

Automated Robot Trajectory Tracking and Path Planning Technology Research

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ABSTRACT

The widespread application of automation robots in both industrial and service sectors has generated a significant demand for efficient and precise trajectory tracking and path planning technologies. Trajectory tracking technology aims to ensure that robots move accurately along predetermined paths, while path planning is responsible for devising the optimal route for robots to navigate through complex environments with multiple constraints. The integration of these two aspects is especially crucial in dynamic settings, directly impacting the stability and operational efficiency of robots. Current research focuses on enhancing the autonomy and flexibility of robots in complex and uncertain environments through advanced algorithms such as model predictive control and sampling-based path planning. This paper will systematically explore the current state and development trends of automation robot trajectory tracking and path planning technologies, analyze the challenges encountered in practical applications, and anticipate future directions.

KEYWORDS

Automated robots; Trajectory tracking; Path planning

1. INTRODUCTION

With the rapid advancements in intelligent manufacturing and automation technology, automated robots have become an indispensable component of modern industry and services. However, in the face of complex and ever-changing operational environments, ensuring that robots can perform tasks efficiently and safely has emerged as a pressing issue. Trajectory tracking and path planning technologies have arisen in this context, becoming key to autonomous navigation and operation for robots. The essence of trajectory tracking lies in enabling robots to move precisely along a predetermined path, which necessitates a control system with high accuracy and responsiveness, as well as the capability to adapt to dynamic environmental changes. Path planning focuses on designing an optimal obstacle-avoiding movement path for robots within known or unknown environments. The close integration of these technologies provides a theoretical foundation and technical support for autonomous decision-making and actions in dynamic environments. Current research continues to innovate at the algorithmic level and explores practical applications to address the multifaceted challenges of complex task scenarios.

2. AUTOMATION ROBOT TRAJECTORY TRACKING TECHNOLOGY

2.1. Basic Concept of Trajectory Tracking

Trajectory tracking is a crucial technology in the realm of automated robotics, designed to ensure that robots move with precision along predetermined paths to accomplish specific tasks or objectives.

This process encompasses not only the adherence to a given trajectory but also the meticulous control of velocity, acceleration, and posture, ensuring that the robot maintains high precision even in dynamic environments. The central challenge of trajectory tracking lies in managing uncertainties and disturbances in the environment, such as sudden obstacles or sensor noise. This demands that control algorithms possess not only robust capabilities but also the ability to adjust in real time to ever-changing external conditions. As Industry 4.0 advances, the precision and responsiveness of trajectory tracking have become key indicators of a robot's level of intelligence, affecting not only the efficiency of task execution but also the safety and stability of the entire automation system. Thus, the evolution of trajectory tracking technology represents a series of significant leaps in the autonomous control capabilities of robots [1].

2.2. Trajectory Tracking Algorithm

Trajectory tracking algorithms play a crucial role in automation robotics, directly impacting the precision and stability of robots during task execution. These algorithms can be broadly categorized into classical control algorithms and advanced control algorithms, each with distinct theoretical foundations and application scenarios. Classical control algorithms, such as Proportional-Integral-Derivative (PID) control, are widely utilized in industrial contexts. PID control maintains stability and responsiveness by adjusting the proportional, integral, and derivative parameters, enabling the robot to follow a predetermined trajectory. The advantages of PID control lie in its simple design, ease of implementation, and robust performance, making it suitable for most common linear systems. However, PID control reveals certain limitations when confronted with nonlinear systems or complex dynamic environments. Its parameter tuning demands the expertise of experienced engineers and may struggle to converge quickly in nonlinear or time-varying systems, potentially leading to system oscillations or instability. Advanced control algorithms exhibit greater adaptability in complex environments. Model Predictive Control (MPC), a representative of advanced control algorithms, predicts the system's state changes over a future period and optimizes control inputs in real-time, enabling more precise trajectory tracking in dynamic settings. MPC excels in handling multi-constraint problems and integrating the nonlinear characteristics of the system into the predictive model, thus better addressing intricate dynamic environments. Despite its computational intensity, the growing computational power continues to uncover the potential of MPC for real-time applications. Intelligent control algorithms represent the future trajectory of tracking technology. By incorporating artificial intelligence techniques such as neural networks and fuzzy logic control, intelligent control algorithms can effectively manage complex systems even in the absence of precise models through learning and adaptive mechanisms. Particularly in unstructured environments, intelligent control algorithms can self-learn environmental features and adjust control strategies accordingly, allowing robots to perform tasks with greater flexibility and intelligence [2].

