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Robust Look-ahead Cruise Control Design Based on the $\mathcal{H}_\infty$ Method ⋆

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Abstract: The paper focuses on the robust control design of a look-ahead cruise control system. The aim of the look-ahead control is to consider the topographic conditions and speed regulations of the oncoming road sections. The look-ahead cruise control leads to an optimization method, which generates a fuel and time optimal reference speed for the vehicle. It requires external topographic and road information, and measurements concerning the vehicle, such as speed and acceleration. Since the signals of the vehicle are considered in the generation of the reference speed, the generator has an impact on the stability of the cruise control system. In the paper a robust $\mathcal{H}_\infty$ cruise control design method is proposed, which considers the effect of the reference speed generation, and guarantees the stability and the speed tracking performance of the entire system. The efficiency of the method is analyzed through a simulation example with real highway data.

Keywords: look-ahead control, $\mathcal{H}_\infty$ control, uncertainty modeling

1. MOTIVATION OF LOOK-AHEAD CONTROL

The look-ahead concept is a novel cruise control design method, which involves various information about the environment to compute a fuel and time optimal reference speed trajectory. The topographic information of the oncoming road section is useful to utilize the forthcoming acceleration/deceleration possibilities of the road inclinations, see Figure 1. Speed limitation data are important to consider the necessary speed reductions on the road. Since the route of the vehicle is considered as known, the loading of this information requires the measurement of the current position, e.g. using GPS. Figure 1 illustrates that the vehicle receives information about the motion of the preceding vehicle (distance and speed) and the follower vehicle (distance, speed, acceleration). It gives the possibility to accommodate the vehicle motion to the current traffic conditions. Moreover, the cruise control uses on-board measurements of the vehicle, such as speed and acceleration signals.

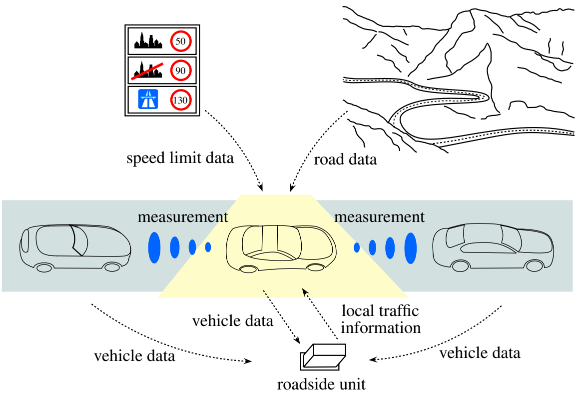

Fig. 1. Communication and information flow

Several methods in which the road conditions are taken into consideration have already been proposed, see Ivarsson et al. (2009); Nouveliere et al. (2008); Németh and Gáspár (2013a). The look-ahead control methods assume that information about the future disturbances to the controlled system is available. To find a compromise solution between fuel consumption and traveling time leads to an optimization problem. The optimization was handled by using a receding (sliding) horizon control approach in Hellström et al. (2010); Passenberg et al. (2009). In another approach the terrain and traffic flow were modeled stochastically using a Markov chain model in Kolmanovsky and Filev (2009).

The communication possibilities and information process for the future cruise control methods are dealt with in Ebnre and Hermann (2001) Nuevo et al. (2010) presented a computer vision-based approach for tracking surrounding vehicles and estimating their trajectories. An extension of adaptive cruise control with traffic information considering vehicle-to-roadside and vehicle-to-vehicle communication was proposed in Kesting et al. (2007). Festag et al. (2008) combined vehicle-to-vehicle communication and vehicle-to-roadside sensor communication to assist investigations. In the following, the information about the road terrain

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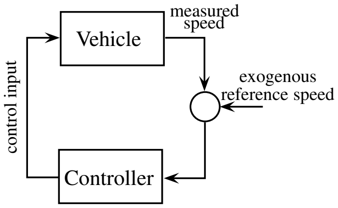
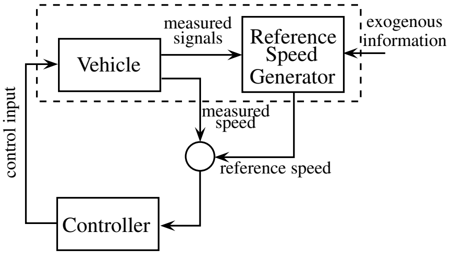
characteristics, the forthcoming speed limitations and the oncoming route trajectory is assumed.

