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Adaptive-neural-network-based robust lateral motion control for autonomous vehicle at driving limits

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ABSTRACT

Parametric modeling uncertainties and unknown external disturbance are major concerns in the development of advanced lateral motion controller for autonomous vehicle at the limits of driving conditions. Considering that tyre operating at or close to its physical limits of friction exhibits highly nonlinear force response and that unknown external disturbance can be caused by changing driving conditions, this paper presents a novel lateral motion control method that can maintain the yaw stability of autonomous vehicle while minimizing lateral path tracking error at the limits of driving conditions The proposed control scheme consists of a robust steering controller and an adaptive neural network (ANN) approximator. First, based on reference path model, dynamics model and kinematics model of vehicle, the robust steering controller is developed via backstepping variable structure control (BVSC) to suppress lateral path tracking deviation, to withstand unknown external disturbance and guarantee the yaw stability of autonomous vehicle. Then, by combining adaptive control mechanism based on Lyapunov stability theory and radial basis function neural network (RBFNN), the ANN approximator is designed to estimate uncertainty of tyre cornering stiffness and reduce its adverse effects by learning to approximate arbitrary nonlinear functions, and it ensures the uniform ultimate boundedness of the closed-loop system. Both simulation and experiment results show that the proposed control strategy can robustly track the reference path and at the same time maintains the yaw stability of vehicle at or near the physical limits of tyre friction.

1. Introduction

Vehicles have become an indispensable means of transportation in our present-day world, but the mobility brought by vehicles comes at a price (Eskandarian, 2012; Funke, Brown, Erlien, & Gerdes, 2017; He, Yang, Ji, Liu, & Deng, 2017; Zhang & Wang, 2017). In 2015, about 1.3 million people around the world are killed in traffic accidents, ranking tenth on the World Health Organization's list of top causes of death (World Health Organization, 2015). 72% of the traffic accidents can be traced to human error (Thomas, Morris, Talbot, & Fagerlind, 2013). With the rapid development of artificial intelligence and automobile technology, autonomous vehicle is expected to take more burden and stress from human driver, thus enhancing safety and reducing driver's workload, etc. (Brown, Funke, Erlien, & Gerdes, 2017; Lam, Leung, & Chu, 2016; Petrov & Nashashibi, 2014). Autonomous vehicle is a product of multi-disciplinary knowledge and theories, in which environment recognition system, decision-making system, motion control system are the three main components of the software system (González, Pérez, Milanés, & Nashashibi, 2016; Li, Chen, Li, Shaw, & Nuchter, 2014; Liu, Fan, Lv, et al., 2018). Many researchers have reported the progress made on overall architecture and the feasibility of autonomous vehicle technology (Gao, Gray, Tseng, & Borrelli, 2014; Kritayakirana & Gerdes, 2012a). This paper focuses on the motion control system of autonomous vehicle.

In designing the motion control scheme for autonomous vehicle, one of the most important considerations is to eliminate lateral path tracking error while ensuring vehicle stability during driving. In general, the motion control of autonomous vehicle can be achieved by longitudinal control and lateral control based on the information of current vehicle states and the road (Guo et al., 2017; Kim, Son, & Chung, 2016). Longitudinal control seeks to maintain a desired cruising speed and a safe distance between the leading vehicle and controlled vehicle for collision avoidance (Chen & Wang, 2011; Lefèvre, Carvalho, & Borrelli, 2016). Lateral control not only guides vehicles along the desired path, but also maintains vehicle stability. Therefore, it has become a hotspot for researchers. A linear time-varying model predictive control (MPC) which uses active front steering system in an autonomous vehicle is

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proposed to follow a given path in Falcone, Borrelli, Asgari, Tseng, and Hrovat (2007). Guo, Hu, Li, and Wang (2012) designed automatic steering controller for trajectory tracking of unmanned vehicles using genetic algorithms. Lee, Choi, Yi, Shin, and Ko (2014) focused on developing a hierarchical control algorithm for lane-keeping of vehicle using differential braking to prevent unintended lane departures. The local path tracking for autonomous vehicles was discussed using model predictive control (MPC) method, where the front wheel steering angle was used as the control variable, and the safety and actuator constraint factors were also considered (Yu, Guo, Sun, & Chen, 2015). The path following control for four-wheel independently actuated autonomous vehicles is designed through combining sliding model-based composite nonlinear feedback control of active front-wheel steering with direct yaw-moment control (Wang, Hu, Yan, & Chadli, 2016). An adaptive path tracking strategy for autonomous land vehicle based on neural dynamic programming is designed (Zhu, Huang, Liu, & Dai, 2016). To track the planned trajectory for collision avoidance maneuvers, the path-tracking controller formulated the tracking task as a multi-constrained model predictive control (MMPC) problem and calculated the front steering angle to prevent the vehicle from colliding with a moving vehicle (Ji, Khajepour, Melek, & Huang, 2017). A shared control algorithm using safe envelope of steering wheel angle is proposed to develop a human–machine cooperative steering system to avoid lane departure (Tan, Chen, Wang, & Gao, 2017). Hwang, Yang, and Hung (2017) presented a path tracking method of autonomous vehicle using hierarchically improved fuzzy dynamical sliding-model control.

