IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 12, 2019, accepted April 30, 2019, date of publication May 17, 2019, date of current version May 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2917507

Automatic Steering Control Strategy for Unmanned Vehicles Based on Robust Backstepping Sliding Mode Control Theory

PENGWEI WANG[1], SONG GAO[1], LIANG LI[2], (Senior Member, IEEE), SHUO CHENG[2], AND LIN ZHAO[3]

[1]School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo 255049, China
[2]Department of Automobile Engineering, Tsinghua University, Beijing 100084, China
[3]College of Automotive Engineering, Chongqing University, Chongqing 400044, China

Corresponding author: Song Gao (gs6510@163.com)

This work was supported in the part by the Natural Science Foundation of Shandong Province under Grant ZR2018LF009, and in part by the Subproject of the National Key Research and Development Project of China under Grant 2016YFD0701101.

ABSTRACT Automatic steering system of self-driving vehicles has significant influence on vehicle safety. The performance of automatic steering system is affected by external disturbance, parameter perturbation, and real-time ability of control algorithm. First, to develop a high-performance automatic steering control strategy, a vehicle-road system model based on vehicle dynamics and kinematics is established. Then, the system state equation with direction-angle and lateral-position deviations is derived to describe the tracking accuracy. Finally, based on the sliding mode variable structure control method, an automatic steering control algorithm is proposed and verified. The results show that the dynamic quality of the system is improved with the optimization of the sliding mode. Furthermore, good robustness against vehicular velocity, real-time performance, and tracking accuracy is achieved.

INDEX TERMS Autonomous vehicle, automatic steering system, sliding mode control, path tracking.

I. INTRODUCTION

Unmanned vehicles are gaining increasing attention from academia and industry [1]–[4], which are expected to achieve fully automatic driving on public road within a few years [1], [2]. However, due to the existing problems of traffic context awareness, complex driver-vehicle interactions, driving decision making and motion control [2]–[4], further researches on fully automatic driving are still needed. With the deeper study of unmanned vehicles in recent years the motion control, specially, lateral and longitudinal of unmanned vehicles has become a hot topic[4]–[8]. Nowadays, with the growing concept of connected vehicles, traffic information is expected to be more specific [9], [10]. More specific traffic information means higher requirements of the bottom execution system of vehicle. The stability and reliability of bottom control system are particularly important.

As for unmanned vehicles, automatic steering system operates the steering wheel instead of human driver. Automatic steering system is the bottom execution part of lateral control. Its performance has great influence on the driving performance. By adjusting the steering wheel angle automatically, the lateral motion control and desired path tracking are realized [11], [12]. The path tracking precision is one of the most rudimentary parameters to measure the performance of automatic steering systems [12], [13]. In addition, the adaptability and robustness of steering systems also show important effect on the automatic steering system.

At present, a lot of studies on the control strategy of automatic steering system have been conducted. A variety of stable and effective steering control methods have been presented [14]–[17]. In the Defense Advanced Research Projects Agency (DARPA) Grand Challenge [7], the Pure Pursuit algorithm has been widely applied. And shows good tracking accuracy at low speed, but large errors would occur at higher speed [8]. Based on partial feedback Proportion Integration Differentiation (PID) control theory, Netto M proposed an automatic steering controller [18]. The tracking accuracy still needs to be improved. PID control was also used in Chen's

The associate editor coordinating the review of this manuscript and approving it for publication was Chaoyong Li.

research [7], [8], the steering control parameters at different speeds were optimized. Although the automatic steering control strategies based on PID theory depend less on system model [19], [20]. Due to the inborn limitation of algorithm, the control system based on PID theory is unable to adapt to external disturbances. Alexander K et al designed a lateral controller based on optimal control theory [21]. The controller has achieved good control accuracy without external disturbances. But the stability and robustness of the system are significantly affected with external disturbance [21], [22]. In order to describe the time-varying features of unmanned ground vehicle, J Guo et al designed a Linear Parameter Varying (LPV) model [23], and a robust gain-scheduling steering control strategy was proposed to ensure the control accuracy. In addition to the above theories, advanced control theories, such as fuzzy control [24], immune algorithm [25], neural network control [26], model predictive control (MPC) [27], genetic algorithm and sliding mode control (SMC) [7], [8], [28] have also been widely used in steering control of unmanned vehicles. Sliding mode variable structure control system is robust to parameter perturbation and external disturbance [29]. However, as the chattering is inevitable, sliding mode control is not widely applied to the practice engineering. Robust backstepping sliding mode control has been proved as an effective way for a nonlinear system with parameter perturbation and external disturbance.

Influenced by the uncertain parameters and external disturbance, further study of automatic steering control is required [19]–[21]. In general, the applicability of the control algorithms needs to be improved. Most algorithms could not fully adapt to the unforeseeable problems caused by parameter changes or disturbance. The tracking accuracy and steering control accuracy remain to improve. In the design of control algorithm, key parameters such as longitudinal velocity should also be considered. And lastly, most researches on steering control strategy of unmanned vehicle are based on theoretical research and simulation experiments. The correctness and practicability of strategy have not been tested and verified by real vehicle test.

Given above analysis, an automatic control strategy for unmanned vehicle is developed in this paper. The main contributions of this paper could be summarized as follows: (i) a vehicle-road system model which could describe the dynamics features of autonomous vehicle steering maneuver is proposed. (ii) A sliding mode robust control strategy based on backstepping theory is proposed, which could effectively deal with the features of external disturbance and time varying of unmanned vehicles. (iii) Extensive simulation and real vehicle test are carried out, the steering performance is manifested. The rest of this paper is organized as follows: system models are presented in section II. Section III and section IV give a detailed description about the design and verification of automatic steering control algorithm. Conclusions are achieved in Section V.

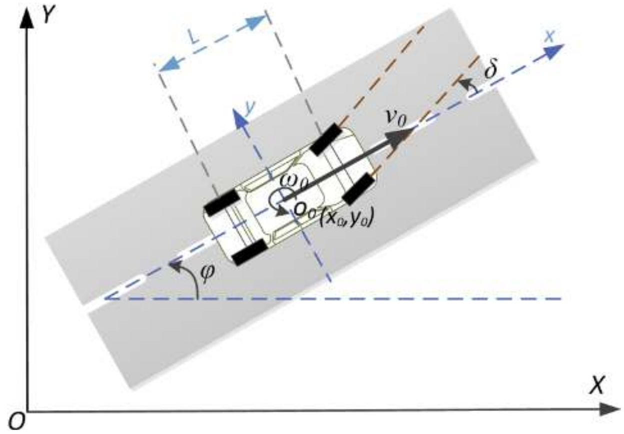


FIGURE 1. The vehicle steering kinematics model.

