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Control Strategies on Path Tracking for Autonomous Vehicle: State of the Art and Future Challenges

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ABSTRACT Autonomous vehicle technology aims to improve driving safety, driving comfort, and its economy, as well as reduce traffic accident rate. As the basic part of autonomous vehicle motion control module, path tracking aims to follow the reference path accurately, ensure vehicle stability and satisfy the robust performance of the control system. This article introduces the representative control strategies, robust control strategies and parameter observation-based control strategies on path tracking for autonomous vehicle. Furthermore, the implementations and disadvantages are summarized. Most importantly, the critical review in this article provides a list and discussion of the remaining challenges and unsolved problems on path tracking control.

INDEX TERMS Autonomous vehicle, path tracking, robust control, parameter observation.

I. INTRODUCTION

In recent years, with the development of artificial intelligence, big data and information processing technology, autonomous vehicles have received more and more attention. Autonomous vehicle technology aims to improve driving safety, driving comfort, and its economy, as well as reduce traffic accident rates [1], [2]. Autonomous vehicle control modules mainly include environment perception and positioning, decision planning and execution control, the autonomous vehicle control system structure shown in Figure 1. The perception positioning module is similar to the human's eyes and ears, and it is mainly used to solve the problems what is on the road and where is the vehicle [3]. The decision planning module is similar to the human's brain and is used to solve the problem of what maneuvers the vehicle to perform and how it plans to drive [4]. The execution control module is similar to human's hands and feet, and it is used to solve the problem of coordinated manipulation among vehicle steering control, drive control, and brake control [5].

The United States is a technical giant for autonomous vehicle research all over the world. Since 1980, the research has been begun in this area. In particular, the DARPA Challenge organized by the United States has inspired researchers from all over the world on autonomous vehicle. Waywo is the leader in autonomous driving research and development, and its road testing distance has exceeded 10 million miles, and the virtual testing distance is as high as 7 billion miles.

Autonomous vehicle technology has huge application prospects in the fields of industry, agriculture, and military. Such as unmanned logistics vehicles are applied in the fields of automatic warehouses, ports and dock. Autonomous agricultural vehicles are applied in automatic navigation control to improve operational efficiency and reduce labor input. Special-purpose automatic control vehicles can achieve battlefield patrol, reconnaissance and exploration on alien planet in the military and aviation fields. Autonomous vehicle is typical high-tech collections, and its research involves multiple disciplines such as mechanical manufacturing,

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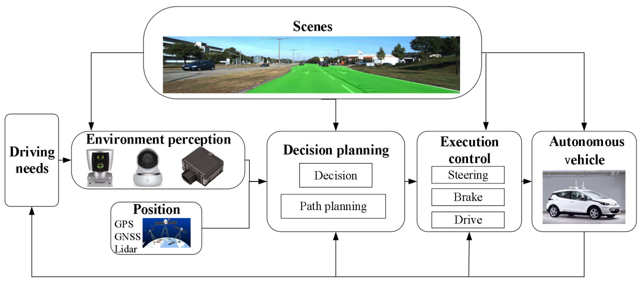

FIGURE 1. Autonomous vehicle control system structure.

artificial intelligence, computer science, and automatic control. It belongs to a new multi-disciplinary interdisciplinary field.

Path tracking control has become the interest of the present research in the field of autonomous vehicle [6], [7]. As the basic part of autonomous vehicle motion control module, it is desired to follow the reference path accurately. In recent years, a large number of research institutes, companies and colleges have used pure pursuit, Stanley, PID, model predictive control (MPC), linear quadratic regulator (LQR) and etc. to study the path tracking control of autonomous vehicle, shown in Table 1. In order to deal with vehicle modeling errors, uncertain parameters and external disturbances, the robust control strategies based on sliding mode control (SMC), H_∞ control and robust MPC are proposed to improve the robustness of the control system, shown in Table 2. Various vehicle parameter observation methods have been proposed to further improve the accuracy of path tracking control, shown in Table 3. In this article, we survey the latest literature on path tracking control strategies, robust control strategies and parameter observation-based control strategies for autonomous vehicle. Based on the reviews, we discuss and summarize the achievements and challenges of the existing methods. The existing path tracking control methods are rarely considering vehicle steering system characteristic and motor characteristic based on the hierarchical control framework and do not specifically analyze the action rules of various uncertain factors based on robust control methods, such as: load changes on vehicle quality, vehicle centre of mass and moment of inertia. Then design the controller based on the action rules of uncertain factors. And the stability analysis of the path tracking system based on MPC is still a challenge.

