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A Systematic Review of Rapidly Exploring Random Tree RRT Algorithm for Single and Multiple Robots

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Abstract**:** *Recent advances in path-planning algorithms have transformed robotics. The Rapidly exploring Random Tree* (*RRT*) *algorithm underpins autonomous robot navigation. This paper systematically examines the uses and development of RRT algorithms in single and multiple robots to demonstrate their importance in modern robotics studies. To do this, we have reviewed 70 works on RRT algorithms in single and multiple robot path planning from 2015 to 2023. RRT algorithm evolution, including crucial turning points and innovative techniques, have been examined. A detailed comparison of the RRT Algorithm versions reveals their merits, limitations, and development potential. The review's identification of developing regions and future research initiatives will enable roboticists to use RRT algorithms. This thorough review is essential to the robotics community, inspiring new ideas, helping problem-solving, and expediting single- and multi-robot system development. This highlights the necessity of RRT algorithms for autonomous and collaborative robotics advancement.*

Keywords**:** *Algorithm, Evolution, Multiple robots, Path planning, Robotics.*

1. Introduction

Significant progress has been made in robotics in recent years, opening up a wide range of potential applications in industries as diverse as manufacturing and healthcare, logistics, and autonomous cars [1]. Path planning is one of the most fundamental difficulties in robotics since it requires robots to go through dynamic and complicated surroundings while avoiding obstacles and maximizing their efficiency [2]. Rapidly exploring Random Trees (RRT) algorithms have emerged as a helpful tool in tackling these difficulties. This review focuses on the significance and future possibilities of RRT algorithms for path planning in single and multiple robot systems.

1.1. Background and motivation

Single or multiple robot path planning is an essential task in robotics. Optimal paths must be calculated from a given starting point to a given destination, with all obstacles avoided and all constraints met [3]. In real-world scenarios with dynamic environments, the difficulty of programming a robot to adapt to new circumstances and navigate increases effectively [4]. Traditional path-planning methods often struggle to cope with the complexity of these situations, which has led to the investigation of more adaptive and efficient ways, such as RRT algorithms [5]. Since the RRT method was invented, path planning has changed forever [6]. The intrinsic ability of RRT and its derivatives to explore the configuration space in a probabilistically complete and efficient manner has made it a popular option. The importance of RRT algorithms is magnified when dealing with a group of robots [7]. Coordinating the mobility of multiple robots to complete tasks collectively while avoiding collisions and optimizing pathways is a multidimensional subject with numerous practical applications, including swarm robotics, multi-agent surveillance, and logistics [8]. One exciting approach to this challenging problem is the use of RRT algorithms. As we move on with this literature study, we will investigate the many varieties of RRT algorithms, their uses in single and multi-robot systems, and the ongoing difficulties and unanswered questions associated with RRT-based path planning. The RRT algorithms in the context of single and multiple robots will be significantly evaluated through this encompassing knowledge.

1.2. Importance of RRT algorithms in robotics

The RRT algorithms play a crucial role in many aspects of robotics [9]. An essential issue in robotics is path planning, the RRT-based techniques provide efficient and realistic answers. Robots that employ RRTs' flexibility and exploration capabilities are well-suited for practical use since they can quickly move around in unfamiliar, crowded settings [10]. As a second point, RRT algorithms allow autonomous robots to make intelligent decisions about their pathways in the case of single robot systems. These algorithms can be quickly customized to various robot kinds and mission conditions [11].

Additionally, if a solution exists, RRTs' probabilistic completeness guarantees that it may be located, ensuring a high degree of confidence in path planning [12]. Finally, RRT algorithms may significantly improve robot teamwork efficiency in multi-robot systems. Coordinated motion planning, swarm intelligence, and collaborative exploration are areas where RRTs can offer unique solutions [13]. In situations where multiple robots must adjust to changing conditions while avoiding collisions with one another, the ability of RRTs to efficiently explore the configuration space is essential [14].

1.3. Aim

This systematic review aims to provide a detailed and up-to-date study of the utilization of RRT algorithms in the context of single and multiple robot path planning. This paper aims to provide readers with an in-depth knowledge of RRT algorithms in robotics, including their current uses, history, and future possibilities.

1.4. Objectives

- To comprehensively investigate and analyze the development and significant highlights in the history of RRT algorithms used in robotics.
- To examine the contexts in which RRT algorithms are applied, hoping to unearth significant insights, difficulties, and developments in single-robot path planning.
- To investigate various ways that the RRT algorithms have been adapted, extended, and modified for multi-robot systems, paying particular attention to their benefits, difficulties, and contributions to collaborative path planning.
- To evaluate the strengths, weaknesses, and potential improvements of different variants of the RRT algorithm for use in single and multi-robot path planning.
- To highlight prospective issues and open problems in RRT-based path planning for single and multiple robots and to provide insights into emerging areas and future directions for study in this area.

These aims will lead the systematic study, providing a complete analysis of the significance and promise of RRT algorithms in robotics for single and multiple robot systems.

1.5. Research questions

1. How have RRT algorithms evolved and been utilized in single robot path planning, and what are the significant findings in this domain?
2. What are the critical insights and developments in multi-robot route planning, and how have RRT algorithms been adapted and extended for use with multiple robot systems?

1.6. Significance of study

This systematic review adds to the growing body of knowledge in robotics. This research elucidates the current state of the art in path planning by analyzing the application of RRT algorithms to single and multiple robot scenarios. This understanding is crucial for developers, researchers, and engineers working on robotics applications, offering a basis for expanding the discipline. Improving the effectiveness of route planning necessitates familiarity with RRT algorithms and their various uses. This study lays bare the pros and cons of different algorithms, giving researchers and professionals more information to decide which path-planning methods to employ. Better and safer robot navigation in a wide range of contexts is possible. In this study, we survey the landscape of RRT algorithm applications in single and multi-robot systems. Researchers and engineers can use this information to enhance the navigating, autonomous driving, and motion planning capabilities of individual robots.

