

Optimization and Control Strategies for Mechanical Vehicle Trajectory Research

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Abstract. With the rapid advancement of contemporary transportation and automation technology, the optimization of mechanical vehicle trajectories and control strategies have gradually become a focal area of research. Precise trajectory optimization not only enhances the driving efficiency of vehicles but also significantly reduces energy consumption and safety hazards. This paper reviews the basic theory of mechanical vehicle motion trajectories, focusing on the methods of trajectory optimization and control strategies. It covers model-based trajectory optimization, data-driven optimization methods, and various control strategies. Through an analysis of existing research, it points out the challenges and prospects of applying trajectory optimization and control strategies in complex environments.

Keywords: Mechanical Vehicles; Motion Trajectory; Trajectory Optimization; Control Strategies; Model Predictive Control.

1. Introduction

Accurate trajectory optimization can not only improve the driving efficiency of vehicles but also effectively reduce energy consumption and safety risks. Although many studies have discussed vehicle motion models and control algorithms, real-time application in complex environments still faces challenges.

2. Basic Theory of Mechanical Vehicle Motion Trajectories

The definition of motion trajectories includes the driving routes of vehicles in various conditions, including straight-line travel, curved travel, and path selection in complex environments. The focus of trajectory optimization research involves the construction of dynamic and mathematical models. Dynamic models analyze the motion performance of vehicles based on their physical properties, such as mass, velocity, acceleration, etc., to predict trajectory changes. Mathematical models establish the relationship between vehicle motion and control variables through equations, providing theoretical support for trajectory optimization. The selection of optimization algorithms is crucial, and common methods include genetic algorithms, particle swarm optimization, etc. These algorithms can effectively find the optimal solution among numerous constraints. In the field of control strategies, traditional PID controllers have been widely used in trajectory tracking, but model predictive control (MPC) has gradually gained attention due to its ability to consider future states in dynamic environments.

3. Trajectory Optimization Methods

3.1. Balancing Accuracy and Efficiency

In practical operations, trajectory optimization algorithms must meet real-time requirements, which means reducing the complexity of calculations while ensuring sufficient accuracy. Common optimization algorithms such as genetic algorithms and particle swarm optimization can find global optimal solutions, but their calculation processes are often complex and difficult to meet real-time standards. To address this, some researchers have proposed hybrid algorithms that combine

traditional optimization algorithms with heuristic algorithms to obtain satisfactory solutions within an appropriate time. Additionally, the use of hierarchical optimization strategies is also an effective approach, optimizing trajectories at different levels step by step to achieve global optimization while maintaining efficiency. The organic integration of these strategies not only enhances the vehicle's adaptability in dynamic environments but also improves overall operational efficiency.

3.2. Model-Based Trajectory Optimization Methods

Dynamic models are generally based on the physical characteristics of the vehicle, constructing equations that describe vehicle motion. These models can accurately display the motion performance of the vehicle under specific conditions, such as factors like vehicle mass, friction, air resistance, etc. By deeply analyzing these factors, vehicle motion trajectories under various control methods can be predicted. Trajectory optimization methods based on dynamics often require nonlinear optimization operations to consider the vehicle's dynamic constraints and environmental factors. Control strategy planning based on this is also crucial, and traditional PID control algorithms and contemporary model predictive control (MPC) algorithms have been widely used in this optimization process.

Mathematical models mainly use mathematical equations and inequalities to explain the problem of trajectory optimization. These models generally include objective functions and constraints, where the objective function reflects the direction of optimization, such as minimizing driving time and reducing energy consumption, and constraints include vehicle dynamics limitations and environmental constraints. By solving these equations, researchers can find the optimal trajectory. Traditional optimization methods like linear programming and quadratic programming are often used in these problems. In recent years, due to enhanced computing power, some mathematical models based on complex algorithms (such as mixed-integer programming) have begun to attract attention, opening up new avenues for trajectory optimization.

3.3. Data-Driven Trajectory Optimization Methods

Machine learning algorithms are often used in trajectory optimization for feature extraction and pattern recognition. By analyzing past driving data, machine learning algorithms can identify key factors and hidden patterns during vehicle operation to guide trajectory optimization. For example, algorithms like support vector machines (SVM) and decision trees can be used to build models that relate vehicle motion to environmental factors for precise trajectory prediction. Clustering algorithms are also often used to analyze the characteristics of trajectories under different driving behaviors, thereby optimizing corresponding control strategies.

