Research on Intelligent Navigation and Path Planning of Mobile Robot Based on RRT

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Abstract. This study investigates the Rapidly-exploring Random Tree (RRT) algorithm's efficacy in mobile robot navigation, focusing on intelligent path planning amidst dynamic, high-dimensional environments. While RRT's foundational principles facilitate quick exploration of state spaces, its adaptability to evolving conditions and compatibility with advanced sensing technologies remain underexplored. This research delves into the RRT's core functionalities and extends its analysis to various enhanced iterations like RRT* and I-RRT*, showcasing their increased efficiency in real-world applications such as autonomous vehicle navigation and robotic manipulator path planning. The paper critically assesses the RRT's algorithmic structure, emphasizing its strategic growth in uncharted territories and its application in navigating through environments laden with static and dynamic obstacles. Through a series of case studies, the paper illustrates the algorithm's real-time responsiveness and its ability to synthesize with genetic algorithms and neural networks for optimal path determination. Prospects of the RRT algorithm are explored, suggesting its integration with AI and machine learning to augment path planning intelligence. The study posits that such integration will lead to more robust and adaptive navigational strategies, catering to the intricate demands of modern automated systems. Concluding, this research elucidates the RRT algorithm's current state, potential enhancements, and future trajectory, offering a pivotal reference for the development of more sophisticated autonomous navigation systems.

Keywords: RRT, Path planning, Autonomous Mobile Robots, Intelligent Navigation.

1. Introduction

Over the past decades, mobile robots have been widely used in various fields, including military, industrial, and security, to undertake important unmanned tasks. In these applications, the autonomous navigation capability of mobile robots is crucial, which accelerates the speed of robot operation while effectively avoiding blind spots and achieving more efficient task completion [1].

Rapid advances in artificial intelligence and machine learning have shifted research towards enhancing the autonomy and adaptability of autonomous mobile robots (AMRs). From the earliest industrial programming robots to today's intelligent robots, the development of mobile robots has been advancing towards autonomy, flexibility, and collaborative capabilities [2]. Although mobile robots have made significant progress in autonomous navigation, how to plan paths efficiently and safely in complex and dynamic environments remains a major challenge.

In the field of path planning, the Rapidly exploring Random Tree (RRT) algorithm stands out for its proficiency in navigating high-dimensional spaces and complex constraints [3]. Its method of incrementally constructing a branching network from the robot's starting position to explore uncharted territories offers a pragmatic approach to path finding. The versatility of the RRT algorithm has made it indispensable for mobile robot navigation, particularly in settings where adaptability and real-time decision-making are paramount.

Recent studies extensively document the RRT algorithm's efficacy in solving complex path planning problems, noting its proficiency in high-dimensional spaces. However, there remains a scarcity of discourse on the adaptability of RRT within rapidly evolving environments and its integration with emerging sensory technologies.

This review aims to fill the gaps in the literature by providing a holistic analysis of the RRT algorithm's applications, coupled with a critical examination of its limitations. Furthermore, it seeks to offer unique insights into the potential evolutionary trajectory of RRT, forecasting its adaptability to future technological landscapes and varied application scenarios. This review is organized as follows: Section 2 delves into the fundamental principles of the RRT algorithm, elucidating its operational mechanisms. Section 3 examines the applications of RRT and its variants (such as enhanced RRT, I-RRT* etc.) in mobile robot navigation, highlighting case studies that demonstrate its practical efficacy. Section 4 will look at the current stage of development of RRT as well as future directions and potential challenges, and how it can be further optimized and applied. Of course, there will also be a brief introduction to some variants. Through this structured exposition, readers are invited to navigate the intricacies of RRT, gaining both a comprehensive understanding of its current applications and an informed perspective on its potential evolution.

2. Fundamentals of the RRT Algorithm

The RRT algorithm was first proposed by LAVALLE at the University of Illinois in 1998 [3], which achieves an efficient search of the state space by constructing a data structure is defined as "Rapid Exploration Random Tree." The tree is constructed from an initial state, and each iteration randomly selects a point in the state space and tries to extend the tree to that point, therefore quickly covering the entire state space [4].

In each iteration, RRT algorithm selects a point randomly in the state space (called the sampling point), then finds the nearest node to the sampling point on the current tree and tries to grow a new point in the direction of the sampling point based on this nearest node with set distance. If the new generated node is located in free space and has not collided with obstacles, then this node is added to the tree.