Logistics, Search And Rescue (SAR), and NSAR benefit significantly from multi-robot systems. In this research, we look into the viability of adapting RRT algorithms for use in collaborative settings with many robots. This knowledge is critical for advancing cooperative robot systems, enhancing path planning in ambiguous environments, and preventing accidents. This research is helpful because it reveals both the difficulties and the opportunities of RRT-based route planning, thereby encouraging original thought. It can be used as a guide for researching obscure or understudied areas. As the study's potential uses expand, it could inspire new approaches to robots. The scientific community gains from systematic reviews. It streamlines the process of finding relevant information in the literature, expands on previous research, and helps scholars gain a deeper grasp of robotics. Robotics students and researchers can benefit from this work. This introduction of RRT algorithm fundamentals, applications, and obstacles helps develop a basis for robot path planning. In conclusion, this systematic study advances robotics research, path planning efficiency, and single and multi-robot system development. It helps roboticists innovate and solve problems by providing resources for researchers, practitioners, and the scientific community.

2. Methodology

To ensure that our findings are understandable, accurate, and actionable, we used a methodical and comprehensive scientific approach to examine this systematic literature. This approach was centered on scholarly articles investigating the Rapidly exploring random tree technique for single and multiple robots. The ACM Digital Library, IEEE Xplore, Google Scholar, and PubMed were only a few reputable literature sites we searched to locate scientific publications published between 2015 and 2023 (Fig. 1).

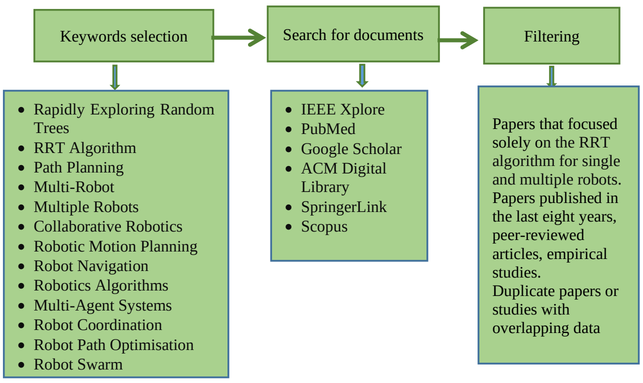

Fig. 1. Methodology for Paper collection

In our preliminary searches of prominent literature databases, we were delighted to discover 500 high-caliber academic publications. We narrowed down the original pool of 500 papers to a manageable sample size of 70 by using strict inclusion and exclusion criteria. We generated articulated research questions and established transparent criteria for inclusion and exclusion to ensure methodological rigor (Fig. 2).

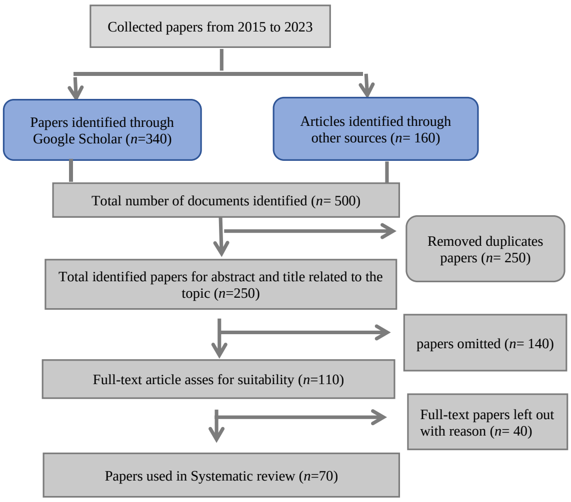

Fig. 2. Prisma Diagram for selected papers

2.1. Inclusion and exclusion criteria

For this literature study, we used strict inclusion and exclusion criteria to make sure that our findings were reliable and applicable. The following are examples of such measures:

2.1.1. Inclusion criteria

- Papers must focus on Rapidly Exploring Random Tree algorithms for robot path planning for single or multiple robots.
- Papers from 2015-2023 to showcase the latest RRT algorithm developments. Started the year 2015 to match the launch of significant RRT variants and developments in the sector. Papers should examine RRT algorithms in robot path planning, including development, application, modification, comparison, and assessment. Papers on RRT algorithm history and use examples are also included.
- Papers on RRT algorithms for single and multiple robots. This allows a complete examination of RRT algorithms in robotics applications.

2.1.2. Exclusion criteria

- Papers not related to RRT algorithms in robot path planning are excluded. This comprises non-robotics and non-RRT algorithm studies.
- Papers published before 2015 have been removed, as they may not have captured recent improvements and innovations in RRT algorithms.
- Papers in languages other than English are eliminated, as they may not be accessible for extensive examination and analysis.
- Papers on conference abstracts, posters, and short papers with low content for analytical purposes due to limited information are excluded.
- Papers with identical content are excluded. Only the latest and most detailed study is presented.

- Exclude papers on non-peer-reviewed sources such as preprints, theses, technical reports, and non-academic articles to maintain paper quality and trustworthiness.

The inclusion and exclusion criteria aim to pick publications that provide current and helpful information on RRT algorithms for robot path planning with single or multiple robots.

2.2. Analysis

To conduct this study, we followed the guidelines outlined in the recommendations for systematic reviews [15]. We devised a method to conduct a comprehensive literature search and synthesize existing data on RRT algorithms for single and multiple robots.