2.3. Trajectory Tracking Performance Evaluation

In the realm of automated robotics, evaluating trajectory tracking performance is a crucial criterion for measuring the accuracy and efficiency of a robot in executing trajectory tracking tasks. An effective evaluation mechanism not only aids in identifying deficiencies within the system but also provides clear direction for algorithm optimization. Trajectory tracking performance is typically assessed through a range of quantitative metrics, encompassing aspects such as error, response time, stability, and energy consumption. Trajectory error is one of the most direct indicators, usually quantified by calculating the deviation between the robot's actual trajectory and the desired trajectory. The magnitude and trend of the error can directly reflect the precision and robustness of the control algorithm. In complex dynamic environments, the ability to maintain the error within an acceptable range is crucial for evaluating the system's quality. However, relying solely on the magnitude of the error as the sole criterion may be overly simplistic, as in some scenarios, brief minor errors may be intended to prevent larger deviations or collisions, and such errors should not be deemed indicative

of poor performance. Response time is also a significant metric for assessing trajectory tracking performance. The robot's response speed to environmental changes determines its ability to timely adjust its motion state, ensuring the smooth execution of tasks. High response speed is often associated with increased energy consumption, necessitating a balance between precision and efficiency. Modern trajectory tracking algorithms can enhance response speed without sacrificing precision by predicting future states and pre-optimizing paths, thereby better managing sudden situations in complex environments. Stability assessment focuses on the system's performance over extended periods, particularly whether it can maintain trajectory tracking continuity and consistency under external disturbances. A high-performance trajectory tracking system should maintain stable performance across multiple task repetitions, without significant performance degradation due to minor environmental or system changes. Such stability is often validated through extensive experimental data accumulation. Energy consumption evaluation is increasingly becoming a crucial aspect of trajectory tracking performance assessment. In an era of heightened focus on energy efficiency, minimizing overall system energy consumption while ensuring trajectory tracking accuracy and speed is a key issue in the advancement of modern robotic technology. Optimizing energy consumption not only extends the duration of robot tasks but also reduces overall operational costs and enhances system sustainability. The multidimensional requirements of trajectory tracking performance evaluation compel researchers to consider various factors in algorithm design and system optimization, striving for a balance between precision, speed, stability, and energy efficiency. This balance will provide vital guidance for achieving more intelligent and efficient trajectory tracking systems in the future of automated robotics.

3. AUTOMATED ROBOT PATH PLANNING TECHNOLOGY

3.1. Basic Concept of Path Planning

Path planning is a crucial element of autonomous behavior in automated robots, aimed at determining the optimal route from a starting point to a destination within a given environment. This process involves not only the selection of positions in space but also requires a comprehensive consideration of multiple factors such as time, energy consumption, environmental complexity, and potential obstacles. In dynamic environments, the challenge of path planning intensifies, demanding that algorithms respond in real-time to environmental changes and swiftly adjust paths to circumvent obstacles or address unforeseen situations. Traditional path planning methods, such as the A* algorithm and Dijkstra's algorithm, rely on graph theory and search techniques to offer efficient and reliable paths in static environments. However, in complex and variable environments, these algorithms often struggle to meet real-time requirements. Consequently, recent years have seen a growing interest in probabilistic graphical models, stochastic sampling algorithms (such as RRT), and intelligent optimization techniques (such as genetic algorithms and particle swarm optimization). These emerging methods introduce randomness and adaptive learning, rendering path planning not only more flexible but also better suited to complex and uncertain scenarios. The success of path planning directly influences the efficiency and safety of a robot's task performance [3]. Therefore, the advancement of path planning technology not only reflects the increased intelligence of robotic systems but also underpins their ability to achieve efficient and reliable operations in practical applications. As technology continues to advance, path planning algorithms are evolving towards greater intelligence and adaptability, propelling automation robots towards higher levels of autonomy.

3.2. Path Planning Algorithm

Path planning algorithms are the cornerstone of automated robotics technology, determining how robots effectively navigate through complex environments to find the optimal path to their targets. The currently prevalent path planning algorithms can be broadly categorized into three types: grid-based algorithms, sampling-based algorithms, and hybrid algorithms, each with its distinct

