Path planning for storage robots using the RRT algorithm

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Abstract. This paper delves into the issue of storage robot path planning, a critical challenge in the field of warehouse automation. To address this challenge, this paper introduces the Rapidly-exploring Random Tree (RRT) algorithm and presents an innovative path planning approach aimed at efficiently handling dynamic environments and multiple constraints.Firstly, this paper extensively explores the complexity of the storage robot path planning problem, emphasizing its crucial nature in practical applications. Next, it provides an in-depth explanation of the principles of the RRT algorithm, particularly highlighting its unique advantages in path planning, especially in high-dimensional spaces and nonlinear constraints. In the implementation section, a detailed description is provided on how to apply the RRT algorithm to storage robot path planning, including the workflow of the algorithm and its key steps.In the discussion section, this paper thoroughly analyzes the potential application value of the RRT algorithm in storage robot path planning and discusses future improvement directions and research areas. Finally, by summarizing the outcomes of this study, the paper emphasizes the pivotal role of the RRT algorithm in storage robot path planning and the positive impact it brings to solving this significant problem.

Keywords: RRT algorithm, storage automation, path planning

1. Introduction

The rapid growth of e-commerce has completely transformed the landscape of the modern warehousing industry, driving a rapid increase in logistics demands. Traditional warehousing management methods are no longer sufficient to meet this challenge, making warehousing automation and intelligence an irreversible trend [1]. In this era of change, storage robots play a vital role, with their path planning serving as a critical component in achieving automation and intelligence.

The path planning problem for storage robots is highly complex, requiring the integration of the robot's mobility and task execution requirements [2]. Traditional path planning methods, such as artificial potential fields, fuzzy rules, and genetic algorithms, often require precise modeling of obstacles in the environment and exhibit limitations in dealing with the path planning problem for multi-degree-of-freedom robots in complex environments. Moreover, the computational complexity of these methods increases exponentially with the robot's degrees of freedom [3].

To address this challenge, this paper introduces a path planning approach for storage robots based on the Rapidly-exploring Random Tree (RRT) algorithm. Traditional path planning methods face issues related to modeling complexity and computational resource requirements, rendering them less effective for multi-degree-of-freedom robot planning in complex environments. The RRT algorithm, as the

backdrop for this solution, relies on random sampling and collision detection, effectively bypassing the need for precise environmental modeling, thereby resolving path planning problems in high-dimensional spaces and complex constraints.

The primary focus of this paper is to employ the RRT algorithm to plan a safe path from the starting point to the destination based on warehouse environment information, ensuring that robots can efficiently and safely perform tasks within the warehouse [4]. The RRT algorithm exhibits global path planning capabilities, potential for adaptation to diverse environments, and effective handling of robot constraints [5]. This approach holds promise for significant advancements in the field of storage robot path planning, promoting further developments in warehousing automation and intelligence.

2. Storage robot path planning problem description

As the e-commerce industry experiences rapid growth, the modern warehousing sector is undergoing a revolutionary transformation driven not only by the swift increase in logistics demands but also by emerging trends propelled by consumers, supply chains, and technology. Traditional warehousing management methods have become inadequate to meet this challenge, making warehousing automation and intelligence an irreversible trend. Within this trend, the role of storage robots has become paramount, with their path planning serving as a crucial component for achieving automation and intelligence.

The core task of storage robot path planning is to find the shortest or optimal path, given a known warehouse environment, starting point, and destination, to ensure efficient task execution while maintaining safety and avoiding collision with obstacles. This field encompasses several vital aspects:

1) Path Search and Safe Obstacle Avoidance: In complex warehousing environments, robots must find a safe path from the starting point to the destination, ensuring obstacle avoidance while possibly optimizing path length, time, or energy consumption.

2) Real-time Collision Avoidance: Storage robots need to perceive their surroundings in real-time while in motion to avoid collision with obstacles. This requires robots to adjust their paths flexibly to ensure safe passage.

3) Path Optimization and Smoothing: Path searching is not just about finding a feasible path but also involves optimizing constructed paths to meet the robot's kinematic and dynamic constraints, making them smoother [6].

4) Autonomous Decision-making and Real-time Responsiveness: Robots need the ability to make autonomous decisions, especially when facing unknown environments or emergency situations. They must autonomously plan paths and adjust their motion strategies based on environmental information while rapidly responding to urgent tasks or unexpected events.

5) Energy Management: Path planning needs to consider the robot's energy consumption to reduce costs and extend the robot's battery life [7].

The complexity and challenges associated with these aspects make storage robot path planning a key driver of warehousing automation and also represent the direction for the future intelligent development of the warehousing industry. Through the research and application of advanced path planning algorithms and technologies, not only can the intelligence and autonomy of storage robots be enhanced, but the warehousing industry can also benefit from more opportunities and challenges.

3. Principles of the RRT algorithm

The RRT algorithm is a powerful global path planning method designed to generate paths from a starting point to a destination [8]. Its core principles involve random exploration, constraints, and path expansion.