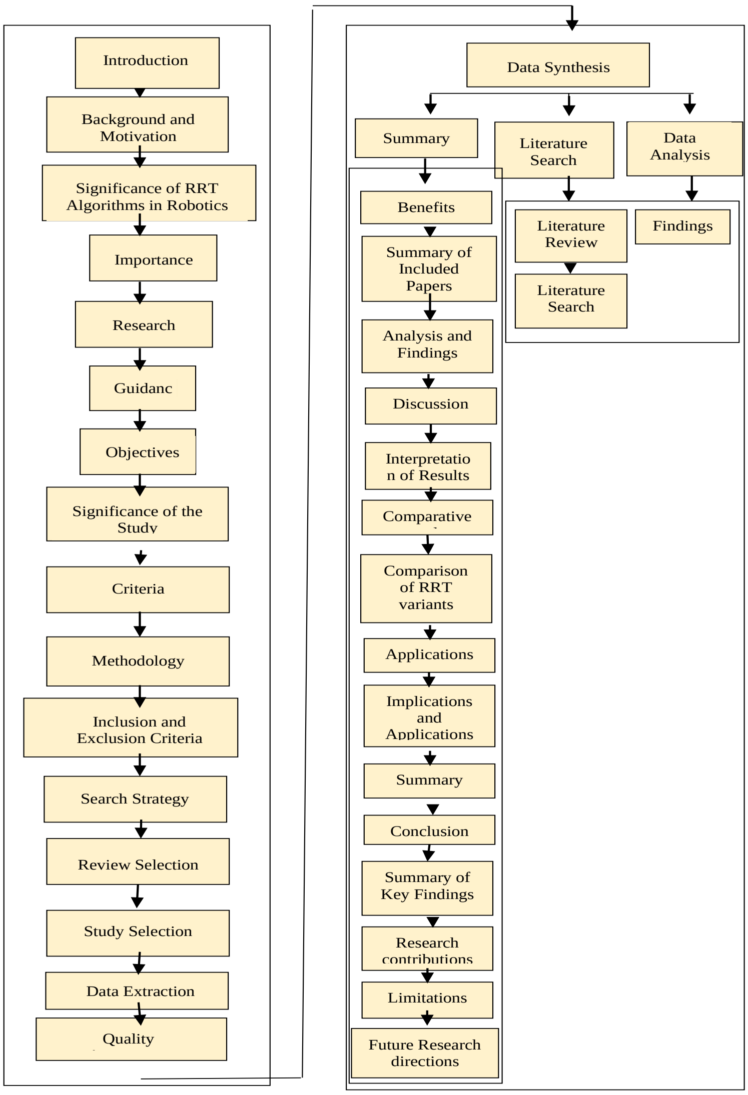

Fig. 3. Conceptual framework

We took a systematic approach, establishing clear study goals and inclusion/exclusion criteria and assessing and synthesizing the findings from all relevant papers. By taking a systematic approach, we could provide a comprehensive review of the literature on this topic. We decided to concentrate on statistically evaluating and synthesizing the included research data to present a comprehensive and evidence-based appraisal of the case. Rapidly exploring the random tree RRT technique for single and multiple robots is an essential but understudied topic; thus, we conducted a thorough review following acknowledged standards and a systematic methodology **(**Fig. 3).

2.3. Descriptive data

A descriptive data table was created to summarize the primary research findings from the included papers. Table 1 lists the study's essentials: its authors, the year it was published, the research approach taken, the size of the study's sample, and the study's primary findings.

Table 1. Review table

Refe-rence	Aim	RRT type	Methods	Findings	Results	Limitations	Optimality	Completeness
1	2	3	4	5	6	7	8	9
[16]	Enhancing path planning in narrow passages	RJ-RRT	Introduced enhancements to RRT	Improved performance in narrow passages	More efficient path planning	Limited to narrow passages	Suboptimal	Probabilistic
[17]	Improving RRT* for robot path planning	RRT*	Enhanced RRT* algorithm with path expansion heuristic sampling	Improved path quality and efficiency	More optimal paths	Limited to specific scenarios	Optimal or suboptimal	Probabilistic
[18]	Investigating Robot Exploration Algorithms	RRT	Comparative analysis of exploration algorithms	Insights into algorithm performance for exploration	Not focused on path planning	NA	Optimal	Probabilistic
[19]	Smooth path planning for non-holonomic mobile robots	RRT*	Continuous RRT* with B-spline curves	Improved path smoothness for non-holonomic robots	Smooth and efficient path planning	Limited to non-holonomic robots	Suboptimal	High
[20]	Simplified and Smoothed RRT Algorithm	RRT	Simplified RRT variant	Simplified and smoothed path planning	Simplified and smoothed paths	May not handle highly complex environments	Suboptimal	Probabilistic
[21]	Obstacle-avoidance path planning for robot arm	RRT	Improved RRT for robot arm	Enhanced obstacle avoidance for robot arms	Effective obstacle avoidance for robot arms	Limited to robot arms	Suboptimal	Probabilistic
[22]	Enhanced discrete RRT for multi-robot planning	RRT	Improved discrete RRT for multi-robot scenarios	Improved coordination in multi-robot scenarios	Enhanced multi-robot coordination	Limited to multi-robot scenarios	Suboptimal	Probabilistic
[23]	Efficient path planning for mobile robots	RRT	Improved double-tree RRT algorithm	Enhanced efficiency in path planning for mobile robots	More efficient path planning	Limited to mobile robots	Optimal	High
[24]	Enhancing RRT for robot path planning	RRT	Improved RRT with midpoint interpolation	Improved exploration and path quality	Enhanced exploration and path quality	Limited to specific scenarios	Suboptimal	Probabilistic
[25]	Adaptive RRT* for mobile robots	RRT*	Adaptive RRT* algorithm	Efficient path planning with adaptability	Adaptive and efficient path planning	Limited to specific scenarios	Optimal	High
[26]	Estimating spatiotemporal fields with multiple sensing robots	RRT	Rapidly exploring random cycles for field estimation	Persistent estimation of spatiotemporal fields	Improved field estimation	Limited to field estimation	Optimal or suboptimal	Probabilistic
[27]	Temporal memory-based RRT exploration for multi-AGVs	RRT	Temporal memory-based RRT for multi-AGVs	Enhanced exploration for multi-AGVs	Improved exploration	Limited to multi-AGVs	Suboptimal	High

Table 1 (c o n t i n u e d)

