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Safe driving envelopes for path tracking in autonomous vehicles

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ABSTRACT

One approach to motion control of autonomous vehicles is to divide control between path planning and path tracking. This paper introduces an alternative control framework that integrates local path planning and path tracking using model predictive control (MPC). The controller plans trajectories, consisting of position and velocity states, that best follow a desired path while remaining within two safe envelopes. One envelope corresponds to conditions for stability and the other to obstacle avoidance. This enables the controller to safely and minimally deviate from a nominal path if necessary to avoid spinning out or colliding with an obstacle. A long prediction horizon allows action in the present to avoid a dangerous situation in the future. This motivates the use of a first-order hold discretization method that maintains model fidelity and computational feasibility. The controller is implemented in real-time on an experimental vehicle for several driving scenarios.

1. Introduction

In an autonomous vehicle, it can be useful to divide motion control into path planning and path tracking (Leonard et al., 2008; McBride et al., 2008; Montemerlo et al., 2008). In this hierarchical structure, the path planner uses data from perception systems to generate a desired path (desired positions and orientations) the vehicle should follow. The path tracker then calculates and applies steering action to guide the vehicle along the path. As long as the vehicle can feasibly follow the path, this paradigm works well (Campbell, 2007; Thrun et al., 2006). This is especially true in normal driving scenarios characterized by low accelerations in which the kinematic vehicle model often used in path planners approximates vehicle behavior well (Dolgov, Thrun, Montemerlo, & Diebel, 2010; Likhachev & Ferguson, 2009). However, a path planner may not have sufficient or accurate information, especially in cases of changing road conditions or nonlinear dynamic limits of the vehicle. Even if a path planner has access to this data, it is challenging to encode all information needed to safely navigate the environment as a single path. If the path cannot be perfectly tracked, a path tracking controller should possess information about where it is safe to deviate from the path, such as within a lane, and where it is not, such as next to another vehicle.

Path tracking controllers that consider the non-linear dynamics of the vehicle have been shown to be effective in extreme conditions such as racing, fast emergency maneuvers, and icy roads. Kritayakirana et al. used feedforward and lanekeeping-based feedback control to track a racing line even as tires approached saturation (Kritayakirana & Gerdes, 2012). Borrelli, Falcone, Keviczky, and Asgari (2005) presented the path tracking problem as a nonlinear model predictive control (MPC) problem. This controller explicitly considered tire nonlinearities to perform a double lane change under icy conditions. As further explored by Falcone, Borrelli, Tseng, Asgari, and Hrovat (2008), a carefully chosen bound on the states and inputs ensures stability, preventing the vehicle from spinning out by deviating from the path. While this approach does stabilize the vehicle, leaving the path in reaction to severe road conditions could result in hitting an obstacle. The need to go off the path to stabilize the vehicle illustrates the potential dangers of a path not suited for the vehicle and situation.

The main contribution of this paper is a path tracking controller that uses knowledge of the environment and the vehicle's dynamics to safely deviate from the path when necessary to avoid spinning out or hitting an obstacle. In order to accomplish this, the controller constrains predicted states to a region in the state space in which the dynamic vehicle model is stable. This region is known as the stable handling envelope, originally presented by Beal and Gerdes (2013). The predicted states are also constrained to a region in the environment between the road edges and free of obstacles, known as the environmental envelope. These two envelopes were first used in conjunction by Erlien, Fujita, and Gerdes (2013) as an advanced driver assistance system that shared control with a driver. The controller would give full control to the driver unless the driver's commands would cause a future violation of either envelope, in which case the controller would intervene. This allowed the driver to have control of the vehicle in most situations,

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with the controller only intervening to prevent the vehicle from spinning out or colliding with an obstacle.

This paper discusses the considerations necessary to adapt the envelope approach to path tracking. The presented controller uses MPC to plan a trajectory (a sequence of states) that best follows the desired path while staying inside the stable handling and environmental envelopes. There is a fundamental difference between an envelope controller designed for automated vehicles and one designed for driver assistance: the controller for the automated vehicle has precise knowledge of the desired path instead of simply a projection of driver intent from the steering angle history. With the uncertainty in the driver action removed, error in the vehicle model becomes the limiting factor for performance. Since the controller should ideally reproduce the planned trajectory exactly in the absence of disturbances, the vehicle modeling must improve to take advantage of the increased information about the upcoming path and its curvature. The solution here is to employ a long prediction horizon divided into two parts. In the first few points of the horizon, the vehicle model discretized with short time steps provides a short term plan that accurately captures vehicle dynamics. At later steps in the horizon, a vehicle model discretized with a first-order hold reduces modeling error and more accurately incorporates future curvature information. This discretization method provides the controller with an accurate model over the prediction horizon using few enough points to make the problem computationally feasible. The controller tracks the path in the absence of obstacles or stability concerns; however, it is not restricted to follow the path if the path is not safe.

