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Path Tracking Control for Intelligent Vehicles: A Comparative Review of PID, LQR, Model Predictive Control, and Sliding Mode Control

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Abstract: Path tracking control is a fundamental technology in intelligent vehicle systems, responsible for converting planned reference trajectories into executable steering and throttle commands that ensure the vehicle follows the desired path accurately and safely. This paper presents a comprehensive comparative review of four widely adopted path tracking control methods: Proportional-Integral-Derivative control, Linear Quadratic Regulator, Model Predictive Control, and Sliding Mode Control. A unified bicycle dynamics model is introduced as the common evaluation basis to ensure fair comparison. The working principles, design considerations, advantages, and practical limitations of each method are systematically analyzed. The four methods are compared across five key engineering dimensions: tracking accuracy, computational complexity, robustness to parameter uncertainties, constraint handling capability, and implementation difficulty. The analysis reveals that Proportional-IntegralDerivative control is simplest but lacks robustness; Linear Quadratic Regulator offers optimal performance under linear assumptions but cannot enforce constraints; Model Predictive Control excels in constraint handling and preview control but demands significant computation; Sliding Mode Control provides strong robustness but suffers from chattering. Hybrid control architectures and learning-enhanced strategies are discussed as promising future directions.

Keywords: Intelligent vehicle; Path tracking; PID control; LQR; Model predictive control; Sliding mode control; Autonomous driving

1. INTRODUCTION

With the rapid advancement of autonomous driving technology and the growing deployment of advanced driver assistance systems, path tracking control has emerged as one of the most critical and fundamental modules in intelligent vehicle systems. The primary objective of path tracking control is to generate appropriate steering angle and longitudinal control commands such that the vehicle accurately and smoothly follows a predefined reference trajectory generated by a higher-level planning module. The quality of path tracking directly influences driving safety, passenger ride comfort, vehicle energy efficiency, and overall traffic efficiency, particularly under challenging conditions such as high-speed cruising, low-friction road surfaces, and emergency obstacle avoidance maneuvers.

Over the past several decades, a wide variety of control methods have been proposed, investigated, and applied to vehicle path tracking problems. Among these, the Proportional-Integral-Derivative controller remains the most widely deployed method in industrial and production vehicle applications, primarily due to its conceptual simplicity, reliable performance, and minimal computational requirements. However, the fixed-gain nature of traditional Proportional-Integral-Derivative control often leads to degraded tracking performance when the vehicle operates under varying speeds, changing road friction conditions, or unexpected external disturbances. Linear Quadratic Regulator, as a classical optimal control method, minimizes a quadratic cost function that balances tracking error magnitude and control effort. Model Predictive Control has gained substantial attention due to its inherent ability to explicitly handle input and state constraints, as well as its natural incorporation of preview information. Sliding Mode Control, a nonlinear robust control technique, is renowned for its strong invariance to parameter variations and external disturbances.

Despite the abundance of research literature in this area, a clear, systematic, and engineering-oriented comparative analysis of these four mainstream path tracking control methods remains insufficient. Many existing reviews focus on a single method or present theoretical comparisons without sufficient discussion of practical implementation considerations. This paper aims to fill this gap by providing a structured, comprehensive, and practically relevant review of the four methods, helping researchers and automotive engineers select appropriate control strategies for different application scenarios, hardware constraints, and performance requirements.

VEHICLE DYNAMICS MODEL

A proper and representative vehicle dynamics model is the essential foundation for controller design, simulation validation, and performance comparison. In this paper, the widely adopted bicycle model is employed as the unified evaluation basis, which captures the essential lateral dynamics of the vehicle while maintaining mathematical simplicity and computational efficiency. In the bicycle model, the left and right wheels on each axle are lumped together into a single equivalent wheel located at the axle centerline, and the vehicle is assumed to move on a flat and level road surface. The state vector typically includes the lateral position error relative to the reference path, the heading angle error, the yaw rate, and the lateral velocity of the vehicle center of mass. The front wheel steering angle serves as the primary control input for lateral path tracking, while longitudinal speed is often assumed to be independently controlled by a separate throttle and braking controller.

The choice between kinematic and dynamic modeling depends on the operating speed range and the required fidelity of the controller. For low-speed scenarios such as automatic parking, low-speed navigation in parking lots, and urban stop-and-go traffic, a kinematic model based purely on geometric relationships is generally sufficient, as tire slip angles remain small and the vehicle dynamics can be approximated by rigid-body kinematics. However, for high-speed maneuvers where lateral acceleration exceeds approximately 0.3 times gravitational acceleration, such as highway lane changes, high-speed obstacle avoidance, and emergency evasive maneuvers, a dynamic model that explicitly considers tire cornering forces, load transfer, and suspension effects becomes necessary to accurately capture the actual vehicle behavior and ensure controller stability.