The configuration of this article is as follows. The control strategies on path tracking for autonomous vehicle are described in section II. In section III, we survey the path tracking robust control strategies. In section IV, we survey the path tracking control strategies based on vehicle parameter observation. Some conclusions and challenges on path tracking of this article are followed in section V.

II. CONTROL STRETEGIES ON PATH TRACKING

Path tracking has become the interest of the present research in the field of autonomous vehicle. As the basic part of autonomous vehicle motion control module, it is desired to follow the reference path accurately. Therefore, this section is presenting the path tracking control covering the available methods and strategies to control both the tire steering angle and lateral force.

A. PURE PRUSUIT AND STANLEY CONTROL METHODS

As shown in Figure 2, the path tracking controller is designed based on Ackerman's steering geometry. Myung-Wook Park *et al.* proposed path tracking control strategy based on pure pursuit method, the preview distance adaptive controllers are designed based on speed deviation and lateral position deviation and compared [8], [9]. Jianhui Zhao *et al.* analyzed the influence of vehicle kinematics time delay for dynamic prediction based on pure pursuit method [10], the vehicle kinematics model shown in Figure 3. To deal with the problem of poor robustness on discontinuous curvature road, a Stanley controller is designed using B-spline curve road modeling method [11]. The preview distance is very important for this kind of controllers. Xiang Li *et al.* studied the adaptive method of preview distance based on particle swarm optimization algorithm [12]. Reference [13] studied the adaptive tire slip rate control method. In order to satisfy the adaptive speed and heading angle deviation of the Stanley controller, the expert library is established based on particle swarm optimization algorithm, and a adaptive parameter mechanism of the stanley controller based on fuzzy supervisory system is studied [14], [15].

Based on the vehicle kinematics information, using the preview distance heading angle deviation and the vehicle position deviation as the controller design basis, the vehicle path tracking control methods are studied [8]–[11]. To further improve the control precision, the adaptive preview distance control strategy to achieve vehicle motion control under different speeds and road curvature conditions are studied [13]–[15]. This type of controllers have a simple layout and are suitable for controlling the position of the vehicle. It does not require the response of vehicle acceleration and force. Under simple road conditions and low speed conditions, the controller perform well. However, when the vehicle is under the driving conditions with large road curvature and high speed, the dynamic characteristics such as vehicle acceleration, yaw rate, and tire force have a significant impact on vehicle path tracking control performance.

B. PID CONTROL METHOD

PID method is a popular path tracking control method among the existing methods. Gaining Han *et al.* proposed a adaptive PID neural network path tracking control strategy, the model parameters are identified through the forgetting factor least squares algorithm, and the PID control parameters are adjusted using BP neural network [16]. In order to explore the feedback control mechanism, the PID controller is designed based model block diagram [17]. Al-Mayyahi *et al.* [18] proposed a fractional-order PID path tracking control strategy to obtain the heading angle and speed control laws, and the controller parameters are adjusted through particle

TABLE 1. Summery of path tracking control methods.

Control methods	Optimization objectives	Advantages	Disadvantages	Reference
Pure Pursuit & Stanley	position deviation & course deviation.	It has a simple layout and is suitable for controlling the position of the vehicle.	It is difficult to apply to high speed and large road curvature conditions.	[8-15]
PID	position deviation & course deviation.	It has the advantages of simplicity and ease of engineering application.	PID controller has the problem of poor versatility, and the control parameters tuning is more difficult.	[16-22]
Model-Free Control	preview course deviation	It has a simple controller structure.	The control system is usually regarded as a black box, and the stability analysis of the control system is more difficult.	[23-25]
LQR	system states & control input	It is easy to achieve the closed-loop optimal control objective	Controller design based on linear model and has poor robustness.	[26-31]
Feedforward and Feedback	feedback error feedforward information	It could deal with external disturbances, modeling errors, and sensor noise	The acquisition of vehicle data require more expensive sensors.	[35-39]
MPC	system states & control input	It has the capability of handing system constraints and future prediction in the design process.	It is difficult to analyze system stability and has high computational cost.	[40-80]
The above research are rarely considering vehicle steering system characteristic and motor characteristic.				

TABLE 2. Summery of path tracking robust control methods.