advantages and applicable scenarios. Grid-based algorithms, such as the A* and Dijkstra algorithms, are among the most classic methods for path planning. These algorithms operate on a discretized environmental model, partitioning the workspace into regular grids, each representing a potential robot position. The A* algorithm combines heuristic estimation with actual path length, balancing optimal pathfinding with computational efficiency, and is thus widely used in more regular and static environments. In contrast, although the Dijkstra algorithm has higher computational complexity, it does not rely on heuristic functions and guarantees finding the absolute shortest path, excelling in scenarios that demand rigor and certainty. However, the limitation of grid-based algorithms lies in the significant increase in computational overhead as the dimensionality of the environment or the grid resolution rises, making them challenging to extend to high-dimensional or continuous spaces. Sampling-based algorithms, such as Rapidly-exploring Random Trees (RRT) and Probabilistic Roadmaps (PRM), build paths by randomly sampling points within the workspace. This approach does not require discretizing the space and can operate directly in continuous environments, making it particularly suitable for high-dimensional and complex scenarios. The RRT algorithm incrementally expands towards the target area through a randomly generated tree structure, offering strong adaptability in handling dynamic obstacles and unstructured environments due to its non-deterministic path generation. The PRM algorithm, on the other hand, constructs a probabilistic roadmap of free space through sampling, making it suitable for applications that involve multiple queries within the same environment. However, the paths generated by sampling-based algorithms are often irregular and may require further smoothing, and their randomness can lead to less stable and optimal results. Hybrid algorithms aim to combine the strengths of both grid-based and sampling-based approaches to overcome their respective shortcomings. The Dynamic Window Approach (DWA) and Timed Elastic Band (TEB) algorithms are typical examples of hybrid methods [4]. The DWA algorithm optimizes the target speed by dynamically sampling feasible velocity spaces within a local window, thereby planning paths in real-time. The TEB algorithm parameterizes the trajectory in time, generating smooth and dynamically feasible trajectories by optimizing constraints in both time and space. These algorithms excel in complex dynamic environments, offering improved global path optimality and local trajectory smoothness, with enhanced adaptability and computational efficiency. In practical applications, the choice of path planning algorithm often involves balancing specific task requirements and environmental characteristics. Grid-based algorithms are suitable for structured environments, sampling-based algorithms excel in handling high-dimensional and dynamic environments, and hybrid algorithms demonstrate unique advantages in scenarios requiring both global optimality and local dynamic response. In the future, with advancements in computational power and intelligent algorithms, path planning technology is expected to evolve further towards multimodal and adaptive directions, providing robust technical support for automated robots to perform tasks in increasingly complex environments.

3.3. Path Planning Performance Evaluation

The evaluation of path planning performance is an indispensable element in the design of automated robotic systems. Its essence lies in the multi-dimensional assessment of the algorithm's actual effectiveness and applicability. The selection of evaluation metrics not only reflects the fundamental requirements of path planning but also highlights the priorities pertinent to specific application scenarios. Path length is the most apparent criterion, directly influencing task completion efficiency; however, the smoothness of the path is equally crucial. Particularly in high-speed scenarios, the continuity of the path and the smoothness of turns determine the fluidity of the robot's movement and the degree of equipment wear. Energy consumption is another significant evaluation dimension. For robots operating over extended periods, energy efficiency is directly linked to the sustainability of the task. If the path planning algorithm can effectively minimize unnecessary turns and redundant movements, it will markedly reduce energy consumption. Moreover, in dynamic environments, the robustness and real-time capability of the path become pivotal. Robustness examines the stability of path planning amidst environmental changes, sensor errors, and external disturbances, ensuring that

the robot can safely reach its destination in complex settings. Real-time capability demands that the algorithm swiftly responds to external changes, continuously updating the path to ensure the robot's adaptability in dynamic surroundings. Taking these factors into account, the merit of path planning performance is not only reflected in the execution of static tasks but also in its true value demonstrated within complex dynamic environments. As application scenarios become increasingly intricate, the evaluation of path planning algorithm performance will evolve towards higher dimensions and greater comprehensiveness to meet the robot systems' ongoing pursuit of efficiency, reliability, and intelligence.

4. INTEGRATION OF TRAJECTORY TRACKING AND PATH PLANNING

4.1. Overview of Integration Methods

In the realm of automation robotics, the integration of trajectory tracking and path planning research has become crucial for enhancing the intelligence and autonomy of robotic systems. Path planning is responsible for determining the optimal route from the starting point to the destination, while trajectory tracking ensures that the robot moves precisely along the planned path. The effective integration of these two elements is directly linked to the overall performance and success rate of task execution. Traditionally, path planning and trajectory tracking have been viewed as separate modules. However, this segmented approach often leads to issues in complex and dynamic environments. The ideal path generated by path planning may be challenging to follow precisely during execution due to changes in the external environment, leading to suboptimal system performance. Therefore, research into integration methods aims to bridge this separation, creating a dynamically coordinated system that closely integrates path planning and trajectory tracking. The essence of integration methods lies in the incorporation of real-time feedback mechanisms and adaptive adjustment capabilities. In such systems, path planning algorithms must not only consider initial conditions but also continually adjust the path based on real-time feedback from trajectory tracking, accommodating environmental changes and fluctuations in the robot's own state. Through this real-time closed-loop control, the integrated system can enhance both the optimality of the path and the accuracy and robustness of trajectory tracking. With advancements in artificial intelligence and machine learning, integration methods are progressively moving towards intelligent, self-learning directions. Utilizing techniques such as reinforcement learning, the system can autonomously optimize the coordination between path planning and trajectory tracking through continuous experimentation and learning, gradually achieving precise adaptation and efficient response to complex environments. This integrated research not only enhances the autonomy of automation robots but also provides robust technical support for overcoming various challenges in practical applications [5].