1	2	3	4	5	6	7	8	9
[28]	Path planning for mobile robots using DGABI-RRT	RRT	DGABI-RRT algorithm	Improved path planning for mobile robots	Efficient path planning	Limited to specific scenarios	suboptimal	Probabilistic
[29]	RRT-Connect for robotic manipulator path planning	RRT	RRT-connect algorithm for robotic manipulator path planning	Pruning apple trees with improved path planning	Improved path quality	Limited to specific applications	optimal	Probabilistic
[30]	Decoupling motion path planning for two manipulators	RRT	Hybrid RRT Algorithm for two manipulators	Efficient path planning for two manipulators	Efficient path planning	Limited to specific manipulator scenarios	Suboptimal	High
[31]	Real-time exploration and path planning	RRT	Rapidly-Exploring Random Trees for combined exploration and path planning	Real-time path planning with exploration	Efficient exploration and path planning	Limited to specific applications	Suboptimal	High
[32]	Regeneration RRT for dynamic path planning	RRT	Area-Optional Regeneration RRT Algorithm	Dynamic path planning for service robots	Improved dynamic path planning	Limited to service robots	Optimal	Probabilistic
[33]	Offline path planning for aerial robots	RRT	Offline RRT-based path planning	Offline path planning for aerial robots	Effective offline path planning	Limited to offline scenarios	Suboptimal	High
[34]	Uncertainty-aware path planning	RRT	Uncertainty-aware RRT algorithm	Uncertainty-aware path planning	Enhanced path planning with uncertainty considerations	Limited to specific applications	Optimal	High
[35]	Multi-agent cooperative path planning	RRT	Cooperative RRT for multi-agent systems	Enhanced cooperative path planning for multi-agents	Improved multi-agent coordination	Limited to multi-agent scenarios	Suboptimal	High
[36]	Prioritized RRT for robot path planning	RRT	Prioritized RRT algorithm	Prioritized path planning for robots	Improved prioritized planning	Limited to specific scenarios	Suboptimal	High
[37]	DART-RRT: A dual-arm robot path planner	RRT	Dual-arm robot path planning using DART-RRT	Improved path planning for dual-arm robots	Efficient path planning	Limited to dual-arm robots	Suboptimal	High
[38]	To address the path planning problem of a biped robot in a static environment	RRT	combining the RRT algorithm and the visibility graph algorithm	The combined approach, utilizing multi-point RRT and visibility graph, aims to solve the path planning problem for a biped robot in a static environment	Improved autonomous exploration	Limited to exploration scenarios	Suboptimal	High
[39]	address the efficient multi-robot autonomous exploration problem in scenarios where robots need to explore unknown environments autonomously.	RRT	dynamic Voronoi diagrams for space partitioning, introducing a new parameter-insensitive utility function to evaluate centroids of unknown regions	CURE approach significantly improves exploration efficiency compared to existing methods. The dynamic Voronoi diagrams and the utility function for centroids contribute to better exploration planning	Exploration time consumption and path cost are reported to be reduced by up to 50.7% and 34.4%, respectively, when compared with an advanced RRT-based multi-robot exploration approach	Potential limitations may include constraints in certain types of environments, scalability issues with a large number of robots	Suboptimal	High
[40]	Moving obstacle avoidance for cable-driven robots	RRT	Improved RRT for moving obstacle avoidance	Enhanced moving obstacle avoidance for cable-driven robots	Improved obstacle avoidance	Limited to cable-driven robots	Suboptimal	High

Table 1 (c o n t i n u e d)

1	2	3	4	5	6	7	8	9
[41]	To propose an autonomous obstacle avoidance dynamic path-planning method, called Smoothly RRT (S-RRT), for a robotic manipulator in a dynamic unstructured environment. The aim is to address limitations in existing RRT algorithms for robotic manipulators in such environments	S-RRT	Introduction of a path optimization strategy based on the maximum curvature constraint Robot Operating System (ROS) dynamic simulation, and a real autonomous obstacle avoidance experiment	Path planning with multi-robot systems	Enhanced path planning for robotic manipulators	Limited to robotic manipulators	Suboptimal	High
[42]	To introduce a new variant, Intelligent Bidirectional-RRT* (IB-RRT*), designed for optimal motion planning in complex cluttered environments. The goal is to improve upon RRT* and Bidirectional-RRT* (B-RRT*) by utilizing bidirectional trees and introducing intelligent sample insertion heuristics for fast convergence to the optimal path solution	RRT*	Utilization of bidirectional trees approach. Introduction of an intelligent sample insertion heuristic for fast convergence to the optimal path solution using uniform sampling heuristics. The algorithm is theoretically evaluated and experimentally compared with RRT* and B-RRT*	IB-RRT* is designed for optimal motion planning in complex cluttered environments, utilizing bidirectional trees and intelligent sample insertion heuristics	Enhanced path planning for robotic manipulators	Limited to dynamic multi-robot systems	Suboptimal	High
[43]	RRT with Rule-Template Sets	RRT	an efficient sampling-based path planning method for mobile robots in dynamic environments	Improved path planning in dynamic environments	Improved path planning in dynamic environments with RRT and rule-template sets	Potential computational complexity in large-scale environments	Suboptimal	High
[44]	Hierarchical path planning for mobile robots	RRT	Skeletonization-informed RRT for hierarchical planning	Hierarchical path planning for mobile robots	Improved hierarchical path planning	Limited to hierarchical scenarios	Optimal	High
[45]	Exploration of implicit roadmaps in multi-robot motion planning	Discrete RRT	Discrete RRT for exploration in multi-robot scenarios	Exploration of implicit roadmaps	Improved exploration in multi-robot scenarios	Limited to multi-robot exploration	Optimal	Probabilistic
[46]	Motion planning for robotic luggage trolley collection	Multi-Risk-RRT	Multi-Risk-RRT algorithm for luggage trolley collection	Efficient motion planning for trolley collection	Improved efficiency in trolley collection	Limited to trolley collection	Optimal	High
[47]	Global path planning for fire-fighting robots	Bi-RRT	Advanced Bi-RRT algorithm for fire-fighting robots	Global path planning for fire-fighting robots	Efficient global path planning	Limited to fire-fighting scenarios	Suboptimal	High
[48]	Mapping and path planning for wheeled mobile robots	RRT	RRT-based mapping and path planning for wheeled robots	Mapping and path planning for wheeled robots in unknown environments	Efficient mapping and path planning	Limited to wheeled robots	Suboptimal	Probabilistic
[49]	Multi-robot map exploration	M-RRT	Multi-robot exploration using M-RRT	Map exploration by multiple robots	Improved multi-robot map exploration	Limited to multi-robot exploration	Suboptimal	Probabilistic

Table 1 (c o n t i n u e d)