II. SYSTEM MODELING

The model describing vehicle motion state can be divided into kinematic model and dynamic model according to its function. In order to satisfy the study of automatic steering control of unmanned vehicles, the kinematic and dynamics characteristics of vehicles should be considered simultaneously in this paper. Therefore, in this section, vehicle kinematics model, dynamics model and vehicle-road system dynamics model are established.

A. VEHICLE KINEMATICS MODELING

The vehicle steering kinematics model is shown in figure 1. In which OXY is the absolute inertial frame, oxy is the vehicle coordinate system, and o is the midpoint of the vehicle's front and rear axle, φ is the angle between x axis of the vehicle coordinate system and the X axis of the world coordinate system. The vehicle's current coordinates are (x_0, y_0),the vehicle's current position can be expressed as (x_0, y_0, φ_0), and δ_0 is the current front wheel angle of the vehicle.

The velocity of vehicle centroid is:

$$v_0 = \dot{X}\cos\varphi + \dot{Y}\cos\varphi \tag{1}$$

The angular velocity of vehicle centroid is:

$$\omega = \dot{\varphi} \tag{2}$$

In order to simplify the control problem, tire lateral slip is ignored. And the motion of vehicles in the OXY plane is the only consideration in this paper. The kinematic model of the vehicle could be simplified as:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi_0 & 0 \\ \sin\varphi_0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_0 \\ \omega_0 \end{bmatrix} \tag{3}$$

B. VEHICLE DYNAMICS MODELING

The movement of unmanned vehicle is simplified as a free movement in the ground plane. The steering system controls the yaw motion and lateral motion of unmanned vehicle.

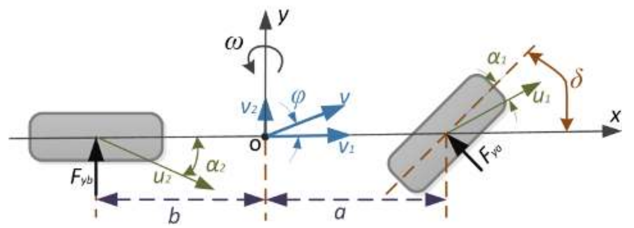


FIGURE 2. Vehicle lateral dynamics model.

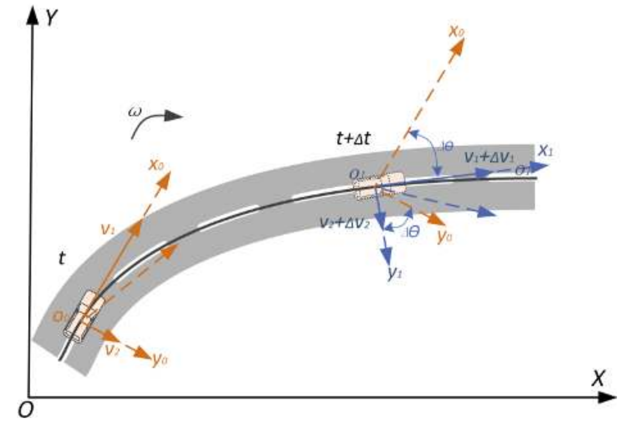


FIGURE 3. The change of vehicle coordinate system.

Vehicle lateral acceleration can be considered to be small under normal working conditions. And the influence of the steering system on the vertical motion of the vehicle can be neglected. Therefore, a simplified two-wheel dynamic mathematical model is derived and established in this paper, as shown in figure 2. Assuming that the centroid of the vehicle is the origin of the vehicle coordinate system and its position remains unchanged.

In steering maneuvers, the motion of vehicle involves the longitudinal movement and rotation. In order to facilitate calculation, the motion of vehicles can be idealized into the form of figure 3. The axle of the vehicle is parallel to the oy axis of the vehicle coordinate system, and the lateral stiffness of tires takes constant value. The speed of the vehicle is constant, only the direction changes. Therefore, when the velocity changes very slowly, the longitudinal velocity variation of the vehicle can be presented as follows:

$$\begin{aligned}&(v_1 + \Delta v_1)\cos\Delta\theta - v_1 - (v_2 + \Delta v_2)\sin\Delta\theta \\ &= v_1\cos\Delta\theta + \Delta v_1\cos\Delta\theta - v_1 - v_2\sin\Delta\theta - \Delta v_2\sin\Delta\theta\end{aligned} \tag{4}$$

When $\Delta\theta$ is very small, the equation (4) can be approximately expressed as: $\Delta u - v\Delta\theta$

According to this equation, the absolute acceleration of vehicle along the ox axis can be obtained:

$$a_x = \left(\frac{\Delta u - \mathrm{v}\Delta\theta}{\Delta t}\right) = \dot{u} - \mathrm{v}\omega \tag{5}$$

The lateral acceleration can also be obtained:

$$a_y = \dot{v} + \mathrm{u}\omega \tag{6}$$

The differential equation of two-degree-of-freedom dynamics model can be described as:

$$\begin{cases} \mathrm{m}\left(\dot{v_1} - \mathrm{v}\omega\right) = C_a\left(\beta + \frac{a\omega}{v_1} - \delta\right) + C_b(\beta - \frac{b\omega}{v_1}) \\ I_z\omega = C_a a\left(\beta + \frac{a\omega}{v_1} - \delta\right) - C_b b\left(\beta - \frac{b\omega}{v_1}\right) \end{cases} \tag{7}$$

Equation (7) can be described with the variable of the front wheel angle:

$$\begin{cases} m\dot{v_2} + \left(mv_1 + \dfrac{2aC_a - 2bC_b}{v_1}\right)\omega + \left(\dfrac{2C_a + 2C_b}{v_1}\right) v_2 = 2C_a\delta \\ I_z\dot{\omega} + \left(\dfrac{2a^2C_a - 2b^2C_b}{v_1}\right)\omega + \left(\dfrac{2aC_a - 2bC_b}{v_1}\right) v_2 = 2aC_a\delta \end{cases} \tag{8}$$

C. VEHICLE-ROAD SYSTEM MODELING

Lateral tracking of self-driving vehicle contains the following processes: firstly, an available path point sequence based on environmental information is generated. Then the bottom execution system operates vehicle to realize path tracking. Its tracking process conforms to the feature of preview follower model [7], [8], [30]. The vehicle dynamics model and the preview-follower model are connected to analyze the effect of different variables. In order to design the steering control strategy, the lateral deviation and heading angle deviation of vehicle centroid are taken as the control variables of steering control system. According to the above analysis, in this section, a vehicle-road system model base on the preview optimal curvature model is established.