RRT's randomness helps to avoid overfocusing near local optimal solutions and promotes broader exploration. Sampling point also ensure that the tree was able to grow up towards the unexplored area. Although RRT exploration is based on random sampling, the goal bias of the algorithm can be increased by occasionally sampling the goal state directly, thus improving the efficiency of finding valid paths.

The main advantage of RRT is its ability to navigate the complex environment efficiently by iteratively extending to unexplored area. Its time computation complexity is usually polynomial in the spatial dimension but can be affected by the density and configuration of obstacles. This property emphasizes the practical value of the algorithm in applications that require real-time or near real-time path planning capabilities. The success rate of the algorithm is highly dependent on the structure of the environment and the algorithm parameters set by user. While RRT can find the path quickly in the environments with fewer obstacle, its performance may decrease in more difficult scenario, and its target sampling strategy needs to be adapted or variants such as RRT* need to be employed to improve the optimality and efficiency of paths. The principle of RRT algorithm can be simplified as follows:

·Let q_{rand} be a random sampling point.

·Let $q_{nearest}$ be the nearest point in the tree to q_{rand}

·Let q_{new} be the new point along the direction from $q_{nearest}$ to q_{rand}

Then the new node is calculated as:

$$q_{new} = q_{rand} + \Delta q \cdot \frac{q_{rand} - q_{nearest}}{\|q_{rand} - q_{nearest}\|} \tag{1}$$

(In this equation, Δq is the preset step size.)

Continuing our exploration from theory to practice, we will then demonstrate the application of the RRT algorithm in different domains through a series of well-selected case studies to further substantiate its effectiveness and applicability in real-world environments.

3. RRT Application Case Studies

3.1. Intelligent Path Planning for Autonomous Vehicles

Although the traditional RRT algorithm has been successfully applied in several fields, it suffers from some fundamental deficiencies in practical applications in complex environments. A notable problem is that the paths planned by the algorithm fail to fully consider the kinematic constraints of intelligent vehicles, resulting in these path planning results not being directly applicable to the path planning process of intelligent vehicles [5].

Focus on the autonomous vehicles, Ren and his team in 2021 select optimal paths based on an enhanced RRT algorithm that prioritizes safety [6]. Their approach improves the accuracy of path planning by combining genetic algorithms and neural computation models, and its efficiency is verified to be superior to traditional RRT methods by a test dataset. In their research, the problem that the algorithm is easy to fall into local minimum value is solved by introducing a chaotic search strategy and a local node generation strategy. In addition, they used chaotic mapping distribution instead of uniform random distribution to generate sample points, which enhances the goal bias of the algorithm and improves the efficiency of path planning. This development is important for path planning in complex environments, especially in autonomous driving scenarios where multiple obstacles need to be bypassed. They designed a weighted path safety cost function, which combines the consideration of static and dynamic obstacles. The safety cost function for static obstacles uses discrete Gaussian convolution combined with a collision risk approach to evaluate the safety of each candidate path; the safety cost function for moving obstacles is based on the estimation of the motion state of the moving obstacles combined with Gaussian convolution.

The simulation results mentioned in the literature show that the paths planned to use the Dynamic Artificial Potential Field method are adjusted accordingly to safely avoid all obstacles in the case of continuous movement of obstacles, which validates the effectiveness of the enhance RRT algorithm. For reference here are the results from a simple model simulation shown in the Figure 1 and Figure 2, which implemented in python for the case studied by Ren et al.

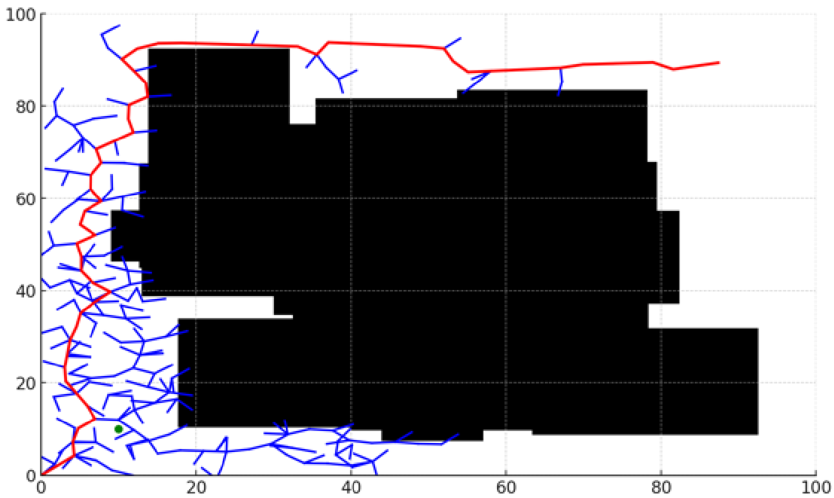

Fig. 1 Simple model simulation result 1 [6]

