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Dual-envelop-oriented moving horizon path tracking control for fully automated vehicles[☆]

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ABSTRACT

A novel description of dual-envelop-oriented path tracking issue is presented for fully automated vehicles which considers shape of vehicle as inner-envelop (I-ENV) and feasible road region as outer-envelop (O-ENV). Then implicit linear model predictive control (MPC) approach is proposed to design moving horizon path tracking controller in order to solve the situations that may cause collision and run out of road in traditional path tracking method. The proposed MPC controller employed varied sample time and varied prediction horizon and could deal with modelling error effectively. In order to specify the effectiveness of the proposed dual-envelop-oriented moving horizon path tracking method, veDYNA-Simulink joint simulations in different running conditions are carried out. The results illustrate that the proposed path tracking scheme performs well in tracking the desired path, and could increase path tracking precision effectively.

1. Introduction

With the rapid development of intelligent transportation systems [1] and automobile [2] technology, fully automated vehicles have arouse many researchers' attention due to various potential applications, for example reducing traffic congestion and traffic accidents, etc [3–5]. Fully automated vehicles are comprehensive applications of multi-discipline knowledge and theories, in which perception, decision and control are the three main components of the software configuration [6]. In the aspect of control, one of the most important issues of fully automated vehicles is the path tracking problem [7,8]. In general, path tracking for fully automated vehicles could be accomplished by steering control and velocity control [9,10] according to the information of current vehicle dynamic states and the road in front of vehicle [11]. Steering control not only calculates and manipulates steering wheel to guide vehicles along the lateral path, but also related to lateral stability of vehicle. Therefore, it is a hot discussion for researchers [12].

The mainly discussed path tracking scheme is pure-pursuit tracking method [13], which considers vehicle as a rigid point with mass and it should track the desired path obtained by different methods [14]. Under this framework, a fuzzy logic controller for the path tracking of a wheeled mobile is presented in [15]. The controller is highly robust and flexible and it follows a sequence of discrete way-points, automatically. In [16], a robust H_∞ output-feedback control strategy for the path tracking of fully automated vehicles is presented. Besides, external disturbances of fully automated vehicles are considered here. For four-wheel independently actuated autonomous ground vehicles, a output constraint strategy using hyperbolic projection method and a integral sliding model-based composite nonlinear feedback control technique are presented in [17–19], respectively to deal with the lateral offset. The methods mentioned above could track the desired path of fully automated vehicles effectively. However, most of these control schemes are developed based on one-dimension vehicle-road model. It regards vehicle as a rigid point and uses a continuous curve or discrete points to describe the desired path. Compared with practical vehicle running situations, it may cause collisions when tracking a more complex road ignoring the size and shape of fully automated vehicles. Moreover, it is easy to run out of the feasible road region due to neglecting of the

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width of the path when using centerline to describe the desired path.

With the rapid development of online optimization [20] and hardware implementation [21], model predictive control (MPC) has attracted many focus on discussing vehicle active safety [22–25] and path tracking issue of fully automated vehicles [7,26,27]. In [28], a nonlinear MPC method is presented to discuss path tracking control for autonomous vehicle system. In [6], it introduces an alternative MPC-based control framework that integrates local path planning with path tracking, in which the nominal path is commonly described in terms of curvature and arc length. In [8], a collision avoidance system for an autonomous vehicle is presented, which consists of a motion planner and MPC-based active vehicle steering and active wheel torque control. MPC is able to systematically handle the constraints on state and control, and predict the dynamics of vehicle system, while generating an optimal sequence of control actions within a finite horizon based on the optimization technique. Accordingly, it is hot discussed and employed in vehicle path tracking issues. Therefore, the proposed methods above could track the desired path. However, the modelling error is not considered in the MPC approaches mentioned above which may affect control accuracy [29]. In addition, the path to be tracked is determined first, and could not changed. Moreover, the width of the vehicle is not considered, too. In order to solve those issues mentioned above, modelling error should be taken into consideration of the presented MPC method. The size and shape of vehicle, the width of the desired path should be considered. Moreover, the path to be tracked should be decided according the road information previewed ahead. The issues are preliminary discussed in [30], in which the description of path tracking for fully automated vehicles is carried out, and constraints that are used to restrict the vehicle position is considered. However, the influence of modelling error to path tracking precision has not been discussed. Besides, the path tracking controller is designed without considering different previewed road information.