The following sections of the paper describe the formulation of nominal paths and the derivation of a continuous time dynamic bicycle model. The multi-timestep prediction horizon leads to a discussion of the first-order hold discretization method. Then the optimization problem is presented, including explanations of the vehicle handling envelope and environmental envelope. Experimental results demonstrate the efficacy of the controller in situations in which the nominal path is unsafe and require a deviation. The first situation is a path that has relatively high curvature but is safe to follow, demonstrating the path tracking ability of the controller. The second situation is a hairpin turn too tight for the vehicle's given speed, which shows the controller's ability to take action early to navigate the corner. The third situation is a path with an obstacle in the middle of a turn taken near the limits of handling, showing the simultaneous consideration of stability and obstacle avoidance.

2. Nominal paths

The nominal vehicle path can be as simple as a road centerline or be a very precise sequence of desired positions from a higher level path planner using its understanding of the vehicle's behavior and environment. This path is then passed to the controller as a reference to track. Nominal paths here are defined in terms of the commonly used values curvature K and arc length s (Fraichard & Ahuactzin, 2001; Theodosis & Gerdes, 2011). $E(s)$ and $N(s)$ are defined to be the East and North measures of the position of the path at s from a local datum. The path's heading $\psi_r(s)$ is defined to be the angle from North to a vector parallel to the path at s. Curvature K is related to heading ψ_r and position (E,N) through the following differential equations:

$$\frac{d\psi_r}{ds} = K(s) \tag{1}$$

$$\frac{dE}{ds} = \cos\ \psi_r \tag{2}$$

$$\frac{dN}{ds} = \sin\ \psi_r \tag{3}$$

An example of a nominal path used in experiments is shown in Fig. 1(a): K against s specifies the path. Fig. 1(b) and (c), integrated from the curvature profile with given initial conditions, show the heading and position of the path implied by the chosen curvature. Important environmental information, such as road edges and obstacle locations and sizes, are provided in terms of s. Parsing environmental information is discussed in Section 5.

3. Continuous-time vehicle model

The controller requires a vehicle model that can adequately capture handling limits and loss of stability under some operating conditions. This can be accomplished using a planar bicycle model with two velocity states and three position states as illustrated in Fig. 2. In this controller, front steering angle δ is the only method of actuation. Allowing longitudinal velocity U_x to be variable in the same optimization as δ makes the problem non-convex; while it is possible to track a desired speed profile with an external controller, the expected speed over the prediction horizon is fixed when forming the model. For the experiments presented here, the desired speed is constant.

The velocity states sideslip (β) and yaw rate (r) are described by the following equations of motion (for constant speed):

$$\dot{\beta} = \frac{F_{yf}\cos(\delta) + F_{yr}}{mU_x} - r \approx \frac{F_{yf} + F_{yr}}{mU_x} - r \tag{4}$$

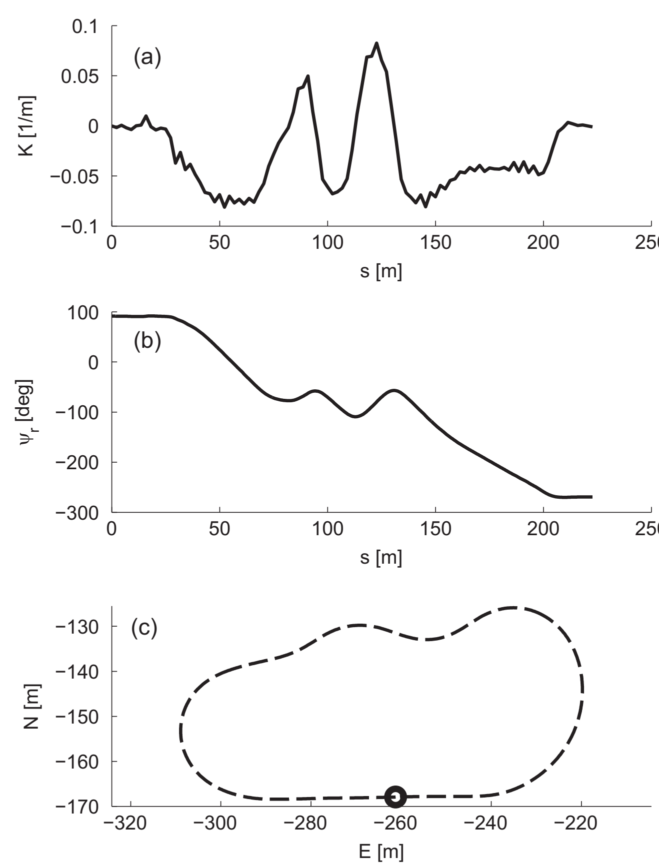

Fig. 1. Curvature (a), heading (b), and position (c) of a nominal path.