The paper proposes a robust $\mathcal{H}_\infty$ cruise control design, which incorporates the reference speed generation method of the look-ahead concept. In the general cruise control problem the controller is designed based on the model of the vehicle, see Figure 2(a). The conventional cruise controller guarantees the tracking of the reference speed, which is an exogenous signal. However, in look-ahead control the reference speed depends on the measured signals of the vehicles. Therefore, the stability of the entire system can be guaranteed through an extended plant, which incorporates the vehicle and the reference speed generator, see Figure 2(b). A previous result of the analysis of the closed-loop stability is presented in Németh and Gáspár (2013b).

As a novelty of this paper, the stability of the vehicle - reference speed generator - controller entire loop is built-in the cruise control design using the robust $\mathcal{H}_\infty$ algorithm. Moreover, the control-oriented modeling of the reference speed generator is proposed.



(a) Conventional problem



(b) Look-ahead problem

Fig. 2. Problem setup

The structure of the paper is the following. The computation of the fuel and time optimal reference speed is detailed briefly in Section 2. Section 3 presents the control-oriented modeling of the reference speed generator. The robust $\mathcal{H}_\infty$ design of the cruise control is proposed in Section 4. Section 5 gives simulation examples about the efficiency and stability of the proposed control design algorithm. Finally, Section 6 contains some concluding remarks.

2. OPTIMAL REFERENCE SPEED GENERATION

In this section the optimal reference speed trajectory computation method is briefly summarized. The results in a detailed form are found in Németh and Gáspár (2013a). The route of the vehicle can be divided into n sections using $n+1$ number of points as Figure 3 shows. The division of the route is not necessarily of equal lengths. The rates of the inclinations of the road and those of the speed limits are assumed to be known at the endpoints of each section. The acceleration of the vehicle is considered to be constant between section points.

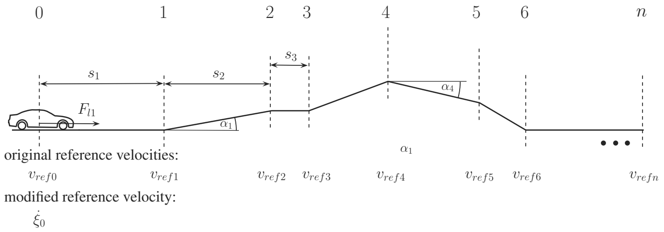


Fig. 3. Division of predicted road

The speeds of the vehicle are described at each section point of the road. The speed at section point j should reach a predefined reference speed $v_{ref,j}^2$ $j \in [1,n]$, which is usually the maximum speed of the vehicle (speed limit). It is an important goal to track the momentary value of the speed, which is formulated in the following form: $\dot{\xi}_0^2 \to v_{ref,0}^2$.

A weight Q is applied to the momentary (initial) speed and weights $\gamma_1, \gamma_2, ..., \gamma_n$ are applied to the reference speeds. The weights should sum up to one, i.e., $\gamma_1 + \gamma_2 + ... + \gamma_n + Q = 1$. While the weights γ_i represent the rate of the road conditions, weight Q determines the tracking requirement of the momentary reference speed $v_{ref,0}$.

A control-oriented vehicle model in which reference speeds and prediction weights are taken into consideration is constructed. The reference speed of a vehicle is calculated:

$$\lambda = \sqrt{\vartheta - 2s_1(1-Q)(\ddot{\xi}_0 + g sin\alpha)} \tag{1}$$

where the value ϑ depends on the predicted road slopes, the reference speeds and the prediction weights:

$$\vartheta = Qv_{ref,0}^2 + \sum_{i=1}^{n} \gamma_i v_{ref,i}^2 + \frac{2}{m}(1-Q)\sum_{i=1}^{n} s_i F_{di,r} \sum_{j=i}^{n} \gamma_j. \tag{2}$$

Consequently, the predicted road conditions can be considered by speed tracking. The calculation of λ requires the measurement of the longitudinal acceleration $\ddot{\xi}_0$.

The optimization of the vehicle speed profile requires the appropriate chosen of the Q, γ_i weights. The aim of this section is to find an optimal speed λ through Q, γ_i, which guarantees the minimization of control force (fuel consumption) and traveling time. By using equation (1) the longitudinal force (F_{l1}) can be expressed as the linear function of prediction weights:

$$F_{l1} = \beta_0(Q) + \beta_1(Q)\gamma_1 + \beta_2(Q)\gamma_2 + \ldots + \beta_n(Q)\gamma_n \tag{3}$$

where β_i are the coefficients of γ_i, and they depend on the prediction weight Q.

When the control force is minimized, $|F_{l1}| \to Min$ must be guaranteed. In practice, however, the