1	2	3	4	5	6	7	8	9
[51]	RRT in narrow environments for insect-like robots	RRT	Application of Improved RRT in Narrow Environments	Path planning for insect-like robots in narrow spaces	Improved navigation in narrow spaces	Limited to narrow environments	Suboptimal	Probabilistic
[52]	Visual servoing of mobile robots with FOV constraint	RRT	Virtual-goal-guided RRT for visual servoing with FOV constraint	Visual servoing with FOV constraint	Improved visual servoing	Limited to FOV-constrained scenarios	Optimal	Probabilistic
[53]	Collision-free path planning for robots	RRT	Collision-free path planning with improved RRT	Collision-free path planning for robots	Enhanced collision avoidance	Limited to collision scenarios	Optimal	Probabilistic
[54]	APF-IRRT*: Path planning with artificial potential fields	RRT*	Integration of artificial potential fields with IRRT*	Improved path planning with APF	Efficient path planning with APF	Limited to certain environments	Suboptimal	Probabilistic
[55]	Moving obstacle avoidance for cable-driven robots	RRT	Improved RRT for moving obstacle avoidance	Enhanced moving obstacle avoidance for cable-driven robots	Improved obstacle avoidance	Limited to cable-driven robots	Suboptimal	High
[56]	Path planning and obstacle avoidance for automated driving systems	RRT	Path planning with RRT for automated driving systems	Path planning and obstacle avoidance for automated driving systems	Improved autonomous driving	Limited to autonomous driving scenarios	Suboptimal	High
[57]	Mobile robot path planning	RRT	Path planning for mobile robots with Improved RRT	Mobile robot path planning	Improved mobile robot path planning	Limited to mobile robot scenarios	Optimal	Probabilistic
[58]	Multi-robot path planning	Disjointed-Trees	Multi-robot path planning with Rapidly-exploring Disjointed-Trees	Multi-robot path planning	Improved multi-robot coordination	Limited to multi-robot scenarios	Suboptimal	High
[59]	Multi-robot map exploration	RRT	Multi-robot map exploration with optimization	Multi-robot map exploration	Improved exploration and mapping	Limited to multi-robot exploration	Suboptimal	High
[60]	Dynamic path planning and replanning for mobile robots	RRT	Extended RRT for dynamic path planning and replanning	Dynamic path planning and replanning for mobile robots	Improved adaptability to dynamic environments	Limited to dynamic scenarios	Optimal or Suboptimal	Probabilistic
[61]	Multi-robot scheduling and path planning	RRT	Path planning and scheduling for non-overlapping operator attention	Multi-robot scheduling and path planning	Enhanced coordination of multiple robots	Limited to multi-robot scheduling	Suboptimal	High
[62]	Path planning with multi-robot systems	RRT	Path planning with multi-robot systems in dynamic environments	Path planning with multi-robot systems	Improved path planning for dynamic environments	Limited to dynamic multi-robot systems	Suboptimal	High
[63]	Path planning for robotic manipulators	RRT	Path planning for robotic manipulators with improved RRT	Path planning for robotic manipulators	Enhanced path planning for robotic manipulators	Limited to robotic manipulators	Optimal	High
[64]	Autonomous robotic exploration	M-RRT	Autonomous exploration using multiple M-RRTs	Autonomous robotic exploration	Improved autonomous exploration	Limited to autonomous exploration	Suboptimal	High
[65]	Mobile robot exploration	RRT	Exploration with RRT and dynamic window approach	Mobile robot exploration	Improved mobile robot exploration	Limited to exploration scenarios	optimal	High
[66]	Path planning of dual-arm robot	VT-RRT	Path planning for dual-arm robot using VT-RRT	Path planning for dual-arm robot	Enhanced path planning for dual-arm robot	Limited to dual-arm robot scenarios	Suboptimal	probabilistic
[67]	Omni-wheeled robot path planning	RRT	Path planning for omni-wheeled robot with RRT	Omni-wheeled robot path planning	Improved path planning for omni-wheeled robot	Limited to omni-wheeled robots	Suboptimal	High

Table 1 (c o n t i n u e d)

1	2	3	4	5	6	7	8	9
[10]	Path planning for mobile robots	RRT	Path planning for mobile robots with Improved RRT	Mobile robot path planning	Improved path planning for mobile robots	Limited to mobile robot scenarios	Optimal	Probabilistic
[68]	Robot path planning with LSTM and RRT	RRT	Path planning based on LSTM and RRT	Robot path planning with LSTM and RRT	Improved path planning with LSTM and RRT	Limited to LSTM-based scenarios	Suboptimal	High
[69]	Autonomous exploration with clustering and RRT	RRT	Improved autonomous exploration with clustering and RRT	Autonomous exploration with clustering and RRT	Enhanced exploration in unknown environments	Limited to autonomous exploration	Suboptimal	High
[70]	Robot-assisted needle insertion with RRT and APF	RRT	RRT algorithm for robot-assisted needle insertion	Enhanced needle insertion with RRT and APF	Improved needle insertion	Limited to needle insertion scenarios	Suboptimal	High
[71]	To address the challenge of hazardous gas exploration in large unknown environments using a robot	RRT	guide the robot's navigation, utilizing vertices as goal candidates and incorporating gas mean and variance values for effective gas concentration mapping	The paper proposes a strategy that addresses the trade-off between frontier exploration and gas exploitation, contributing to more effective gas exploration in large unknown areas	The performance of the proposed strategy is compared with other strategies using ROS, Gazebo, and a 3D gas simulator in a large outdoor environment	Limited to specific applications	Suboptimal	High
[72]	Progressive RRT for global path planning	RRT	Progressive RRT for global path planning	Global path planning using Progressive RRT	Enhanced global path planning	Limited to global path planning	Suboptimal	High
[73]	RRT* FN for mobile robot path planning	RRT* FN	Improved RRT* FN for mobile robot path planning	Mobile robot path planning with RRT* FN	Enhanced mobile robot path planning	Limited to mobile robot scenarios	Optimal	Probabilistic
[74]	Bi-directional RRT* for maze navigation	RRT*	Fast path planning with Bi-directional RRT*	Maze navigation using Bi-directional RRT*	Improved maze navigation	Limited to maze environments	Suboptimal	Probabilistic
[75]	Dynamic window approach with RRT*	RRT*	Implementation of RRT* with dynamic window approach	Dynamic window approach with RRT*	Improved dynamic window approach	Limited to certain environments	Suboptimal	High
[76]	Path planning for multiple robots	RRT	Path planning with A* and RRT for multiple robots	Path planning for multiple robots	Enhanced path planning for multiple robots	Limited to multi-robot scenarios	Optimal	probabilistic
[77]	Informed RRT* for walking robots	RRT*	Informed RRT* for path planning of walking robots	Path planning for walking robots using Informed RRT*	Enhanced path planning for walking robots	Limited to walking robots	Suboptimal	High
[78]	Generalized Voronoi Diagram for Robot Exploration	RRT	Exploration with RRT and Generalized Voronoi Diagram	Robot exploration with Generalized Voronoi Diagram	Improved robot exploration	Limited to exploration scenarios	Optimal	Probabilistic
[79]	Path planning for multiple robot arms	RRT	Path planning for multiple robot arms	Enhanced path planning for multiple robot arms	Limited to multiple robot arms	Suboptimal	High	Probabilistic
[80]	FF-RRT for Flexible Multi-Robot Formations	FF-RRT	Developed FF-RRT for flexible multi-robot formations	Effective path planning for flexible multi-robot formations	Successful implementation of FF-RRT	scalability to larger robot fleets	Optimal	High
[81]	G-RRT* for Mobile Robot Navigation	Goal-oriented sampling-based RRT* path planning algorithm	Developed G-RRT* for mobile robot navigation with an improved convergence rate	Enhanced convergence rate in mobile robot path planning	Successful application of G-RRT*	Limited adaptability to dynamic environments	Optimal	High

