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Vehicle Lateral Motion Control with Performance and Safety Guarantees

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Abstract: This paper explores the use of Model Predictive Control (MPC) techniques to solve vehicle lateral motion control problem on highway scenarios. In particular, the problem of autonomously driving a vehicle along a desired path is formulated, where safety constraints and performance levels must be guaranteed for all possible road curvatures within a compact set. Safety constraints are translated into a maximum lateral deviation and orientation error w.r.t. a desired path, while performance requirements are formulated in terms of bounded lateral acceleration and velocity. Preliminary simulation results show that the designed controller is capable of delivering acceptable performance at the cost of limited online computational costs.

Keywords: Vehicle motion control, safety, model predictive control, autonomous driving

1. INTRODUCTION

Among the technologies advancing within the automotive field, autonomous driving is definitely emerging with most promises of improving many aspects of our lifestyles related to transport. Road safety, traffic congestions and pollutant emissions, transit efficiency, healthiness of urban environments, to name a few, are recognized to be potentially and highly impacted by autonomous driving. It is then natural to question the maturity of the available autonomous driving technologies, especially with respect to the new and demanding requirements on the vehicle motion control imposed by Level 4 NHTSA (2013) of autonomous driving.

While the existing vehicle motion controllers use the driver as a failsafe fall-back, in autonomous driving, the deviation form a given path, for example, must be guaranteed to satisfy an Automotive Safety Integrity Level (ASIL) requirement, see ISO-26262 (2011) for a description of the ASIL standard. The determination of the required ASIL is the result of hazard analysis and risk assessment Smith and Simpson (2010), which means that functionalities with likely potential for severely life-threatening or fatal injury in the event of a malfunction will be classified as ASIL D, requiring the vehicle manufacturer to guarantee a failure rate of 10^{-8} events per hour. In conclusion, in Level 4 autonomous driving, staying within lane will need to be guaranteed with ASIL D. Hence, the ASIL D requirement to stay within the lane will reflect into a stringent requirement on the maximum total deviation from the desired trajectory/path (performance and safety guarantees), compatibly with the sensing technology. It is then clear that, without systematic control engineering approaches to the overall problem of vehicle motion control, climbing the ASIL ladder, from a Quality Measure (QM) to ASIL D, will lead to enormous, costly and time consuming verification problems, which inevitably will stall the product development. In this paper we focus on the problem of designing a vehicle lateral motion controller with performance and safety guarantees and explore the use of Model Predictive Control (MPC) techniques, with the objective of providing systematic design methodologies to satisfy ASIL D-type of requirements.

In Guldner et al. (1996) steering control for passenger cars on automated highways is analyzed and conditions for the safety and performance criteria are proposed. In Lei et al. (2006) a vision-based lane detection method is utilized along with a PID controller for the lateral control. A comparative study of linear controllers for lane keeping can be found in Taylor et al. (1999). A dynamic feedback controller is proposed in Benine-Neto et al. (2010), which considers road curvature as bounded disturbance input. Since the vehicle motion dynamics are nonlinear, constraints related to safety and performance can be naturally accommodated with MPC techniques, like in Falcone et al. (2007), where a MPC strategy for steering control of vehicle on slippery road is proposed. In Lee et al. (2012) a fast MPC strategy is proposed for lateral control. The paper proposes an algorithm to approximate solution of the optimization problem underlying the MPC controller, by using precomputed solutions. A MPC controller is designed to resemble the driver behavior in Gray et al. (2012). The controller is designed to only apply the correcting control action that is necessary to avoid violation of the safety constraints. A MPC problem for obstacle avoidance and lane keeping is proposed in Turri et al. (2013), based on linear decoupled lateral and longitudinal dynamics, thus helping

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in framing a convex QP problem for fast calculation of the solution.

In this paper, we explore MPC approaches to the vehicle lateral motion control problem. We focus on the problem of controlling the lateral vehicle motion subject to safety and performance requirements, along low curvature paths like in, e.g., highways. The road curvature is considered as disturbance input to the system. Safety and performance requirements are formulated in terms of the maximum deviation from the desired path and constraints on the vehicle states stemming from a desired comfort envelope. These constraints are guaranteed to be persistently satisfied within a known set of vehicle states for a curvature of the desired path within given boundaries. Preliminary simulation results show the performance and the viability of the proposed approach, encouraging further developments.

The paper is structured as follows. In Section 2 we introduce a vehicle model, notations, and formally state the vehicle lateral motion control problem. Section 3 presents few preliminary results on invariant set and an algorithm to calculate the invariant set. In Section 4, the design procedure is shown. while Section 5 show the results of numerical simulations. The paper is concluded is in Section 6 with final remarks about the presented results and future research directions.

