A Review of Autonomous Vehicle Path Tracking Algorithm Research

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Abstract

Driverless technology aims to improve driving safety, accuracy and comfort. Path tracking is a basic component of the motion control module of autonomous vehicles, and its control algorithm directly affects the path tracking effect. Based on the preliminary results of the application of path tracking control algorithm, this paper analyzes the principles, advantages and disadvantages, applications and current research progress of the path tracking algorithm under different working conditions from the perspective of different working conditions at low speed and high speed, and provides an outlook on the future development, aiming to provide reference for future in-depth research.

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Abstract : Driverless technology aims to improve driving safety, accuracy and comfort. Path tracking is a basic component of the motion control module of autonomous vehicles, and its control algorithm directly affects the path tracking effect. Based on the preliminary results of the application of path tracking control algorithm, this paper analyzes the principles, advantages and disadvantages, applications and current research progress of the path tracking algorithm under different working conditions from the perspective of different working conditions at low speed and high speed, and provides an outlook on the future development, aiming to provide reference for future in-depth research.**Keywords** : Autonomous vehicles; Motion control; Path tracking; Pateral control

Introduction

In recent years, autonomous vehicle have become increasingly popular in the automotive markets, which mainly consist of task decision, environment sensing, path planning, path tracking and vehicle control subsystems [1,2]. As a crucial part of the architecture of driverless vehicles, path tracking control is undoubtedly a key research focus for scholars from various countries. The role of path tracking control is to control the actuator action based on the vehicle state information given by each on-board sensor and the planned reference path to ensure that the vehicle travels along the planned path, and to control the actuator in time to reduce the deviation between the vehicle position and the planned path when the vehicle deviates from the planned path [3]. Therefore, the accuracy of path tracking control directly determines whether the driverless vehicle can follow the planned trajectory, which is of great significance for traffic safety. Many research results have been generated around path tracking algorithms in recent years, and there are common problems and solutions in solving the problem of reducing tracking errors.

In this paper, the path tracking control algorithms are divided into two categories for low-speed and high-speed conditions according to the speed of the car. Low-speed conditions mainly refer to the driving environment where the vehicle speed is lower than 30km/h, including scenarios such as factories, ports, campuses, farms, mines, and parking lots [4,5]. Low-speed driverless cars do not need to consider the influence of vehicle dynamics characteristics due to low vehicle speed, and only need to control the accuracy of path tracking, which requires high control accuracy [6-8]. High-speed conditions mainly refer to the driving environment where the vehicle speed is higher than 30 km/h. Due to the high speed and the existence of high-speed lane changing and high-speed cornering conditions, the influence of vehicle dynamics on the maneuvering stability needs to be considered when path tracking control is carried out, and the control effect directly affects the driving safety of the vehicle [9].

Although the same path tracking control algorithm can be used for driverless vehicles under both low-speed and high-speed conditions, the path tracking control faces different challenges and the controller design differs due to the difference in control objectives. Under low-speed conditions, considering the motion characteristics of the vehicle, the path curvature of the vehicle driving is larger and the vehicle heading angle changes more, which makes the optimal solution of the nonlinear problem more difficult and leads to the problem of low path tracking accuracy [10]. Under high-speed conditions, due to the contradiction between the complexity of the vehicle dynamics model and the computational real-time, driverless vehicles in high-speed situations need a longer prediction time domain for hazard avoidance, further increasing the difficulty of vehicle controller design [11,12]. Therefore, in this paper, the problems faced by path tracking control and their algorithms are sorted out according to two operating conditions, low-speed and high-speed, respectively, and the characteristics of different algorithms are analyzed with the aim of providing references for future in-depth research.

2. Research status of low-speed path tracking algorithm

The kinematic characteristics of the vehicle are more influential when the driverless vehicle is at low speed, and due to its own small lateral acceleration and the existence of the minimum turning radius constraint, the influence of vehicle dynamics is generally not considered, i.e., there is no need to consider the maneuvering stability of the vehicle, and the kinematic model of the vehicle can be directly used as the control model of the path tracking algorithm, at which time the path tracking controller designed based on the kinematic model has reliable control performance [13-16]. At present, the path tracking algorithms that are more applied in low-speed conditions are PID control method (Process Identifier Derivative, PID), pure tracking control algorithm (Pure Pursuit, PP), Stanley algorithm, model predictive control (Model Predictive Control, MPC), etc. [17-19].

2.1 PID algorithm

The PID control method is a widely used automatic controller that controls by proportional (P), integral (I), and differential (D) of deviation, which has the advantages of simple principle, easy implementation, wide applicability, and relatively independent control parameters [20,21]. Figure 1 and Figure 2 show the PID control schematic and feedforward PID control framework, respectively, in which the proportional link can reflect the state deviation of the controlled object in a timely and proportional manner, the integral link improves the non-differential degree of the controlled object through the memory of the state deviation, the differential link can reflect the trend of the state deviation to speed up the system action, and the feedforward control can compensate the disturbance and weaken the effect of the disturbance on the system output [22]. of the system [22].

