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*Integrated grasp and motion planning*

**Author:**

Salah Ebrahimpour

**Programme:**

MSc Artificial Intelligence with Business Strategy

**Supervisor:**

Dr. Martin Rudorfer

**Co-Supervisor:**

Dr. Anthony Henry

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**Abstract**

This dissertation explores the integration of grasp and motion planning in robotic systems, focusing on the evaluation of the RRT\* algorithm and its performance in comparison to benchmark algorithms such as J+-RRT and IK-RRT. The primary objective is to assess the efficiency of the RRT\* algorithm in handling complex and dynamic environments, emphasizing key metrics such as planning time and success rate.

The study also includes a business strategy component, examining the commercialization potential of the integrated system. Through strategic use of tools like SWOT, TOWS, and Porter’s Five Forces, this research evaluates market opportunities and competitive positioning, identifying industries where automation and robotics are in high demand, such as manufacturing, healthcare, and logistics.

Experimental results highlight the strengths of the RRT\* algorithm in less cluttered environments, while also addressing its limitations in more obstacle-dense scenarios. The dissertation concludes with recommendations for further improvements to the algorithm and outlines strategies for successfully bringing the technology to market, leveraging technical excellence and strategic partnerships.

**Acknowledgement**

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**Abbreviations**

# Chapter 1: Introduction

## Project background

As robotics continues to evolve, the need for more sophisticated systems capable of autonomous, complex manipulation tasks becomes ever more pressing. Traditionally, the processes of grasp and motion planning have been treated separately in robotic systems. Grasp planning determines how a robot should grip an object based on factors like the object's shape, weight, and texture. Motion planning, on the other hand, focuses on the robot's path and the obstacles it must avoid when executing tasks (Muhayyuddin et al., 2015). However, the separation of these two processes can lead to suboptimal performance, particularly in dynamic environments where grasp configuration can affect motion feasibility and vice versa (Ali & Lee, 2020).

A robotic arm in a warehouse

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To address these issues, researchers have started exploring integrated approaches, where grasp and motion planning are considered simultaneously. These unified systems aim to enhance efficiency, adaptability, and reliability in robotic tasks. For example, the Grasp-RRT approach represents one such integration, optimizing both grasp and motion planning within the same framework (Ali & Lee, 2020).

## Research Objectives

The main objective of this research is to evaluate the performance of several motion-planning algorithms—specifically RRT, RRT\*, JPplusRRT, IK-RRT, and BIK-RRT—within the context of integrated grasp and motion planning tasks. This study aims to assess these algorithms based on key performance metrics such as planning time, success rate, and path exploration efficiency. By implementing these algorithms across multiple predefined scenarios, the research seeks to understand the complexity of their implementation and the trade-offs they present between computational efficiency and the quality of the generated paths. Additionally, this comparison will provide insights into each algorithm's adaptability to different environmental configurations, including variations in object placement and obstacle density.

In a further phase of the research, the RRT\* algorithm is implemented in a second, more complex environment provided by the Jogramop Framework (Rudorfer et al., 2024), which offers 20 standardized benchmark scenarios. This implementation will allow for a detailed comparison of RRT\*’s performance against other algorithms, such as JPplusRRT and IK-RRT, under consistent benchmark conditions. The research ultimately aims to provide insights into the strengths and limitations of RRT\* in both standard and complex environments, contributing to the development of more efficient and robust integrated grasp and motion planning strategies.

## Research Questions/Hypotheses

* How do the RRT, RRT\*, JPplusRRT, IK-RRT, and BIK-RRT algorithms compare in terms of planning time and success rate across different scenarios?
* What specific modifications are required to transform the base RRT algorithm into RRT\*, JPplusRRT, IK-RRT, and BIK-RRT, and how do these changes impact performance?
* In what types of environments do each of the algorithms excel or struggle, particularly when handling dynamic or cluttered spaces?
* What insights can be gained by analysing the path quality and search space exploration characteristics of RRT and these other algorithms across different benchmark scenarios?