However, as autonomous vehicles leave the research laboratory and enter public traffic, they must can react to emergency scenarios, some of which may necessitate maneuvering like in an emergency collision avoidance which happens in a short time horizon and requires large actuator inputs together with high yaw rates. Tyres will be highly saturated and begin to sideslip. In this situation, the characteristics of tyre force become highly nonlinear, which means the cornering force of tyre does not increase linearly with the increase of its slip angle, instead, it barely changes or even decreases with the increase of its slip angle. That is, vehicle is at the limits of driving conditions. The Dynamic Design Lab (DDL) in Stanford University has conducted a great deal of research for lateral motion control of autonomous vehicle in these conditions (Brown et al., 2017; Funke et al., 2017; Kapania & Gerdes, 2015; Kritayakirana & Gerdes, 2012a,b; Laurense, Goh, & Gerdes, 2017). In addition, several other researchers have also made important contribution in this area. In Rosolia, Carvalho, and Borrelli (2017), a learning nonlinear model predictive control is presented for autonomous racing problem that exploits information from previous laps to improve the performance of closed loop system over iterations. In Ni and Hu (2017), a hierarchical dynamics controller scheme is designed based on desired G–G diagram to push the autonomous vehicle to the driving limits on a given path, and the test of the controller is conducted based on an autonomous Formula SAE race car on an oval race track.

Although the above research achievements were successful to some extent, there are still two main challenges for lateral motion control of autonomous vehicle. Parametric modeling uncertainty and unknown external disturbance are of common occurrence in practical vehicle systems. If lateral tyre force in nonlinear region is treated as linear or driving environment changes abruptly, the behavior of the vehicle may become uncontrollable, and then autonomous vehicle will lose path tracking capability and stability. In the literature, though some researchers considered both parametric modeling uncertainty and unknown external disturbance in the design of lateral motion controller for autonomous vehicle, most of these researches do not focus on lateral motion control in the conditions of high lateral acceleration or low adhesion coefficient (Gao, Gray, Carvalho, Tseng, & Borrelli, 2014; Hang, Chen, Luo, & Fang, 2017; Hu, Jing, Wang, Yan, & Chadli, 2016; Kim et al., 2016; Ostafew, Schoellig, & Barfoot, 2016; Xia, Pu, Li, & Gao, 2016). As a matter of fact, in the linear region of tyres it is very easy to achieve good vehicle stability and controllability, which offers very limited scope for the consideration of parametric modeling uncertainty and disturbance on vehicle motion control.

Based on what has been mentioned above, it is necessary to investigate how to reduce the adverse effect of the parametric modeling uncertainty and unknown external disturbance on the lateral motion control of autonomous vehicle at the limits of driving conditions. The adaptive neural network (ANN) can effectively improve control performance against large uncertainty of system by learning to approximate arbitrary nonlinear functions, and the adaptation law is derived using Lyapunov function so that the stability and the convergence of the entire system are ensured (He, Chen, & Yin, 2016; Liu, 2013). However, there is the approximation error due to the employment of ANN, and the lateral motion control of autonomous vehicle should have strong robustness. The backstepping variable structure control (BVSC) is a specific type of robust control, which combines the merits of both backstepping control and those of variable structure control. This approach has shown its effectiveness in dealing with approximation error, multiple dynamics and mismatched uncertainties (Coban, 2017; Piltan, Mansoorzadeh, Zare, Shahryarzadeh, & Akbari, 2013). Nonetheless, this type of methods are developed on the basis of an assumed mathematical model, whose imperfections can lead to lowered performance of the controller. Hence, there is need to design some kind of compensator.

In the paper, a novel lateral motion control strategy is proposed to maintain yaw stability of autonomous vehicle while minimizing lateral path tracking deviation at the limits of driving conditions. The proposed control scheme consists of a robust steering controller and an ANN approximator. In the first stage, based on reference path model, dynamics model and kinematics model of vehicle, the robust steering controller is developed via the BVSC to suppress the lateral path tracking error, to withstand unknown external disturbance and ensure yaw stability for autonomous vehicle. In the second stage, by combining adaptive control mechanism based on Lyapunov stability theory and radial basis function neural network (RBFNN), ANN approximator is designed to compensate the uncertainty of tyre cornering stiffness by learning to approximate arbitrary nonlinear functions, and it guarantees the global asymptotic stability of the closed-loop system. Finally, a Matlab/Simulink–CarSim co-simulation and a test in hardware-in-the-loop (HIL) system are conducted to verify the effectiveness of the proposed lateral motion control method.

This paper is organized as follows: in Section 2 system models are built for controller design, including reference path model, vehicle kinematics model and vehicle dynamics model. In Section 3, the structure of the proposed control scheme is given, and a robust steering controller and an ANN approximator are designed. In Sections 4 and 5, the simulation results and experiment results are analyzed. Finally, the conclusion of this paper is made in Section 6.

2. System modeling for controller design

To design control law, the system models are developed in this section, which consist of reference path model, vehicle kinematics model, vehicle dynamics model.

2.1. Reference path model

This paper focuses on how to control the autonomous vehicle to maintain stabilization and track a reference path at the limits of driving conditions, so that the reference path will be given directly, without path planning.

The reference path model is described in terms of lateral position Y_{ref} and yaw angle ψ_{ref} as a function of the longitudinal position X (Falcone et al., 2007)

$$Y_{ref}(X) = \frac{d_{y_1}}{2}\left[1+\tanh\left(z_1\right)\right] - \frac{d_{y_2}}{2}\left[1+\tanh\left(z_2\right)\right], \tag{1}$$