The nonlinear dynamic model can be linearized around a nominal operating point, typically defined by a constant longitudinal speed and a small steering angle, yielding a linear time-varying or linear parametervarying system representation. This linearized form is particularly well-suited for the design of Linear Quadratic Regulator and linear Model Predictive Control, as it allows the application of well-established linear control theory and efficient convex optimization techniques. For nonlinear control approaches such as Sliding Mode Control and nonlinear Model Predictive Control, the full nonlinear bicycle model can be used directly to preserve modeling accuracy under extreme operating conditions, at the cost of increased controller complexity and computational burden.

3. CONTROL METHODS

3.1 PID Control

Proportional-Integral-Derivative control is the most classical, intuitive, and widely deployed feedback control method in automotive systems and industrial automation. In the context of vehicle path tracking, a Proportional-Integral-Derivative controller typically computes the desired front steering angle based on the proportional, integral, and derivative terms of the lateral tracking error or the heading angle error. The proportional term provides an immediate and proportional response to the current tracking error, the integral term accumulates past errors to eliminate steady-state offset caused by constant disturbances or modeling biases, and the derivative term anticipates future error trends by responding to the rate of error change, thereby improving transient response and reducing overshoot.

The primary advantage of Proportional-Integral-Derivative control lies in its remarkable simplicity and practicality. It requires no detailed vehicle dynamics model, involves only three tunable parameters, and demands minimal computational resources, making it extremely easy to implement on low-cost embedded microcontrollers and legacy automotive electronic control units. However, the performance of traditional fixed-gain Proportional-Integral-Derivative control deteriorates significantly under high-speed driving or low-friction road conditions, primarily because it cannot explicitly account for vehicle dynamics, actuator saturation limits, or changing operating conditions. The fixed gain parameters are typically tuned and calibrated for a specific nominal operating point and cannot automatically adapt to variations in vehicle speed, road surface friction coefficient, or vehicle load.

To address these limitations, various improved Proportional-Integral-Derivative variants have been proposed in the literature. Gain scheduling is the most common approach, where the controller parameters are adjusted according to the current vehicle speed or other measurable operating variables. More advanced variants include fuzzy logic-based Proportional-Integral-Derivative control, neural network-enhanced self-tuning Proportional-Integral-Derivative, and adaptive Proportional-Integral-Derivative with online parameter estimation. These methods can automatically adjust controller parameters in real time to maintain consistent performance across a wider range of operating conditions, but they come at the cost of increased design complexity, higher calibration effort, and greater computational requirements.

3.2 LQR Control

Linear Quadratic Regulator is a well-established optimal control method that minimizes a quadratic cost function involving weighted state tracking errors and control effort over an infinite or finite time horizon. In vehicle path tracking applications, the cost function typically penalizes the lateral position error, heading angle error, and the magnitude or rate of the steering angle input. The weighting matrices, commonly denoted as Q for state errors and R for control effort, provide a systematic and intuitive mechanism for designers to balance the trade-off between tracking accuracy and control smoothness. A larger weight on state errors yields more aggressive tracking with faster error convergence but may result in larger and less smooth steering commands, while a larger weight on control effort produces smoother and more comfortable steering behavior at the expense of slower error convergence and potentially larger tracking errors.

Linear Quadratic Regulator generally provides better stability and tracking performance than traditional Proportional-IntegralDerivative control, especially when an accurate linearized vehicle model is available and the operating range is limited around the nominal design point. The optimal gain matrix can be computed offline using well-established algorithms such as the Riccati equation solution, and the resulting controller has a simple static state feedback structure that is easy to implement in real time. Additionally, the Linear Quadratic Regulator framework can be extended to include integral action, resulting in the Linear Quadratic Integral controller, which eliminates steady-state tracking errors caused by constant disturbances or modeling inaccuracies.

The main limitation of Linear Quadratic Regulator is that it cannot explicitly handle actuator constraints such as maximum steering angle, maximum steering rate, or acceleration limits. When the optimal control command exceeds these physical limits, actuator saturation occurs, which can lead to performance degradation, windup issues, and even instability in extreme cases. Furthermore, Linear Quadratic Regulator relies on a linearized model, and its performance degrades noticeably when the vehicle operates far from the linearization point, such as during high-speed aggressive maneuvers or on low-friction surfaces where tire nonlinearities become significant. To overcome these issues, researchers have proposed gain-scheduled Linear Quadratic Regulator for varying operating conditions, adaptive Linear Quadratic Regulator with online model parameter updating, and anti-windup compensators. These extensions improve practical applicability but inevitably increase the overall design complexity.