The lateral deviation of preview point is:

$$\dot{\Delta y} = \frac{v\cos\beta + \Delta y\omega}{\cos\Delta\varphi}\sin\Delta\varphi + v\sin\beta + L\omega \tag{9}$$

where the L is the forward preview distance, Y is the lateral position deviation, β is the sideslip angle of the vehicle, ω is the yaw rate. $\Delta\varphi$ is the direction angle deviation, which can be expressed as

$$\Delta\dot{\varphi} = \omega - \rho v_1 \tag{10}$$

where the ρ is the curvature of road at the preview point. In order to ensure the stability and comfort of vehicles during steering maneuver, the curvature of the ideal path should be changing continuously and slowly. In this case, the value of β could be neglected. The expression formula of vehicle preview lateral position deviation and heading angle deviation can be simplified to:

$$\dot{\Delta y} = v\Delta\varphi + v\beta + L\omega \tag{11}$$

The vehicle-road system dynamics model can be obtained by combining equation (11) with vehicle kinematics model and vehicle dynamics model.

$$\begin{bmatrix} \dot{\omega} \\ \dot{v}_2 \\ \Delta\dot{\varphi} \\ \Delta\dot{y} \\ \dot{\delta} \end{bmatrix} = \begin{bmatrix} -\frac{2(a^2C_a+b^2C_b)}{I_z v_1} & -\frac{2(aC_a-bC_b)}{I_z v_1} & 0 & 0 & \frac{2aC_a}{I_z} \\ -v_1-\frac{2(aC_a-bC_b)}{mv_1} & \frac{2(C_a+C_b)}{mv_1} & 0 & 0 & \frac{2C_a}{m} \\ 1 & 0 & 0 & 0 & 0 \\ L & 1 & v_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \omega \\ v_2 \\ \Delta\varphi \\ \Delta y \\ \delta \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\rho v \\ 0 \\ \dot{\delta} \end{bmatrix} \tag{12}$$

where the v_1 is the longitudinal speed of unmanned vehicle, v_2 is the lateral speed of vehicle, ρv could be seen as the known curvature interference of the road.

The input and output of the model could be obtained based on the system state space. The purpose of designing control law is to minimize the values of $\Delta\varphi$ and Δy. Therefore, based on equation (12), the vehicle road system model can be described by deviations. Second order form of the output variables is introduced into the state vector and the state vector space is converted to $[\Delta\dot{\varphi}, \Delta\varphi, \Delta\dot{y}, \Delta y, \dot{\delta}]^T$. The vehicle-road system model system state space is expressed as:

$$\dot{x} = Ax + Bu + D \tag{13}$$

where

$$x = \begin{bmatrix} \Delta\dot{\varphi} \\ \Delta\varphi \\ \Delta\dot{y} \\ \Delta y \\ \delta \end{bmatrix}, \quad A = \begin{bmatrix} 0 & \alpha_{12} & \alpha_{13} & \alpha_{14} & \alpha_{15} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & \alpha_{32} & 0 & \alpha_{34} & \alpha_{35} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\alpha_{12} = -\frac{2(aC_a+bC_b)}{I_z v_1}, \quad \alpha_{13} = \frac{2v_1(aC_a+bC_b)}{I_z v_1},$$

$$\alpha_{14} = \frac{2L(aC_a+bC_b)-2(a^2C_a+b^2C_b)}{I_z v_1},$$

$$\alpha_{15} = \frac{2aC_a}{I_z}, \quad \alpha_{32} = -\frac{2L(aC_a+bC_b)}{I_z v_1} - \frac{2(C_a+C_b)}{mv_1},,$$

$$\alpha_{34} = = \frac{2L(C_a+C_b)-2(aC_a-bC_b)}{mv_1} + \frac{2L^2(aC_a-bC_b)-2L(a^2C_a+b^2C_b)}{I_z v_1},$$

$$\alpha_{35} = \frac{2C_a}{m} + \frac{2aC_a}{I_z}.$$

$$B = \begin{bmatrix} -\frac{2(a^2C_a+b^2C_b)\rho v}{I_z v_1} \\ 0 \\ \left(-v_1-\frac{2(aC_a-bC_b)}{mv_1}+L\frac{2(a^2C_a+b^2C_b)}{I_z v_1}\right)\rho v \\ 0 \\ \dot{\delta} \end{bmatrix}$$

III. DESIGN OF AUTOMATIC STEERING CONTROL ALGORITHM

Sliding mode variable structure control has the advantages of fast response and strong robustness [27], [29]. It is proved to be effective on the control of nonlinear time-varying systems [23], [24]. The robust sliding mode control system based on backstepping is widely applied because of its high convergence performance [31], [32]. The robust sliding mode control based on backstepping can comprehensively consider the control law and the robustness of the system. It could be used to improve the performance of unmanned vehicle automatic steering control system. The basic idea of this algorithm is to decompose the complex nonlinear or linear system into a number of subsystems [33]. Then independent Lyapunov functions are designed for each subsystem. And the intermediate virtual control variables are introduced to satisfy the stability of system. The robust sliding mode control based on backstepping could meet the real-time requirements of on-line control [34], [35]. The essence of introducing virtual control is to achieve static compensation. The subsystem must be controlled by the system to achieve the goal of stabilization.

