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Experimental verification of robustness in a semi-autonomous heavy vehicle platoon

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ABSTRACT

Novel numerical methods for analyzing robust peak-to-peak performance of heterogeneous vehicle platoons are presented. The goal is to compute worst-case spacing error peaks in terms of platoon heterogeneity, communication delays, disturbances and uncertainties in the vehicle dynamics. First, a convex set of parametric linear vehicle models is employed to analyze the effect of platoon heterogeneity. Then, a data-driven uncertainty modeling algorithm is developed that computes the least conservative spacing error bound for a given disturbance model class. The methods are demonstrated on three platoon controllers. One of them is a new constant spacing controller receiving control information from both the platoon leader and the immediate preceding vehicle.

1. Introduction

Organization of road vehicles in autonomous platoons has advantages in several scenarios including reduction of fuel consumption of heavy duty vehicles, increasing road capacity and automating some vehicle capabilities. The control aim in a platoon is to keep short gaps between the vehicles while maintaining a high level of security (Alam, 2011; Hedrick, McMahon, Narendran, & Swaroop, 1991; Naus, 2010; Rajamani, Tan, Law, & Zhang, 2000; Varaiya, 1993; Yanakiev & Kanellakopoulos, 1995). Very short safety gaps can be guaranteed under certain constraints on lead vehicle maneuvers when detailed system models are available (Gerdes & Hedrick, 1997; Liang, Chong, No, & Yi, 2003; Nouveliere & Mammar, 2007). However, the required engine/gearbox/brake system models are usually not available and depend on changing technical conditions of the aging vehicle. In addition, these controllers try to directly excite the brake cylinder pressures and throttle valve of the engine, which can conflict with the existing control units, such as Electronic Brake System (EBS) and Engine Control Unit (ECU). In a recent project TruckDAS (Rödönyi, Gáspár, & Bokor, 2013; Rödonyi et al., 2012a,b; Rödönyi, Gáspár, Bokor, & Palkovics, 2012) the goal was to explore the performance of an automated vehicle string based on low investments, few experiments and an appropriate control algorithm which, in contrast to most of the former solutions, does not use non-robust feedback-linearization techniques, but exploits only the standardized and general services[1] available on every modern commercial heavy truck. Utilizing existing, standardized services allows the widespread applicability of the platooning concept. As a disadvantage, model uncertainty increases as compared to the case of direct brake cylinder pressure and throttle valve control. This problem motivated the data-driven analysis approach presented in this paper.

1.1. ℓ_2- and ℓ_∞−string stability

All practical control approaches have the common goal of ensuring both vehicle and platoon stability with a sufficient level of performance. The notion of *string stability* was introduced by Peppard (1974), as the property of the vehicle string to attenuate disturbances as they propagated down the chain. String stability and ℓ_p-string stability were mathematically formalized in Swaroop (1994) and Swaroop and Hedrick (1996). If ℓ_∞−string stability holds for a platoon then there exists a bounded set of initial states such that the spacing error peaks remain uniformly bounded along

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[1] External deceleration demand provided by EBS, and external engine torque demands provided by ECU.

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the string. A weaker condition is ℓ_2-string stability. It guarantees that the energy of the spacing errors does not amplify along the platoon. The two conditions are equivalent for a homogeneous[2] platoon if the impulse response of the linear operator mapping one spacing error to the next in the chain is positive.

Shaw introduced the notion of *heterogeneous*[3] *string stability* and provided numerically tractable condition for ℓ_2-string stability for a predecessor following and a predecessor and leader following architecture, where the controllers utilized spacing information (Shaw & Hedrick, 2007). The stability result was independent of the vehicle ordering. Heterogeneous vehicle strings were also studied by means of simulation studies in Sheikholeslam and Desoer (1990). A collision free, safe platooning can be guaranteed only in terms of $\ell_\infty-$string stability (Alam, 2011; Alvarez & Horowitz, 1997; Canudas de Wit & Brogliato, 1999; Swaroop, 1994). A set theoretic approach for analyzing $\ell_\infty-$string stability was initiated in Canudas de Wit and Brogliato (1999), where a maximal invariant set[4] was explored by means of many simulations starting from different initial conditions. A more systematic set theory based approach was presented in Kianfar and Fredriksson (2012) and Kianfar (2013) where emergency braking of the lead vehicle was analyzed for a two vehicle platoon with parametric model uncertainty. A Hamilton–Jacobi–Isaacs partial differential equation was solved in Alam, Gattami, Johansson, and Tomlin (2014) for a two vehicle platoon, where the control action of the second vehicle was computed in terms of the worst-case control action of the lead vehicle.

1.2. Spacing policies and control architectures

Platoon controllers can be classified based on the applied spacing policy and the control architecture. The spacing policy, i.e. the desired distances between the vehicles in a platoon, can be constant (Rajamani & Zhu, 2002), velocity dependent (Ioannou & Xu, 1994) and nonlinear policies (Yanakiev, Eyre, & Kanellakopoulos, 1998). A possible control architecture is *predecessor following*, where the control action depends on the information received from the immediate preceding vehicle. It was shown in Chu (1974) that using only relative spacing information in a constant spacing control strategy, predecessor following leads to instability. Seiler, Pant, and Hedrick (2004) showed that this limitation is due to a complementary sensitivity integral constraint. The instability problem can be circumvented by using a constant time-headway (i.e. velocity dependent) spacing policy. The stability can be restored also by using a *predecessor and leader following* architecture (Swaroop & Hedrick, 1996). A bidirectional control architecture was studied in Seiler et al. (2004) and Barooah and Hespanha (2005), where controllers received information from both the immediate preceding and following vehicles. These analysis results were generalized in Middleton and Braslavsky (2010) to heterogeneous platoons and a wide spectrum of spacing policies and communication architectures.