3.3 Model Predictive Control

Model Predictive Control is an advanced optimal control methodology that solves a finite horizon constrained optimization problem at each control time step using an explicit prediction model to forecast the future evolution of the vehicle states At each sampling instant the controller optimizes a sequence of future control actions over a prediction horizon considering both the reference trajectory tracking objective and the system constraints Only the first control action of the optimal sequence is actually applied to the vehicle and at the next time step the entire optimization is repeated using the latest measured state information forming a receding or rolling horizon framework This receding horizon strategy provides inherent feedback correction and robustness to modeling errors and external disturbances as the optimization is continuously updated with fresh state measurements.

The most prominent and valuable advantage of Model Predictive Control is its ability to explicitly and systematically handle a wide variety of constraints, including limits on steering angle, steering rate, longitudinal acceleration, lateral acceleration for passenger comfort, and even tire slip angles for vehicle stability. This constraint handling capability is particularly important in automotive applications, where actuator limits and safety constraints must be rigorously enforced to ensure vehicle stability and passenger safety. Additionally, Model Predictive Control naturally incorporates preview information from the future reference trajectory, enabling anticipatory control actions that prepare the vehicle for upcoming curves or maneuvers before they are reached, resulting in smoother and more efficient tracking performance.

The main drawback of Model Predictive Control is its relatively high computational demand, especially for nonlinear Model Predictive Control that requires solving a non-convex nonlinear programming problem at each time step. This computational burden has historically limited the real-time implementation of Model Predictive Control on resource-constrained automotive embedded controllers. However, recent advances in efficient quadratic programming solvers, explicit Model Predictive Control that precomputes the optimal control law offline, and linear time-varying Model Predictive Control that approximates the nonlinear system with successive linearizations have significantly reduced the computational requirements. Combined with the increasing computational power of modern automotive microcontrollers and system-on-chip platforms, these advances have made real-time Model Predictive Control implementation feasible and increasingly common in production vehicles, particularly for high-level autonomous driving functions and advanced chassis control systems.

3.3 Sliding Mode Control

Sliding Mode Control is a nonlinear robust control technique designed to drive the system state onto a predefined sliding surface in the state space and maintain it there for all subsequent time. The sliding surface is typically designed as a linear combination of the tracking errors, representing the desired dynamic behavior of the closed-loop system. The control law consists of two components: an equivalent or nominal control term that ensures the system behaves according to the desired sliding dynamics when on the surface, and a discontinuous switching control term that forces the system state toward the sliding surface from any initial condition. Once the system state reaches and remains on the sliding surface, the system response becomes insensitive to parameter variations, modeling uncertainties, and bounded external disturbances, a remarkable property known as the invariance property or sliding mode invariance.This strong robustness property makes Sliding Mode Control particularly attractive for automotive path tracking applications, where vehicle parameters such as mass, moment of inertia, and tire cornering stiffness can vary significantly due to load changes, passenger configuration, tire wear, and varying road surface conditions. Unlike model-based optimal control methods that rely heavily on accurate system models, Sliding Mode Control can maintain consistent tracking performance even when the vehicle model is imprecise or when significant unmodeled dynamics exist. The controller design is relatively straightforward, and the resulting control law has a simple structure that is amenable to real-time implementation with moderate computational requirements.

However, the discontinuous switching nature of the traditional Sliding Mode Control law causes an undesirable phenomenon known as chattering, characterized by high-frequency, low-amplitude oscillations in the control signal and potentially in the system states. Chattering can excite unmodeled high-frequency dynamics such as actuator resonance and structural vibration, increase wear on steering actuators and mechanical components, reduce passenger ride comfort, and potentially degrade tracking performance. To mitigate this issue, several effective approaches have been developed. The boundary layer method replaces the discontinuous switching term with a continuous saturation or hyperbolic tangent function within a thin boundary layer around the sliding surface, trading a small amount of robustness for significantly improved control smoothness. Higher-order Sliding Mode Control and terminal Sliding Mode Control further improve performance by acting on higher derivatives of the sliding variable and achieving finite-time convergence, respectively. These advances have substantially reduced chattering and made Sliding Mode Control increasingly practical and attractive for automotive path tracking applications.

4 COMPARATIVE ANALYSIS

The four path tracking control methods reviewed in this paper are systematically compared across five key engineering dimensions to provide practical guidance for method selection. In terms of tracking accuracy under nominal operating conditions, Model Predictive Control generally achieves the highest accuracy due to its optimal constrained optimization and preview capability, followed closely by Linear Quadratic Regulator when an accurate model is available. Sliding Mode Control offers medium to high tracking accuracy, while traditional Proportional-Integral-Derivative control typically provides the lowest tracking accuracy, particularly at higher speeds. However, it should be noted that the actual tracking accuracy of any method depends heavily on the quality of the vehicle model, the care taken in controller tuning, and the specific operating conditions.

