

Adaptive Control Strategy for Robot Motion Planning in Complex Environments

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Abstract

Adaptive control strategies play a crucial role in robot motion planning in complex environments, enabling robots to dynamically adjust their behavior based on environmental changes and task requirements. This article reviews various adaptive control methods and their applications in robot motion planning. These methods improve the autonomy, robustness, and safety of robots through real-time perception of the environment and optimization of path planning. This article aims to review the application of adaptive control strategies in robot motion planning in complex environments, explore the collaborative work of various methods and technologies to achieve efficient and reliable robot motion planning, and provide useful references and guidance for the future development of robot technology through the research in this article.

Keywords

Adaptive Control Strategy; Complex Environment; Robot Motion Planning.

1. Introduction

With the rapid development of robotics technology, more and more robots are deployed in various complex environments to perform diverse tasks; In these environments, robots face many challenges such as dynamic obstacles and uncertain environmental conditions. In order to address these challenges, adaptive control strategies have become a key technical means that allow robots to dynamically adjust their behavior based on real-time environmental information and task requirements, thereby improving the system's autonomy, robustness, and safety.

2. Overview of Adaptive Control Strategy

Adaptive control is an advanced control theory that allows control systems to automatically adjust their parameters based on environmental changes or changes in the internal state of the system, in order to maintain or improve system performance. The adaptive control strategy is suitable for dealing with complex systems with uncertainty, nonlinearity, and time-varying characteristics. The core of adaptive control lies in its ability to address these challenges through continuous learning and self optimization, thereby maintaining robustness and efficiency in dynamic environments.

Adaptive control can be divided into two categories: direct adaptive control and indirect adaptive control. Direct adaptive control directly modifies the parameters of the controller to improve performance, while indirect adaptive control first estimates the parameters or states of the system, and then adjusts the controller based on these estimated values. In addition, with the development of artificial intelligence, neural network control and fuzzy logic control are widely used in adaptive control. They can handle situations where it is difficult to establish accurate mathematical models and have good nonlinear processing capabilities. Adaptive control has a wide range of applications in multiple fields, with the advantages of high flexibility,

strong robustness, and the ability to automatically adjust under different operating conditions, thereby improving system performance.

3. Challenges Faced by Robot Motion Planning

3.1. Environmental Perception and Processing

Environmental perception refers to robots collecting information about their surrounding environment through sensors and transforming this information into data that can be used for decision-making. However, the performance limitations of sensors are a major obstacle. For example, although LiDAR can provide high-precision distance measurement, it may not perform well in rainy, snowy, or strong light conditions; Although visual sensors can capture rich environmental details, how to effectively synchronize and fuse data from different sensors is also a complex problem. In a dynamic environment, the position, velocity, and shape of objects may change at any time, which places higher demands on the real-time perception ability of robots. For example, autonomous vehicles driving on city streets must be able to quickly identify and track pedestrians, other vehicles, and other moving obstacles.

3.2. High Computational Complexity

As robot tasks become increasingly complex, there are also more factors to consider, such as the shortest time path and safety, which often constrain each other and increase the complexity of the problem. For example, in an environment full of dynamic obstacles, robots not only need to find a safe path from the starting point to the endpoint, but also need to ensure that this path is optimal while avoiding collisions with other moving objects. Another reason for the high computational complexity is that modern robots typically have multiple degrees of freedom, each of which increases the dimension of the state space. This means that when performing motion planning, the space that needs to be searched grows exponentially. Although traditional grid based methods are intuitive, they quickly become impractical in high-dimensional spaces. In addition, for some specific application scenarios, such as unmanned vehicles or drones, real-time performance is a mandatory requirement.

3.3. Human Computer Interaction Needs Improvement

The challenges faced by robot motion planning in human-computer interaction mainly lie in how to achieve more natural, safe, and efficient interactions. As robots increasingly enter human living and working environments, they need to be able to understand and respond to human behavior, intentions, and commands, while ensuring operational safety and user experience. Firstly, robots must be able to accurately recognize and understand human actions, expressions, voice commands, and even subtle emotional changes through visual, auditory, or other sensors. This not only requires high-precision sensors, but also powerful data processing capabilities and advanced pattern recognition algorithms. For example, in a shared workspace, robots need to be able to track a person's position and actions in real-time to avoid potential collisions and adjust their path or task based on human behavior. In addition, robots should not only execute explicit instructions, but also be able to infer users' implicit needs or preferences, which involves complex cognitive modeling and reasoning processes. For example, in scenarios that assist the elderly or disabled, robots may need to observe users' behavior to determine whether they need help or predict their next actions in specific situations. This ability can be achieved through machine learning techniques, however, even with the support of these technologies, designing interaction methods that conform to user habits and cultural backgrounds remains a complex issue.

4. Method and Strategy of Adaptive Control for Robot Motion Planning in Complex Environments

4.1. Model Predictive Control

Model predictive control is an advanced control strategy that plays an important role in robot motion planning in complex environments. The core idea of MPC is to use the dynamic model of the system to predict the state for a certain period of time in the future, and determine the optimal control input sequence through optimization algorithms to meet a series of constraints and optimize performance indicators. In robot motion planning, MPC can provide a global perspective that allows robots to not only consider their current state, but also anticipate possible future changes and make optimal decisions based on this. In addition, in complex environments, robots often need to comply with multiple constraints, and MPC can directly consider these constraints in the optimization process to ensure that the generated path is not only optimal but also feasible. In addition, MPC can also handle nonlinear and time-varying systems, which is particularly important in robot dynamics modeling because many robot systems have complex nonlinear characteristics. In summary, model predictive control provides a powerful tool for robot motion planning in complex environments. By combining dynamic models, optimization algorithms, and rolling optimization mechanisms, MPC can generate safe and efficient paths and adapt to changes in the environment in real time.