Currently, many studies are based on PID algorithms or joint control with PID for path tracking. For example, the literature [23,24] designed a path tracking controller based on PID algorithm and verified the advantages of this algorithm in low speed conditions. Based on the idea of hierarchical control, the literature [25] designed the method of joint control of PID and MPC and verified that the controller has good tracking effect in low-speed conditions. Considering the characteristics of low speed and small curvature working conditions, literature [26] designed a transverse controller based on neural network parallel PID, and used PID algorithm to adjust the error caused by the neural network training to further improve the control accuracy.

For the problem of difficult adjustment of PID controller parameters, literature [27] proposed a method based on the combination of PID control and pre-scanning control, and designed a PID controller with adaptive parameter values using fuzzy inference control.Mashadi B et al. introduced a genetic algorithm to adjust the parameters and compared the control effect of the traditional PID controller, proving that the controller has better tracking accuracy, real-time performance and vehicle driving stability [28].

PID control is simple and effective, but due to the delay between the sensor and the actuator, the PID controller can only get the position deviation of the previous moment, so there is an unavoidable delay in the system, and this error is not negligible when the vehicle speed is fast, so the PID algorithm is poorly adaptable and vulnerable to the change of the road environment, and each parameter is difficult to adjust and cannot meet the requirements of path tracking under high-speed conditions, so In practical applications, it is generally used in conjunction with other control algorithms.

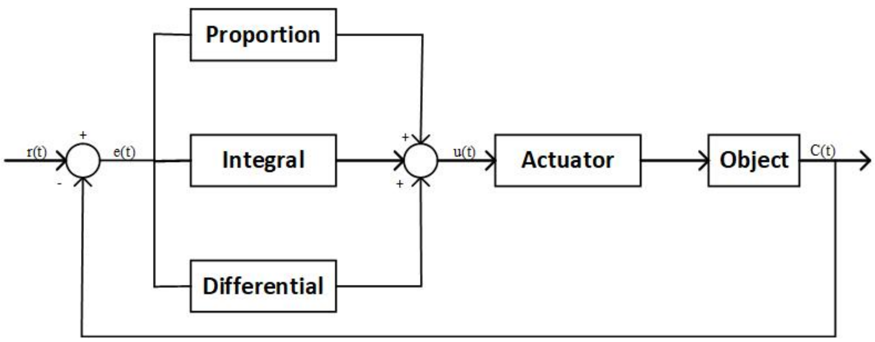

Figure 1.PID control principle

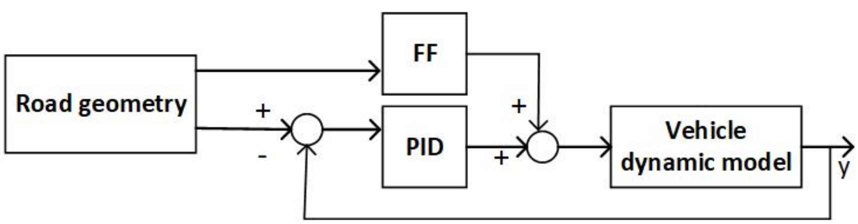

Figure 2.PID feed-forward control

2.2 PP algorithm

PP algorithm is a more reliable path tracking control algorithm, Figure 3 shows the geometric relationship schematic diagram of PP algorithm, its principle is to control the vehicle turning radius R, so that the vehicle rear axle center point along the arc to reach the reference path target point (gx, gy) with forward-looking distance l, and then based on Ackermann steering model to calculate the required front wheel turning angle δ for control [29]. This control method has simple control and better robustness, even if large lateral errors and curvature changes occur in the tracking process still achieve better tracking results [30].

Previous studies have shown that the PP-based algorithm or the improved PP algorithm can effectively achieve path tracking under low-speed conditions. For example, literature [31] designed a path tracking controller based on PP algorithm, verified the effectiveness of the controller in tracking under low-speed conditions, and proved that the algorithm leads to complete loss of vehicle stability under high-speed conditions.Yang et al. proposed an improved PP tracking algorithm based on the optimal target point based on the problem of forward distance calculation, which finds the optimal target point by simulating the driver's forward behavior, and compared with traditional PP algorithm, the tracking error is reduced by more than 20% [32].

The PP algorithm or the improved PP algorithm also has more applications in the path tracking control of parking and farm scenarios. For example, Yu et al. implemented path tracking in a parking scenario based on the PP algorithm, and the results showed that the algorithm met the requirements of smoothness, ride comfort, and safety through the continuous transformation of the steering wheel angle [33].Zhang et al. designed a path tracking algorithm for autonomous navigation of agricultural machines using PP and fuzzy control algorithms [34], and Wang et al. designed a PP model for agricultural applications by adding the heading error rate PP model for agricultural applications, and both showed good tracking accuracy and convergence of the improved algorithm through testing [35].