The above analysis methods cannot be directly applied to two of the controllers presented in the paper, where predecessor and leader following controllers with constant spacing policy receive both spacing and acceleration/acceleration demand information.

1.3. Numerical analysis methods

In the analysis methods discussed above the applicable set of control architectures, spacing policies, platoon dynamics and error norms are determined and the algorithms cannot be trivially extended to general heterogeneous platoons and ℓ_∞ performance concept. The main contribution of this paper is an alternative analysis approach for $\ell_\infty-$bounds on the spacing errors, when the heterogeneous platoon starts from zero initial conditions and is subject to modeling uncertainties, disturbances and arbitrary lead vehicle maneuvers.[5] Based on the superposition principle of linear systems, the proposed approach consists of two numerical methods. The first one computes bounds due to lead vehicle maneuvers. The bounds are robust against platoon heterogeneity, which means that the bounds are valid for arbitrarily ordered vehicles of different dynamics. The approach was introduced in Rödönyi et al. (2012a). The second method introduced by Rödönyi et al. (2013) computes bounds that are robust against vehicle modeling uncertainties, nonlinearities and disturbances. The latter method computes an unfalsified disturbance model based on data acquired from individual vehicle experiments. The approach can be applied to analyze worst-case peak spacing errors for a great variety of platoon control architectures and spacing policies. The effects of communication delays can also be analyzed. A drawback of the numerical approaches is that the number of vehicles in the platoon is limited to about 10 due to the computational burden of the algorithms, however, in many cases, the platoon performance can be inspected based on the convergence of the spacing error bounds along the first 10 vehicles in the platoon.

The paper is organized as follows. After the formulation of the analysis problem in Section 2, the platoon model including communication network is presented in Section 3. The platoon controllers are specified in Section 4. The two analysis methods are presented in Sections 5 and 6. The analysis methods are verified by simulation examples and experiments in Section 7. In Section 8 some conclusions are provided.

1.4. Notations

Let $\mathbb{N}$ denote the set of non-negative integers and $\mathbb{R}$ denote the set of real numbers. Let $\mathbb{R}^n$ denote the space of n dimensional real vectors. The ith element of vector $f \in \mathbb{R}^n$ is referred as f_i. The ith row, jth column and ij element of a matrix $f \in \mathbb{R}^{mn}$ are denoted by f_{i*}, f_{*j} and f_{ij}, respectively. Let ℓ_1 and $\ell_1^{m\times n}$ respectively denote the normed spaces $\{f : \mathbb{N}\mapsto\mathbb{R},\ \|f\|_1 := \sum_{k=0}^{\infty}|f(k)| < \infty\}$ and $\{f : \mathbb{N}\mapsto\mathbb{R}^{m\times n},\ \|f\|_1 := \max_{i\in\{1,2,\ldots,m\}} \sum_{j=1}^{n}\|f_{ij}\|_1 < \infty\}$. Let ℓ_∞ and ℓ_∞^n respectively denote the normed spaces $\{f : \mathbb{N}\mapsto\mathbb{R},\ \|f\|_\infty := \sup_{k\in\mathbb{N}}|f(k)| < \infty\}$ and $\{f : \mathbb{N}\mapsto\mathbb{R}^n,\ \|f\|_\infty := \max_{i\in\{1,2,\ldots,n\}}\ \|f_i\|_\infty < \infty\}$. The corresponding induced norm of a causal system $G : \ell_\infty^q \mapsto \ell_\infty^p$ is denoted by $\|G\|_1$ and defined by the $\ell_1^{p\times q}-$norm of the system's Markov parameters $h_{ij}(k)$. Let system G have state-space representation (A, B, C, D), then $h_{ij}(0) = D_{ij}$ and $h_{ij}(k) = C_{i*}A^{k-1}B_{*j}$ for $k > 0$ and

$$\|G\|_1 = \max_{i\in\{1,2,\ldots,p\}} \sum_{j=1}^{q}\sum_{k=0}^{\infty} |h_{ij}(k)| \tag{1}$$

The set of all sequences in ℓ_∞^n that are bounded in norm by a scalar $\nu \geq 0$ is denoted by $\mathcal{B}(\nu) := \{f : \mathbb{N}\mapsto\mathbb{R}^n,\ \|f\|_\infty \leq \nu\}$. Let ℓ_2 and ℓ_2^n respectively denote the normed spaces $\{f : \mathbb{N}\mapsto\mathbb{R},\ \|f\|_2^2 := \sum_{k=0}^{\infty}|f(k)|^2 < \infty\}$ and $\{f : \mathbb{N}\mapsto\mathbb{R}^n,\ \|f\|_2^2 := \sum_{i=0}^{n}\sum_{k=0}^{\infty}|f_i(k)|^2 < \infty\}$. The corresponding induced norm of a causal system $G : \ell_2^q \mapsto \ell_2^p$ is defined by $\|G\|_\infty = \sup_{u\in\ell_2^q, \|u\|_2 = 1} \|Gu\|_2/\|u\|_2$. The space of all such systems with finite induced norm is denoted by $\mathcal{H}_\infty^{p\times q}$. Its subspace of real rational transfer functions is denoted by $\mathcal{RH}_\infty^{p\times q}$. Discrete-time real rational transfer functions are denoted by capital letters, and as functions of the forward shift operator q.

[2] In a homogeneous platoon all vehicles have equal dynamics.

[3] In a heterogeneous platoon the dynamics of the vehicles and/or the controllers may differ.

[4] The set of initial conditions, if from where the system starts, then given state constraints are not violated.

[5] I.e. the projection of the minimal disturbance invariant set to a spacing error output is computed.