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Switched LQR/H_∞ steering vehicle control to detect critical driving situations

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ABSTRACT

This paper proposes a switching steering vehicle control designed using the linear quadratic regulator (LQR) problem, the Linear Matrix Inequality (LMI) framework and the H_∞ norm. The proposed switched control law comprises two levels: the first level is a switched Proportional–Integral-Derivative controller of lateral deviation (PID_y) and the second is a switched Proportional-Derivative controller of yaw angle (PD_ψ). These two levels are used to ensure an accurate tracking of the vehicle's lateral deviation y and yaw angle ψ. This control strategy makes use of a common Lyapunov function design method used for the stability analysis of switched continuous-time systems. Sufficient conditions for global convergence of the switched control law are presented and proved under arbitrary switching signals. All these conditions are expressed in terms of LMIs. The switched steering control was developed for an application seeking to identify approximately the maximum achievable speed in a bend. This application requires a steering control for simulating a realistic nonlinear four-wheel vehicle model and for performing a speed extrapolation test to evaluate the physical limits of a vehicle in a bend. This study includes the performance tests using experimental data from the Peugeot 307 prototype vehicle developed by IFSTTAR Laboratory.

1. Introduction

Knowledge of a vehicle's dynamic behavior is essential for improving vehicle safety, vehicle handling and passenger comfort. Active safety systems such as ABS and ESP can considerably reduce the number of accidents, and these safety systems can be enhanced by the knowledge of the vehicle's dynamic behavior.

This study presents a switched steering vehicle control strategy for simulating nonlinear vehicle behavior in a closed loop with high accelerations in a bend. The steering control problem has been addressed by a number of studies. Two controllers for vehicle steering control presented in Ackermann, Guldner, Sienel, Steinhauser, and Utkin (1995) are based on a linear and a non-linear control respectively. An inventory of driver models and their application in automobile dynamics is given in Plochl and Edelmann (2007). Recently, Cerone, Milanese, and Regruto (2009) developed a driver model combining two tasks, namely automatic lane-keeping and driver steering for either obstacle avoidance or lane-change maneuvers. In Nouvelière and Mammar (2007), a second-order sliding mode control is described, based on super-twisting. Other steering controllers based on a predictive LQ control and the second-order decoupling controller are presented in Cole, Pick, and Odhams (2006) and Marino and Cinili (2009) respectively. The problem of improving ground-vehicle handling is addressed in Poussot-Vassal et al. (2011) using braking and suspension control; this approach is extended through the introduction of steering control in Zheng, Ho, Han, and Zhang (2006). A steering control based on PID multi-controllers with two degrees of freedom is proposed in Menhour, Lechner, and Charara (2011). Other studies address the steering control problem via a steering torque control approach. The vehicle steering torque control problem is also covered in a number of publications including Fujiwara and Adachi (2002), Chong, Namgoong, and Sul (1996), and Enache, Sebsadji, Mammar, Lusetti, and Glaser (2009). In these studies, there has been relatively little focus on the performance of controllers under high dynamic loads.

The aim of this work is the design of switched steering vehicle control for an uncertain switched linear vehicle model. The proposed control law comprises two levels, the first containing a switched PID_y control for lateral deviation, and the second containing a switched PD_ψ control for yaw angle. The control strategy makes use of a convex LMI (Linear Matrix Inequality) framework, the LQR control problem, the H_∞ norm and the common Lyapunov function approach. It should be noted that

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the common Lyapunov function approach is currently used for the stability analysis of switched linear continuous-time systems (Liberzon & Morse, 1999; Lin & Antsaklis, 2009; Sun & Ge, 2005). This control law is used to control the system with a single input (steering angle input) and two outputs (lateral deviation and yaw angle). In our study longitudinal speed serves as a switching rule to determine the PID_y and PD_ψ controllers to be used.

Switching systems are generally used when the knowledge of nonlinear models or the design of control laws using the nonlinear model becomes a hard or impossible task. Consequently, a finite number of local models and switching rules are used to define the switched model. Switched systems are a class of hybrid systems, and stability and design problems relating to switched systems have also been addressed in Branicky (1998), Liberzon and Morse (1999), Daafouz, Riedinger, and Iung (2002), Sun and Ge (2005), Koenig, Marx, and Jacquet (2008), and Lin and Antsaklis (2009). In fact, the stability analysis of linear continuous-time and discrete-time switched systems have been covered quite widely in the literature: for switched continuous-time systems, a common Lyapunov function approach is used (Liberzon & Morse, 1999; Lin & Antsaklis, 2009; Sun & Ge, 2005), while for switched discrete-time systems, switched Lyapunov functions approach is applied (Branicky, 1998; Daafouz et al., 2002; Koenig et al., 2008). Several similar approaches for designing robust controllers, including LPV/H_∞ control (Apkarian, Gahinet, & Becker, 1995), gain scheduling state feedback control (Stilwell & Rugh, 1999), and fuzzy systems (Castillo & Melin, 2008; Mendel, 2004; Sugeno & Kang, 1988) have been developed. In Apkarian et al. (1995) a method is proposed for solving the control problem in LPV systems via a standard H_∞ norm and Linear Matrix Inequalities (LMIs). An alternative approach based on a gain scheduling state feedback control for LPV systems is proposed in Stilwell and Rugh (1999). This approach uses an interesting structure involving less number of interpolation coefficients and readability of the algorithm using physical variables.