Control method	Optimization objectives	Advantages	Disadvantages	Reference
H_∞ Control	system H_∞ performance index	The control system is easy to establish H_∞ constraints and has strong robustness.	This type of controller has the complex solution process and requires complicated theoretical derivation. It can only handle bounded disturbances.	[85-91]
SMC	position deviation & course deviation	It has the advantages of fast response and insensitivity to parameter changes and disturbances.	It has the problem of chattering on path tracking based SMC and need an adaptive mechanism to eliminate chattering.	[92-118]
Robust MPC	system states & control input	It has the capability of handing system constraints and has strong robustness.	It is difficult to analyze system stability and has high computational cost.	[119-123]
The above research do not specifically analyze the action rules of various uncertain factors, such as: load changes on vehicle quality, vehicle centre of mass and moment of inertia. Then design the controller based on the action rules of uncertain factors.				

TABLE 3. Summery of parameters observation-based path tracking control methods.

Observation method	Advantages	Disadvantages	Reference
Least squares Algorithm	Simple structure and easy for engineering application.	The square of error is minimized to realize the online adaptive estimation of parameters using online vehicle I/O data.	[71,139,141]
Kalman Filter Algorithm	When the noise is white noise with known statistical characteristics, the observation effect of the Kalman filter is very good.	when the vehicle is under high-speed maneuvering limit conditions, the vehicle dynamics are nonlinear, and the error of this type of methods is large.	[49,93,116]
Vehicle Model-Based Observation	Simple structure and easy for engineering application.	The observation error is large to deal with vehicle modeling error and disturbance.	[13,33,100, 141]
Neural Network-Based Observation	It has the advantages of optimal approximation, rapid training and fast convergence.	This type of method requires a large amount of vehicle state information to train the neural network.	[79,142-144]
T-S Fuzzy Model-Based Observation	It is easy to establish T-S fuzzy model based on boundary value conditions.	This kind of methods are more conservative and the more difficult for determination of fuzzy rules.	[90,132,145-146]

swarm optimization algorithm. Some controller are designed using fuzzy PID [19], [20]. Muhammad Aizzat Zakaria *et al.* studied the adaptive PID control strategy by adaptive road curvature observation [22]. The above research used PID control theory to design the vehicle path tracking controller with reference of vehicle position deviation and heading angle

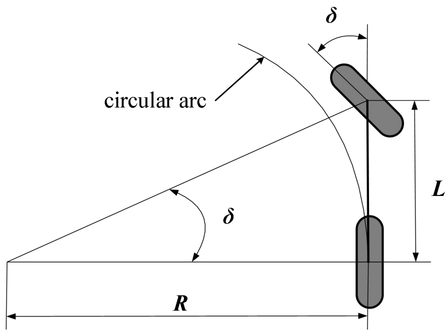

FIGURE 2. Ackerman's steering geometry method.

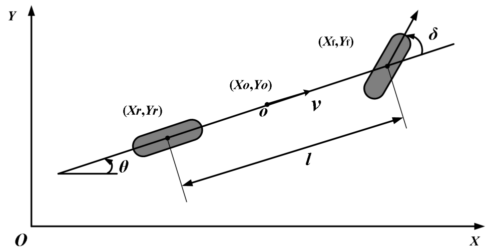

FIGURE 3. Vehicle kinematics model.

deviation [16], [17]. In order to improve vehicle stability, vehicle yaw rate is introduced into the controller design, which significantly improves the control performance [18]. This type of control methods have the advantages of simplicity and engineering application. However, the PID controller has the problem of poor versatility. When the operating conditions change greatly, the control parameters are no longer optimal. For this reason, some scholars have proposed adaptive PID control methods [19], [20], [22]. However, adaptive parameters tuning are more difficult.

C. MODEL-FREE CONTROL METHOD

During the operation of autonomous vehicle, a large amount of I/O data will be generated, and these data contain a large amount of vehicle kinematics and dynamics information. Zhongsheng Hou *et al.* proposed a path tracking control strategy based on model-free adaptive control using vehicle I/O data, and the vehicle path tracking control is switched to the preview deviation angle tracking problem [23]–[25]. This type of method has a simple controller structure. However, the control system is usually regarded as a black box, and the stability analysis of the control system is more difficult, and the acquisition of vehicle data require more expensive sensors.

