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Fractional-order-based ACC/CACC algorithm for improving string stability

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A B S T R A C T

Traffic flow optimization and driver comfort enhancement are the main contributions of an Adaptive Cruise Control (ACC) system. If communication links are added, more safety and shorter gaps can be reached performing a Cooperative-ACC (CACC). Although shortening the inter-vehicular distances directly improves traffic flow, it can cause string unstable behavior. This paper presents fractional-order-based control algorithms to enhance the car-following and string stability performance for both ACC and CACC vehicle strings, including communication temporal delay effects. The proposed controller is compared with state-of-the-art implementations, exhibiting better performance. Simulation and real experiments have been conducted for validating the approach.

1. Introduction

Car-following systems are of the most promising Advanced Driver Assistance System (ADAS) for improving both traffic safety and flow. It is based on a front range sensor for detecting the preceding vehicle, adapting the ego-vehicle speed accordingly–i.e. Adaptive Cruise Control (ACC). This technique permits to efficiently track the preceding vehicle maintaining a desired distance. The evolution of such already commercial technology is the Cooperative-ACC (CACC), which proposes to add vehicle-to-vehicle (V2V) communication links to maintain tigher string formations.

Recent works have demonstrated CACC benefits with respect to ACC (Milanés and Shladover, 2014). The main contributions of CACC systems are an improvement in traffic throughput due to shorter inter-vehicle distances and the enhancement of drivers' safety and comfort (Shladover et al., 2015). As main limitations, the V2V communications must be guaranteed for achieving these results. Moreover, the temporal delay that these links may present affects the dynamic performance of the car-following maneuver, threatening directly the string stability and leading to undesirable behavior.

Platooning systems have been firstly tested on real roads by the Partners for Advanced Transportation Technology (PATH) in 1997 (Rajamani and Shladover, 2001), performing platoon formations with highly short inter-distances, which required high interaction with the leader vehicle and dedicated lanes. More recently, the PATH has also contributed with several research works in CACC (Nowakowski et al., 2010; Shladover et al., 2014; Shladover et al., 2012). Other projects as Connect & Drive (Ghouti et al., 2009) have approached CACC considering possible interaction with other cars in highways. They have shown positive results that demonstrate an increase in terms of safety and traffic throughput. In addition, this technique has gained more attention recently

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through research competitions as the first Grand Cooperative Driving Challenge (GCDC) 2011 (Geiger et al., 2012) and the second GCDC in 2016 under the i-Game EU project[1] umbrella. The platoon frequency response and the string stability notion are addressed by the work of Naus et al. (2010a). Other approaches have applied different control structures and techniques to provide encouraging performances; such as Model Predictive Control (MPC) (Liu et al., 2017), sliding mode control (Lu et al., 2002) or $\mathscr{H}_\infty$ controller-based approaches (Ploeg et al., 2014; Gao et al., 2016). Robust performances have been obtained when more complex topologies are used (Zhang and Orosz, 2016; Salvi et al., 2017). Finally, one-vehicle look-ahead feedforward structures with Proportional-Derivative (PD) feedback controllers (Milanés et al., 2014; Ploeg et al., 2011) have been widely employed in the literature providing great results due to its damping properties, practical implementation and low computational cost.

Almost all state-of-the-art approaches that address this problem are based in integer order control (IOC), which encourages the usage of non-integer order techniques to reach even more exigent performances. Fractional order control has arisen as a frequently employed mathematical tool to fulfil more demanding design requirements, due to its capabilities to provide a more precise and adaptable frequency response (Vinagre Jara et al., 2005). This technique has been already employed in car-following approaches, firstly for a hybrid ACC control design (Hosseinnia et al., 2014), a low level throttle and brake control for ACC (Hosseinnia et al., 2018) and finally a CACC controller robust against plant gain disturbances (Flores et al., 2016).

This work proposes to employ fractional control to design feedforward structures for both ACC and CACC, aiming to enhance the stability and achieve formations with shorter time gaps and improved system performance. It is proposed to profit from the more adaptable frequency response that fractional-order control (FOC) provides in comparison to classical controllers. The performance is studied through string stability analysis of the designed controller and state-of-the-art solutions for ACC and CACC. The improvements in terms of string stability of the FOC approach with respect to state-of-the-art IOC solutions are demonstrated in simulations and real platforms tests.

The rest of this paper is structured as follows: Section 2 introduces the concepts and definitions associated to ACC/CACC systems. An introduction to fractional-order calculus and its applications in control is stated in Section 3. Section 4 describes the model of the experimental platform that is going to be used for the controller synthesis. The proposed feedforward structure and the controller design procedure for ACC and CACC are presented in Sections 5 and 6 respectively. In Section 7, a comparative study of the proposed algorithm for both ACC and CACC systems is described, including a comparison with state-of-the-art developments. The conclusions derived from the obtained results and possible future work are stated in the Section 7.

2. Concept and definitions

When it comes to analyze car-following string of vehicles, there are two main concepts to be considered: (1) the adopted car-following policy; and (2) the string stability of the formed platoon. This section reviews both concepts.

Attending to the car-following policy, different strategies can be found in the literature:

1. **Constant clearance** was conceived as a strategy aimed mainly for platooning maneuvers (Swaroop and Huandra, 1998), which consists on driving in highway with really close distance gaps. This approach requires dedicated lanes and low latency V2V communication links with the leader vehicle to handle very short spacing.
2. **Constant Time Gap** (CTG) constitutes one of the most employed and flexible spacing policies. It suggests to perform a vehicle tracking with non fixed distances (Swaroop and Rajagopal, 2001). It simulates the way how humans drive since it proposes to set higher distances when the speed increases, using a time gap multiplied by the ego-speed added to a fixed standstill distance.
3. **Constant safety factor** is another frequently employed spacing policy (Ioannou and Chien, 1993). This technique proposes to have a more reactive and conservative behavior in case a hard braking is executed by a forward vehicle, adding a term that penalizes the difference between both vehicles' speeds.
4. **Variable Time Gap** (VTG) is a spacing policy that has been addressed by some recent research works, suggesting to variate the time gap while driving, with different purposes and in function of the ego-speed. For example, accomplishing improved traffic flow stability (Zhao et al., 2009) or enhanced safety (Zhang and Ioannou, 2005) and comfort (Martinez and de Wit, 2007).

Another fundamental notion and important design requirement of car-following techniques is the string stability, which states that every string formation must not propagate the disturbances upstream. This concept can be understood from the scope of Lyapunov stability, where it may be interpreted as the asymptotic stability of a finite number of interconnected individual exponentially stable systems (Swaroop and Hedrick, 1996). The main objective of the car-following-oriented approaches that address this phenomenon is to ensure the attenuation of any perturbation along the string, avoiding undesired behaviors. This concept is better described in equations:

$$\|z_i(t)\|_\infty \leqslant \|z_{i-1}(t)\|_\infty \ ;\forall \ \ t \geqslant 0; 2 \leqslant i \leqslant m; \tag{1}$$

$$\|\Gamma(j\omega)\|_\infty \equiv \left\| \left| \frac{Z_i(j\omega)}{Z_{i-1}(j\omega)} \right| \right\|_\infty \leqslant 1 \ ;\forall \ \ \omega > 0; \tag{2}$$

where $z_i(t)$ is understood as a representative dynamic variable of the i^{th} vehicle of an homogeneous string of m members–i.e. spacing

[1] http://www.gcdc.net/en/i-game.