The aim of the automatic steering control system is to make the heading deviation and lateral position deviation of vehicle-road system close to *0*. Therefore, front wheel steering angle is selected as control variable to design the controller in this paper. And the main control objective is to make lateral position deviation and its derivatives converge to *0*. Besides, heading deviation should satisfy the convergence condition. The yaw angle of vehicle lateral motion under normal working conditions is generally small and its value could be measured by sensors. Therefore, both the heading deviation and its derivatives are known as disturbances in the system, which denoted by H. Since higher order derivatives of state variables would be derived from the feedback system using the Back-stepping method, model reduction is needed. For steering control system of unmanned vehicle, besides restricting the centroid position of vehicle, the driving stability and safety under various working conditions should also be considered. For these reasons, the design value and rate of the control system should be limited by the mechanical saturation interval of vehicle. In this case, the change value and rate of front wheel angle would be lower than the saturation value of the steering system.

$$\begin{cases} x_1 = \dot{\Delta y} \\ \dot{x}_1 = x_2 \\ x_2 = \left(-\frac{2L\left(ac_a + bc_b\right)}{I_z v_1} - \frac{2\left(C_a + c_b\right)}{mv_1}\right)\dot{\Delta y} \\ \quad + \left(\frac{2C_a}{m} + \frac{2aC_a}{I_z}\right) \\ u + \left(-v_1 - \frac{2\left(ac_a - bc_b\right)}{mv_1} + L\frac{2\left(a^2c_a + b^2c_b\right)}{l_r v_1}\right)\rho v \\ y = x_1 \end{cases} \tag{14}$$

The purpose of the controller is to solve u, which makes the error between the actual value Δy and the expected value Δy_d of the system approaches to *0*. That means when $t \to \infty$, the tracking error $e = \Delta y - \Delta y_d \to 0$. The partial interference of unmanned vehicle could be regarded as known interference input. The robustness of the system can be improved by estimating unknown disturbances by the algorithm.

The design process of steering controller based on sliding mode control for the steering system of unmanned vehicle is as follows:

Set the lateral position deviation function of path tracking:

$$z_1 = \Delta y - \Delta y_d \tag{15}$$

Differentiate the lateral position deviation function of path tracking:

$$\dot{z_1} = \dot{\Delta y} - \dot{\Delta y_d} \tag{16}$$

Define the Lyapunov function:

$$V_1 = \frac{1}{2}z_1^2 \tag{17}$$

In order to make the value of z_1 approaches to *0*, $\dot{x_2}$ is selected as the virtual control input variable based on equation (14). And record the error as z_2, which could be expressed as:

$$z_2 = x_2 - \dot{\Delta y_d} - c_1 z_1 \tag{18}$$

where c_1 is constant. By substituting equation (18) into equation (16), $\dot{z_1}$ could be expressed as:

$$\dot{z_1} = z_2 - c_1 z_1 \tag{19}$$

$$\dot{V_1} = z_1\dot{z_1} = z_1 z_1 - c_1 z_1^2 \tag{20}$$

The sliding surface is defined as:

$$s = cz_1 + z_2 \tag{21}$$

where c is the coefficient of the switching function and c is positive.

Define the Lyapunov function:

$$V_2 = \frac{1}{2}s^2 + V_1 \tag{22}$$

$$\dot{V_2} = s\dot{s} + \dot{V_1} = s\dot{s} + z_1 z_1 - c_1 z_1^2 \tag{23}$$

The sliding mode variable structure control law is designed as follows:

$$\begin{aligned} u &= \frac{\left(-\frac{2L(aC_a+bC_b)}{I_z v_1} - \frac{2(C_a+C_b)}{mv_1}\right)\dot{\Delta y}}{\left(\frac{2C_a}{m} + \frac{2aC_a}{I_z}\right)} \\ &\quad + \frac{\left(-v_1 - \frac{2(aC_a-bC_b)}{mv_1} + L\frac{2(a^2C_a+b^2C_b)}{I_z v_1}\right)\rho v}{\left(\frac{2C_a}{m} + \frac{2aC_a}{I_z}\right)} \\ &= \frac{-z_1 - c\dot{z}_1 - z_2 + c_1 z_1 - c_1\dot{z_1} - H - ks - \varepsilon sgn(s)}{\left(\frac{2C_a}{m} + \frac{2aC_a}{I_z}\right)} \end{aligned} \tag{24}$$

where the H is known interference, and c, c_1, k, and ε are the control parameters that need to be designed.

In order to eliminate the chattering phenomenon, in practice, the saturation is adopted to replace sign function. Where ρ is a constant.

$$sat\left(s\right) = \begin{cases} sgn\left(s\right), & s \geq \rho \\ s\rho, & s < \rho \end{cases} \tag{25}$$

To improve the robustness of backstepping sliding mode, the sliding mode term is introduced to overcome the disturbance and enhance the robustness of the controller.

Substitution control law u into the formula, then:

$$\begin{aligned} \dot{V_2} &= z_1 z_2 - c_1 z_1^2 - hs^2 - h\beta\left|s\right| + Fs - \bar{F}\left|s\right| \\ &\leq z_1 z_1 - c_1 z_1^2 - hs^2 - h\beta\left|s\right| \end{aligned}$$

where:

$$z_1 = \Delta y - \Delta y_d = Q = \begin{bmatrix} c_1 + hk_1^2 & hk - \frac{1}{2} \\ hk - \frac{1}{2} & h \end{bmatrix}$$

Therefore:

$$\begin{aligned} z^T Qz &= \begin{bmatrix} z_1 & z_2 \end{bmatrix} \begin{bmatrix} c_1 + hk_1^2 & hk - \frac{1}{2} \\ hk - \frac{1}{2} & h \end{bmatrix} \begin{bmatrix} z_1 & z_2 \end{bmatrix}^T \\ &= z_1 z_2 - c_1 z_1^2 + hs^2 \end{aligned} \tag{26}$$

In order to ensure that Q is positive definite matrix, then there is:

$$\dot{V_2} \leq z^T Qz - h\beta\left|s\right| \leq 0$$

There exist:

$$\left|Q\right| = h\left(c_1 + hk_1^2\right) - \left(hk - \frac{1}{2}\right)^2 = h\left(c_1 + k_1\right) - \frac{1}{4} \tag{27}$$

By adjusting the value of h, c_1, k_1, make the value of the equation above satisfy $|Q| > 0$, so that Q is positive definite matrix and $\dot{V_2} \leq 0$. Thus, the system state always lies on the sliding mode surface when it tends to zero, which enhances the robustness of the system.