D. LQR OPTIMAL CONTROL METHOD

As one of the classic optimal control methods, LQR obtain the optimal control law based on state linear feedback, which is easy to achieve the closed-loop optimal control objective. LQR method is widely used for vehicle path tracking control. Fen Lin *et al.* taken into consideration of the vehicle position and the states of vehicle dynamics, the desired yaw rate is generated through the back-stepping feedback dominance, and an integrated control strategy coordinating active front steering and direct yaw moment control based on LQR is proposed [26], the vehicle dynamics model shown in Figure 4. Chuan Hu *et al.* analyzed the relationship between the expected heading angle and the tangent direction on expected path, and a control strategy based on the combination of the heading angle and the vehicle slip angle is proposed [27]. Xizheng Zhang *et al.* studied LQR path tracking control strategy based on visual road detection [28]. The preview distance LQR controllers are designed to deal with road curvature and control error [29]–[31]. In addition, considering the noise in the localization and planning stage, a model-based linear quadratic gaussian control method with adaptive Q-matrix is proposed for tracking controller design [32]. The above research have proposed control strategies based on LQR for path tracking control, and established a simplified vehicle dynamics model and system state space model to obtained the optimal control input. This kind of controllers have a simple structure. When the vehicle under a low speed and simple road conditions, a better control performance can be achieved. However, when the vehicle behaves non-linearly, with modeling errors and external disturbances, the effect of the controller decreases significantly due to linear feedback and model simplification. Therefore, some research introduced feedforward control based on road information [29], [30], and feedback control based vehicle dynamics [26], [30], [31] into controller design to compensate unmodeled vehicle dynamics and disturbance. However, this type of controllers need to be optimized online, which requires high computing power. And the design of the controllers are based on linear assumption, which limits its application.

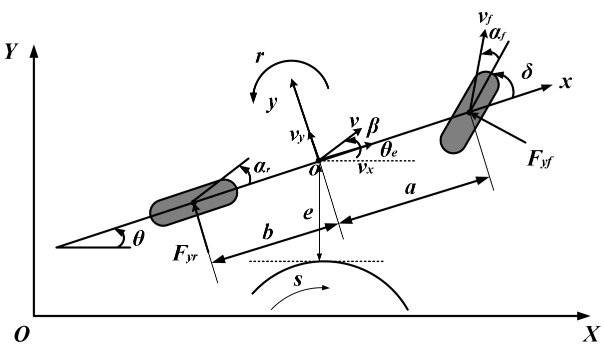

FIGURE 4. Vehicle dynamics model.

E. YAPUNOV METHOD

Reference [33] aimed at the adhesion coefficient and external disturbance uncertainty, a layered control strategy for path tracking is proposed. The upper layer control generates the desired lateral, longitudinal forces and yaw moments based on state feedback control; the middle layer control generates the desired lateral and longitudinal slip laws; the lower layer control design steering angle control law and braking torque control law based on characteristics of tire slip using Lyapulov function. Reference [34] proposed the concept of the optimal state point and the optimal reference point of the vehicle, and the deviations of the vehicle from reference path point to optimal state point are used to design the Lyapulov controller ensuring the vehicle safety margin when pass through the narrow road area.

F. FEEDFORWAR AND FEEDBACK CONTROL METHOD

In order to make full use of feedforward information such as road curvature, vehicle steady-state steering characteristics and transient characteristics, Xue Yunxiao Li *et al.* designed a lateral motion controller based on feedforward steering angle and deviation feedback of position and heading [35], [36]. J. Christian Gerdes *et al.* decoupled the deviation of position and heading to minimize the lateral path tracking deviation under limited operating conditions, and designed feedforward-feedback steering controller using the vehicle Centro of Percussion as the reference point. Furthermore, the vehicle real-time sideslip angle is introduced into the feedback control law and the vehicle steady-state sideslip angle is introduced into the feedback control law [37]–[39]. The above mentioned research have proposed the control method based on the combination of feedforward control and feedback control. The feedforward input control law is designed based on feedforward information such as vehicle steady-state steering characteristics and road curvature. In order to deal with external disturbances, modeling errors, and sensor noise, the feedback control law is designed based on vehicle dynamics state information (yaw rate, sideslip angle, etc.), vehicle lateral position deviation and heading angle deviation. However, the feedforward control mainly considers the vehicle steady-state steering characteristics lacking the vehicle transient characteristics, and feedback control use the precise vehicle dynamics information to design feedback control law which needs high quantity measurement cost, such as the measurement of vehicle lateral speed.

