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Implementation of a robust cruise control using look-ahead method

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Abstract: The paper proposes the implementation of a robust cruise control system which is able to ensure the fuel-efficient travel of the vehicle with a look-ahead control algorithm. The $\mathcal{H}_\infty$-based feedforward-feedback control method guarantees robustness against varying vehicle mass, longitudinal disturbances and the consideration of actuator dynamics. The advantage of the method is the application of a small number of vehicle parameters. Therefore, a method for various passenger cars without significant modifications is needed. The proposed cruise control and the look-ahead method are implemented in a software-in-the-loop (SIL) environment using DSpace Autobox, which cooperates with the high-fidelity CarSim software through CAN communication.

Keywords: Robust control design, Look-ahead control, Software-in-the-loop application

1. INTRODUCTION AND MOTIVATION

In the last decade, the longitudinal vehicle control based on the look-ahead approach has been in the focus of the automotive research centers. It is widespread in the cruise control, which is able to guarantee energy-efficient driving, see Sciarretta et al. [2015]. Since Adaptive Cruise Control (ACC) allows to maintain a desired travel speed set by the driver by acting on the throttle and brakes, the combination of look-ahead control and ACC is a novel trend in the vehicle control design.

Several publications and patents deal with the topics of driveline control implementation and look-ahead strategies. The design and the implementation of a predictive speed controller are presented by Hellström et al. [2009], Passenberg et al. [2009], Hellström et al. [2010]. The intervention of the look-ahead control is connected to the reference signal of the PID-based speed controller, which modifies the fuel injection of the engine. A dynamic longitudinal model for the design of the speed controller is applied by Kiencke and Nielsen [2000]. It influences the engine torque based on the engine rpm and the fuel injection, which are control inputs in the architecture. The speed design for road vehicles based on road inclinations, speed limits, a preceding vehicle in the lane and traveling time is proposed by Németh and Gáspár [2013]. A road type and congestion level estimation method is combined with the principal components analysis for a variety of purposes, e.g. traffic information systems, intelligent real-time control systems, energy consumption/emissions in Zhu and Barth [2006].

A test platform for the implementation of look-ahead control is introduced in Gustafsson [2006]. The platform contains the user interface, the controller structure together with the look-ahead optimization, CAN softwares and interfaces. The proposed device is in connection with the CAN bus of the vehicle. The look-ahead method of the platform considers the engine torque, the gear position and road geometry information. The implementation of an optimal ACC for passenger cars is presented by Li et al. [2013]. The system uses radar and acceleration sensor measurements, from which the acceleration of the preceding vehicle are derived. The optimization algorithm yields a reference acceleration signal, which is the input of the vehicle dynamic controller together with the estimated preceding vehicle acceleration.

Further automotive industrial patents on the predictive speed control algorithms are presented in Lattemann et al. [2004]. The method of Eriksson and Steén [2003] is based on the forthcoming terrain characteristics to select gear position, according to the required driver's performance

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(fuel-consumption, emission, traveling time). An algorithm which computes the optimal driveline torque considering the road inclinations is presented by Takahashi et al. [1998].

In this paper, the implementation of a robust cruise control together with a look-ahead control is proposed. The applied method guarantees robustness against varying vehicle mass, and longitudinal disturbances, such as rolling resistances, aerodynamic forces. Moreover, the dynamic properties of the actuator are considered in the control design phase. In the presented method, the look-ahead strategy and the robust longitudinal control are connected through the reference velocity signal. The output of the look-ahead computation is the optimal velocity, which is considered as an input of the controller. The advantage of the method is the application of a small number of vehicle parameters. Then the method can be applied to various passenger cars without significant modifications. The preliminary results of the cruise control design can be found in Németh et al. [2015]. As a novelty, in this paper the cruise control and the look-ahead method are implemented in a software-in-the-loop (SIL) environment using DSpace Autobox.

The organization of the paper is the following. Section 2 presents the formulation of the longitudinal vehicle dynamics for the look-ahead cruise control. The robust $\mathcal{H}_\infty$ control strategy of the cruise control system considering the formulation of the uncertainties is described in Section 3. The concept of the speed design using a look-ahead approach is presented in Section 4. The implementation of the robust control system is found in Section 5. The evaluation of the proposed control method is presented through simulation examples in Section 6.