As regards the design of PID and PD controllers, several methods have been developed and published. These controllers are designed using gain and phase margin methods (Fung, Wang, & Lee, 1998), convex and non-convex optimization methods (Astrom, Panagopoulos, & Hagglund, 1998; Ge, Chiu, & Wang, 2002; Lin, Wang, & Lee, 2004), relay-feedback auto-tuning PID methods (Hang, Astrom, & Wang, 2002; Ho, Honga, Hanssonb, Hjalmarssonc, & Denga, 2003), as well as oscillation and step response (Ziegler & Nichols, 1942).

The outline of this paper is as follows: the following section formulates the problem and introduces the concept of speed extrapolation. The reference trajectory and the vehicle models used are presented in Sections 3 and 4 respectively. The different steps in the design of the switching steering vehicle control (SSVC) are described in Section 5. Section 6 compares the steering control with real data acquired under high loads using a Peugeot 307 laboratory vehicle. The SSVC is also tested for low friction coefficients and parameter variations. The obtained Results prove the effectiveness of the control law. Section 7 contains concluding remarks.

2. Problem formulation

The control law is used to estimate the maximum achievable speed in a bend. For this purpose, the speed extrapolation tests are performed using experimental data acquired in normal driving situations. Extrapolation is based on several instances of nonlinear vehicle models coupled with the same number of control laws, which are executed to extrapolate the behavior of the vehicle in a bend. In other words, this real-time application makes use of an embedded simulation function, executing a dynamic model with incremented speeds, in order to extrapolate the vehicle behavior, starting from a normal driving situation and moving towards a virtual loss of control. This work was carried out on the laboratory vehicle (Lechner, 2008).

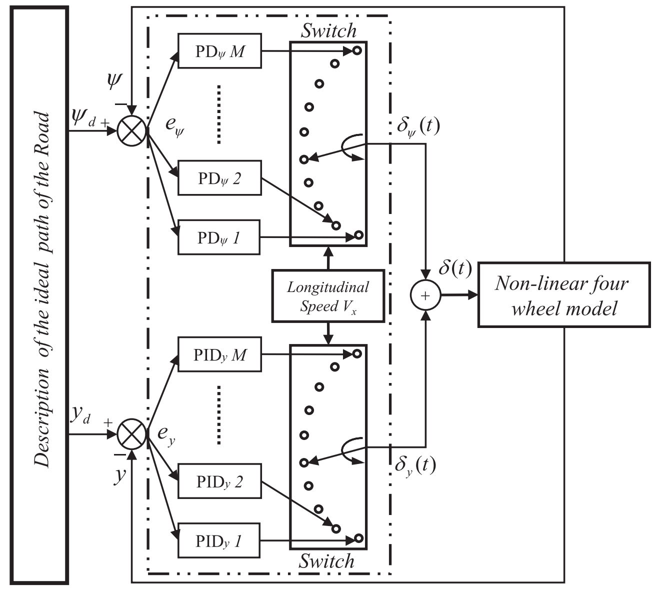

Fig. 1. Steering control coupled with a nonlinear model and a road trajectory.

The block diagram in Fig. 1 shows the system comprising the reference trajectory of the road, the switched steering vehicle control and the nonlinear vehicle model. The proposed switched steering control has two degrees of freedom: a single input (steering angle) and two outputs. Fig. 1 shows the control law with two levels: the first level controls the lateral deviation via the switched PID_y control, while the second controls the yaw angle via the PD_ψ control. The switched control approach is able, on the one hand, to overcome the uncertainties of the linear vehicle (2) used to design the control law and, on the other hand, to perform the speed extrapolation tests in a closed loop and to estimate the maximum speed of the vehicle in a bend. Such tests require a robust control law capable of operating under high dynamic loads and which can be used to characterize the nonlinear behavior of the vehicle. It should be noted that a definition of the speed extrapolation problem along with the different steps that yield an approximation of the maximum achievable speed are presented in Menhour et al. (2011).

3. Reference trajectory of the road

The parameters characterizing the trajectory are the yaw angle ψ_d, the curvature ρ_d, the path length coordinate s_d and the x_d and y_d coordinates computed by

$$\begin{cases} \psi_d(s_d) = \psi_{d0} + \int_{s_{d0}}^{s_d} \rho_d(s_d)\, ds \\ x_d(s_d) = x_{d0} + \int_{s_{d0}}^{s_d} \cos(\psi_d(s_d))\, ds \\ y_d(s_d) = y_{d0} + \int_{s_{d0}}^{s_d} \sin(\psi_d(s_d))\, ds \end{cases} \tag{1}$$

ψ_{d0}, x_{d0}, y_{d0}, s_{d0} and $\rho_d(s_d) = a_y(s_d)/V_x^2(s_d)$ are the original terms of the trajectory.

4. Vehicle models used

In this study two vehicle models (Jazar, 2008; Milliken & Milliken, 1995; Rajamani, 2006) are used: a linear two-wheel