However, the tracking performance of the PP algorithm depends on the choice of the forward-looking distance, which is difficult to obtain the optimal value, and the tracking performance deteriorates due to the large difference between the system model and the actual vehicle characteristics under high-speed conditions, so the PP algorithm is generally suitable for path tracking control under low speed and small lateral acceleration.

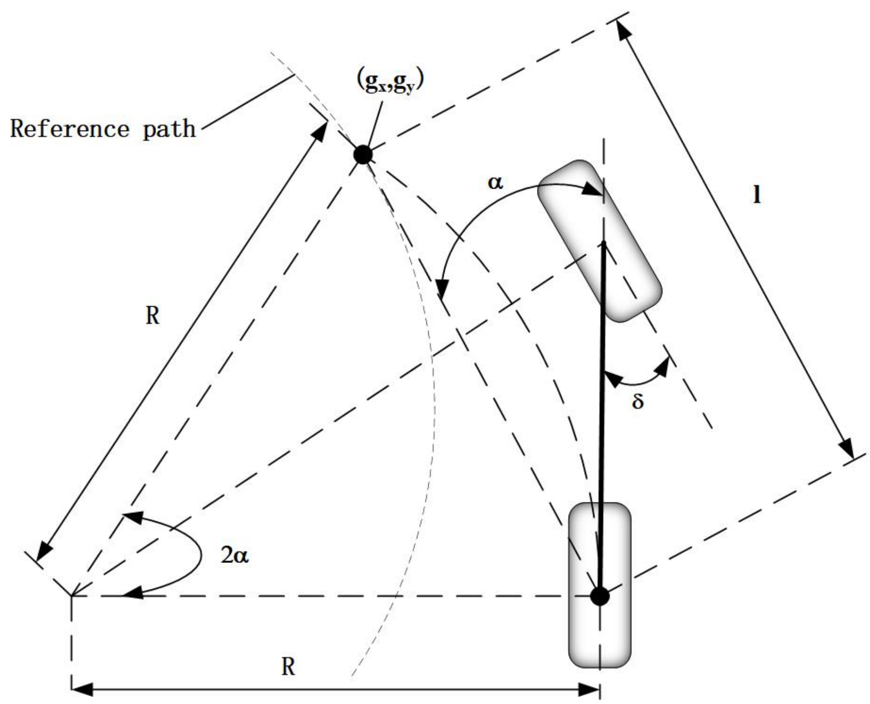

Figure 3.Schematic diagram of geometric relation of PP

2.3 Stanley's algorithm

The principle of Stanley algorithm is to control the front wheel turning angle φ according to the lateral position error ye and heading angle error from the front axle center control point to the nearest reference trajectory point (gx, gy), and Figure 4 shows the geometric relationship diagram of Stanley algorithm.Stanley algorithm has good low-speed driving stability and small path tracking error, but there is the problem of not being able to meet the path tracking accuracy and smooth line requirements at the same time. problem, and in order to further improve the control performance of the algorithm, the Stanley algorithm is usually improved [36].

For example, in the literature [37], the Stanley controller was optimized by genetic algorithm; Ahmed AbdElmoniem et al. proposed to add a predictive Stanley controller that mimics the driver's behavior under low-speed operating conditions [38]; Sun et al. proposed an improved fuzzy Stanley model based on particle swarm optimization for unmanned operation of agricultural machines [39]; Wang et al. designed an improved Stanley algorithm [40]. These improved Stanley controllers are usually able to reduce lateral errors and improve yaw stability compared to the original Stanley controller, resulting in a large improvement in control performance.

The Stanley algorithm requires a higher degree of path smoothing and is prone to the problem of excessive vehicle response overshoot in the case of unsatisfactory road curvature smoothness, and the tracking performance is poor when the vehicle has high lateral acceleration due to the neglect of vehicle dynamics and steering actuator dynamic characteristics.