Table 1 (c o n t i n u e d)

1	2	3	4	5	6	7	8	9
[82]	RRT-based Optimal Motion Planning for 6-DOF Industrial Robots	Rapidly exploring random tree-based optimal motion planning algorithm for 6-DOF industrial robots	Inclusion of RRT-based optimal motion planning for 6-DOF industrial robots	Efficient motion planning for 6-DOF industrial robots	Successful integration of RRT for optimal motion planning	Lack of discussion on real-world applicability	Suboptimal	High
[83]	Weighted Multi-tree RRT	Weighted Multi-tree RRT algorithm for efficient path planning	Developed Weighted Multi-tree RRT algorithm for path planning	Enhanced path planning efficiency for mobile robots	Successful implementation of Weighted Multi-tree RRT	Adaptability to different terrains	Optimal	High
[84]	RRT*	Improved RRT* path planning algorithm for dynamic environments	Implemented Improved RRT* for dynamic environment path planning	Enhanced path planning performance in dynamic scenarios	Successful application of Improved RRT*	Real-time performance	Optimal	High
[85]	RRT* FN	path planning and collision avoidance approach based on the RRT* FN framework for a robotic manipulator	Developed a path planning and collision avoidance approach using the RRT* FN framework for robotic manipulators	Effective collision avoidance and path planning for robotic manipulators	Effective collision avoidance and path planning with RRT* FN for robotic manipulators	Limited validation in cluttered and confined environments	Optimal	RRT* FN for Robotic Manipulator

Fig. 4 summarizes the number of articles published each year. A total of 70 papers were evaluated in the analysis, which implies a growing tide of publications. The following table shows how many articles were published yearly on RRT algorithms for single and multiple robots. Evidence suggests that the volume of studies investigating this topic has increased over time. While only a few papers appeared in print in 2015 and 2016, that number has steadily risen yearly since 2019. Particularly, 2023 has the most significant number of papers, suggesting the current relevance and continued research interest. This points to the growing importance and vitality of research into RRT algorithms for robot path planning. This area of robotics is exciting since researchers are always looking for novel ways to tackle the problem.

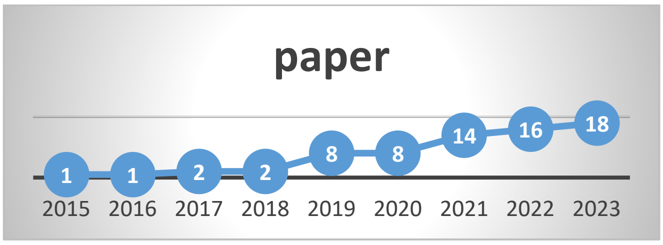

Fig. 4. No of the papers used in the study

3. Applications of RRT in single and multiple robot systems

Both in standalone robot systems and in the coordination of teams of robots, RRT algorithms have found widespread use [86]. Among the many possible uses for this technology are six.

- RRT algorithms are commonly used in autonomous mobile robots' path planning, allowing them to navigate unfamiliar terrain and avoid collisions successfully [87]. Drones, autonomous vehicles, and robot hoover cleaners are just a few examples.

- To avoid collisions when performing manipulation activities like pick-and-place in manufacturing, RRT-Connect variations are utilized in robotic arm settings [17].
- RRT-based algorithms are used to plan individual pathways that consider the presence and mobility of other agents, ensuring collision-free and efficient motions when numerous robots are working collaboratively or coordinating activities.
- RRT-based path planning aids in navigating robots over complicated and hazardous terrains for search and rescue missions, allowing them to better locate and rescue people in need [88].
- Agricultural robots used for harvesting or spraying in a controlled setting can benefit from RRT algorithms that aid path planning.
- The flexibility of RRT-based path planning is demonstrated by these examples, which all deal with the mobility difficulties faced by various robotic systems.

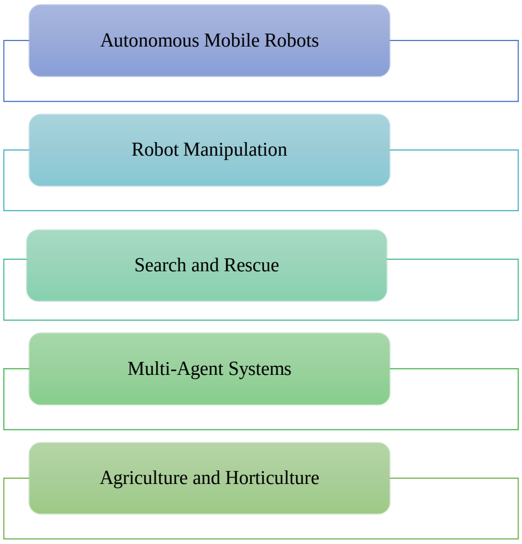

Fig. 5. Applications of the RRT in single and multiple robot systems

4. Challenges and open problems in RRT-based path planning

Although RRT algorithms have shown promise in various robotic settings, they have some difficulties:

- Computational resources are commonly stressed in high-dimensional regions as robots explore complicated situations. The real-time performance of RRT algorithms is still complex to guarantee.
- Exploring configuration spaces can be challenging for high-DOF robots. It is not easy to create RRT variations that work well with high-dimensional settings.

