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Design and implementation of parameterized adaptive cruise control: An explicit model predictive control approach

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A R T I C L E I N F O

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A B S T R A C T

The combination of different characteristics and situation-dependent behavior cause the design of adaptive cruise control (ACC) systems to be time consuming. This paper presents a systematic approach for the design of a parameterized ACC, based on explicit model predictive control. A unique feature of the synthesized ACC is its parameterization in terms of key characteristics, which, after the parameterization, makes it easy and intuitive to tune, even for the driver. The effectiveness of the design approach is demonstrated using simulations for relevant traffic scenarios, including Stop-&-Go. On-the-road experiments show the proper functioning of the synthesized ACC.

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1. Introduction

Adaptive cruise control (ACC) is an extension of the classic cruise control (CC), which is a widespread functionality in modern vehicles. Starting in the late 1990s with luxury passenger cars, ACC functionality is now available in a number of commercial passenger cars as well as trucks. The objective of CC is to control the longitudinal vehicle velocity by tracking a desired velocity determined by the driver. Only the throttle is used as an actuator. ACC extents CC functionality, by automatically adapting the velocity if there is a preceding vehicle, using the throttle as well as the brake system. Commonly, a radar is used to detect preceding vehicles, measuring the distance and the relative velocity between the vehicles. Hence, besides CC functionality, ACC enables also automatic following of a predecessor. In Fig. 1, a schematic representation of the working principle of ACC is shown.

ACC systems typically consist of two parts: a vehicle-independent part and a vehicle-dependent part (Moon, Moon, & Yi, 2009; Prestl, Sauer, Steinle, & Tschernoster, 2000). The vehicle-independent part determines a desired acceleration/deceleration profile for the vehicle. The vehicle-dependent part ensures tracking of this profile via actuation of the throttle and brake system. Hence, the latter part can be regarded as a controller for the longitudinal vehicle acceleration. In Fig. 2, a schematic representation of the ACC control loop is shown. The vehicle-independent part and the vehicle-dependent part form an outer and an inner control loop, respectively. This paper addresses the design of the vehicle-independent part of an ACC.

Focusing on the outer control loop, the primary control objective is to ensure following of a preceding vehicle. Considering the corresponding driving behavior, ACC systems are generally designed to have specific key characteristics, such as safety, comfort, fuel economy and traffic-flow efficiency (Vahidi & Eskandarian, 2003). In general, however, these characteristics typically impose contradictory control objectives and introduce constraints, complicating the controller design. For instance, to ensure safe following, the system should be agile, requiring high acceleration and deceleration levels, which is not desirable concerning comfort or fuel economy (Moon & Yi, 2008). To account for different characteristics, a weighted optimization can be employed. For example, a model predictive control (MPC) approach may be adopted, which also facilitates taking into account constraints (Corona & De Schutter, 2008).

Besides these key characteristics, driver acceptance of the system requires ACC behavior to mimic human driving behavior to some extent (Van Driel, Hoedemaeker, & Van Arem, 2007). Apart from the fact that human driving behavior is driver specific and time varying, it is also situation dependent. Generally, situation-dependent behavior is incorporated in the ACC in an ad-hoc manner, by switching between different modes according to different situations. This switching is either based on logic rules, using a specific tuning for each mode (Moon et al., 2009; Persson, Botling, Hesslow, & Johansson, 1999; Widmann et al.,

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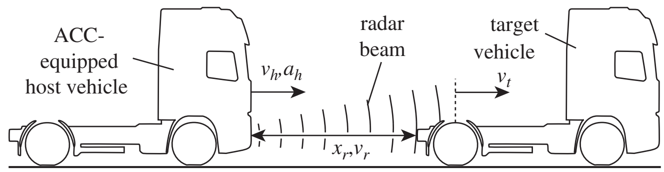

Fig. 1. Example of the ACC working principle. The host vehicle, driving with velocity v_h and acceleration a_h, is equipped with an ACC, which ensures automatic following of the preceding target vehicle, driving with velocity v_t. A radar measures the distance x_r and the relative velocity $v_r = v_t - v_h$ between the vehicles.

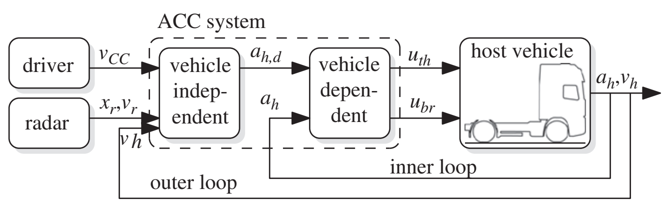

Fig. 2. Schematic representation of the ACC control loop. The ACC is divided into a vehicle-independent, outer control loop determining a desired acceleration $a_{h,d}$ and a vehicle-dependent, inner control loop determining the throttle and brake control signals u_{th} and u_{br}, respectively. The distance x_r and relative velocity v_r with respect to the preceding vehicle are measured using a radar. The driver switches the ACC on and off, regulates characteristic system settings and determines a desired cruise control velocity.