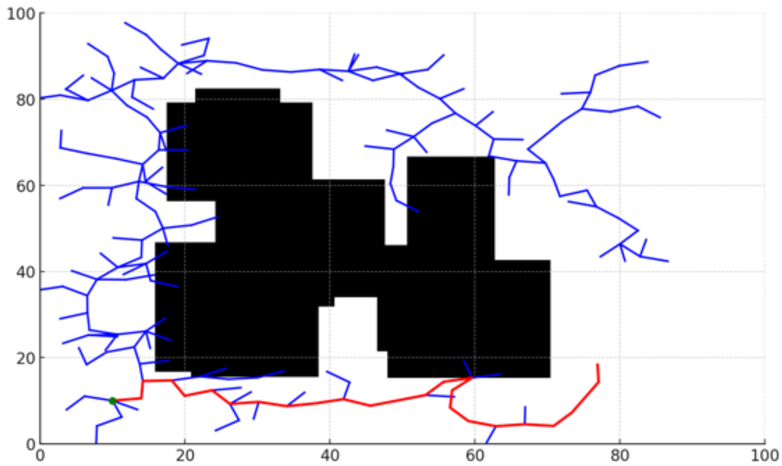

Fig. 2 Simple model simulation result 2 [6]

This study presents a system for robot path planning and multi-objective, multi-directional RRT*, showcasing its application in navigating complex environments raised by Jiunn-Kai Huang and his team [7]. This system based on an anytime, informable RRT algorithm to path planning and ensuring that effective navigation strategies can be developed even in the presence of incomplete data. Furthermore, by generating a connectivity graph, the system provides a structured framework for path planning, which in turn optimizes destination access sequences and path selection. The algorithm not only optimizes the node expansion and path selection process, but also effectively balances the requirements of shortest path, lowest cost, and highest security through multi-objective optimization techniques.

They designed experiments to comprehensively simulate complex traffic environments, including multiple dynamic and static obstacles, as well as different route planning requirements. With this setup, the research team was able to accurately evaluate the performance of the improved RRT algorithm in multi-objective and multi-direction planning tasks. The experimental results show that the improved RRT* algorithm exhibits significant advantages in terms of efficiency and accuracy of route planning compared to the traditional RRT algorithm. Specifically, this algorithm can find safe and efficient paths faster, considering vehicle dynamics and environmental uncertainties. This not only confirms the effectiveness of the algorithm, but also demonstrates its ability to solve complex path planning problems in real-world applications. Therefore, this study provides valuable insights into path planning for mobile robot and lays a solid foundation for future research and applications.

3.2. Path Planning of Manipulator Based on RRT* Improved Algorithm

This study next illustrates the application scenarios of the RRT algorithm and its variants from a different perspective through another research case. Li and his team proposed an improved RRT algorithm, (I-RRT*), for the problem of path planning of robotic arms in their study in 2022 [8]. It must be mentioned that the RRT* algorithm first proposed by Karaman and Frazzoli in 2010 [9], achieved the initial optimization of the algorithm, however, there are some shortcomings in it, such as: low efficiency of path planning; low utilization of path planning, and the tree must be re-generated for each planning; and the generated paths are not smooth. The I-RRT* algorithm speeds up the path convergence rate by introducing the multi-point region attraction strategy; by introducing the multi-point region attraction strategy, it speeds up the path convergence rate; by introducing the multi-point region attraction strategy, the path convergence rate is accelerated. The I-RRT* algorithm is able to reuse the previously searched paths by introducing the multi-point region attraction strategy, which accelerates the convergence speed of the paths. This approach not only improves the utilization of paths, but also reduces the number of times the tree needs to be regenerated for each planning; the I-RRT* algorithm generates smoother paths through the improved node expansion strategy and path smoothing; this is particularly important for the operation of the robotic arm as smooth paths can reduce vibration and mechanical wear and tear during the movement of the robotic arm.