2. MODELING LONGITUDINAL DYNAMICS

In this section the modeling of longitudinal dynamics is presented. The longitudinal dynamics is described in the approach by the following simplified model:

$$m\ddot{\xi}_0 = F_{l1} - F_{d1} \tag{1}$$

where m is the mass of the vehicle, ξ_0 is the vehicle position, F_{l1} is the realized longitudinal force on the wheels. F_{d1} includes the longitudinal disturbances, such as the aerodynamic forces, rolling resistance and road slope:

$$F_{d1} = C_a\dot{\xi}_0^2 + C_r gm\cos\vartheta + mg\sin\vartheta \tag{2}$$

where ϑ is road slope and C_a, C_r are vehicle parameters related to aerodynamic and resistances forces.

In the following the transformation of the vehicle model has two focuses. Firstly, the mass of the vehicle is an uncertain parameter of the vehicle. The mass has a nominal value m_0, which is known, but the variation of the mass m_v is unknown. However, the variation is assumed to be a bounded parameter, e.g. $m_v/m_0 = \pm 15\%$. Secondly, the road inclination is assumed to be known. In practice, the slope of the road can be obtained in two ways: either a contour map which contains the level lines is used or an estimation method is applied, see e.g., Bae et al. [2001], Hahn et al. [2004].

Since the handling of vehicle mass uncertainty is a requirement for the control system, it is necessary to define the actual mass m of the vehicle such as: $m = m_0 + m_v$. Thus the longitudinal motion equation is reformulated in the following way:

$$m_0\ddot{\xi}_0 = F_{l1} - F_{d1} - m_v\ddot{\xi}_0 \tag{3}$$

Considering that $\ddot{\xi}_0$, the actual longitudinal acceleration, is a measurable and bounded signal of the vehicle, $m_v\dot{\xi}$ is handled as a disturbance of the vehicle. Combining it with F_{d1}, the next expression is yielded:

$$F_{d1} + m_v\ddot{\xi}_0 = F_{d1,1} + m_v f_{d,2} \tag{4}$$

where $F_{d1,1} = C_a\dot{\xi}_0^2 + C_r g m_0\cos\vartheta + m_0 g\sin\vartheta$ and $f_{d,2} = C_r g\cos\vartheta + g\sin\vartheta + \ddot{\xi}_0$.

$F_{d1,1}$ and $f_{d,2}$ incorporate measurable signals, such as velocity, road slope and longitudinal acceleration. Thus, $F_{d1,1}$ is handled in this approach as a measured disturbance. Since there is no information about the mass variation m_v, the term $m_v f_{d,2}$ is considered as an unknown disturbance - where actually $f_{d,2}$ is a measurable part of the disturbance expression.

3. ROBUST CONTROL STRATEGY

In this section, the control design for the longitudinal velocity tracking control problem is proposed. The realized total longitudinal control force on the wheels F_{l1} is divided into two elements:

$$F_{l1} = F_{l1,0} + F_{l1,1} \tag{5}$$

where the purpose of $F_{l1,1}$ is to compensate for the measured disturbance $F_{d1,1}$, while $F_{l1,0}$ guarantees the unknown disturbance rejection and the performances. In the following, a robust control design method is presented, which combines the advantages of the feedforward and feedback control design.

3.1 Design of the feedforward control

In the first step the feedforward control is designed. If $F_{d1,1}$ is fully compensated for, then the feedforward control input is

$$u_1 = F_{l1,1}, \tag{6}$$

where $\dot{\xi}_0, \vartheta$ are measured and estimated parameters, see Vahidi et al. [2005]. Thus, the efficiency of the feedforward disturbance compensation is based on the accuracy of the measured signals. Since the measurement of the speed and the estimation of the road slope are inaccurate, the feedforward compensation has an error $F_{d,11}$. The longitudinal motion of the vehicle is formed in the following way:

$$m_0\ddot{\xi}_0 = F_{l1,0} - F_{d1,11} - m_v f_{d,2} \tag{7}$$

In the next step a feedback control input $F_{l1,0}$ is designed, which is able to handle the disturbances $F_{d1,11}, f_{d,2}$.

3.2 Design of the feedback control

The feedback control input $F_{l1,0}$ has three main goals in the control strategy: the rejection of unknown disturbances ($F_{d1,11}$, $f_{d,2}m_v$), the handling of the unmodelled actuator dynamics and the guarantee of the performance. The state-space representation of the system is the following:

$$\left[\ddot{\xi}_0\right] = [0]\left[\dot{\xi}_0\right] + \begin{bmatrix} -\dfrac{1}{m_0} & -\dfrac{1}{m_0} \end{bmatrix} \begin{bmatrix} F_{d1,11} \\ F_{d1,2} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{m_0} \end{bmatrix} F_{l,0} \tag{8}$$