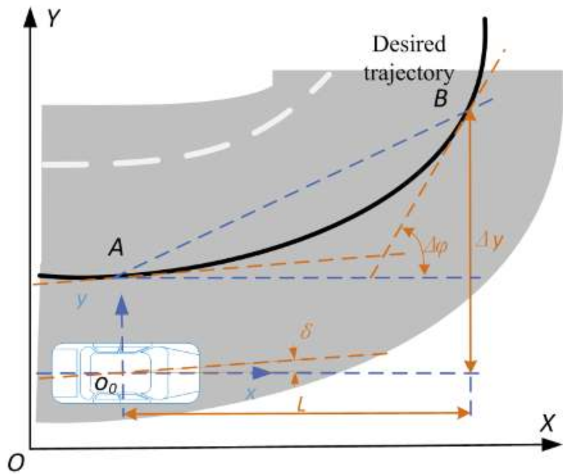


FIGURE 4. Vehicle-road system dynamics model.

TABLE 1. Vehicle model parameters.

Model parameter	Value/(units)
Vehicle mass	1525/(kg)
Yaw inertia	2305/(kg·m2)
Cornering stiffness of front wheel	67/(kN/rad)
Cornering stiffness of rear wheel	67/(kN/rad)
Distance from center of mass to front wheel	1.10/(m)
Distance from center of mass to rear wheel	1.67/(m)

IV. SIMULATION AND EXPERIMENT

A. SIMULATION TEST

In order to test the steering performance of the proposed automatic steering control strategy. Co-simulation based on CarSim and MATLAB/Simulink is presented to compare the proposed approach with sliding mode control strategy. In CarSim, a virtual vehicle dynamics model with tire model is built. In order to ensure the comprehensiveness of simulation research, multiple simulation experiments under different conditions and speed are required. Ring road scenario is selected in the simulation experimental conditions.

The specific parameters of the simulation experiment are as follows: A ring road scenario is constructed in CarSim environment. The radius of the constructed ring road is 150m; the vehicle driving condition is good and the road adhesion coefficient is 0.85; the vehicle runs in the ring road according to the preplanned trajectory. The constructed virtual vehicle model parameters are shown in Table 1. To compare the performance of proposed controller, the tracking performance of sliding mode controller is given. The parameters of approach law of sliding mode are 0.25 and 0.7, respectively.

The vehicle is moving with constant velocity (20km/h, 40km/h, 60km/h, 80km/h, 100km/h); the simulation architecture and the constructed ring road are shown as figure 5.

The simulation results are shown in figure 6. As shown in figure 6(a), the proposed approach has higher

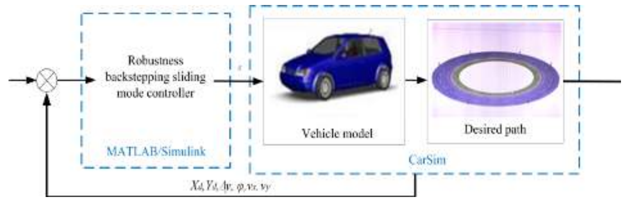


FIGURE 5. Simulation environment.

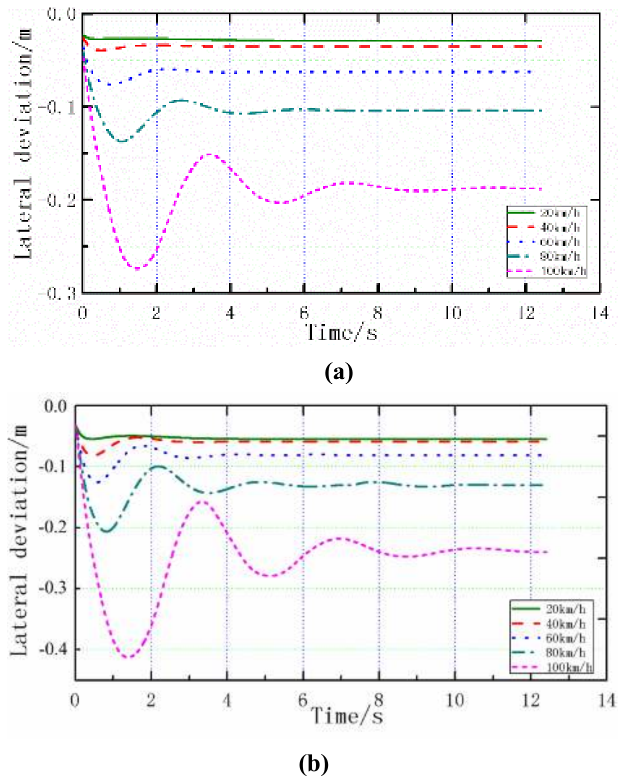


FIGURE 6. Simulation result of path tracking, (a) Lateral deviation of pathing tracking with proposed controller, (b) Lateral deviation of pathing tracking with sliding model controller.

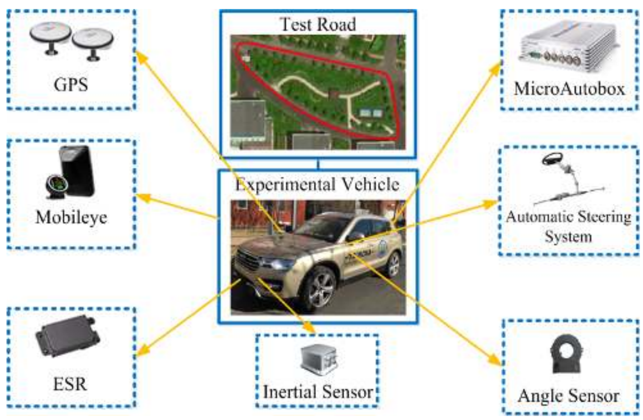


FIGURE 7. Unmanned experimental vehicle.

control accuracy. It could improve tracking accuracy of ring road experiment effectively. The lateral tracking error of the unmanned vehicle is stable to 0.029m when the velocity is 20km/h; the lateral tracking error is stable to 0.035m when