Regarding computational complexity and real-time feasibility, Proportional-Integral-Derivative control is by far the least demanding, requiring only basic arithmetic operations that can be executed on even the simplest microcontrollers. Linear Quadratic Regulator and Sliding Mode Control require moderate computational resources, involving matrix multiplications and nonlinear function evaluations that are easily handled by modern automotive controllers. Model Predictive Control is the most computationally intensive method, as it requires solving an optimization problem at every time step, although efficient formulations and powerful hardware have made realtime implementation increasingly practical. For robustness to parameter uncertainties and external disturbances, Sliding Mode Control is clearly superior due to its invariance property, followed by Model Predictive Control with its receding horizon feedback, while Linear Quadratic Regulator and Proportional-Integral-Derivative control are more sensitive to modeling errors and parameter variations.

In the dimension of constraint handling capability, Model Predictive Control is unmatched, as constraints are explicitly incorporated into the optimization formulation and rigorously enforced at every time step. Sliding Mode Control can handle constraints to a limited extent through appropriate sliding surface design, while Linear Quadratic Regulator and Proportional-Integral-Derivative control cannot explicitly handle constraints and may suffer from actuator saturation issues. Finally, regarding engineering implementation difficulty, Proportional-Integral-Derivative control is the easiest to design, calibrate, and implement, followed by Linear Quadratic Regulator and Sliding Mode Control, while Model Predictive Control is the most difficult due to the need for prediction model development, constraint formulation, solver integration, and real-time performance optimization. In practical automotive applications, the choice of control method should be based on a careful consideration of all these dimensions in light of the specific application requirements, available hardware resources, and expected operating conditions.

?? DISCUSSION AND FUTURE TRENDS

While the four control methods reviewed in this paper have been extensively studied and widely applied, several important challenges and promising research opportunities remain for the future development of vehicle path tracking control. First and foremost, the integration of path tracking control with higher-level trajectory planning and lower-level vehicle stability control is becoming increasingly important. Traditional While the four control methods reviewed in this paper have been extensively studied and widely applied, several important challenges and promising research opportunities remain for the future development of vehicle path tracking control. First and foremost, the integration of path tracking control with higher-level trajectory planning and lower-level vehicle stability control is becoming increasingly important. Traditional hierarchical control architectures that separate planning, decision, and control into independent modules may lead to suboptimal overall performance due to information loss and interface limitations at module boundaries. Integrated control architectures that coordinate steering, braking, drive torque distribution, and active suspension in a unified framework can potentially improve overall vehicle performance, safety, and energy efficiency beyond what lateral path tracking control alone can achieve.

Second, learning-enhanced control methods are emerging as a promising and rapidly growing research direction. Reinforcement learning can be used to optimize the parameters of Model Predictive Control or to directly learn control policies from data, while deep neural networks can approximate complex nonlinear vehicle dynamics for more accurate prediction in Model Predictive Control. Datadriven methods can also complement model-based approaches by learning residual dynamics, compensating for unmodeled effects, and adapting to changing conditions. However, ensuring the safety, stability, and reliability of learning-based controllers in safetycritical automotive applications remains a significant open challenge, and the development of formally guaranteed safe learning-based control methods is an active area of research. Third, the rapid development of connected and automated vehicle technology provides new opportunities for path tracking control through the availability of preview information beyond the vehicle line of sight, including traffic signal timing, road curvature and gradient, and the intentions of surrounding vehicles, which can be leveraged by predictive controllers to improve tracking smoothness, energy efficiency, and traffic efficiency.

?? CONCLUSION

This paper presented a comprehensive comparative review of four mainstream path tracking control methods for intelligent vehicles: Proportional-Integral-Derivative control, Linear Quadratic Regulator, Model Predictive Control, and Sliding Mode Control. Each method possesses distinct strengths and inherent weaknesses. Proportional-Integral-Derivative control is simple and easy to implement but lacks robustness and constraint handling capability. Linear Quadratic Regulator provides optimal linear control with systematic tuning but cannot explicitly handle actuator constraints. Model Predictive Control excels in constrained optimization and preview control but is computationally expensive. Sliding Mode Control offers strong robustness against parameter variations but suffers from chattering issues. The selection of an appropriate control method should be based on a careful assessment of specific application requirements, available computational resources, and expected operating conditions. Future research will likely focus on integrated control architectures, learning-enhanced control strategies, and connected vehicle-enabled predictive control to further improve path tracking performance, safety, and energy efficiency in complex and dynamic driving environments.

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