G. MPC CONTROL METHOD

Model Predictive Control has the capability of handing system constraints and future prediction in the design process. It minimizes the gap between the reference path and the actual path by the vehicle dynamics model in a prediction horizon, and it has become a popular method in the control of autonomous vehicle. For the 4WS4WD vehicle path tracking control, Qifan Tan *et al.* proposed a force-driven control method based on the combination of MPC and sequential quadratic programming using cascade control framework [40], [41]. Chuanyang Sun *et al.* studied the path tracking for autonomous vehicle based MPC and believed that path tracking accuracy and vehicle stability can hardly be accomplished by one fixed control frame in various conditions. Then, the authors presented a novel MPC controller with switched tracking error which mainly involves different treatments regarding sideslip angle in computing the heading deviation [42]–[44]. In order deal with dynamics of slip and roll for high-speed autonomous vehicle, the MPC path tracking control method with discretization of variable step model is proposed [45]–[47]. References [48], [49] studied the path tracking control method based on the combination of active steering and differential steering. Reference [50] proposed the path tracking control method combining direct yaw control based on linear time-varying model MPC. Reference [51] proposed a MPC path tracking control method for mining articulated vehicle based on preview distance. In order to achieve the goal of expressway emergency collision avoidance, the collision avoidance path planning and path tracking control method based on the MPC are proposed [52]–[55]. Luqi Tang *et al.* proposed a cascade control method, a MPC controller is designed based on the vehicle kinematics in upper layer to ensure the prediction accuracy and calculation efficiency and a PID controller is designed to track the upper layer control information [56]. Shaosong Li *et al.* proposed the MPC-based vehicle stability control method in order to enhance the stability of the vehicle under dynamic limit conditions considering the change trend of tire force in the prediction [57]–[61]. Hu Jiaming *et al.* designed a controller based on MPC for autonomous tracked vehicle and introduced feedback correction to deal with modeling error and disturbance [62]. References [63]–[65] proposed hierarchical control framework for path tracking based on MPC. Joseph Christian Gerdes *et al.* established the stability constraint envelope and environmental road constraint envelope to solve the vehicle tracking and tracking stability control problem based on MPC [66]–[68]. The above research have proposed MPC-based control methods for vehicle control, combined with PID, sequential quadratic programming, and pseudo-inverse algorithms, etc. Based on a hierarchical control framework, the upper control outputs the vehicle reference states (yaw rate, vehicle steering angle, yaw moment, etc.), the lower layer control implements or distributes the upper layer control signals. In order to improve the calculation efficiency of MPC, the above studies use the simplified vehicle dynamics model as the vehicle state prediction model through a series of linearization methods. In this type of research, some vehicle kinematics and dynamics information are lost due to modeling errors caused by model simplification and linearization. Therefore, when the vehicle is under high-speed conditions and large curvature road, the controller will have a large overshoot due to a large difference between the predicted future error and the actual future error.

To realize vehicle path tracking MPC control under different speed and different curvature conditions, References [69]–[72] proposed parameters adaptive MPC control strategies using fuzzy rules and multiple controllers combination to achieve adaptive adjustment of control parameters under different operating conditions. References [73]–[77] studied the MPC fast online solution methods of path tracking for autonomous vehicle using differential evolution algorithm, Laguerre function, and look-up table to improve the efficiency of MPC controller calculations. When the vehicle is under high-speed, large curvature and complex operating conditions, the vehicle dynamics show non-linearity, strong coupling, and parameter uncertainty. To further apply the vehicle nonlinear characteristics and improve the vehicle states prediction accuracy, References [78]–[80] proposed control methods based on nonlinear MPC. However, the nonlinear MPC methods make a amount of calculation and may produce computational disasters. This kind of controllers are more difficult for real-time application. The above research have proposed path tracking control methods based on linear MPC, nonlinear MPC and adaptive MPC. Through multi-objective optimization, the controllers finally output control signals such as vehicle tire steering angle and tire longitudinal force. In addition to the huge amount of calculation and poor real-time performance of the MPC control method, another challenge is that if the initial value is not suitable, the optimization may fail, and the calculation time of each step is unpredictable. The stability analysis of the path tracking system based on MPC is still a challenge. So the most of MPC controllers are verified through simulation.

H. OTHER CONTROL METHODS

There are still some other methods for vehicle path tracking control research. Reference [81] proposed a comprehensive trajectory optimization method based on driving efficiency, safety, comfort and handling stability to solve the problems of insufficient consideration of vehicle handling stability in local trajectory planning, excessive simplification of vehicle models, and lack of objective evaluation of vehicle comfort. References [82], [83] proposed a hierarchical control framework based on SMC. Yangyan Gao *et al.* studied the vehicle yaw rate follow control method based on Hamilton algorithm [84].