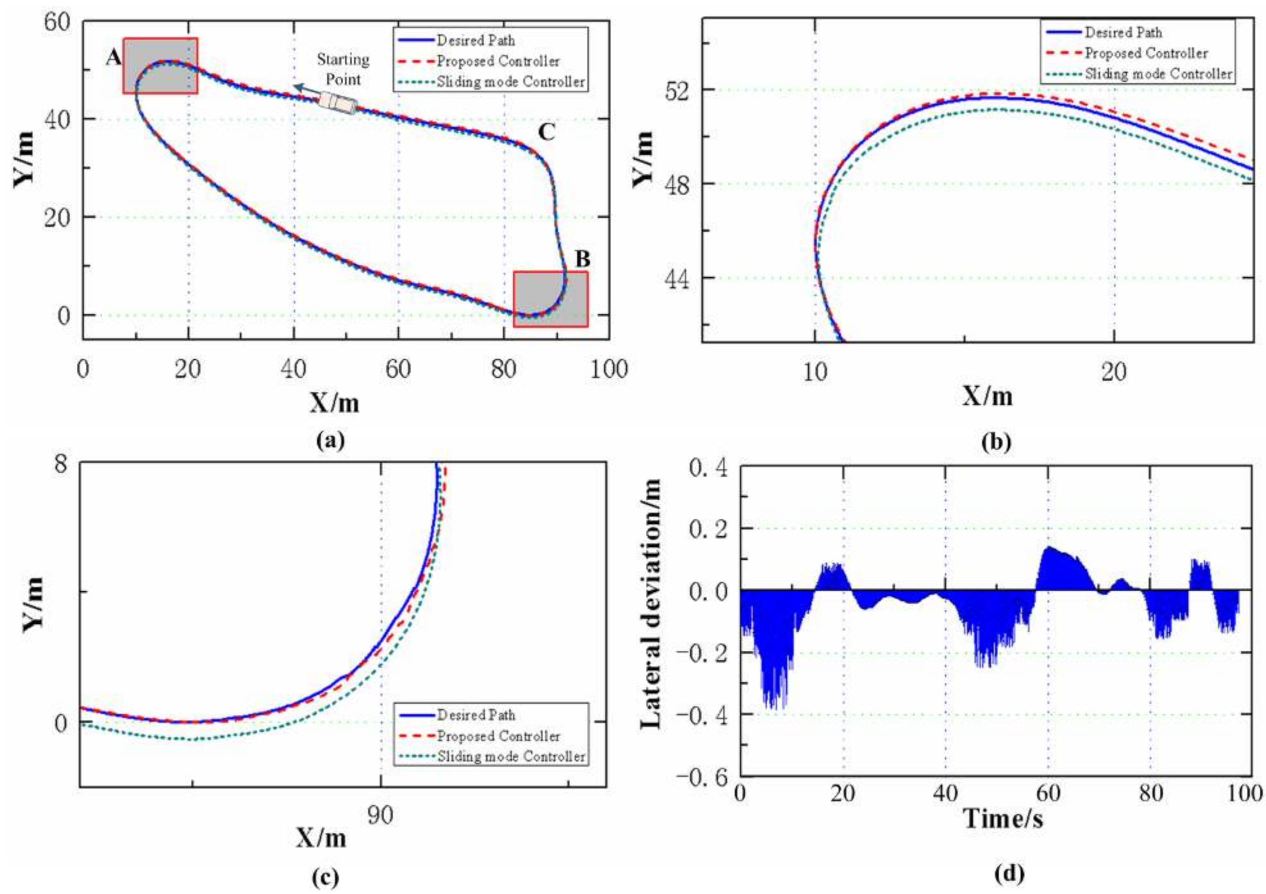


FIGURE 8. Trajectory of the unmanned experimental vehicle, (a) Global tracking trajectory of unmanned vehicle, (b) Enlarged view of part A, (c) Enlarged view of part B, (d) Lateral deviation of trajectory tracking.

the velocity is 40km/h; the lateral tracking error is stable to 0.063m when the velocity is 60km/h; the lateral tracking error is stable to 0.104m when the velocity is 80km/h; the lateral tracking error is stable to 0.188m when the velocity is 100km/h. Figure 6(b) shows the simulation results of sliding mode control strategy. As shown in the figure, the lateral deviation is obviously larger than the proposed approach at same speed. Besides, with vehicle speed variation, the control precision and the convergence speed of algorithm are affected obviously. These simulation results show that: Firstly, the proposed automatic steering control strategy based on robust backstepping sliding mode control theory has higher lateral tracking accuracy in ring road path tracking experiment. Secondly, the proposed control algorithm could converge quickly and reduce steady state error effectively. Thirdly, the proposed control algorithm shows good robustness which could against the external disturbance such as velocity variation.

B. EXPERIMENTAL TEST

In order to verify the performance of the autonomic steering control strategy proposed in this paper. A series of comparative experiments are carried out on an experimental vehicle as show in figure 7. The experimental vehicle is equipped with dSPACE-MicroAutobox, differential Global Positioning System (GPS) and automatic steering system. The driving trajectory and the real-time running data of experimental vehicle could be recorded accurately. The velocity of experimental vehicle varies from 15km/h to 20km/h in the experiment.

An irregular circular reference trajectory as shown in figure 7 is applied to test the proposed approach. As shown in figure 8(a), the selected trajectory consists of a small curvature turn (C), a right-angled turn (B) and a large curvature U-turn (A), which could ensure the diversity of experimental scenarios. Figure 8 shows the path tracking performance comparison of the proposed controller and sliding mode controller. The experiment results show that both controllers could make vehicle track desired path. The controller proposed in this paper has better tracking performance and stronger robustness against external disturbance. Figure 8(a) shows the desired path and the real path in the experiment. It can be found that the tracking accuracy is relatively high on the straight road. Figure 8(b) and figure 8(c) show the enlargement of the error between desired path and real path. It can be found that the lateral error increases gradually when the vehicle is turning from straight road to curved road, and

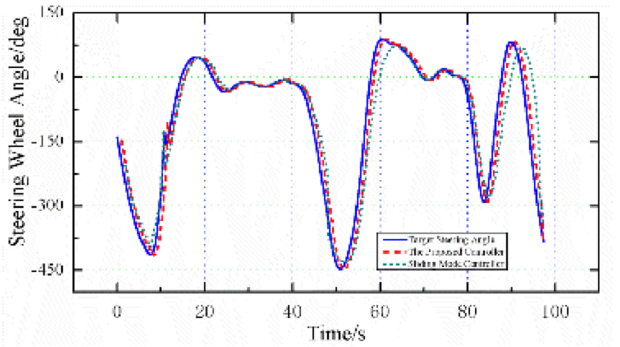


FIGURE 9. The response of steering wheel angle.

decreases gradually in the turning process, which means the algorithm has chattering phenomenon, but it could quickly converge and stabilize. In this experiment, the lateral tracking error is the minimal while the unmanned experimental vehicle passing through the small curvature turn (C). The average lateral error of turn (C) is 0.063m. The lateral tracking error is moderate while the unmanned experimental vehicle passing through the right-angled turn (B). The average lateral error of turn (B) is 0.087m. The lateral tracking error of is the maximal while unmanned experimental vehicle passing through the large curvature U-turn (A). And the average lateral error of turn (A) is 0.128m. Figure 8(d) shows the lateral error of vehicle tracking in experiment, the maximum lateral error of tracking is 0.394m, the minimum value is 0.029m, and the average value is 0.063m.