This research uses a UR5 robotic arm as the object of study to analyze in detail the kinematic model of the robotic arm and its application in path planning, and to design experiments for simulation. We can understand how the algorithm adapts to complex mechanical structures by understanding the experimental process. To investigate the performance of the I-RRT algorithm in robotic arm path planning, the experiments examine the effect of different numbers of sampling points on the efficiency and cost of path planning. The experiments first determine the optimal number of sampling points in multi-point area attraction. The start and target points are set, and the number of sampling points is tested from 1 to 6, and the experiment is repeated five times for each number. The experimental results show that the time cost and path cost are minimized when the number of sampling points is 5, so the optimal number of sampling points in this environment is determined to be 5. Using a cost comparison table, the experiment shows that the I-RRT* algorithm outperforms the RRT algorithm in terms of both time and path cost, demonstrating the improvements in efficiency and cost optimization of the I-RRT* algorithm. The experiments utilize a path storage query strategy which reduces time cost and speeds up the search by recording and querying existing path fragments to quickly generate paths. This approach validates the benefits of the I-RRT* algorithm for fast response and efficient path planning. Using the start and end points to generate and perform path smoothing, experiments demonstrate the changes before and after the path smoothing process, further confirming the efficacy of the I-RRT* algorithm in improving path smoothing. The application of the I-RRT* algorithm to robotic arm path planning highlights its advantages in optimizing path cost, improving planning efficiency and path smoothing.

4. Advancements and Prospective Challenges in RRT Algorithms

4.1. The Current State of RRT Development

The RRT algorithm has made significant progress in the field of mobile robot path planning since it was proposed by LaValle in 1998. Over time, researchers have made various improvements to the RRT algorithm to increase its efficiency and applicability. such as KF-RRT [10], which effectively improves the dynamic path planning efficiency of UAVs, reduces the planning time and path length, and is particularly suitable for dealing with path planning problems in dynamic obstacle environments. Also, Bi-RRT*-Smart, the algorithm is able to plan paths to avoid obstacles while satisfying the constraints and quickly converge to a relatively optimal solution [11]. The improved Informed-RRT* algorithm proposed in the literature effectively improves the speed of finding the initial solution by introducing the Metropolis acceptance criterion and is faster in converging to the same initial path length [12]. Of course, there are many other optimized RRT algorithms that are being used in a wide range of industries.

4.2. Future Directions and Potential Challenges

In the future, RRT algorithms are expected to be integrated with more cutting-edge technologies, such as artificial intelligence, machine learning, and deep learning, to improve the intelligence and adaptivity of path planning. Through this multidisciplinary integration, RRT algorithms can handle unknown environments and dynamic changes more effectively and achieve more intelligent decision support. Improving the environment awareness of RRT algorithms will be an important direction for future development. By integrating more advanced sensor data and environment models, the algorithms can understand the surrounding environment more accurately and thus make more effective path planning in complex scenes.

As RRT continues to evolve, there are potential challenges such as how to make RRT algorithms better adapted to highly dynamic and uncertain environments. The algorithms need to be able to respond quickly to changes in the environment while maintaining the accuracy and efficiency of path planning. RRT algorithms need to have good scale scalability and generalization capabilities. This means that the algorithm should be able to adapt to different scales and types of path planning tasks while maintaining efficient and stable performance.

5. Conclusion

This paper confirms the efficiency and reliability of the RRT algorithms and their improved versions in solving path planning problems in complex environments by analyzing in detail the application of these algorithms to mobile robots and robotic arms path planning. Not only does it enhance our understanding of the application of RRT algorithms in dynamic and uncertain environments, it also provides valuable insights into the design and optimization of automated systems. Future research could explore how RRT algorithms can be effectively combined with current cutting-edge technologies to further improve the intelligence and adaptability of path planning. While offering insights and recommendations to other researchers in the field. For example, the evolution of RRT algorithms requires not only technological breakthroughs, but also consideration of specific needs and constraints in practical applications. And consider the dynamics and complexity of the environment, as well as the real-time and scalability etc. of the algorithms when developing new path planning algorithms. This work stand at the forefront of technological development and face tremendous opportunities to apply these advanced algorithms for the betterment of human life and social development. As the RRT algorithms and its variants continue to evolve, we expect to develop smarter and more autonomous robotic systems that will revolutionize several fields such as autonomous driving, disaster relief, and urban planning. Ultimately, these technologies will shape our future, creating a smarter and more connected world.

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