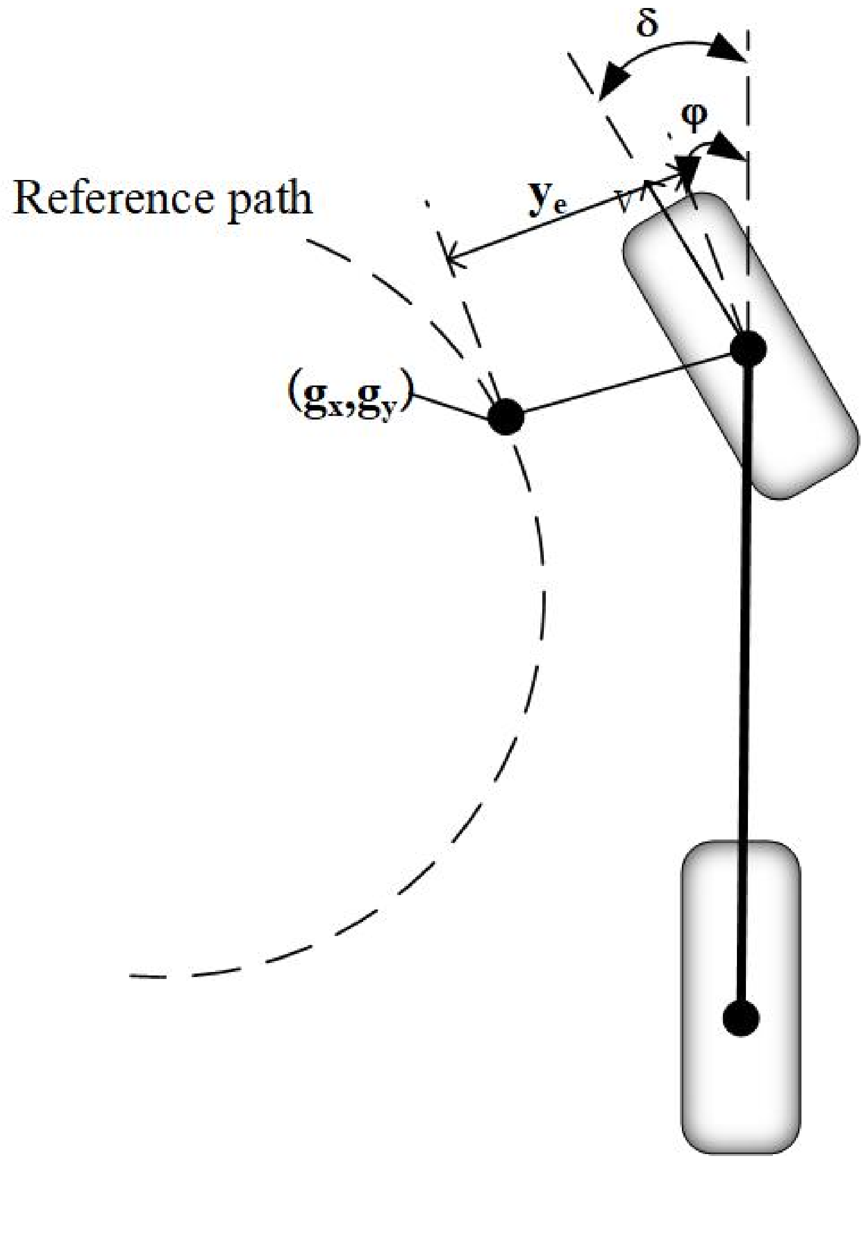

Figure 4. Geometric diagram of Stanley's algorithm

2.4 MPC algorithm

MPC is one of the most widely used path tracking algorithms, which can add a variety of constraints in the process of control, which is extremely critical in the control of vehicle path tracking. The principle of MPC algorithm is shown in Figure 5, MPC controller combines the prediction model, optimization function, and system constraints to optimally solve to obtain the error model and perform feedback correction.

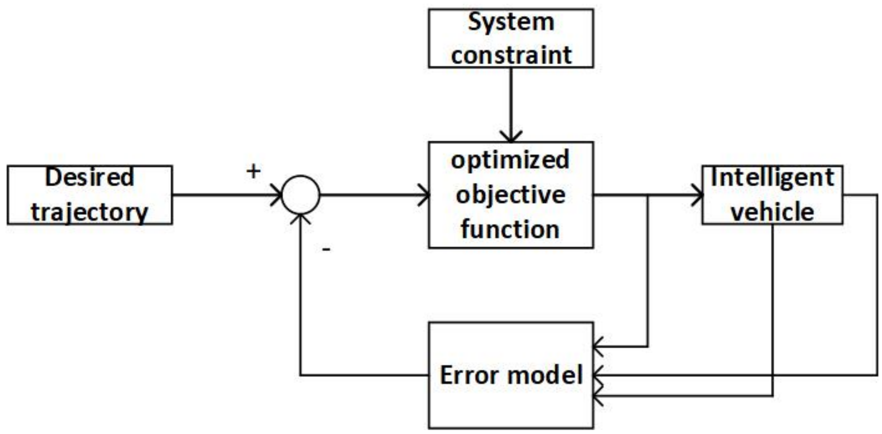

Figure 5.Schematic diagram of MPC

MPC algorithm is widely used for automatic parking in low-speed conditions [41]. For different parking accuracy problems of different parking scenarios, researchers have made different solutions based on MPC. For example, Qiu et al. designed an MPC-based autonomous parallel parking trajectory tracking algorithm for solving the problem of parallel parking in a narrow space, and the simulation results showed that the method could make the vehicle park safely, quickly, and accurately in the parking space [42].Wang designed two MPC- and PP-based vertical parking trajectory tracking controllers with automatic reverse parking charging as the application scenario, and combined with PI-based The simulation results proved the feasibility and stability of the controller [43]. Song et al. proposed a tracking control method combining MPC and Iterative learning control (ILC), and the simulation results proved that the method has higher tracking accuracy than open-loop control, linear quadratic regulator (LQR) and traditional MPC The simulation results proved that this method has higher tracking accuracy than open-loop control, linear quadratic regulator (LQR) and traditional MPC algorithm [44].