- In situations where obstacles or goals are subject to fast change, RRT algorithms must be flexible. It is challenging to solve the problem of ensuring resilient and adaptive planning in real-time dynamic contexts.
- When numerous robots operate together, coordinating their trajectories without collisions is challenging. Research is still needed to develop scalable multi-robot path planning strategies using RRT algorithms [89].
- By resolving these issues, researchers hope to make RRT-based path-planning approaches even more flexible and effective in a wide range of robotic settings. This systematic review uses these difficulties as a springboard for additional investigation and analysis.

5. Results

We present brief descriptions of the articles used in our systematic literature review. To provide context for future studies, a summary of each paper is provided, including the paper's title, authors, publication year, and significant contributions. Both single-robot and multi-robot applications of RRT algorithms are discussed in these works. The critical findings in single robot RRT algorithms are as in Table 2, and the critical findings in multi-robot RRT algorithms are as in Table 3.

Table 2. The critical findings in single robot RRT algorithms

Key findings	Description
Specialised variants for constrained spaces	RRT variants like RJ-RRT enhance exploration efficiency in narrow or constrained environments, making them valuable for single-robot path planning in challenging spaces
Improved RRT variants	Enhanced versions of RRT* with path expansion heuristic sampling improve path planning efficiency in various single robot applications.
Non-holonomic mobility	Continuous RRT* variants are effective for non-holonomic mobile robots, enhancing their navigation capabilities in complex environments
Robot manipulator planning	Advanced RRT algorithms address complex motion and obstacle avoidance for single robot manipulator systems operating in cluttered environments
Adaptive RRT	Intelligent adaptive RRT* algorithms offer adaptability to diverse scenarios, contributing to versatile single-robot path planning
Real-time exploration and mapping	Research focuses on persistent estimation of spatiotemporal fields using rapidly exploring random trees, providing comprehensive solutions for robot navigation
Safety-constrained motion planning	Efficient RRT*-based approaches address safety-constrained motion planning in dynamic environments, specifically for continuum robots
Obstacle avoidance	RRT algorithms enhance path planning in environments with obstacles, improving obstacle avoidance strategies for single robots
Robot-assisted applications	RRT-based path planning is employed in specialized domains like agriculture and medical robotics, enhancing the practicality of these systems
Visualization and analysis	Combining RRT algorithms with other methods, such as artificial potential fields, enhances precision in robot navigation in 3D environments

Table 3. Critical findings in multi-robot RRT algorithms

Key findings	Description
Coordinated multi-robot planning	Improved discrete RRT variants enhance the efficiency of coordinated path planning for multi-robot systems
Efficient path planning	Advanced RRT algorithms contribute to the efficiency of single-robot path planning in multi-robot scenarios
Multi-robot exploration	RRT algorithms are employed for efficient multi-robot exploration and mapping, enhancing coordinated exploration strategies
Enhancing operator efficiency	Multi-robot scheduling and path-planning methods minimize operator attention overlaps, improving multi-robot system coordination
Dynamic environments	Path planning algorithms for multi-robot systems operate effectively in dynamic environments, offering robust and adaptable navigation
Manipulator systems	Path planning in multi-obstacle environments addresses manipulation and collision avoidance challenges for multi-robot systems
Machine learning integration	Combining RRT algorithms with machine learning techniques advances path planning in multi-robot systems
Adaptive exploration	The Progressive Rapidly-exploring Random Tree (PRRT) offers efficient and adaptive path planning, especially in dynamic and complex environments
Fast path planning	Bi-directional RRT* enhances the efficiency of path planning for mobile robots in intricate and constrained spaces
Robust navigation	Integrating informed Rapidly Exploring Random Tree* (iRRT*) with dynamic window approaches provides comprehensive solutions for robot navigation

5.1. Comparative analysis (performance metrics and evaluation)

Establishing a set of performance indicators and assessment criteria to analyse the efficacy of different RRT variations for single and multiple robots is necessary before diving into comparison analyses. A primary statistic is the length of the created path, as shorter paths typically denote more effective solutions [90]. For real-time applications, the time it takes to calculate the path is critical. When it comes to navigation, nothing is more important than avoiding crashes. How well the algorithm creates optimal pathways is a crucial factor to consider. Although optimality is not always necessary, it can make a huge difference when performance is crucial. For multi-robot scenarios, the algorithm’s capacity to scale with an increasing number of robots is a critical element [91].

5.1.1. Comparing RRT variants for single robots

Understanding the benefits and drawbacks of each RRT version designed for individual robot systems requires careful comparison. Some of the possible permutations of this analysis are as in Table 4.

Table 4. Comparing RRT variants for single robots

RRT Variants for single robots	Analysis
RRT and RRT comparison*	It contrasts the classic RRT and its more optimal counterpart, RRT*, regarding path optimality and computation time [92]
PRM vs. RRT	A comparison of Probabilistic RoadMaps (PRM) and RRT, exploring their efficiency in handling various environments and path planning complexities [93]
RRT-connect and RRT	We are analyzing the differences between RRT-Connect and the basic RRT Algorithm regarding path quality, computation time, and robustness [94]

5.1.2. Comparing RRT variants for multiple robots

Similarly, when choosing the best algorithm for various collaborative robot applications, it is essential to compare RRT variations developed for multi-robot systems. Some such analogies are as in Table 5.

Table 5. Comparing RRT variants for multiple robots

RRT variants for multiple robots	Analysis
Decentralized vs. centralized multi-robot RRT	It was contrasting decentralized and centralized multi-robot RRT approaches regarding scalability, coordination, and path optimality [95]
Distributed vs. decentralized multi-robot RRT	Comparing distributed and decentralized multi-robot RRT strategies focused on communication overhead and autonomy
Multi-robot RRT vs. single robot RRT	Evaluating whether multi-robot RRT variants outperform single-robot RRT variants in various single-robot scenarios, identifying situations where a multi-robot approach is advantageous

The purpose of these comparisons is to shed light on which form of RRT is the most appropriate for various single-robot path planning scenarios. Considering characteristics like collaboration, efficiency, and scalability, the comparative analysis for multiple robot systems is essential for making educated decisions about which RRT version matches best with the objectives of a particular multi-robot application. These evaluations of RRT variants for single and multi-robot systems compare and contrast their pros and cons, allowing academics and practitioners to choose the algorithms that best meet their needs.