1) Random exploration: The fundamental idea of the RRT algorithm is to explore the state space using random sampling. The algorithm begins by selecting a random node within the configuration space as the initial point and gradually constructs a tree-like structure by connecting to the nearest neighbor nodes with a fixed step size. This randomness in exploration makes RRT particularly suitable for high-dimensional spaces and endows it with remarkable robustness. In each iteration, RRT selects a point randomly from the existing tree and generates a new node by connecting to the nearest neighbor nodes,

continually extending the tree. This process repeats until the goal point is included in the tree or the tree's growth reaches a predetermined number of iterations.

2) Constraints: Throughout the RRT search process, adherence to constraints is essential. These constraints may include collision avoidance, staying within the boundaries of the search space, and others. If a randomly generated node conflicts with these constraints, it is discarded to ensure that the generated path is both valid and safe [9]. Collision detection typically involves comparing the robot's trajectory with obstacles in the environment to ensure the path does not intersect with obstacles.

3) Path expansion: The RRT algorithm incrementally constructs a path from the starting point to the destination [10]. It does so by repeatedly sampling randomly and connecting to the nearest neighbor nodes, gradually expanding the tree-like structure. When the tree's leaf nodes include the goal point or enter the goal region, a path from the initial point to the goal point can be found through backtracking [11]. The quality and length of the path can be optimized by adjusting parameters such as the random sampling strategy, step size, and collision detection.

Advantages of the RRT Algorithm include [12]:

1) Applicability to high-dimensional spaces: Due to its use of random sampling and tree structure construction, the RRT algorithm is highly suitable for high-dimensional spaces, exhibiting exceptional robustness [13].

2) Rapid expansion: The RRT algorithm's ability to quickly expand the search space through random sampling and connection to nearest neighbor nodes typically results in efficient path planning.

3) Adaptation to obstacle environments: Thanks to its randomness, the RRT algorithm can automatically circumvent obstacles and find safe paths, adapting to complex environments [14].

4) Compatibility with other algorithms: The RRT algorithm can be combined with other path planning algorithms (e.g., A* algorithm, genetic algorithms) to further enhance path planning performance and efficiency [15].

In summary, the RRT algorithm is a robust global path planning method, especially well-suited for storage robot path planning in multi-dimensional spaces and complex environments. By employing random sampling and tree structure construction, it efficiently finds safe paths from the initial point to the destination, thereby enhancing the autonomy and intelligence of storage robots [16].

4. Implementation of storage robot path planning with the RRT Algorithm

The practical application of the Rapidly-exploring Random Tree (RRT) algorithm in storage robot path planning involves the following key steps and considerations [17]:

1) Graph representation: The primary task is to map the warehouse environment into a graphical representation, where elements such as storage robots and obstacles are transformed into nodes and edges within the graph. This graphical representation provides the foundational structure for path planning. Typically, environment maps can be provided by sensor data or pre-constructed maps, which are then converted into data structures that the RRT algorithm can process.

2) Search strategy: Following the core principles of the RRT algorithm, the path planning process begins by randomly selecting a node from the graph as the expansion node and then searching for adjacent unvisited nodes, designating them as new expansion nodes. This strategy propels the gradual construction of the path. Node selection strategy can affect search efficiency, commonly favoring nodes farthest from the goal point to expedite path exploration. Local search strategies can also expedite path planning, such as selecting the node closest to the goal point as the new expansion node.

3) Path optimization: Throughout the search process, continuous optimization of the constructed path is essential to make the path smoother and safer [18]. This includes eliminating unnecessary turns and enhancing path feasibility. Path optimization can be achieved through methods like smoothing the path (e.g., fitting Bézier curves).

4) Constraint handling: During the search process, various constraint conditions, such as the robot's kinematic and dynamic constraints and collision avoidance with obstacles, must be adhered to. Ensuring that the generated path is both legal and safe is crucial. Collision detection typically involves comparing

the robot's trajectory with obstacles in the environment to ensure the path does not intersect with obstacles.

5) Termination conditions: When the discovered path satisfies specific termination conditions, such as reaching the goal point or achieving a maximum number of iterations, the search is halted, and the final path is output. Termination conditions can be determined based on specific requirements.

The specific implementation process of the RRT algorithm is as follows [19]:

1) Initialization: Choose a starting point and construct an initial empty random tree structure.

2) Select expansion Node: Choose a node from the random tree as the expansion node, often selecting the node farthest from the goal point to expedite path exploration.

3) Random expansion: Randomly select a point in the configuration space and connect it to the expansion node, then add the new node to the random tree.

4) Local search: Select a point on the line segment connecting the new node and the expansion node, choosing the point closest to the goal point as the new expansion node to accelerate path searching.

5) Repeat steps 2-4: Repeatedly execute Steps 2-4 until the goal point is found or predefined termination conditions are met.

6) Path backtracking: Backtrack the path from the random tree to obtain the path from the starting point to the goal point.

When implementing the RRT algorithm, special attention should be given to the following aspects:

1) Obstacle handling: During the expansion process, real-time detection of whether the newly expanded path intersects with obstacles is required. If an intersection occurs, a new expansion direction must be chosen to avoid collisions. Effective collision detection algorithms and data structures can enhance path planning efficiency.