4.2. Realization Strategy

In the realm of automation robotics, the effective integration of trajectory tracking and path planning presents a technologically intricate and challenging endeavor. The crux of this task lies in harmonizing the global perspective of path planning with the local precision of trajectory tracking within a dynamic environment, ensuring that the robot maintains both the continuity and stability of its movement while achieving its designated objectives. A prevalent strategy for achieving this is the implementation of a hierarchical control architecture, which separates path planning and trajectory tracking into distinct layers, each addressing global path optimization and local trajectory adjustment, respectively. Path planning is responsible for identifying the optimal path on a global scale, while trajectory tracking fine-tunes the path based on real-time environmental feedback. This layered approach allows the system to adeptly respond to real-time changes while preserving the globally optimal path, thus avoiding deviations or execution failures caused by environmental shifts. Another strategy involves the adoption of Model Predictive Control (MPC) technology. MPC predicts the robot's future state of motion and dynamically adjusts the trajectory based on real-time environmental

data and path planning results. This method not only identifies potential path deviations in advance but also proactively adjusts before deviations occur, thereby enhancing the overall robustness and accuracy of the system. The strength of MPC lies in its formidable predictive and optimization capabilities, particularly in complex and variable environments where it exhibits superior performance. Additionally, strategies integrating deep learning and reinforcement learning technologies are garnering increasing attention. By leveraging deep learning models to process extensive sensory data, robots can gain a more accurate understanding of environmental information and optimize the synergy between path planning and trajectory tracking. Meanwhile, reinforcement learning, through continuous experimentation and interaction with the environment, progressively enhances the system's adaptability in complex scenarios. This intelligent approach not only fosters greater autonomy in intricate environments but also continually improves performance through ongoing learning, laying a foundation for broader future applications.

4.3. Experiments and Applications

The integration of trajectory tracking and path planning has demonstrated its practical value and challenges during experimental and application stages. In experimental design, constructing a diverse range of test scenarios is crucial. These scenarios should encompass both static and dynamic complex environments to thoroughly evaluate the system's performance under various conditions. By simulating a variety of real-world situations, such as sudden obstacles, terrain changes, and sensor data uncertainties, the robustness and adaptability of the integrated system can be effectively tested. High-precision sensors and control systems are required to ensure that the collected data accurately reflects the robot's movement and environmental feedback, thereby facilitating precise performance assessment. In practical applications, the integration technology of trajectory tracking and path planning is widely utilized in fields such as autonomous driving, industrial automation, and service robotics. In autonomous driving, vehicles must achieve precise path planning and trajectory tracking within complex urban road environments to ensure driving safety and passenger comfort. Such applications demand not only real-time responses to external environmental changes but also efficient decision-making capabilities to swiftly adapt in emergency situations. In industrial automation, the application of integration technology has significantly enhanced the flexibility and efficiency of robots on dynamic production lines. Through precise trajectory tracking and path planning, robots can accurately perform tasks such as assembly and handling in complex production environments, markedly reducing production costs and improving product quality. Moreover, the application of integration technology in service robots within domestic and healthcare settings also highlights its immense potential. For instance, in elderly care, service robots can navigate complex indoor environments with ease through precise path planning and trajectory tracking, providing personalized services. The experimental and application stages are critical for translating the research outcomes of trajectory tracking and path planning integration into practical productivity. Through continuous optimization and testing, this technology will foster broader innovation and development opportunities in the automation sector and play a significant role in the construction of future intelligent societies.

5. CONCLUSION

The advancement of automated robot trajectory tracking and path planning technologies has profoundly impacted both modern industry and service sectors. The continual progress in these fields, both in theoretical research and practical application, has significantly enhanced the autonomy and flexibility of robots. However, as application scenarios become increasingly complex, the limitations of traditional algorithms and methods have become apparent, necessitating more intelligent and adaptive solutions. Future research will focus on the deep integration of artificial intelligence and machine learning technologies, aiming to enhance robots' autonomous decision-making capabilities

in dynamic and uncertain environments. To meet these challenges, it is essential to bridge the gap between theory and practice, thereby driving the comprehensive upgrading and widespread adoption of automated robots.

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