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A Parameter Estimator for a Model Based Adaptive Control Scheme for Longitudinal Control of Automated Vehicles

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Abstract: In order to improve the longitudinal control behavior of automated vehicles, a predictive control scheme with an adaptive vehicle state and parameter observer is proposed. The underlying nonlinear model of vehicle and powertrain dynamics makes use of the estimated torque signal which is calculated in the engine management system, as well as of vehicle speed and acceleration measurements. An Extended Kalman Filter is implemented to both estimate filtered vehicle states and the vehicle mass. Simulation results show good convergence of the parameter estimate. The contributions of this paper build the foundation to further examine the potential of improvement in fuel savings, planning accuracy and passenger comfort.

Keywords: Autonomous vehicles, Automotive control, Vehicle dynamics, Velocity control, Estimators, Extended Kalman filters

1. INTRODUCTION

The general task of motion control of automated vehicles can be separated in three main parts: First, a motion planning instance is planning a path and speed profile or a trajectory. This instance needs to deal with the nonholonomic properties of the vehicle and plans several maneuvers to a goal. Second, a path following or trajectory controller calculates a steering angle command for lateral motion and a desired vehicle acceleration (or tire force in some implementations) for the longitudinal motion of the vehicle. Third, these commands are passed to actuator controllers which transform them into input commands for the actuators. In case of longitudinal control, this input command is the accelerator pedal, engine throttle or torque demand value (depending on the interface to the engine control unit) as well as a brake demand value. The controller also has to consider vehicle and powertrain dynamics or compensate for the resulting effects and other disturbances.

Precise trajectory following is essential for different reasons. For example, big deviations from the reference point on the trajectory do not allow to perform time critical scenarios. If for example a vehicle plans to enter an intersection just before an intersecting car and the vehicle lags behind its planned position, the risk to create unwanted traffic scenarios or even accidents increases significantly. Or, assuming that this effect is known to the engineers calibrating the planning algorithms, it has to be considered as uncertainty which leads to an overly defensive planning behavior. For the same reason, if longitudinal deviations are too high, vehicles trying to build a platoon need to keep larger safety distances up to a point where the fuel saving effect of forming the platoon is reduced drastically. Also in regular automated operation, the efforts of the controller to compensate for deviations from the planned trajectory lead to overshoots in the torque demand to the engine, which has a negative effect on fuel consumption. There is big potential in fuel savings if smooth accelerations can be realized. Furthermore, speed and acceleration overshoots can be felt by passengers and hence have a negative effect on passenger comfort. High efforts have been done in recent years to optimize driveability for conventional vehicles working in open loop manual operation, where the driver sets the desired acceleration via the throttle pedal, but they mostly focus on reducing disturbances at high frequencies due to gearshifts or load changes.

Fully automated vehicles need to be able to cope with conditions appearing at steep hill climbing and parking a vehicle onto a target point at an accuracy of a few centimeters. These scenarios require a very accurate longitudinal actuator controller which is capable of compensating for road slope, friction and rolling resistances and takes into account changes in vehicle mass.

Available solutions for closed loop operation highly focus on cruise control or adaptive cruise control mode, scenarios in which vehicles are operating at higher speeds in areas where the influence of road gradients can be neglected.

To realize such a controller, it is necessary to take into account major effects of powertrain and longitudinal vehicle dynamics whilst keeping complexity low to reduce computational resource demand. This paper proposes an improved control scheme for longitudinal control of automated vehicles. The implementation of this control scheme consists of three parts. First, the derivation of a dynamical longitudinal vehicle model containing the effects of road slope, friction and rolling resistance. Second, the imple-

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mentation of a state and parameter estimator which is able to quickly adopt for changes in vehicle mass. These two parts together with the definition of the control scheme are contributions of this paper, whereas the third part, the implementation of the model based controller is left to future work.

In the following, the remainder of the paper will give an overview over related work in Section 2, explain the planned controller structure in Section 3, derive the longitudinal vehicle dynamics in Section 4, before explaining the state and parameter estimator in Section 5. Simulation results are given in Section 6 before Section 7 gives a conclusion.