2) Node selection strategy: In the random tree, selecting the appropriate nodes for expansion to expedite the search process is critical. Common strategies include choosing the nearest neighbor node or the median node. Different strategies can affect path planning performance.

3) Parameter settings: The performance of the RRT algorithm is influenced by parameter settings, such as step size, node selection strategy, etc. Parameter adjustment should be based on specific circumstances to achieve the best path planning results [20]. Parameter selection often needs to consider factors like robot dynamics and environmental complexity [21].

4) Data structure selection: To efficiently store and manage the random tree, it's important to choose suitable data structures, such as quad-trees, octrees, etc. Selecting the appropriate data structure can improve path planning efficiency and memory utilization.

5) Real-time requirements: Considering the real-time requirements of storage robot path planning, optimizations should be applied to the algorithm to complete path planning tasks within a short timeframe [22]. This may include parallelizing path planning algorithms and using hardware acceleration to enhance real-time performance.

In conclusion, the RRT algorithm is an efficient global path planning method, particularly well-suited for multi-dimensional spaces and complex environments [23]. Applying the RRT algorithm in storage robot path planning helps enhance the autonomy and intelligence of robots, enabling them to better adapt to various complex scenarios within warehouse environment [24].

5. Discussion

The RRT algorithm offers several advantages in storage robot path planning. Firstly, it is a probabilistically complete algorithm capable of finding solutions even in complex environments, even when unknown obstacles are present. Secondly, the RRT algorithm is a heuristic search method, allowing for rapid exploration of potential solutions. However, the RRT algorithm also has some limitations, including challenges in high-dimensional state spaces, the generation of suboptimal paths, and the inability to guarantee a global optimum. To overcome these limitations, researchers have proposed improved variants of the RRT, such as RRT*, PRM, and RRT-Connect. Future research can focus on optimizing the performance and application of the RRT algorithm to overcome these limitations.

Potential future research directions may include the following aspects:

1) Efficiency: Continued improvements to the RRT algorithm to enhance its efficiency in large-scale environments, reducing path planning times.

2) Multi-agent: Research on path planning problems when multiple storage robots collaborate to enhance warehouse operational efficiency.

3) Integration with Deep Learning: Combining deep learning techniques with the RRT algorithm to improve path planning performance and adaptability.

4) Practical Applications: Applying path planning algorithms to real-world storage robot systems to solve practical problems and continually improve algorithms to adapt to changing needs.

In summary, the RRT algorithm holds significant potential for applications in storage robot path planning but also presents challenges. Future research should focus on improving algorithm efficiency, addressing multi-agent scenarios, introducing deep learning, and other aspects to overcome these challenges and drive advancements in the field. This will provide more opportunities for innovation and improvements in storage robot path planning.

6. Conclusion

This paper provides an in-depth exploration of the storage robot path planning method based on the Rapidly-exploring Random Tree (RRT) algorithm, aimed at delivering more efficient and intelligent path planning solutions for the field of warehousing management. Through core principles including random exploration, constraint handling, and path expansion, the RRT algorithm empowers storage robots with increased autonomy and intelligence, helping them navigate obstacles, find safe paths, and execute tasks efficiently in complex environments.

However, despite the outstanding performance of the RRT algorithm in storage robot path planning, it is recognized that there are still some potential limitations. When dealing with large-scale complex environments, performance may be constrained. Therefore, future research directions should encompass several key aspects:

1) Optimize algorithm performance to accommodate larger-scale environments: By further enhancing algorithm structures and parameter settings, the performance of the RRT algorithm can be strengthened to handle larger and more complex path planning problems. This includes improving search efficiency, path quality, and real-time capabilities.

2) Research more intelligent search strategies to enhance search efficiency: Introducing intelligent search strategies, such as heuristic-based search or methods based on deep learning, holds the potential to further improve the search efficiency and path quality of the RRT algorithm, making robots more intelligent.

3) Implement more adaptive path planning by integrating technologies such as machine learning: Leveraging machine learning technologies can enable adaptive learning and inference about the environment, enhancing the adaptability and intelligence of the RRT algorithm, allowing robots to better adapt to ever-changing warehouse environments.

4) Consider the motion characteristics and task requirements of robots: In practical applications, it is essential to consider the motion characteristics and task requirements of robots to enhance their motion performance and task efficiency. This includes detailed kinematic and dynamic modeling and research on task optimization algorithms.

5) Implement multi-robot collaborative path planning: By implementing multi-robot collaborative path planning, overall efficiency and performance of the warehousing system can be improved, leading to a more intelligent warehousing management. This involves research in multi-robot collaborative control, task allocation, and path coordination.

In conclusion, the RRT algorithm, as an effective global path planning method, has made significant advancements in the field of storage robot path planning. Future research will further expand this field, enhancing the autonomy and intelligence of storage robots, and bringing forth more opportunities and innovative solutions for the future development of warehousing management.

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