturbance signals and different norm sense (Ploeg, van de Wouw, & Nijmeijer, 2014). In this work, string stability is defined as the

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capability of a vehicle platoon in attenuating the energy of the acceleration signals as moving toward the tail of the platoon, as proposed by Grand Cooperative Driving Challenge (GCDC) (2011). However, it should be noted that string stability cannot guarantee safety. This motivates the fact that controllers should be equipped with a tool such that they can handle constraints (e.g., safety) explicitly.

Alternative designs of string stable vehicle platoons in the frequency domain with capability of handling model uncertainty are given in, e.g., Swaroop (1997), Eyre, Yanakiev, and Kanellakopoulos (1998), Seiler, Pant, and Hedrick (2004), Papadimitriou and Tomizuka (2004), and Shaw and Hedrick (2007).

Combining string stability and constraints satisfaction requirements in a single controller is not trivial. In general, guaranteeing constraints satisfaction, is not trivial in frequency domain designs. On the other hand translating the frequency domain definition of string stability into time domain settings as MPC, is not trivial either. In Dunbar and Caveney (2012) and Kianfar, Falcone, and Fredriksson (2013b), the string stability requirement is translated into inequality constraints in an MPC controller. However, the proposed methods require that each vehicle broadcasts an intended trajectory to its followers which might be impractical.

In this work, we propose a predictive control design procedure for vehicle platoons, accommodating both string stability and constraints (e.g., physical and safety) satisfaction. This is a two-step procedure. In the first step, a linear controller is designed in order to guarantee string stability. It is important to point out that the design can be based on any string stability definition and by resorting to any design procedure leading to a linear control structure. In this paper, as an example, a controller based on $H_{\infty/2}$ is designed to guarantee string stability. The choice of an H_∞ controller is well motivated considering the $\mathcal{L}_2$ string stability criterion adopted in this work. However, any other linear controller which can result in a string stable vehicle platoon can be suitable as well. Then, in the second step, the control problem is formulated in an MPC framework with the ability of handling the time domain constraints. Furthermore, a controller matching approach is used to tune the weighting matrices of the MPC controller such that its behavior matches the string stable controller while the constraints are not active (Di Cairano & Bemporad, 2010). In particular, the physical, safety and design constraints are embedded in an MPC controller. Then a convex optimization problem is solved to find the weighting matrices of MPC controller such that the same behavior as the string stable controller achieved by MPC controller. Accomplishing the aforementioned two steps results in a string stable MPC controller with the capability of fulfilling constraints, e.g., safety and actuator limitation.

2. Vehicle modeling

Consider two adjacent vehicles, as shown in Fig. 1. Let p_{i-1}, v_{i-1} and a_{i-1} denote the position, velocity and acceleration of the vehicle preceding the i-th vehicle (ego vehicle) in a platoon and p_i, v_i and a_i denote the position, velocity and acceleration of the i-th vehicle. Denote by e_p the position error w.r.t. a desired distance from the preceding vehicle, i.e., $e_{p,i} = p_{i-1} - p_i - d_0 - v_i h_i$, where d_0 and h_i are a constant safety distance and the constant headway time, respectively. The headway time is the time necessary to the ego vehicle to travel the distance to the preceding vehicle, at its current speed. The error dynamics are then described by the following set of equations:

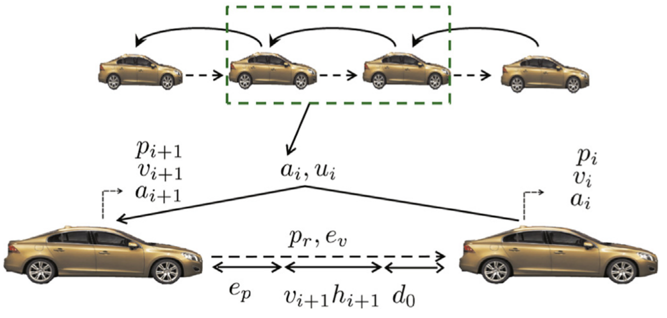

Fig. 1. Two adjacent vehicles in the platoon.

$$\begin{aligned} \dot{e}_{p,i} &= e_{v,i} - a_i h_i, \\ \dot{e}_{v,i} &= a_{i-1} - a_i, \end{aligned} \tag{1}$$

where $e_{v,i}$ is the relative velocity. The longitudinal acceleration dynamics can be described by

$$a_i = \frac{K_i}{\tau_i s + 1} e^{-\theta_i s} a_i^{\text{des}}, \tag{2}$$

where K_i, τ_i and θ_i are the steady state gain, the time constant of the actuator (engine and brake) and the actuator delay, respectively, and a_i^{des} is the demanded acceleration (Rajamani, 2005). The model (1)–(2) can then be written in a state-space form as

$$\dot{x}(t) = Ax(t) + B_u u(t-\theta) + B_\omega \omega(t), \tag{3}$$

where

$$A = \begin{bmatrix} 0 & 1 & -h_i & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & -1/\tau_i & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \tag{4}$$

$$B_u = \begin{bmatrix} 0 \\ 0 \\ \dfrac{K_i}{\tau_i} \\ 0 \end{bmatrix}, \quad B_\omega = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \tag{5}$$

and

$$x = \begin{bmatrix} e_{p,i} & e_{v,i} & a_i & v_i \end{bmatrix}^{\mathrm{T}}, \tag{6}$$

$$u_i = a_i^{\text{des}}, \tag{7}$$

$$\omega = a_{i-1}, \tag{8}$$

are the state, control and disturbance vectors, respectively. Notice that the acceleration of the preceding vehicle is considered as a measured disturbance.

3. Constraints and time domain requirements

Control objective is to minimize the position and velocity errors while satisfying a number of requirements described next. The requirements are written for a vehicle i.

3.1. Safety

The safety requirement is introduced to guarantee that a safe *minimum* distance is maintained from the preceding vehicle in order to prevent rear-end collisions. Based on the notation introduced in Section 2, the safety requirement can be written as