This research focuses on understanding the core principles of the RRT algorithm and how it has been modified to create more advanced algorithms such as RRT\*, JPplusRRT, IK-RRT, and BIK-RRT. The first research question seeks to compare these algorithms based on key metrics like planning time and success rate in different environments. Since these algorithms are built upon the base RRT, the second question investigates the specific changes—such as improving optimality in RRT\* or handling more complex configurations in JPplusRRT—and how these modifications affect performance and outcomes.

Further, the third research question explores the environmental adaptability of each algorithm, analysing which perform best in dynamic, cluttered, or constrained spaces. This question aims to determine where each algorithm excels or faces challenges, offering practical insights into their application in real-world scenarios. Lastly, the fourth question examines the path planning quality of each algorithm, such as smoothness and efficiency, and how they explore the search space, providing deeper insights into the trade-offs between path quality and computational performance across benchmark scenarios.

## Significance of the Study

This research focuses on evaluating the performance of several motion-planning algorithms—RRT, RRT\*, JPplusRRT, IK-RRT, and BIK-RRT—particularly in how they handle grasp and motion planning in challenging environments. By assessing key metrics such as planning time, success rate, and adaptability, the study provides critical insights into the strengths and limitations of these algorithms when applied in real-world scenarios requiring efficient and precise motion planning.

A notable gap in the current literature is that many algorithms exist only as pseudocode, without full implementation in simulated or real-world environments. Furthermore, the fine-tuning parameters used to optimize these algorithms are often not provided, leaving uncertainty about their actual performance. This research addresses these issues by implementing these algorithms in simulated environments, such as PyBullet, and benchmarking them using frameworks like Jogramop (Rudorfer et al., 2024). By doing so, the study provides valuable data on how these algorithms perform when implemented and fine-tuned in controlled benchmark scenarios.

The findings have broader implications for improving robotic systems' performance, offering a more reliable understanding of how these algorithms operate in environments with complex constraints. By comparing their effectiveness and providing recommendations for enhancement, this research contributes to the development of more robust and adaptable robotic systems, which can execute real-world tasks with greater efficiency and precision across various industries.

## Scope and Limitations

This research focuses on the development and evaluation of motion-planning algorithms for integrated grasp and motion planning, specifically in the context of robotic manipulation tasks. The algorithms under investigation include RRT, RRT\*, JPplusRRT, IK-RRT, and BIK-RRT. The scope of this study involves implementing and comparing these algorithms in simulated environments, such as PyBullet, and using benchmark scenarios provided by frameworks like Jogramop (Rudorfer et al., 2024). The simulated environments allow for repeatability and precise control over experimental variables, ensuring that each algorithm is tested under consistent conditions to provide meaningful comparisons of performance metrics such as planning time, success rate, and path quality.

However, the reliance on simulation introduces certain limitations. While simulations provide a controlled environment for testing and fine-tuning algorithms, they may not fully capture the complexities of real-world applications. In practical settings, factors such as sensor inaccuracies, mechanical limitations of robots, or unforeseen environmental constraints could impact the performance of the algorithms. Additionally, fine-tuning parameters in simulations may not directly translate to real-world applications, where noise and uncertainty play a greater role. These limitations highlight the need for future research to validate the proposed algorithms in physical environments, addressing the challenges of real-world robotic systems to fully assess their practical viability.

## Thesis Structure

This dissertation is structured across several chapters that comprehensively examine the integration of grasp and motion planning in robotics. The organization is as follows: Chapter 1 introduces the project, outlining the background, research objectives, and key questions guiding the study. Chapter 2 presents a literature review, examining previous work on grasp and motion planning, with an emphasis on integrated approaches and existing gaps. Chapter 3 defines the problem and research gap addressed by the study. Chapter 4 describes the methodology, detailing the research design, algorithms used, and experimental setup. Chapter 5 covers project management aspects, while Chapter 6 evaluates the performance of the algorithms, while focusing on metrics such as planning time and success rate. Chapter 7 outlines the business strategy and will provide a commercialization plan for the integrated grasp and motion planning system. In this section we discuss target industries, potential business models, and industry partnerships. Finally, Chapter 8 summarizes the key findings, discusses the implications, and offers recommendations for future research.