2. PROBLEM FORMULATION

2.1 Vehicle Modeling

Consider the vehicle model sketched in Figure 1. For small road bank angle, the vehicle motion w.r.t. the path Γ_{des}, subject to the lateral and yaw dynamics, is described by the following set of differential equations (Rajamani, 2006).

$$m\dot{v}_y = -mv_x\dot{\psi} + 2\left[F_{y_f} + F_{y_r}\right], \tag{1a}$$
$$J_z\ddot{\psi} = 2[l_f F_{y_f} - l_r F_{y_r}], \tag{1b}$$
$$\dot{e}_\psi = \dot{\psi}_{des} - \dot{\psi}, \tag{1c}$$
$$\dot{e}_y = -v_y + v_x e_\psi, \tag{1d}$$
$$\dot{\psi}_{des} = v_x\gamma, x \tag{1e}$$

where m and J_z denote the vehicle mass and yaw inertia, respectively, l_f and l_r are the distances of the vehicle center of gravity from the front and rear axles, respectively, v_x and v_y are the longitudinal and lateral velocities, respectively, in the vehicle body frame, $\dot{\psi}$ is the turning rate, where ψ denotes the vehicle orientation w.r.t. the fixed global frame (X, Y) in Figure 1. F_{y_f}, F_{y_r} are the lateral tire forces at the front and rear axles, respectively. In (1c) and (1d), e_ψ and e_y denote the vehicle orientation and position, respectively, w.r.t. the path Γ_{des} and ψ_{des} is the desired vehicle orientation, i.e., the slope of the tangent to the path Γ_{des} in the point O.

The lateral tire forces in (1a) and (1b) are generated at the tire contact patch and are, in general, nonlinear functions of the vehicle states. In this paper, we compute the lateral tire forces as,

$$F_{yi} = -C_i\alpha_i, \;\; i \in \{f, r\}, \tag{2}$$

where C_i are the tire cornering stiffness coefficients at the two axles and α_i are the tyre slip angles which, for small values, can be approximated as,

$$\alpha_f = \frac{v_y + l_f\dot{\psi}}{v_x} - \delta, \quad \alpha_r = \frac{v_y - l_r\dot{\psi}}{v_x}, \tag{3}$$

where δ denotes the front steering angle as depicted in Figure 1. In order to use the steering rate as control input, the model (1) is augmented with an integrator. Hence, for a given vehicle longitudinal speed v_x, the model (1)-(3) can be compactly written as,

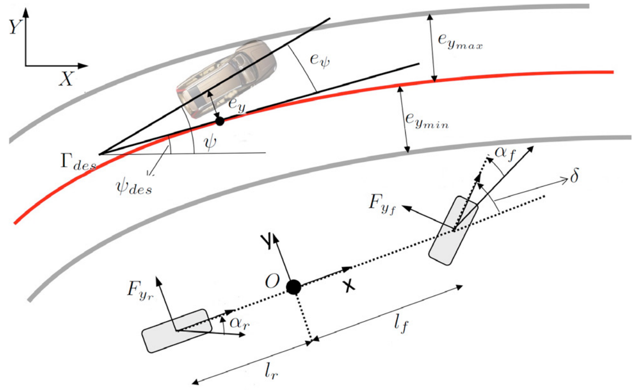

Fig. 1. Vehicle in a desired path based coordinate system

$$\dot{x}(t) = Ax(t) + Bu(t) + Ew(t), \tag{4}$$

where $x = \left[v_y,\ \dot{\psi},\ e_\psi,\ e_y,\ \delta\right]^T$ and $w = \gamma$ are the state and the disturbance vectors and $u = \dot{\delta}$ is the steering input command.

2.2 System Constraints

The input, state and disturbance vector in (4) is subject to a set of physical and design constraints. These constrains are the result of safety, performance and physical limitation of a vehicle. The safety requirements, for the considered problem, translate into the following constraints on the position e_y

$$e_{y_{min}} \le e_y \le e_{y_{max}}, \tag{5}$$

To preserve the driving comfort, we impose bounds on the lateral vehicle speed and acceleration, which, for a given speed v_x, can be written as,

$$v_{y_{min}} \le v_y \le v_{y_{max}}, \tag{6a}$$
$$\frac{a_{y_{min}}}{v_x} \le \dot{\psi} \le \frac{a_{y_{max}}}{v_x}, \tag{6b}$$

Further physical constraints stem from the limited steering and steering rate of the steering actuator.

$$\begin{aligned} \delta_{min} &\le \delta \le \delta_{max}, \\ \dot{\delta}_{min} &\le \dot{\delta} \le \dot{\delta}_{max}. \end{aligned} \tag{7}$$

The constraints (5)-(7) can be compactly rewritten for the system (4) as,

$$\begin{aligned} \mathcal{X} &= \{x \in \mathbb{R}^4 : \;\; H_x x \le h_x\}, \\ \mathcal{U} &= \{u \in \mathbb{R} : \;\; H_u u \le h_u\}. \end{aligned} \tag{8}$$

Finally, we assume that the curvature γ of the reference path Γ_{des} is bounded, i.e., it belongs to the set,

$$\mathcal{W} = [\gamma_{min}, \gamma_{max}]\,. \tag{9}$$