The MPC algorithm also has many applications in low-speed steering conditions [45]. For example, in the literature [46-50], the MPC algorithm was improved to improve the path tracking accuracy and driving stability of driverless cars under right-angle turns, continuous curves and arc curves, and MPC-based integrated control algorithm was proposed and the tracking accuracy and driving stability were verified. There are also studies combining MPC with other algorithms, for example, Shi et al. proposed a path tracking algorithm based on MPC and PID, added front wheel side bias constraints on the basis of traditional MPC and introduced relaxation factors, and designed hybrid PID controllers for different road conditions to improve the accuracy of vehicle speed control, and simulation results proved that the algorithm greatly improved the stability and tracking accuracy of vehicle control [51].

MPC algorithm also has many applications in low-speed complex driving conditions [52]. Considering that the longitudinal speed, road curvature, and adhesion coefficient changes under low-speed complex driving conditions have a large impact on the tracking accuracy and stability of unmanned vehicles, the literature [53-55] proposed an optimized MPC controller to improve the tracking performance and stability by considering the influence of road constraints, but the study had the problem of being unable to track the reference path with large curvature changes. Therefore, the literature [56,57] proposed the use of Nonlinear Model Predictive Control (NMPC) control method, and the simulation results showed that the tracking performance and stability of the NMPC controller were substantially improved under low-speed large curvature conditions. In addition, Mohammad Rokonuzzaman et al. proposed an MPC controller that can be applied to vehicle models of different complexity, which can avoid more complex models in the tracking process, improve computational efficiency, and track better at low speeds compared with the traditional MPC controller [58]; Jin et al. proposed a path tracking algorithm for driverless cars considering driver characteristics. The drivers were classified into normal, conservative and aggressive types, and the path tracking controller was designed according to the MPC algorithm, and the experimental results showed that the speed tracking error of the controller did not exceed 2% and the lateral tracking error was less than 0.13m [59].

For MPC algorithm, with the increase of constraint dimension, the computational volume of its optimal solution will increase, and the difficulty of its optimal solution will further increase with the increase of vehicle speed, so the real-time of computation is a major bottleneck of MPC in path tracking control technology at present. In addition, the traditional MPC has limited ability to handle system uncertainty, and it is often difficult to achieve the established tracking target task when the system model is perturbed.

3.Research status of high-speed working condition path tracking algorithm

Compared with the low-speed conditions where only the path tracking accuracy needs to be considered, the high-speed path tracking control needs to ensure not only the accuracy of path tracking but also the driving stability of the vehicle due to the vehicle dynamics characteristics, and the complex dynamics model brings certain challenges to the research in this area and has become a hot spot for scholars' research in recent years [60]. At present, the path tracking algorithms with more applications in high-speed conditions are LQR, MPC, ADRC, H[?], SMC, RL, etc. [61].

3.1 LQR algorithm

Linear Quadratic Regulator (LQR) is a linear system given in a state space model, and in vehicle path tracking, the feedforward and feedback control system of LQR is used to achieve closed-loop optimal control through feedback of the state [62,63].The advantage of LQR algorithm is that, by effectively combining with steering feedforward It can solve the steady-state tracking error when the vehicle is driving in a curve, and its steady-state error tends to zero when driving in a curve at medium speed, thus greatly improving the tracking performance. Therefore, the LQR algorithm is very suitable for highway and city driving scenarios with smooth paths, and has good vehicle speed control performance, which is also used in engineering.

For example, Yin et al. used the LQR controller to obtain the desired longitudinal acceleration, and predicted the driving risk based on the collision time and following time distance on the basis of collision avoidance, and the simulation results showed that the algorithm has high stability [64]. Although the conventional LQR controller can make the system stable, the disturbance of the disturbance term makes the steady-state error of the system not 0. For this reason, some scholars have introduced a road curvature feedforward link to the conventional LQR controller to eliminate the lateral displacement steady-state error. For example, Meng et al. designed an LQR control strategy based on foresight information [65], literature [66,67] proposed LQR controller with feedforward control, Liu et al. designed a multimodal controller based on the combination of MPC and LQR, by judging the path tracking curvature, the controller selects the corresponding control mode, and the simulation results show that the introduction of feedforward control can eliminate the system The simulation results show that the introduction of feedforward control can eliminate the steady-state error of the system and obtain good control performance [68]. However, because there is no pre-sight distance at the control point at the center of mass, the feedforward term can only react passively, which will produce more obvious overshoot. For example, the literature [69] designed an LQR controller with pre-scanning PID corner compensation and verified that the controller has high tracking accuracy under high-speed conditions by real vehicle tests.

For the lateral motion control problem, Ma et al. disassembled the dynamics model of the vehicle into a lateral error dynamics model, used a fuzzy control method to adjust the weight coefficients of the LQR in real time according to the vehicle state, and designed an update mechanism based on the cosine similarity, and the simulation results showed that the tracking accuracy and computational efficiency of the algorithm were greatly improved at 25 m/s vehicle speed [70].Gu et al. added a lateral error integral, constructed an energy function, and introduced a genetic algorithm to achieve optimization of the LQR controller, and the simulation results showed that the algorithm can effectively reduce the overshoot of the system and improve the convergence speed and stability of the system compared with the traditional LQR algorithm [71].