4.2. Adaptive PID Control

Adaptive PID control is an effective method for improving the motion planning performance of robots in complex environments. It optimizes the system response by adjusting the parameters of the PID controller in real-time. Traditional PID (Proportional Integral Derivative) control is widely used in industrial automation due to its simplicity and robustness. However, when facing nonlinear, time-varying, or uncertain systems, fixed parameter PID controllers often struggle to achieve optimal performance. Adaptive PID control solves this problem. In robot motion planning, adaptive PID control can significantly improve the accuracy and stability of path tracking. Traditional PID controllers may perform poorly due to the inability of preset parameters to cope with changes in road friction, load fluctuations, or other external disturbances; Adaptive PID control can maintain good path tracking performance by monitoring the error between actual output and expected output, and dynamically adjusting PID parameters based on these errors. In summary, adaptive PID control enables robots to maintain efficient and stable motion performance in complex and changing environments by adjusting PID parameters in real-time. This method not only improves the robustness and adaptability of the system, but also enhances its resistance to uncertainty and external disturbances.

4.3. Improve the Design of Human-Computer Interaction

In the motion planning of robots in complex environments, improving the design of human-computer interaction is the key to enhancing the overall performance and user experience of the system. Firstly, adaptive control can be used to improve the perception ability of robots, enabling them to accurately understand and respond to human behavior. For example, by using adaptive visual processing algorithms, robots can analyze users' facial expressions, gestures, and body postures in real time, thereby better understanding users' intentions and emotional states. Secondly, adaptive control can be applied to speech recognition and natural language processing (NLP), enabling robots to more accurately understand and generate natural language; Through online learning and model updates, robots can continuously optimize their language processing abilities in conversations with users, improving the fluency and accuracy of conversations. In addition, adaptive control can also be used to adjust the human-machine interface of robots, making them more intuitive and easy to operate; By analyzing user

interaction behavior and feedback, robots can automatically adjust interface layout to meet the needs and preferences of different users.

5. Application of Adaptive Control Strategy in Robot Motion Planning

5.1. Online Learning and Adaptive Adjustment

Online learning and adaptive adjustment are important applications of adaptive control strategies in robot motion planning. They enable robots to continuously collect new data during operation and update their internal models or adjust control strategies accordingly to better adapt to complex and changing environments. Online learning is typically based on artificial intelligence technologies such as machine learning and reinforcement learning, which allow robots to gain experience from practical operations and optimize their behavioral strategies through a continuous trial and error process. Adaptive adjustment focuses on automatically adjusting controller parameters based on the current state and environmental conditions to maintain stability and optimality of system performance. For example, adaptive PID control can automatically adjust the proportional, integral, and derivative gains based on sensor feedback information to cope with different loads or external disturbances.

5.2. Multiple Mode State Fusion

Multi mode state fusion is an important application of adaptive control strategy in robot motion planning. It provides a more comprehensive and accurate environment model by integrating data from different sensors and information sources, thus improving the perception ability and decision-making quality of robots in complex and changing environments. In practical applications, multimodal fusion includes data level fusion, which directly combines raw sensor data to form a comprehensive perception result. This method requires all sensors to have high-precision time synchronization and efficient algorithms to process large amounts of data. Multimodal fusion not only improves the perception ability of robots, but also enhances the robustness and fault tolerance of the system.

5.3. Control Hardware Design and Algorithm Implementation

The application of adaptive control strategy in robot motion planning not only relies on advanced algorithms, but also requires powerful control hardware design to support its real-time and reliability. The design of control hardware must be able to handle complex computing tasks, respond quickly to environmental changes, and ensure system stability and robustness. In order to ensure real-time data transmission, robots need to have high-speed and reliable communication interfaces; High speed buses can be used for data exchange between internal components, while wireless communication can be used for connection with external systems or cloud platforms. An efficient power management system should be able to optimize power consumption and extend working time; This can be achieved through the use of low-power components, dynamic adjustment of processor frequency, and intelligent sleep mode. In addition, in order to improve the reliability and fault tolerance of the system, redundant design is usually adopted for control hardware. When one sensor fails or is interfered with, other sensors can continue to provide necessary information to avoid system performance degradation.

6. Conclusion

The adaptive control strategy has shown great potential and value in robot motion planning in complex environments. By combining advanced algorithms and optimized hardware design, these strategies can enable robots to exhibit higher autonomy, robustness, and safety in dynamic and uncertain environments. With the continuous advancement of technology, we can

expect more intelligent and flexible robot systems to bring greater convenience to human society.

References

- [1] H.L. Yang, Robot Adaptive Trajectory Generation and Control Strategy for Complex Surface Welding, Office Informatization, 2024,29(17):62-64.
- [2] Y.M. Ge, J.H. Chen, Model Predictive Contour Control for Robot Crowd Motion Planning, Research and Exploration in Laboratory, 2024,43(07):28-33+58. DOI:10.19927/j.cnki.syyt.2024.07.006.
- [3] X.Q. Han, Motion Planning Method for Mobile Robots, Anhui University of Science and Technology, 2024.
- [4] H.C. Chen, Design and Implementation of Robot Motion Planning System Based on Machine Learning, University of Electronic Science and Technology, 2024.
- [5] H.H. Tang, Application and Performance Analysis of Adaptive Control Strategy in Motor Control, Electronic Technology, 2024,53(03):292-293.
- [6] Zhou Tao, Zhao Jin, Hu Qiuxia, et al. Global Path Planning and Tracking of Mobile Robots in Complex Environments [J]. Computer Engineering, 2018, 44 (12): 7. DOI: 10.19678/j.issn.1000-3428. 0049 046.