III. ROBUST CONTROL STRATEGIES ON PAYH TRACKING

A. H_∞ CONTROL METHOD

In order to deal with the vehicle modeling uncertainty and external disturbance, a large number of scholars have studied the path tracking robust control methods based on the H_∞ control theory. H_∞ norm performance index constraints and LMI are used to obtain the feedback control law. References [85], [86] studied robust control methods based on the H_∞ control theory to deal with vehicle modeling uncertainty and external disturbance. The H_∞ controllers are designed and system state space control models based on the T-S fuzzy model are established considering vehicle modeling errors, external disturbances, loads, speeds, road adhesion coefficients, and etc. [87]–[90]. Chuan Hu *et al.* considered the difficulty of vehicle lateral speed measurement, model uncertainty and external disturbances, an output feedback control method based on H_∞ is proposed, and the feedback control gain is obtained through genetic algorithm and linear matrix inequality [91]. Reference [92] considered the randomly occurring uncertainty in the external yaw moment, a resilient controller is designed and the resilient control condition is proposed to guarantee the sideslip angle and yaw rate satisfying the prescribed H_∞ and L_2-L_∞ performance indexes of the control outputs for lateral motion regulation of intelligent vehicle. However, this type of controllers have complicated structure and requires complicated theoretical derivation. When the autonomous vehicle is carrying passengers or goods, the vehicle load changes greatly, which affects the position of vehicle center of mass and rotational inertia. In order to deal with the problem of vehicle load change, H_∞ path tracking control method based on T-S fuzzy observer is proposed considering simplified load change conditions [90].

B. SMC CONTROL METHOD

The SMC method has the advantages of fast response and insensitivity to parameter changes and disturbances. The vehicle control methods based on SMC are studied to deal with the problems of strong coupling, non-linearity, parameters uncertainty, and load transfer [63], [93]–[97]. In order to deal with the non-linearity and failure of the steering system, the active fault-tolerant path tracking control method based on SMC is proposed and the influence of disturbance torque, time delay and noise on trajectory tracking control are analyzed [98], [99]. Chih-Lyang Hwang *et al.* studied hierarchical fuzzy dynamic sliding mode control strategy and designed a dynamic adjustment mechanism to adapt the uncertain of friction and torque caused by different load [100]. Ruijie Wang *et al.* designed an adaptive sliding mode controller satisfying H_2 and H_∞ performance indexes, and established a T-S state space model based on lateral dynamics to deal with non-linear input of lateral control and uncertainty of tire corner stiffness for 4WS autonomous vehicle [101]. Aiming at deal with high non-linearity, external disturbance and uncertainty of the active suspension system driven by hydraulic actuators, a high-gain observation high-order based on terminal sliding mode control method is proposed [102]. Gilles Tagne *et al.* analyzed control performance of lateral controller based on high-order SMC, immersion and invariance theory and adaptive PI method [103].

To solve the problem of chattering on path tracking based on SMC, a vehicle following control strategy based on adaptive SMC control is proposed considering load transfer characteristic [50], [83], [104]–[114]. Chuan Hu *et al.* proposed adaptive SMC control strategy based on combination composite nonlinear feedback control (state feedback and state deviation feedback) and radial basis function neural network considering the effect of vertical motion on lateral velocity to improve tracking transient response and robustness [115]. Considering the problems of rollover and input saturation of the vehicle, an adaptive sliding mode controller is designed to ensure the vehicle stability based on the prescribed performance function [116]. A robust adaptive path tracking control strategy based on sliding mode-fuzzy type 2 network is proposed and a multi-sliding mode tracking controller is designed, considering the uncertainty of vehicle parameters (road adhesion coefficient, inertia parameters, longitudinal velocity) [117]. In order to solve the chattering problem of

SMC, the adaptive sliding mode control methods are studied using fuzzy rules and radial basis neural network. However, the adaptive control strategy based on fuzzy rules and the dynamics information compensation strategy based on neural networks increase the complexity of the system and the difficulty of physical implementation caused by determining fuzzy rules and training neural networks. All above research based on SMC are only to solve the problem of robust control on path tracking from a broad perspective (modeling error, parameter uncertainty and external disturbance), this kind of methods do not specifically analyze the action rules of various uncertain factors, such as: load changes on vehicle quality, vehicle centre of mass and moment of inertia.