6. Discussion

There have been a few significant developments in RRT algorithm design recently. These tendencies shed light on what the future holds for research and what it means for single and multi-robot path planning. Complex environments present unique problems, but RRT algorithms can be tailored to meet those needs. Recent studies have highlighted the need for improved efficiency and robustness in RRT algorithms in the face of confined locations, non-holonomic motion, and dynamic obstacles. Integrating RRT algorithms with sophisticated approaches, such as machine learning, artificial potential fields, and spatiotemporal field estimation, has gained attention. The goal of this research is to integrate the best features of various approaches to enhance the accuracy and robustness of path planning and collision avoidance. There are specific fields where RRT algorithms have proven useful, such as robotics in agriculture and medicine. These context-aware enhancements demonstrate the flexibility and utility of RRT algorithms in the real world. There is a rising trend in research interest in multi-robot systems. Multi-robot exploration strategies and improved RRT variations have been developed to increase coordination, efficiency, and flexibility in challenging situations.

6.1. Addressing the research questions

Research question 1. How have RRT algorithms evolved and been utilised in single robot path planning, and what are the significant findings in this domain?

The development of RRT algorithms for single robot path planning shows a transition from rudimentary exploration algorithms to sophisticated, domain-specific approaches. Some of the most important discoveries in this field show how well RRT variations deal with obstacles, including constrained spaces, non-holonomic mobility, and complex motion. These results have improved the safety and effectiveness of single-robot navigation in many different settings.

Research question 2. What are the critical insights and developments in multi-robot route planning, and how have RRT algorithms been adapted and extended for use with multiple robot systems?

Critical insights for multi-robot route design center on enhancing coordination, flexibility, and productivity. Cooperative multi-robot planning in uncertain and complicated situations is now possible due to modified RRT algorithms. These modifications provide an understanding of the benefits and drawbacks of multi-robot systems, which helps advance their use in tasks that call for robust and efficient collaboration.

6.2. Limitations

It is possible that a publishing bias was introduced into the study's conclusions due to the selection of papers used to create the review. Some essential contributions were left out since not all relevant research was included.

- Robotics and motion planning are an ever-evolving field. Therefore, the review may include only some recent innovations and trends after the date it was based on.
- The breadth and accuracy of the conclusions could be affected by the varying quality of the examined studies. Some articles may present more thorough methods and findings than others.
- Research in robotics frequently draws from multiple disciplines, including those of computer science, engineering, and artificial intelligence. The breadth and depth of the interdisciplinary research on this topic may be beyond the scope of this review.

Despite these limitations, this comprehensive evaluation is an invaluable tool for robotics academics, professionals, and enthusiasts. It contributes to the development and advancement of robotics by laying the groundwork for knowing the background, current status, and probable future directions of RRT algorithms in single and multi-robot path planning.

6.3. Emerging areas and future directions

- There is much potential in the combination of RRT algorithms and machine learning methods. Real-time adaptation and decision-making in path planning can be significantly improved by machine learning, especially in dynamic settings.

- Using RRT algorithms in human-robot collaboration settings is a promising new direction to explore. Future advances may focus on enhancing the efficiency and safety of interactions between robots and human operators.
- Another developing topic is the application of RRT algorithms to autonomous systems like self-driving cars and Uncrewed Aerial Vehicles (UAVs). The accuracy and reliability of autonomous navigation can be improved with the help of refined RRT algorithms.
- Going forward, we will focus on creating RRT algorithms that can easily adjust to new conditions. Fast thinking, flexibility, and the ability to adapt to changing circumstances are all required.
- There is a rising interest in extending RRT algorithms to enable multi-robot swarming and collective intelligence. The focus of this area is to find ways to make large-scale multi-robot systems more efficient and flexible.
- Underwater exploration and space missions are two resource-constrained areas that could benefit from RRT algorithms. Extremely effective path-planning techniques are needed in these cases.
- RRT algorithms have the potential to contribute significantly to emergency and relief efforts. Search-and-rescue robots need better path-planning strategies. Therefore, researchers should work to improve those.
- There will be a great deal of potential for new uses and developments as RRT algorithms advance for both single-robot and multi-robot path planning. To fully utilize RRT algorithms in tackling complicated real-world issues, researchers and practitioners need to keep abreast of these developments and emerging fields.

7. Conclusion

An in-depth investigation of RRT algorithms for single and multiple robots has revealed a developing landscape of path-planning techniques, which is shaping robotics research. The purpose of this study is to provide a comprehensive overview of RRT algorithms by critically examining 70 carefully selected publications released between 2015 and 2023. This systematic review intended to thoroughly explore the landscape of Rapidly Exploring Random Tree (RRT) algorithms and their applications in single and multi-robot path planning. Throughout the review, we looked at how RRT algorithms have evolved, how they differ from one another, how they are used in the real world, and what researchers have learned about these topics. Analysing numerous scholarly works, we learned how RRT algorithms have developed to meet the changing demands of various surroundings and robot types.

Implications for Robotics Research are numerous:

- The implications of this systematic review for robotics research are manifold. They highlight the significance of RRT algorithms in path planning and the need for ongoing research and development in this area.
- The results of different RRT versions and adjustments have the potential to significantly improve the navigation of a single robot under challenging environments. Researchers can use this knowledge to enhance the dependability and

safety of autonomous robots by creating more powerful and efficient algorithms for them.

- Optimal teamwork among robots has been better understood because of research into RRT algorithms for multi-robot coordination and planning. These results can be expanded upon in future studies to create more flexible, scalable, and robust solutions for multi-agent systems.
- The flexibility of RRT algorithms has been proved in several fields, including agriculture, medical robots, and autonomous driving. These results highlight the need for more study into how path-planning technologies can be adapted to the individual needs of various sectors and tasks.
- With more and more robots working with humans, RRT algorithms can help improve the state of the art regarding security and productivity in this field. Incorporating RRT-based path planning into collaborative robots can result in more intuitive and cooperative robotic systems.
- This comprehensive analysis has shed light on promising new research avenues, such as combining machine learning with autonomous systems, real-time adaptation, and swarms of many robots. These results show that RRT algorithms will play a significant role in the future of robotics research.
- Finally, this research has provided an in-depth look at how RRT algorithms have developed over time and how they can be used for path planning with one or more robots. This study shows that robotics is still vital due to research trends, significant findings, and upcoming fields. RRT algorithms contribute significantly to robotics and its practical applications by simplifying previously intractable problems and enhancing navigation and coordination.

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