In order to further discuss path tracking issue mentioned above, extended the path tracking scheme in [30], dual-envelop-oriented path tracking issue for fully automated vehicles is originally described in this manuscript. It takes the shape of vehicle as inner-envelop (I-ENV) and the feasible road region that considers the road width as outer-envelop (O-ENV). Then, a moving horizon path tracking controller employing implicit linear MPC method is designed considering the road boundaries, and actuator saturation as constraints. In order to obtain better control accuracy, the proposed MPC-based moving horizon path tracking scheme is considered the following aspects: the modelling error is discussed in the vehicle model, and the sample time and predictive horizon are varied according to road curvature. Finally, veDYNA-Simulink joint simulations are carried out to specify the effectiveness of the proposed moving horizon path tracking method.

The main contributions of this paper lie in two aspects: (1) the original description of dual-envelop-oriented path tracking issue of fully automated vehicle is presented which considers the shape of vehicle as inner-envelop and feasible road region as outer-envelop. (2) the moving horizon path tracking controller that adopts varied sample time and varied prediction step is proposed, which could deal with the modelling error and increase path tracking precision effectively.

The remainder of the paper is organized as follows. Section 2 presents the dual-envelop-oriented path tracking problem. In Section 3, vehicle model is built and MPC-based moving horizon path tracking controller is designed. Simulations are carried out in Section 4. Brief conclusions of this paper are presented in Section 5.

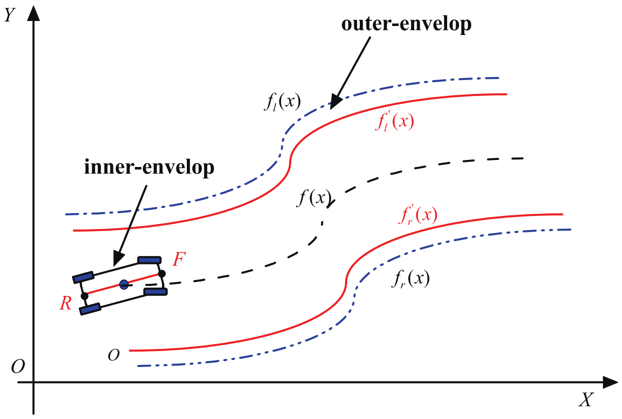

Fig. 1. Dual-envelop for fully automated vehicles.

2. Dual-envelop-oriented path tracking issue for fully automated vehicles

2.1. Dual-envelop-oriented path tracking issue

Considering the width and length of vehicle and the feasible road region in path tracking problem, a dual-envelop-oriented path tracking issue is shown in Fig. 1. The O-ENV that describes the feasible road region is represented by three curves: the centerline $f(x)$, the left boundary $f_l(x)$ and the right boundary $f_r(x)$. The left and right boundaries could be obtained by onboard camera. The I-ENV that represents the vehicle running in the feasible region is described as a rectangle, in which the width of vehicle is expressed as w and the length is described as l. Then the dual-envelop-oriented path tracking problem of fully automated vehicles could be split into two parts: searching the optimal path and tracking the optimal path. When searching and tracking the optimal path in the dual-envelop-oriented region, it is essential to avoid crashing the road boundary in order to ensure the safety of fully automated vehicles. Based on the relationship between I-ENV and O-ENV, the aim could be achieved by restricting the lateral positions of the vehicle front end F and the rear end R within the O-ENV, that is

$$f_l(x) \le y_i \le f_r(r), i = F, R. \tag{1}$$

In addition, in order to simplified the path tracking problem, the I-ENV is shrink as a rigid bar. Accordingly each boundary of O-ENV is subtracted by a half width of vehicle to ensure the rationality of the simplification. Therefore, the simplified O-ENV could be described as

$$\begin{aligned} f_l'(x) &= f_l(x) - \frac{w}{2}, \\ f_r'(x) &= f_r(x) + \frac{w}{2}. \end{aligned} \tag{2}$$

Then the lateral positions of front and rear end of vehicle should satisfy the following conditions

$$f_r'(x) \le y_i \le f_l'(x), i = F, R. \tag{3}$$

where $y_i, i = F, R$ represents the lateral positions of the front end and rear end, respectively. Moreover, in order to keep vehicle running stably, it is better to make the vehicle follow the road centerline. It means that the difference between lateral vehicle position y and road centerline $f(x)$ should be as small as possible.

2.2. Outer-envelop determination

Considering the road information obtained from onboard sensors in the inertial coordinate system and the controller design

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