The LQR algorithm is usually based on a linear vehicle dynamics model, and when the vehicle motion does not satisfy the assumptions that the dynamics model steers to small angles or linearizes the tire dynamics, the tracking performance of the LQR algorithm is significantly reduced, which leads to control failure. Therefore, the combination of LQR and feedforward control cannot solve all tracking control problems, so the LQR algorithm is often combined with other path tracking algorithms in engineering for layered control to complement each other's strengths and weaknesses.

3.2 MPC algorithm

MPC algorithm is not only applicable to low-speed operating conditions, but also applicable to high-speed operating conditions. For the design of MPC controller in this condition, scholars often divide into hierarchical control and centralized control.

Hierarchical control refers to the use of two or more controllers to control different targets independently, and this control method is relatively simple to implement and can be designed in a coordinated manner based on transverse and longitudinal path tracking control algorithms [72]. For example, in the literature [73], MPC controllers were used to handle perturbations in pavement curvature, PID feedback control to suppress instability and modeling errors; MohammadRokonuzzaman et al. proposed an MPC algorithm designed with a neural network-based vehicle learning dynamic model [74]; Yao et al. proposed an MPC path with longitudinal speed compensation in the predictive time domain tracking controller and longitudinal speed compensation strategy [75]; Cui et al. designed a traceless Kalman filter and proposed a multi-constraint model prediction controller (MMPC) [76]; Wael Farag et al. proposed a framework for a path tracker (SDC) for self-driving cars based on the NMPC approach [77]. After simulation verification, all of the above decentralized control methods improve the path tracking accuracy and vehicle driving stability under high-speed conditions.

In hierarchical control, lateral control is usually implemented by an MPC controller, and longitudinal control is implemented by another independent controller. However, hierarchical control is often coordinated only for longitudinal control, ignoring the coupling between the two. When encountering kinematic coupling enhancement with large changes in road curvature or sharp changes in vehicle speed or kinetic coupling enhancement under extreme operating conditions such as high vehicle speed and low road adhesion coefficient, the controller may suffer from large overshoot, leading to the problem of tracking failure.

The centralized control structure, from the perspective of the system as a whole, can more fully consider the coupling between the horizontal and vertical motion control during the control process. For high-speed large curvature or low road adhesion coefficient working conditions, some scholars have conducted in-depth research. For example, Huang et al. proposed an MPC controller based on the vehicle error state-space equation [78]; Tian et al. proposed an adaptive path tracking strategy based on MPC algorithm to coordinate active front wheel steering and direct transverse sway moment, and used recursive least squares with forgetting factor to identify the lateral deflection stiffness of the rear tire, and based on the MPC control framework, used the side slip angle, transverse sway angular velocity and zero moment methods to construct optimization constraints [79]; literature [9] proposed an MPC controller based on line-walk time variation; Fan et al. designed an improved MPC control method from a three-degree-of-freedom vehicle dynamics model by analyzing the vehicle transverse sway stability and adding envelope constraints to the model [80]; Tian et al. proposed a strategy for forced switching MPC path tracking control and coordinated the active front wheel steering with the external transverse sway moment [81]; Liu et al. proposed a path tracking control method adaptive to lateral adhesion [82]. Simulation results show that the above MPC algorithm-based centralized controllers have good tracking accuracy and driving stability under high-speed large curvature or low road adhesion coefficient conditions.

For dynamic obstacle avoidance problem, RezaHajiloo et al. proposed an integrated controller based on MPC algorithm using differential braking to improve the lateral flexibility and responsiveness of the vehicle, and the simulation results showed that the obstacle avoidance capability, path tracking capability and driving stability of the controller were better [83].Shi et al. realized the tracking of fifth-order polynomial obstacle avoidance path by driverless car based on MPC algorithm Sun et al. proposed an optimized MPC path tracking steering controller based on a linear model to reduce the lateral path tracking error at high speed, and the simulation verified the tracking performance of the controller at high speed[9] . . Overall, most of the current research on dynamic obstacle avoidance problems at high speeds focuses on simple scenarios with only static obstacles, and adding obstacle trajectory prediction to the research on dynamic obstacle avoidance is a future research development direction.

For the acceleration overtaking conditions of self-driving cars, Zhang et al. proposed a desired transverse swing angular velocity calculation method considering path curvature, lane change time, and longitudinal vehicle speed, and established a multi-objective MPC topologizable coordination control strategy for self-driving car trajectory tracking, and the simulation results showed that the proposed trajectory tracking control strategy not only can accurately track the planned path, but also has high lateral stability [85].

The centralized control structure is from the perspective of the system as a whole, which can more fully consider the coupling between the horizontal and vertical motion control in the process of control, but the increase in the system model dimension, complexity, computation and application cost brings difficulties to the controller design and application compared to the hierarchical control.