C. ROBUST MPC CONTROL METHOD

Javad Taghia *et al.* proposed path tracking based on adaptive min-max MPC control method for crawler-trailer agricultural vehicle considering rough and uneven terrain [118]. References [119]–[121] studied Tube-based MPC control methods. Ramón González *et al.* established a time-varying trajectory tracking error model considering the longitudinal sliding of mobile robot and studied a tube-based trajectory tracking robust control method [122]. In order to solve robust control problem of agricultural vehicle (mobile robot, uncertain systems, etc.), min-max MPC strategy is proposed by optimizing the worst-case conditions. The control system has strong robustness. However, the vehicle does not always work under the worst working conditions. Therefore, min-max MPC method are more conservative. In order to deal with system uncertainty and robot longitudinal slip, the Tube-based MPC control method is proposed, which combines feedback control and nominal model MPC control. This kind of methods effectively suppress uncertainty and reduce the conservatism of control system.

D. OTHER ROBUST CONTROL METHOD

There are still some other methods for vehicle path tracking robust control research. Considering the longitudinal speed and tire lateral stiffness, a new two-point polyhedron modeling method is proposed. Considering the transient response characteristics of the system, an energy-peak robust control method based on D stability analysis is studied [123], [124]. References [125]–[127] studied the vehicle path tracking control methods based on auto disturbance rejection control to deal with modeling error, parameter uncertainty and external disturbance. The path tracking robust control method based on LMI is proposed [128]. WangChun Yan *et al.* designed robust path tracking controller based on μ synthesis method [129]. The robust path tracking control method based on fuzzy disturbance observer is studied, and the stability of the system without disturbance is analyzed based on Lyaprov method [130]–[132]. Filipe Marques Barbosa *et al.* proposed a path tracking control strategy based on robust linear quadratic programming optimization control for autonomous heavy truck vehicle to deal with uncertain load, and established a robust linear quadratic programming performance function with penalty coefficients [133]. Amir Benloucif *et al.* established a vehicle dynamics model based on the T-S fuzzy model for vehicle obstacle avoidance control, and proposed LMI steering control method based on the T-S fuzzy model [134]. References [135]–[137] focused on the the finite-time asynchronous output feedback control for a class of Markov jump systems subject to external disturbances and nonlinearities, an asynchronous output feedback controller and an observer-based finite-time asynchronous H_∞ control law are designed. The the feasibility and validity of the proposed methods are illustrated through a DC motor experiment.

IV. PARAMETER OBSERVATION-BASED CONTROL STRATEGIES

A. LEAST SQUARES ALGORITHM

Wenbo Chu *et al.* proposed vehicle mass and road slope angle estimation methods based on recursive least squares method using high-frequency information of driving force and longitudinal acceleration [138]. A parameter estimation method based on recursive least squares is proposed to update the vehicle model parameters online considering the effects of tire corner stiffness and road adhesion coefficient [71]. Reference [139] studied the estimation method of key parameters of light electric vehicles considering the change of vehicle load parameter. In order to improve the vehicle control accuracy, the above research have studied the estimation method of vehicle basic parameters based on least squares such as vehicle mass and tire slip, etc. The square of error is minimized to realize the online adaptive estimation of parameters using online vehicle I/O data.

B. KALAM FILTER ALGORITHM

Jinghua Guo *et al.* used GPS/INS measurement information to study the estimation method of vehicle sideslip angle based on Kalman filter [49]. Te Chen *et al.* studied the active fault-tolerant path tracking control method using the reduced-order Kalman filtering method to estimate vehicle sideslip angle dealing with the steering system fault [93]. In order to improve the accuracy of vehicle state estimation, a state estimation algorithm based on extended Kalman filtering using yaw rate and roll rate is proposed [115]. Vehicle yaw rate and sideslip angle are the key performance indicators of vehicle stability. Therefore, some scholars have considered the linear vehicle dynamics model and studied the vehicle sideslip angle observation method based on Kalman filtering using the system input and output information. However, when the vehicle is under high-speed maneuvering limit conditions, the vehicle dynamics are nonlinear, and the error of this type of methods is large.

