Research on Real-Time Path Planning and Control Technology for Autonomous Mobile Robots

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Abstract. The problem of path planning and control of autonomous mobile robots (AMRs) in dynamic environments is an important factor limiting their performance. Among them, the lack of environmental information has a direct impact on path planning. The control algorithms are mostly limited to the real-time adjustment of the robot body and lack of co-optimization with the path planning results, resulting in poor control flexibility of the robot in complex dynamic environments. In this paper, the focus is mainly on how the environment model and control algorithm can improve the performance of path planning in complex and changing dynamic environments. This paper concludes that accurate environment information and the combination of path planning information to adjust the control algorithm will be the key to improving the performance of AMRs in the real world. Accurate environment modeling provides more accurate planning directions for path planning, while the control algorithm combined with path planning improves the dynamics of AMRs, both of which provide research ideas for future research in the field of path planning for AMRs.

Keywords: Dynamic Environment; Path Planning; Real-Time Control

1 Introduction

Autonomous mobile robots (AMRs) play a very important role in modern life and have become a key technology in industrial automation, logistics, services and many other fields [1]. Path planning and control are the core of mobile robots to accomplish practical tasks. As AMRs penetrate real production life, complex scenarios put forward higher requirements for real-time path planning and control technology of AMRs. Traditional path planning algorithms have good planning effects for static environments where environmental information is known. However, traditional path planning methods are often difficult to meet real-time requirements, especially in complex and dynamically changing environments. Therefore, researchers are committed to developing new algorithms to improve the efficiency and adaptability of path planning.

Real-time path planning is the core of the safe and efficient operation of AMRs [2]. It not only needs to consider the dynamic characteristics of the robot and the uncertainty uncertainty of the environment but also respond in real time to dynamic changes in

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the environment, such as the sudden appearance of obstacles or changes in the structure of the environment. Control technology, as the execution guarantee of path planning, faces the same challenge [3]. Based on the path planning results, AMRs need to precisely control their motion to avoid collisions and maintain stable operation. This requires control algorithms that are not only highly responsive but also robust and able to maintain performance in the face of sensor noise and model uncertainty.

Path planning techniques predict and optimize the robot's movement path through intelligent algorithms, enabling it to avoid obstacles and quickly reach its destination in different application scenarios such as warehouses and factories. For the 2D map path planning problem with constraints, Muhammad proposed a generalized laser simulator that enables a wheeled mobile robot to find a path under constraints in both known and unknown environments, which is 7.8 times faster than the A* algorithm and 1.2 times shorter than the A* algorithm [4]. Path planning helps the mobile robot to adapt to changes in the environment and dynamically adjust its path, while real-time control techniques ensure that the robot can quickly respond to external changes while performing its tasks. Taghavifar proposed an adaptive indirect controller for tracking control of wheeled mobile robots in the presence of external disturbances and wheel slip, which uses an improved integrated sliding-mode control and neural network [5]. With accurate sensor feedback, the control algorithm tracks and controls the path points planned by the path in real time. The combination of the two not only improves the efficiency of the mobile robot but also enhances its adaptability in uncertain environments, providing a solid technical foundation for the application of robotics in industrial, service and exploration fields.

The purpose of this paper is to discuss the recent advances in real-time path planning and control techniques for AMRs and to look into the future development direction. In this paper, the basic concepts and key techniques of real-time path planning are first overviewed, including classical graph search algorithms, sampling-based methods, and learning methods that have emerged in recent years. Then, this paper will explore the recent advances in control techniques, especially the application of model predictive control (MPC) and adaptive control strategies in AMRs. Finally, this paper will discuss the challenges and future research directions of real-time path planning and control techniques, including multi-robot collaboration, path planning in large-scale scenarios, and robustness issues in complex environments.

2 Application of path planning and control techniques to mobile robots

2.1 Path planning techniques

Path planning for mobile robots computes a set of path points for a mobile robot to travel an unobstructed path from a starting point to a goal point in a complex environment. Depending on whether the environment is dynamic or not, path planning algorithms can be categorized into online and offline path planning. Traditional path-planning methods are graph-based algorithms such as A* and

Dijkstra's algorithm. The A* algorithm is usually used for static global planning to find the optimal path in a known model of the environment and to ensure that the mobile robot reaches its destination [6]. Zengyu proposed an augmented A* algorithm for AMRs [7]. The Dijkstra's algorithm computes a set of path points in a known path from the start point to the shortest path between each point and finds the next closest vertex by maintaining the new vertex in the priority minimum queue [8]. However, the environmental information in real applications changes in real-time, i.e., obstacle information, ground information, etc., in dynamic environments, so the traditional path planning has limited effectiveness in dynamic environments, and it is easy to fall into local optimization, and path planning in dynamic environments can solve this problem.