3.3 ADRC algorithm

Other algorithms applied to the path tracking control of driverless cars under high-speed conditions are the Active Disturbance RejectiongControl (ADRC), which attributes all uncertainties acting on the controlled object to unknown perturbations and estimates and compensates them by designing extended state observations [86].

For example, Kang et al. proposed an improved selfadverse control (IADRC) method, including an improved extended state observer and an LQR-based error compensator, and designed a vehicle path tracking controller based on IADRC considering lateral stability, and the simulation results showed that the controller has better path tracking effect and robustness against disturbances [87].Yun et al. proposed a new method for high-speed Wang et al. proposed an ANN-based ADRC method for high-speed automatic emergency vehicle avoidance technology, and the simulation results proved that the method has better path tracking accuracy and robustness at different vehicle speeds, and the tracking error is smaller at 60 km/h lateral wind interference at 100 km/h vehicle speed [88].Wang et al. proposed an integrated feedforward-feedback and ADRC compensation lateral control algorithm and achieved better tracking effect and stability [89]. And Yang et al. verified that the tracking performance of nonlinear ADRC is slightly worse, but it has strong robustness [90].

At present, the research of ADRC-based path tracking is still in the stage of simulation or simple experiments, and compared with linear ADRC, nonlinear ADRC stability proof and control parameter optimization still need to be studied in depth.

3.4 Robust control

Robust control is a class of research methods for uncertain systems, which is based on parametric theory and structural singular values, and provides a more complete theoretical system for model error and uncertainty description. h[?] control takes external disturbances into account, and it is able to find a control gain K that makes the system stability and error convergence optimal [91].

For example, Tian et al. proposed a robust control strategy based on MPC and H[?] and verified that the controller can improve path tracking accuracy and ensure vehicle lateral and lateral stability under extreme conditions of high speed and large curvature, while showing superiority in suppressing parameter uncertainty, modeling errors and external disturbances [92].Feng et al. designed a static feedback controller based on H[?] observer. Simulation results under different operating conditions showed that the proposed controller was effective regardless of road condition variations, vehicle longitudinal speed variations, and external disturbances [93]. To address the fact that model uncertainty and noise are two factors that degrade the path tracking accuracy and system stability in autonomous vehicle systems, Li et al. proposed an adaptive robust controller to solve this problem [94].

Because the robust control theory-based unmanned vehicle path tracking controller has a large amount of operations and relies more on a high-performance hardware processor, the current study only verified the effectiveness of the controller under simulation conditions, and there is a lack of in-depth research in practical engineering applications.

3.5 Sliding mode control

Sliding mode control (SMC) is a relatively simple and superior control performance of the control method, is essentially a nonlinear control, its nonlinear performance is the control of the discontinuity, and the system "structure" is not fixed, can be in the dynamic process according to the current state of the system It has the advantages of sliding mode designability, few adjustment parameters, fast response time, and insensitivity to disturbances [95-98].

For example, Cao et al. proposed a model-based optimal trajectory tracking architecture, in which the SMC controller with a fuzzy adaptive preview time policy can effectively track the target path and avoid large lateral accelerations [99]. Chen et al. used hierarchical control and designed the upper layer controller using SMC control method to reduce the heading deviation and lateral deviation during path tracking while ensuring the driving stability of the vehicle [101]. Some papers also combine SMC and particle swarm optimization or replace the symbolic function with a continuous function to improve the commonly used exponential convergence law to improve the control performance [102].

The above methods only address the tracking robustness from the perspectives of modeling error, parameter uncertainty and external disturbances, without specifically analyzing the specific action laws of various uncertainties, and more in-depth experimental research on real vehicles is needed for practical applications in engineering.

3.6 Reinforcement learning

ReinforcementLearning (RL), a class of adaptive optimal control algorithms, has received increasing attention in solving complex control problems [103].

To solve the problem of feature representation and online learning capability in learning control of uncertain dynamic systems, a multicore online RL method for path tracking control was proposed in the literature [24], where a multicore feature learning framework was designed based on pairwise heuristic planning, and simulations under S-curve and urban road conditions verified that the controller has better tracking accuracy and stability performance than LQR controller and PP controller.Ma et al. combined RL and PID were combined to propose a self-seeking optimal path tracking control based on the interactive learning mechanism of the RL framework to achieve online optimization of the PID control parameters, and the simulation and real vehicle tests proved that the control method has better tracking performance in high-speed conditions (maximum speed above 100 km/h) [104].

A challenge for RL-based controllers is the need to design accuracy reward functions and utilize them efficiently to avoid falling into local optima. Moreover, despite the fact that simulation can provide a large amount of data to RL, the gap between engineering applications and simulation is still the main reason that prevents its diffusion in practical engineering.