2. RELATED WORK

In several publications about autonomous vehicles one can find solutions for longitudinal controllers. Many publications appeared about the participants of the DARPA Urban Challenge during which many teams including the winning Tartan Racing Team (Urmson et al. (2008) as well as Ben Franklin Racing Team (Bohren et al. (2009) were using a solution directly actuating throttle and brake pedal via an electromechanical actuator instead of being able to use the torque interface. With such a solution, due to mechanical backlash effects it is very hard to accurately control vehicle acceleration. They further mention the use of a proportional-integral (PI) controller after linearization of throttle and brake dynamics.

Team AnnieWAY as well as Daimler's Bertha Drive Vehicle described in Ziegler et al. (2013) mention to use the integral anti-windup feedback controller from Geiger et al. (2012) to reactively compensate for disturbances like aerodynamic drag and road slope, but do not actively consider the resulting forces in their controller.

The vehicle described in Aeberhard et al. (2015) about BMW Group's Highly Automated Driving Project uses a combination of controllers published in Werling (2010) and Bartono (2004). Werling (2010) mentions to calculate the desired tire force in the trajectory controller part and uses a separate controller with a simple anti windup integrator to compensate for wind drag, road slope and vehicle mass changes. It does not make use of the torque interface but mentions to directly calculate the desired throttle angle out of a map with desired longitudinal force and engine speed as inputs. This map together with a speed dependent compensation term needs to be calibrated in vehicle experiments with much effort.

Bartono (2004) uses an inverse powertrain model to calculate the desired engine torque out of the desired vehicle acceleration. To reduce modeling effort, the model does not directly take into account road slope, wind- or rolling resistance nor the effect of changing vehicle mass. The sum of all these effects are modeled as a resulting disturbing acceleration which is estimated in a disturbance observer. Since the work focuses on the special case of following a lead vehicle in Adaptive Cruise Control (ACC) and Stop & Go scenarios, this disturbance observer is implemented using the distance information to the lead vehicle and hence cannot be used in scenarios without a lead vehicle.

Gehrling (2000) focuses on control schemes for vehicle platoons and presents a control loop for acceleration control using feed forward control to linearize the nonlinear vehicle dynamics. Throttle angle is used as input variable to the engine, probably lacking the existence of a modern torque based engine control management. The relation of acceleration, speed and throttle angle is approximated in an experimentally derived map. The influence of vehicle mass, road grade is not considered in this approach, except that resulting disturbances are compensated by a PID controller.

Sauter and Flad (2014) designs an ADAS which decreases the drivers pedal position value in order to realize savings in fuel consumption. A Model Predictive Controller (MPC) scheme is used to determine this accelerator pedal value difference, although the paper also states the difficulty of this approach due to missing predictions of the drivers future pedal values. Since the accelerator pedal is used as an input variable to realize torque, a lookup table is used to map the engine torque prediction depending on engine speed and accelerator pedal, an approach which is not as accurate as using the more complex model inside of an engine control unit. In the vehicle model, road slope and friction is considered, whereas vehicle mass is modeled as a constant value.

André et al. (2015) converts accelerator pedal value into half shaft torque, which is considered proportional to acceleration but neglecting resistance. This approach is considered good enough for a more or less exact interpretation of the pedal value as the drivers acceleration demand but not suitable for achieving an exact acceleration value in automated trajectory control. Vehicle mass is estimated in a Kalman filter but the paper does not take into account aerodynamic drag or road resistance.

As seen in this section, todays longitudinal controllers for highly automated vehicle operation have the following drawbacks: First, none of the controllers actively take into account the effects of changing vehicle mass or changes in road slope but treat them as disturbances. This leaves compensation to the feedback controller in a reactive way, which is less effective than proactively take countermeasures before deviations from the desired trajectory occur. Second, although the planning module calculates trajectories containing future demand values, none of the control schemes make use of this information but only use the current acceleration or longitudinal force demand value to command an actual torque demand value to the engine (or brake in case of deceleration). With the knowledge of future demand values in the case of automated driving in contradiction to the case of manual operation, where no information about the future plans of the driver is available but has to be predicted, one can make use of this information throughout the whole controller chain.

Different theoretical foundations exist for designing stabilizing nonlinear MPCs (see de Nicolao et al. (1998), Wan and Kothare (2003), Magni and Scattolini (2006)). Another difficulty for nonlinear MPC is the real time implementation on an embedded platform. Here recent advances have been made to create solutions with reduced computational load. For example, many advances have been made on solving the involved optimal control problem