Figure 9 shows the response of steering wheel angle. The curve of target steering angle is smoother than the real steering angle curve. That's because the controller kept working at high frequency during the experiment. Small change of the external state would be reflected in the output of steering wheel angle. In figure 9, the proposed controller exhibits better performance with higher control accuracy and better dynamic performance than that of sliding mode controller. The average value of steering wheel error is less than 2 degree. The result shows the proposed automatic steering system has good real-time performance and steering accuracy. The latency of steering wheel and steering wheel angle error are within reasonable limits.

V. CONCLUSION

This paper proposes an automatic steering control strategy for unmanned vehicles. In order to describe the time-varying dynamic variables in the process of steering maneuver, vehicle dynamics, kinematic and vehicle-road system models are established in this paper. Based on robust back-stepping sliding mode control theory, an automatic control strategy is proposed. In order to verify the performance of the proposed algorithm, co-simulation of CarSim/Simulink is carried out under various operations. Moreover, the proposed strategy is verified by real vehicle test. Results show that the proposed control strategy improves the automatic steering performance significantly.

However, due to potential danger of high-speed experiment, the experiment was carried at a relatively low speed under closed road conditions.

Future work will focus on the longitudinal and lateral integrated coupling control of unmanned vehicles, obstacle avoidance path planning and tracking.

VI. ACKNOWLEDGMENT

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article:

REFERENCES

[1] C. Lv, X. Hu, A. Sangiovanni-Vincentelli, Y. Li, C. M. Martinez, and D. Cao, "Driving-style-based codesign optimization of an automated electric vehicle: A cyber-physical system approach," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2965–2975, Apr. 2019.

[2] Y. Xing, C. Lv, H. Wang, D. Cao, E. Velenis, and F. Wang, "Driver activity recognition for intelligent vehicles: A deep learning approach," *IEEE Trans. Veh. Technol.*, to be published.

[3] Y. Xing *et al.*, "Driver lane change intention inference for intelligent vehicles: Framework, survey, and challenges," *IEEE Trans. Veh. Technol.*, to be published.

[4] Y. Liu, X. Wang, L. Li, S. Cheng, and Z. Chen, "A novel lane change decision-making model of autonomous vehicle based on support vector machine," *IEEE Access*, vol. 7, pp. 26543–26550, 2019.

[5] K. Zhang, "Research on intelligent vehicle's path tracking control strategy," Ph.D. dissertation, Harbin Inst. Technol., Harbin, China, 2013.

[6] Y. Lan, "Research on intelligent vehicle steering control system based on immune mechanism," Ph.D. dissertation, North Univ. China, Taiyuan, China, 2017.

[7] H. Chen, G. Xiong, and J. Gong, *Introduction to Self-Driving Car*. Beijing, China: Beijing Institute of Technology Press, 2014.

[8] J. Gong, Y. Jiang, and W. Xu, *Model Predictive Control for Self-driving Vehicle*. Beijing, China: Beijing Institute of Technology Press, 2014.

[9] J. Nie, J. Zhang, W. Ding, X. Wan, X. Chen, and B. Ran, "Decentralized cooperative lane-changing decision-making for connected autonomous vehicles," *IEEE Access*, vol. 4, pp. 9413–9420, 2016.

[10] S. E. Li, *et al.*, "Dynamical modeling and distributed control of connected and automated vehicles: Challenges and opportunities," *IEEE Intell. Transp. Syst. Mag.*, vol. 9, no. 3, pp. 46–58, Jul. 2017.

[11] A. F. Idriz, A. S. A. Rachman, and S. Baldi, "Integration of auto-steering with adaptive cruise control for improved cornering behaviour," *IET Intell. Transp. Syst.*, vol. 11, no. 10, pp. 667–675, Dec. 2017.

[12] R. Yu, "Automatic steering control for autonomous vehicles," M.S. thesis, Jilin Univ., Changchun, China, 2016.

[13] M. Wu, F. Zhang, and G. Wen, "The control strategy of unmanned vehicles steering-bywire system," *Comput. Simul.*, vol. 33, no. 12, pp. 163–168, Dec. 2016.

[14] J. Huang, "The research of steering control for autonomous vehicle," M.S. thesis, Central China Normal Univ., Wuhan, China, 2013.

[15] S. M. Cui, K. Zhang, J. F. Wang, and J. M. Wang, "Steering control of an autonomous vehicle based on RBF neural networks compensation and dynamic systems," *Adv. Mater. Res.*, vol. 460, pp. 98–102, Feb. 2012.

[16] J. Guo, Y. Luo, and L. Qiang, "Adaptive nonlinear trajectory tracking control for lane change of autonomous four-wheel independently drive electric vehicles," *IET Intell. Transp. Syst.*, vol. 12, no. 7, pp. 712–720, Apr. 2018.

[17] D. Soudbakhsh and A. Eskandarian, "Steering control collision avoidance system and verification through subject study," *IET Intell. Transp. Syst.*, vol. 9, no. 10, pp. 907–915, Dec. 2015.

[18] M. Netto, J.-M. Blosseville, B. Lusetti, and S. Mammar, "A new robust control system with optimized use of the lane detection data for vehicle full lateral control under strong curvatures," in *Proc. IEEE Intell. Transp. Syst. Conf.*, Toronto, ON, Canada, Sep. 2006, pp. 1382–1387.

[19] R. Marino, S. Scalzi, G. Orlando, and M. Netto, "A nested PID steering control for lane keeping in vision based autonomous vehicles," *Control Eng. Pract.*, vol. 19, no. 12, pp. 1459–1467, Dec. 2011.