3.7 Other algorithms

In addition to the above-mentioned path-tracking algorithms with more applications in high-speed conditions, new control algorithms continue to emerge as the research progresses. For example, Huang et al. of Hunan University studied an adaptive enhanced path tracking system (AEPTS) [60], and Sun proposed a new algorithm using a hierarchical control structure and local linearization of the nonlinear path tracking model [105]. Others study model-based adaptive Q-matrix linear quadratic Gaussian (LQG) control [106], some use pure tracking algorithms with rolling time-domain strategies, etc. [107]. These algorithms have been validated by simulations or real vehicle tests to verify the performance of path tracking under high-speed conditions.

4. Analysis of the characteristics of the path tracking algorithm

In order to facilitate the selection of path tracking control algorithms under different working conditions, the characteristics of different control algorithms are listed and compared in this paper.

The PID, PP, MPC and Stanley algorithms, which are more frequently used in the path tracking control algorithm under low speed conditions, and their advantages and disadvantages are shown in Table 1.

Table 1.Path tracking algorithm at low speed conditions

Control method	Advantages	Disac
PID	Controls are simple to use and do not rely on specific models.	PID c
PP	Its easy to use and the line speed is strictly on course, while the angular speed does not oscillate.	It is c
MPC	It has the capability of handing system constraints and future prediction in the design process.	It is c
Stanley	It has a simple layout and is suitable for controlling the position of the vehicle.	High

Under low-speed conditions, the focus of different path tracking control algorithms research is usually on the impact of system constraints on tracking accuracy, which include speed constraints, acceleration constraints, front wheel turning angle constraints and front wheel turning angle acceleration constraints. Among them, the speed constraint is the constraint that the vehicle maintains the driving state, the acceleration constraint affects the driving comfort, while the front wheel turning angle and its acceleration constraint have a greater impact on the path tracking control accuracy. According to the automotive theory, the front wheel turning angle determines the turning radius of the vehicle. If the radius of the planned path is smaller than the minimum turning radius of the vehicle, then the vehicle will deviate from the planned path because it cannot achieve tracking, while the front wheel turning angle acceleration constraint affects the steady-state steering characteristics of the vehicle, resulting in the vehicle not being able to accurately track the planned path.

Unlike the control of low-speed conditions, the problems of control accuracy and vehicle driving stability faced by path tracking control under high-speed conditions cannot be solved by simple PID, PP and Stanley algorithms, etc. Table 2 shows the commonly used path tracking algorithms under high-speed conditions and their advantages and disadvantages. As the path tracking control in the dynamics level, the position error, heading angle error and lateral speed, lateral acceleration and other optimization objectives have a coupling relationship, that is, in reducing the position error, heading angle error while the lateral speed or lateral acceleration will increase, so only rely on the fixed optimization objective function is unable to take into account the tracking accuracy and vehicle driving stability, that is, the algorithm listed in Table 2 is difficult to solve the coupling problem alone. The coupling problem. In order to achieve the purpose of controlling the path tracking accuracy and vehicle driving stability, most of the studies have applied two or more path tracking algorithms optimally combined, except for a few studies that use improved LQR, MPC, ADRC, SMC and other algorithms alone.

Table2.Path tracking algorithm at high speed conditions

Controlmethod	Advantages	Disadvantages
LQR	It is easy to achieve the closed-loop optimal control objective.	It is easy to a

Controlmethod	Advantages	Disadvantages
ADRC	Strong robustness to parameter uncertaninty and external perturbations.	Strong robust
Robust Control	The control system is easy to establish H[?]constraints and has strong robustness.	The control sy
SMC	It has fast response and insensitivity to parameter changes and disturbances.	It has fast res
RL	No reliance on environmental models,no a prioriknowledge required and good robustness.	No reliance on

5. Summary and outlook

(1) Path tracking control is one of the research hotspots in the field of unmanned vehicles, and the preliminary research is usually based on the methods of vehicle kinematics and dynamics, using information such as front wheel turning angle and vehicle position and heading angle error and road curvature for path tracking control.

(2) In the research of path tracking control for low-speed conditions, the more applied are PID, PP, Stanley and MPC algorithms. By improving and using the related algorithms in combination, the influence of the front wheel rotational speed constraint on the path tracking accuracy is reduced. As the path tracking control in low-speed conditions requires low real-time, the current research basically meets the needs of low-speed path tracking control, and has more mature applications in automatic parking and special vehicles.

(3) In the research of path tracking control in high-speed conditions, the more applied are LQR, MPC, ADRC, H[?], SMC and RL algorithms. In order to achieve the purpose of controlling the path tracking accuracy and vehicle driving stability, and to solve the coupling relationship of optimization objectives, the current research usually combines two or more algorithms according to the actual needs to achieve complementary advantages and disadvantages.

(4) MPC algorithm has become a mainstream method for path tracking control of driverless vehicles at present, but its computational real-time and ability to handle system uncertainty are still the future development direction.

(5) Since the decision indexes of speed regulation and weight distribution are usually related to environmental factors such as ground adhesion coefficient and lateral wind speed, and there is less research in this direction by scholars concerned, with the parallel development of machine learning theory and unmanned vehicle computing power, its application under extreme working conditions is also an important research direction.

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