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Model predictive path following control for autonomous cars considering a measurable disturbance: Implementation, testing, and verification ☆

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ABSTRACT

Model predictive control (MPC)-based path following schemes for autonomous cars represent a novel and highly debated control approach. Their high online computational load poses a challenge for practical real-time application in vehicle systems with fast dynamics. This paper proposes an implementation scheme for an MPC path following controller that considers the feasible road region and vehicle shape. Moreover, the model mismatch induced by varying road conditions and small-angle assumptions is considered in the form of a measurable disturbance. To solve the optimization problem for the proposed MPC path following controller, a differential evolution (DE) algorithm is adopted. To verify the computational performance of the proposed implementation scheme, an experimental platform was developed that consists of the Hongqi autonomous car HQ430, various sensors, and systems for communication and data processing. The experimental results indicate that the proposed DE-based implementation strategy for the MPC path following controller achieves good computational performance and satisfactory control performance for path following in autonomous cars.

1. Introduction

Increasing demand for driver assistance systems and advancements in automobile technologies for improved safety, efficiency, and mobility have motivated the rapid development of intelligent transportation systems (ITSs) [1]. As a vital class of ITSs, autonomous cars have attracted attention from many researchers due to their various potential applications, such as improving security and road utilization and reducing traffic accidents [2]. One of the most fundamental issues related to autonomous cars is the path following problem [3,4], which serves as the basis for the design of control laws that enable a vehicle to reach and follow a predefined path that is not parameterized by time [5].

The constantly varying nature of road and traffic conditions poses great difficulties in path following control for autonomous cars. It also leads to disturbances in the vehicle/environmental parameters and vehicle states. Several control

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schemes have been proposed to address these problems, such as fuzzy logic control [6], robust H_∞ output-feedback control [7], sliding mode control [8], and chained system theory [9]. These schemes enable the effective following of a desired path for an autonomous car. However, in most of these control schemes, the vehicle is treated as a rigid point, and the desired path is described by either a continuous curve or discrete points. Such an approach may result in collision with the road boundary when following a complex road because the size and shape of the autonomous car are ignored. Moreover, when only the centerline of the road is used to describe the desired path, it is easy for the car to drift out of the feasible road region because the width of the path is neglected. For practical applications, the variations in the road and traffic environments, the shape of the vehicle, and the road boundaries should all be considered. Model predictive control (MPC) enables the systematic handling of both state and control constraints and the prediction of the dynamics of a vehicle system while generating an optimal sequence of control actions within a finite horizon by means of optimization techniques. Consequently, MPC is a feasible means of realizing path following control for autonomous cars [10].

MPC has been proven to be very successful in enabling path following for autonomous cars [11] because of its ability to handle multi-variable/multi-objective problems and explicitly consider hard constraints [12]. However, the accompanying online computational burden has limited the application of MPC in vehicle systems because of the necessity of solving a quadratic or nonlinear programming problem at each sampling instant. To speed up online MPC computations, various approaches have been adopted in the literature, including the development of fast numerical optimization algorithms and the implementation of MPC algorithms in hardware. One such fast numerical algorithm that has been proposed is the generalized minimum residual (GMRES) approach, which can reduce the computation time at each sampling instant [13]. GMRES was applied for nonlinear model predictive control (NMPC) in [14]. Another scheme that combines several approaches to improve the computational speed of MPC algorithms is described in [15]. This scheme provides a method for achieving fast control computations when the dimensions of the optimization problem are small. Regarding hardware implementations, schemes based on field programmable gate arrays (FPGAs) are under discussion [16]. The use of systems on programmable chips (SoPCs) or full hardware implementations in combination with parallel computing and reconfigurable hardware could improve online computing performance and decrease computation times for MPC applications [17].

Nevertheless, few entries in the literature have simultaneously addressed an MPC path following scheme that considers varying road conditions and an implementation scheme for use in autonomous cars. In [18], a regional path moving horizon tracking controller was presented and implemented. However, the control performance was affected by varying road conditions and the control error was relatively large under many vehicle operation conditions. In [19], the concept of dual-envelope-based path following control was originally presented. That study focused on the selection of predictive horizon and the sample time and their influence on control performance. However, no specific implementation scheme was discussed. Based on that study, an MPC path following scheme that considers the feasible road region and vehicle shape constraints is proposed here, in which the model mismatch induced by varying road conditions and small-angle assumptions is also considered in the form of a measurable disturbance, and a corresponding implementation scheme is discussed. Considering that the source code for the optimization approach is needed for the implementation of a path following controller on an autonomous car, a differential evolution (DE) algorithm is adopted to solve the MPC optimization problem. To verify the control performance and computational performance of the proposed MPC path following implementation scheme, an experimental platform was developed based on the Hongqi autonomous car HQ430, and experiments were conducted to investigate the proposed implementation approach.

The main contributions of this paper are twofold: (1) To improve the control precision, the model mismatch induced by varying road conditions and the small-angle assumptions used to simplify the model is considered in the form of a measurable disturbance, and an MPC path following scheme that considers this measurable disturbance is presented. (2) An implementation scheme is presented for the proposed MPC path following controller. An experimental verification of the proposed controller is reported, demonstrating a computation time that can satisfy real-time requirements.

The remainder of the paper is organized as follows. Section 2 briefly presents the description of the path following problem and the model used in the controller design. In Section 3, the MPC path following controller is introduced. In Section 4, the implementation of this controller is discussed, and the DE algorithm that is used to solve the optimization problem is introduced. The experimental platform implemented based on the Hongqi autonomous car HQ430 is described in Section 5. The experiments and an analysis of the results are presented in Section 6. A brief conclusion to this paper is provided in Section 7.

2. Problem statement and system modeling

2.1. Problem statement

The path following problem is illustrated in Fig. 1. In this problem, the objective is to ensure that the lateral offset between the vehicle's center of gravity (CoG) and the closest point O on the desired path is as small as possible. In addition, to ensure its safety, the operating vehicle should remain within the boundaries of the road. More specifically, neither the front nor the rear end of the vehicle should collide with the road boundary. To satisfy these conditions, both the feasible road region and the shape of the vehicle should be considered. The feasible road region is represented by three curves: the centerline of the road, $f(x)$; the left road boundary, $f_l(x)$; and the right road boundary, $f_r(x)$. The left and right road boundaries