[20] Y. Xia, F. Pu, S. Li, and Y. Gao, "Lateral path tracking control of autonomous land vehicle based on ADRC and differential flatness," *IEEE Trans. Ind. Electron.*, vol. 63, no. 5, pp. 3091–3099, May 2016.

[21] A. Katriniok, J. P. Maschuw, F. Christen, L. Eckstein, and D. Abel, "Optimal vehicle dynamics control for combined longitudinal and lateral autonomous vehicle guidance," in *Proc. Eur. Control Conf.*, Zurich, Switzerland, Jul. 2013, pp. 974–979.

[22] Y. Ma, K. Li, F. Gao, L. Guo, and X. Lian, "Design of an improved optimal preview lateral controller," *Automot. Eng.*, vol. 28, no. 5, pp. 433–438, May 2006.

[23] J. Guo, Y. Luo, and K. Li, "Robust gain-scheduling automatic steering control of unmanned ground vehicles under velocity-varying motion," *Vehicle Syst. Dyn.*, vol. 57, no. 4, pp. 595–616, May 2018.

[24] J. Guo, L. Li, K. Li, and R. Wang, "An adaptive fuzzy-sliding lateral control strategy of automated vehicles based on vision navigation," *Vehicle Syst. Dyn.*, vol. 51, no. 10, pp. 1502–1517, Jun. 2013.

[25] Y. Lan, "Research on intelligent vehicle path planning based on artificial immune network algorithm," *J. Inf. Comput. Sci.*, vol. 12, no. 16, pp. 6023–6032, Nov. 2015.

[26] E. Ikbal and T. Ali, "Design of neural network-based control systems for active steering system," *Nonlinear Dyn.*, vol. 73, no. 3, pp. 1443–1454, Aug. 2013.

[27] E. Kayacan, H. Ramon, and W. Saeys, "Robust trajectory tracking error model-based predictive control for unmanned ground vehicles," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 2, pp. 806–814, Apr. 2016.

[28] S. Wu, E. Zhu, M. Qin, H. Ren, and Z. Lei, "Control of four-wheel-steering vehicle using GA fuzzy neural network," in *Proc. Int. Conf. Intell. Comput. Technol. Automat.*, Oct. 2008 pp. 869–873.

[29] Y. Xia, Z. Zhu, and M. Fu, "Back-stepping sliding mode control for missile systems based on an extended state observer," *IET Control Theory Appl.*, vol. 5, no. 1, pp. 93–102, Jan. 2011.

[30] X.-J. Zhao, H.-O. Liu, G.-M. Xiong, J.-W. Gong, and H.-Y. Chen, "Method of parameter selection for automatic steering sliding mode control," *Trans. Beijing Inst. Technol.*, vol. 10, pp. 1174–1178, Oct. 2011.

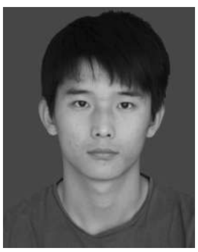
[31] Y. Shtessel, C. Edwards, L. Fridman, and A. Levant, *Sliding Mode Control and Observation*. New York, NY, USA: Springer, 2014.

[32] J. Liu, *MATLAB Simulation for Sliding Mode Control*. Beijing, China: Tsinghua University Press, 2015.

[33] Q.-C. Zhang and R.-Q. Ma, "Backstepping high order sliding mode control for brushless DC motor speed servo control system," *Control Decis.*, vol. 31, no. 4, pp. 961–968, 2016.

[34] N. Esmaeili, A. Alfi, and H. Khosravi, "Balancing and trajectory tracking of two-wheeled mobile robot using backstepping sliding mode control: Design and experiments," *J. Intell. Robotic Syst.*, vol. 87, nos. 3–4, pp. 601–613, Sep. 2017.

[35] F. Chen, R. Jiang, K. Zhang, B. Jiang, and G. Tao, "Robust backstepping sliding-mode control and observer-based fault estimation for a quadrotor UAV," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 5044–5056, Aug. 2016.



PENGWEI WANG received the M.S. degree in mechanical design and theory from Jiangxi Agriculture University, Nanchang, China, in 2015. He is currently pursuing the Ph.D. degree in mechanical engineering with the School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, China.

His research interests include intelligent vehicle dynamic decision and planning, and intelligent vehicle dynamics and control.

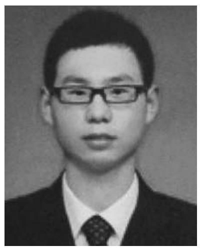
SONG GAO is currently the Dean and a Professor with the School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, China. He is a Middle-Aged Expert with outstanding contribution in Shandong Province and the Executive Director of the China Automotive Engineering Society. He has published over 80 papers. He has presided over the national 863 plan of electric vehicle major project and more than 30 other projects. His current research interests include energy system matching theory and the control technology of electric vehicle, intelligent vehicles, and intelligent transportation systems.

Dr. Gao has received the second prize of national level teaching achievements and six prizes of provincial level scientific and technological progress.

LIANG LI received the Ph.D. degree from the Department of Automotive Engineering, Tsinghua University, in 2008, where he has been a Tenured Professor, since 2017.

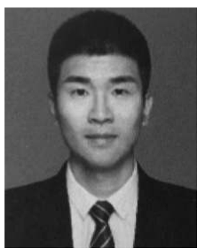
From 2011 to 2012, he was a Researcher with the Institute for Automobile Engineering, RWTH Aachen University, Aachen, Germany. His research interests include vehicle dynamics and control, adaptive and nonlinear system control, and hybrid vehicle develop and control.

Dr. Li has received the China Automotive Industry Science and Technology Progress Award for his achievements in hybrid electrical bus, in 2012, and the National Science Fund for Excellent Young Scholars, China, in 2014.



SHUO CHENG received the B.S. degree in mechanical engineering from the Harbin Institute of Technology, Harbin, China, in 2016. He is currently pursuing the Ph.D. degree in mechanical engineering with the Department of Automotive Engineering, Tsinghua University, Beijing, China.

His research interests include vehicle dynamics states estimation, and intelligent vehicle dynamics and control.



LIN ZHAO was born in Hebei, China. He is currently pursuing the master's degree with the College of Automotive Engineering, Chongqing University, Chongqing, China, and the master's degree in co-cultivation with the State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China.

His research interests include vehicle system dynamics and control, and electric vehicle chassis coordinated control.