C. VEHICLE MODEL BASED OBSERVATION

Xiang Li *et al.* studied the adaptive sideslip estimation method based on the kinematics model of the trajectory tracking for the unicycle robot to deal with kinematics level uncertain slip problem [13]. Changfang Chen *et al.* estimated the coefficient of lateral and longitudinal friction of tires based on the tire slip characteristics to deal with the problem of unknown and uneven road conditions, and proposed the adaptive control law of lateral and longitudinal friction of vehicle [33]. Xiangkun He *et al.* studied the backstepping sliding mode lateral motion control method based on tire lateral force estimation in order to solve the problem of stable collision avoidance under limited driving conditions [100]. Eric Lucet *et al.* studied the robot slip angle method based on the extended kinematics model and the dynamics model under wet and slippery surface environment [140]. In order to deal with the tire non-linearity under complex road conditions, the above literature study the tire corner stiffness and longitudinal slip rate estimation methods based on the vehicle kinematics model and the extended kinematics model. Vehicle path tracking accuracy control is improved through the online adaptive estimation of tire parameters.

D. NEURAL NETWORK BASED OBSERVATION

Hamid Taghavifar *et al.* proposed a nonlinear compensation method based on the neural network autoregressive model to compensate the non-linearity of the vehicle [79]. Ruochen Wang *et al.* studied the SMC path tracking control method based on radial basis function neural network. To further compensate the heading angle error, the iterative learning steering angle compensation control method based on open loop PID is studied [141]–[143]. In order to compensate for vehicle nonlinear characteristics, modeling errors, and external disturbances, the above literature uses the advantages of radial basis function neural network best approximation, concise training, and fast learning convergence speed to study the information observation methods. However, this type of methods require a large amount of vehicle state information to train the neural network.

E. T-S FUZZY MEDEL BASED OBSERVATION

Changzhu Zhang *et al.* designed a state observer based on the T-S fuzzy model and studied path tracking control method based on state observer considering the vehicle load, speed and road adhesion coefficient [90], [144]. Hyo-Seok Kang *et al.* established a fuzzy model including parameter uncertainty, time-varying parameters, input disturbance and slip and designed fuzzy disturbance observer [131]. Huihui Pan *et al.* studied the adaptive tracking control method for nonlinear system with uncertain parameter, and designed a disturbance observer based on terminal sliding mode control to deal with external disturbance and actuator saturation [145]. Reference [146] considered the influence of sensor failure, signal quantization and signal packet loss of the vehicle lateral system based on the communication network, a nonlinear system model with uncertainty is modeled using the T-S fuzzy method and the vehicle sideslip angel observer is designed. The above literature studied the disturbance observation methods based on T-S fuzzy modeling method, and proposed a robust control strategy based on observation information. The boundary values of uncertain parameters need to be considered in the process of modeling the T-S vehicle dynamics model. Therefore, this kind of methods are more conservative and the more difficult for determination fuzzy rules.

V. CONCLUSION AND CHALLENGES ON PATH TRACKING

This article has reviewed the current technologies on path tracking control strategies for autonomous vehicle including hierarchical control, robust control and parameter observation-based control. The results and problem of all kind of methods are analyzed, and some conclusions are summarized as follows.

1) The path tracking control for autonomous vehicle is still one of the hotspots in the field of autonomous vehicle research. Scholars have studied path tracking control for autonomous vehicle using the information of vehicle dynamics, kinematics, tire dynamics, deviation of position and heading and road curvature.

2) The path tracking and obstacle avoidance control are studied for autonomous vehicle using pure pursuit algorithm, Stanley, PID, model-free data-driven control, Lyapulov method, feedforward-feedback control, LQR and MPC, etc. However, the characteristics of the vehicle steering system and motor have a greater impact on vehicle control. The current research are rarely considering vehicle steering system. The existing path tracking control methods based on the hierarchical control framework considering vehicle stability, economy and comfort and other performance indicators to obtain the optimal solution (suboptimal solution), and then obtains the final control input through the lower control framework. This type of control methods separately obtain the optimal solution for the upper and lower layer, and it may lack global performance optimization.

3) Model Predictive Control has become a popular method in the control of autonomous vehicle. However, the stability analysis of the path tracking system based on MPC is still a challenge.

4) In order to deal with vehicle non-linearity, modeling errors, parameter uncertainties and external disturbances, SMC, H_∞ control, robust MPC and auto disturbance rejection control, etc. are widely used to study vehicle path tracking robust control. However, vehicle non-linearity, modeling errors, parameter uncertainties and external disturbances are mainly dealt at a broad level in this type of research process. There is a lack of factor response characteristics analysis, and then a robust control method is studied based on the response relationship of one uncertain factor. For example, when the load of automatic driving changes, the response characteristics of the load change and the vehicle mass, center of mass, and rotational inertia are analyzed, and then a robust control strategy is studied based on the response characteristics.

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