The application of deep learning is a new trend in trajectory optimization research in recent years. Deep learning models can handle high-dimensional data and build complex relationships through multi-layer non-linear transformations. For example, models like convolutional neural networks (CNN) and recurrent neural networks (RNN) can be used to process time series data for real-time optimization of trajectories in dynamic environments. By training deep learning models, researchers can accurately capture the behavioral patterns of vehicles in complex scenarios to achieve more precise trajectory prediction and optimization. Especially in situations involving complex road conditions or emergencies, deep learning technology has shown its unique advantages.

4. Trajectory Control Strategies

4.1. PID Control Strategy

The PID control strategy focuses on real-time monitoring of the deviation between system output and target values, and adjusts it through proportion, integration, and differentiation to achieve precise control of the system state. Specifically, the proportional term responds quickly to current deviations, the integral term eliminates steady-state errors, and the derivative term predicts future changes in the system to improve response speed and system stability. In practical applications, PID controllers have

been widely used in the trajectory control of autonomous vehicles. For example, in an autonomous bus project in a city, the system uses a PID controller to regulate the vehicle's speed and direction. The bus uses sensors to obtain real-time deviations between the vehicle and the target trajectory, and adjusts its acceleration and steering using the PID algorithm. After multiple field tests, the results show that this control strategy effectively reduced the vehicle's deviation during driving, ensuring its stability in complex traffic environments. However, PID control may experience response lag and overshoot when dealing with highly dynamic nonlinear environments, which limits its application in some complex scenarios.

4.2. Model Predictive Control (MPC)

The key concept of MPC is to predict the system's performance over a certain period in the future based on the current state of the system and obtain the optimal control input through optimization algorithms. Its main advantage is the ability to deal with various constraints, including dynamic constraints and environmental obstacles, which is very suitable for changing driving scenarios. For example, in the application of autonomous vehicles, MPC can calculate the optimal driving path for vehicles in urban roads. In a specific example, an autonomous driving development project used MPC control strategy to skillfully handle various situations in complex urban traffic. During driving, the system obtains real-time road condition data through sensors and predicts the vehicle's movement trajectory in the next few seconds in conjunction with the vehicle's dynamic model. Through optimization of the predicted trajectory, MPC effectively guides the vehicle to avoid pedestrians and other obstacles in multi-lane traffic flow, ensuring safety and efficiency.

4.3. Adaptive Control Strategy

Adaptive control strategy is a method that can dynamically change control parameters to adapt to changing environments and system characteristics, especially suitable for applications facing uncertainty and changing conditions. This strategy can autonomously adjust the controller's parameters through real-time monitoring of the system state, thereby ensuring the stability and performance of the system under various driving conditions. In the field of vehicle motion control, adaptive control is crucial, especially during high-speed driving or complex road conditions. For example, in the application of a high-performance racing car, a research team built an adaptive control system specifically for improving the car's performance under different track conditions. The system collects real-time information such as road friction coefficient, vehicle speed, and steering angle, and dynamically changes the hardness of the suspension system and steering characteristics using adaptive control algorithms. In an important race, this system effectively dealt with sudden slippery conditions on the track, ensuring optimal grip and stability during rapid turns, and ultimately helped the car achieve excellent results.

4.4. Intelligent Control Methods

Intelligent control methods have gradually evolved into a research focus in the field of trajectory optimization and control in recent years, relying on artificial intelligence technologies such as fuzzy logic, neural networks, and reinforcement learning. The advantage of these methods is that they can handle complex nonlinear systems and their uncertainties, with excellent self-learning and adaptability. Take fuzzy control as an example; this method imitates human decision-making processes and forms corresponding control commands by analyzing the fuzzy characteristics of input variables. In the application of autonomous vehicles, fuzzy controllers are used to deal with dynamic traffic conditions. In a practical example, an autonomous bus system in a city used fuzzy control technology to cope with complex traffic flows. In a multi-lane traffic environment, the system can dynamically adjust its speed and position according to the speed, distance, and lane conditions of the vehicle in front, ensuring safe driving.

5. Conclusion

By deeply exploring dynamic and mathematical models, integrating data-driven methods, and cutting-edge control strategies, the driving efficiency and safety of vehicles can be greatly enhanced. Although current technologies have achieved a certain level of breakthrough, real-time application in complex environments still faces many challenges. In the future, with the continuous evolution of artificial intelligence and big data technology, more innovative solutions will be provided for trajectory optimization and control, thereby promoting the continuous development and application of intelligent transportation systems.

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