2000), or nonlinear filters are employed to combine all modes (e.g. Yanakiev, Eyre, & Kanellakopoulos, 2000; Zhang & Ioannou, 2004). Another, more crude method is to ignore specific traffic situations or consider them separately. For example, slow driving or standing still is only incorporated if so-called Stop-&-Go (SG) functionality is included (Venhovens, Naab, & Adiprasito, 2000).

The key characteristics and the desired situation dependency of the designs give rise to many tuning variables. This makes the design and tuning time consuming and error prone. In this paper, a systematic procedure for the design and tuning of the vehicle-independent part of an ACC is presented. The contribution is the design of an ACC which is parameterized by the key characteristics, with at most one tuning variable for each characteristic. Hence, after the parameterization, the specific setting of the ACC can easily be changed, possibly even by the driver. Next to presenting this systematic design approach, the implementation of the ACC and the results of on-the-road experiments are discussed.

An explicit model predictive control (MPC) synthesis is adopted to design the ACC, following Corona and De Schutter (2008) and Möbus, Baotić, and Morari (2003). One reason to use the MPC synthesis is that it enables to take into account contradictory controller requirements as well as possible constraints imposed by the key characteristics of the system. A second reason is that, when implemented in a receding horizon fashion, an optimization problem is solved in every time step. This enables the controller to adapt to actual working conditions, i.e. traffic situations, and, as such, the controller is situation dependent. For the implementation, it is desirable to solve the optimization problem offline in an explicit manner via a multi-parametric program, instead of direct online implementation of the controller. This yields an explicit, piecewise affine (PWA) control law (Bemporad, Heemels, & De Schutter, 2002; Bemporad, Morari, Dua, & Pistikopoulos, 2002).

The organization of the paper is as follows. The problem formulation is presented in Section 2. In Sections 3 and 4, the controller design and the corresponding tuning, including the parameterization of the controller are discussed. The implementation, experimental results and the working of the parameterization are presented in Section 5. Finally, conclusions and outlook on future work are given.

2. Problem formulation

2.1. Quantification measures

In this paper, safety and comfort are chosen as the key characteristics of the desired behavior of an ACC. Considering safety, however, it has to be remarked that the ACC is not a safety system such as an emergency braking system or a collision avoidance system. ACC is primarily a comfort system that incorporates safety in the sense that appropriate driving actions within surrounding traffic are guaranteed. To enable quantification of the key characteristics, desirable properties of these characteristics, so-called quantification measures, have to be defined.

The safety of the driving behavior is typically related to the inter-vehicle distance and the relative velocity of the vehicles (Naus et al., 2008). Typically, the safety of a traffic situation increases for an increasing inter-vehicle distance and a decreasing relative velocity. Furthermore, higher deceleration levels are beneficial, as a wider range of traffic situations can be handled in a safe manner. Hence, regarding safety, the inter-vehicle distance and the relative velocity will be used as quantifications measures.

The comfort of a driving action is often related to the number, size and frequency of vibrations or oscillations in the longitudinal acceleration of the vehicle due to, for example, external disturbances, engine torque peaks, driveline characteristics, etc. (Dorey, McLaggan, Harris, Clarke, & Gondre, 2001; ISO2631, 1997; Mo, Beaumont, & Powell, 1996). Besides that, specifically focusing on ACC systems, maximum deceleration values are often related to comfort (Motor Presse Stuttgart, 2006). Furthermore, the (peak) jerk levels are often considered as a measure to reflect human's comfort (Martinez & de Wit, 2007). In designing trains and elevators for example, the jerk is typically limited to $2.0\,\mathrm{m\,s^{-3}}$. Hence, regarding comfort, the (peak) acceleration and (peak) jerk levels will be used as quantification measures (Naus et al., 2008).

2.2. Parameterization

This paper presents the design of a parameterized ACC, with, at the end, only a few design parameters, i.e. tuning knobs, that are directly related to the key characteristics of the behavior of the ACC. The limited number of intuitive tuning variables enables quick and easy adaptation of the ACC to different desirable driving behavior. Importantly, these variables can also be used by non-experts in (MPC) control, like the driver, to change the behavior of the ACC system. Enabling the driver to set these variables, really makes the ACC driver dependent.

An explicit MPC approach is used to design the parameterized ACC. The MPC synthesis accommodates constraints, an optimal situation-specific controller results when implemented in a receding horizon fashing, and the minimization of a cost criterion enables making trade-offs between contradictory characteristics. However, a disadvantage of the MPC synthesis is the large number of tuning parameters, which follow from the definition of the control objective, the constraints and the choice of the cost criterion.

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