Path planning in dynamic environments has artificial potential field methods, rapidly exploring random trees (RRT), and probabilistic roadmap algorithms [9]. The RRT algorithm rapidly explores the configuration space by random sampling and generates a tree structure to find the goal point. The advantages include the ability to effectively handle complex environments and high-dimensional spaces, and faster computing speed [10]. However, the disadvantages of the RRT algorithm are that it is not guaranteed to find an optimal solution and the generated paths may not be the shortest paths. Multi-objective path planning (MOPP) models the environment by constructing a map, considers multiple efficiency metrics, and traverses multiple manually-designed goals as the mobile robot moves to compute the path point that minimizes the cost from the start to the endpoint. Zhang proposed a hybrid algorithm to solve the MOPP problem for mobile robots in static nuclear accident environments [11]. Ajeil computes the shortest path while considering the shortest distance and path smoothness [12]. However, MOPP has some drawbacks, including the high complexity of the algorithm and the large computational cost, especially when the number of nodes is large and the search space is wide, and the requirements of security and real-time make the problem more complicated.

2.2 Real-time control techniques

Path planning determines the path of travel for a mobile robot, and real-time control techniques ensure that the robot can execute that path accurately. The control technique centers on adjusting the robot's state quantities (position and attitude) by changing control quantities such as velocity and steering angle. Motion control tasks for mobile robots mainly include path following, trajectory following and point calibration. Path following requires the robot to move along a predetermined path, trajectory following requires movement along a trajectory over time, and point calming is when the robot reaches a specified position and stops. Control techniques need to consider speed, accuracy and stability. Classical control methods include proportional-integral-derivative control (PID) and model predictive control.PID control is capable of controlling each joint of an industrial robot by three parameters and is widely used in application scenarios with low requirements [13]. Xinxin proposed an MPC control algorithm with dynamic constraints to realize high-speed trajectory following control. By modeling an AMR, combining current motion information as well as future desired goals, adjust the control output of MPC to realize trajectory tracking while satisfying dynamic constraints. This study compares the tracking effect of the MPC controller and PID controller, and due to the need to model the AMR, MPC is more accurate than PID control and robust to the system state that can be constrained based on obstacle information [14]. Intelligent control methods, such as deep reinforcement learning algorithms, are based on the theoretical framework of reinforcement learning (RL), in which an intelligent body learns the optimal policy by interacting with the environment, and a neural network is used to approximate the value function or the policy function in RL to handle high-dimensional input data. Guobin proposed a framework for dynamically generating the reward function (DIAYN), augmenting the weights of the policy network, which is different from the traditional reinforcement learning deep deterministic policy gradient with faster convergence and more stable arrival at the target point compared to traditional reinforcement learning [15]. Sampo utilizes deep reinforcement learning for real-time control and analysis in dynamic environments [16], which is widely used in mobile robot control due to its independence from mathematical models and good robustness. Real-time control of mobile robots not only executes motion commands but also responds to the results of path planning in real-time to reduce shocks.

3 Robot manipulation and path adjustment in dynamic environments to reduce shocks

Manipulation and path adjustment of mobile robots in dynamic environments is a complex process that requires robots to be able to respond to environmental changes and optimize their path of action in real-time. Such path-planning methods are capable of adapting to environmental changes and quickly re-planning paths. For example, cooperative path planning allows multiple robots to accomplish goals without interfering with each other in a cooperative environment. In addition, some algorithms, such as D*, provide faster path planning than A* in dynamic environments and usually find better solutions. However, path planning in dynamic environments also has drawbacks. For example, although the DWA algorithm is computationally fast and capable of real-time path planning, it only considers local environment information and is prone to the local minimum problem, resulting in a robot that may not be able to reach the target state. In addition, although the RRT-Connect algorithm is guaranteed to find feasible paths and is suitable for multi-robot path planning problems, the path quality may be poor and the convergence speed may be slow. These issues point out the key features of real-time, global versus local optimality, and scalability that need to be weighed when performing path planning in dynamic environments. Therefore, robot manipulation and path adjustment in dynamic environments is a complex task that requires comprehensive consideration of multiple factors, and the selection and design of its algorithms are crucial to the performance of the robot. In this paper, the operation and adjustment of AMRs in dynamic environments will be studied from three aspects: multi-sensor fusion, SLAM, and replanning.

Single sensors such as encoders and cameras provide motion information and image information respectively, which alone are utilized to lack the process of image information processing during motion. Multi-sensor fusion technology plays a vital role in obstacle recognition and avoidance. By combining the advantages of different sensors such as LiDAR, vision sensors and ultrasonic sensors, mobile robots are able to realize a more comprehensive environment perception.

LIDAR, with its high accuracy and powerful 3D modeling capability, can detect obstacles at a distance and build an environment model, which is applied to identify the distance between the vehicle and the surrounding environment obstacles, providing distance information for the assisted driving function. Vision sensors utilize cameras to capture images and identify targets through image processing techniques, and are particularly good at identifying traffic signs, pedestrians, and vehicles. Ultrasonic sensors, on the other hand, play a role in proximity obstacle detection with their low cost and simple implementation and are commonly used for parking assistance. Xiang introduces collaborative strategies in automated driving through sensor fusion to improve the safety of automated driving [17]. Thus, data from multiple sensors are fused under a unified coordinate system to provide multidimensional environment information, and constructing complete and accurate environment information helps to allow mobile robots to plan a more desirable path. For example, data fusion of millimeter-wave radar and cameras enables all-weather, all-terrain obstacle detection. Through multi-data fusion, mobile robots can more accurately determine their own position, recognize surrounding obstacles and environmental conditions, and achieve safer and more reliable path planning.

SLAM technology realizes real-time localization and map construction for mobile robots in unknown environments by fusing sensor data such as LIDAR and cameras. In dynamic environments, SLAM systems are able to separate static and dynamic features and reduce the influence of noise, thus enhancing the accuracy of maps. Meanwhile, SLAM supports real-time applications and provides fast environment sensing and response, enabling the robot to avoid obstacles in time to ensure safety. In addition, SLAM technology assists robots inefficient path planning through accurate environment modeling, especially when the environment changes dynamically, enabling dynamic adjustment of paths. For example, SLAMWARE integrates SLAM and path planning functions based on LiDAR, and users can utilize autonomously constructed map data for flexible path planning. Li realizes path planning for indoor disinfection robots through sensor fusion and SLAM map building [18]. However, SLAM methods based on artificial markers, require a large number of markers to be placed in the environment, which limits the flexibility and applicability of their applications. Therefore, Muñoz-Salinas proposed the use of keypoints and markers for localization to improve the accuracy and real-time performance of SLAM [19].SLAM can be regarded as a pre-processing for mobile robot path planning, which enables mobile robots to be more environment-aware by building a more accurate model and combining multi-sensor fusion.

Path adjustment when the task changes usually involves dynamic path planning and replanning strategies. First, the mobile robot needs to monitor environmental changes and task updates in real time, which can be realized by a multi-sensor fusion system, such as the integration of sensor data from LIDAR, camera and IMU. Once task changes or environmental obstacles are detected, the system will trigger the path replanning mechanism. The global path planner will calculate a new optimal path based on the new mission requirements and environment information. Meanwhile, the local path planner will perform fine-tuning to avoid immediate obstacles and ensure the smoothness and safety of the path. In addition, the path planning process takes into account the size and kinematic constraints of the robot, as well as the different characteristics of the sensors and the application scenarios. With this combination of global and local planning, the system can effectively respond to task changes and dynamically adjust the path to ensure successful task completion. Bruce proposed the enhanced rapidly exploring random tree algorithm, which penalizes the search by caching waypoints at an adaptive cost. The mobile robot is constrained in the process of moving, and the algorithm interleaves path planning and motion commands to improve the quality of generated paths [20]. Therefore, the replanning strategy is able to cope with the environmental changes during the movement of the mobile robot and enhance the perception of the mobile robot, while the method needs to consider the issue of when to plan and the effect on the controller after planning.

4 Conclusion

This paper draws the following conclusions by studying the technical realization of mobile robot path planning and control and the effect of combining it with other advanced intelligent technologies. Path planning requires an in-depth exploration of the current environment information before planning. Real-time control needs to consider its motion while also focusing on combining with path planning. The exploration of the environment mainly includes multi-sensor fusion and SLAM to establish an accurate environment model, which provides the possibility to improve the performance of path planning. When the environment changes, replanning is an immediate adjustment strategy that enhances the connection between path planning and real-time control, making path planning capable of real-time adjustment. The conclusions of this study can be used as a summary of the current path planning and real-time control of mobile robots as well as the direction of development, providing ideas for researching more forward-looking algorithms for path planning and control. This study is helpful for the development of mobile robots in the direction of embodied intelligence. The construction of an algorithm that combines the advantages of path planning and control is the development direction of mobile robots with high dynamics and intelligence.

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