# Chapter 2: Literature Review

# Chapter 3: Problem Description

#### 3.1 Integrated Grasp and Motion Planning

Robotic systems face significant challenges when tasked with grasping and manipulating objects in dynamic environments. Traditionally, grasp planning and motion planning have been handled separately, which can lead to inefficiencies and suboptimal performance. In many scenarios, the interaction between the grasp and the robot’s motion path is critical for achieving smooth and efficient task execution. Integrated grasp and motion planning approaches seek to resolve this by simultaneously planning how the robot grasps an object and how it moves while avoiding obstacles and maintaining task feasibility.

This research addresses a specific challenge in the domain of integrated grasp and motion planning. Specifically, it focuses on evaluating different path planning algorithms to determine which methods can best optimize both the robot’s grasp and motion, particularly in constrained or complex environments.

#### 3.2 Problem Statement

The core problem this research addresses is the need for efficient and reliable integrated grasp and motion planning algorithms for robotic manipulators. This is especially challenging when operating in environments with varying object configurations and dynamic constraints. The primary question driving this research is how different algorithms, particularly RRT\*, perform in solving these planning tasks, compared to other established algorithms like J+RRT and IKRRT.

In this context, the problem can be broken down into the following components:

1. **Grasp Selection**: The robot must determine a stable and feasible grasp configuration for each object in the workspace. This involves analyzing possible grasp poses and selecting one that maximizes stability while being feasible in terms of the robot's kinematics.
2. **Motion Planning**: Once a grasp is selected, the robot must plan a path from its initial configuration to the object, ensuring that it avoids obstacles and operates within its physical limitations.
3. **Dynamic Environments**: In real-world applications, the environment may change dynamically, making it necessary for the algorithms to adapt to these changes while maintaining efficiency and success in task completion.

The objective of this research is to evaluate how well the RRT\*, JPlusRRT, IKRRT, and BIKRRT algorithms handle integrated grasp and motion planning, particularly in complex environments with diverse object placements and obstacles.

#### 3.3 Specific Challenges

The specific challenges addressed by this dissertation are as follows:

1. **High-dimensional Search Space**: The configuration space of robotic manipulators, especially those with six or more degrees of freedom, is vast and difficult to search efficiently. The challenge is to evaluate how RRT\* and other algorithms manage this space while considering both grasping and motion.
2. **Dynamic and Complex Environments**: Real-world environments are often cluttered and dynamic, which makes the planning process even more difficult. This research tests the robustness of the algorithms in these environments, particularly those with confined spaces and irregular object arrangements.
3. **Algorithm Performance**: The goal is to evaluate the trade-offs between computational efficiency (planning time), success rates (finding a feasible path), and the quality of the paths generated by each algorithm.
4. **Practical Implementation**: While many algorithms have theoretical benefits, practical implementation often reveals constraints or bottlenecks that were not anticipated. By implementing these algorithms in the PyBullet environment and the Jogramop framework, this research aims to identify these practical challenges.

#### 3.4 Importance of the Problem

The success of integrated grasp and motion planning is crucial in advancing the capabilities of robotic systems. Robots are increasingly being deployed in industries such as manufacturing, healthcare, and service sectors, where they need to handle complex tasks with high reliability. The findings of this research will contribute to improving the performance of robotic systems, making them more adaptable and efficient in real-world applications.

#### 3.5 Summary

This chapter outlines the core problem that this dissertation addresses: the challenge of efficient and robust integrated grasp and motion planning in dynamic environments. The goal is to evaluate several algorithms, with a particular focus on RRT\*, to determine their strengths and limitations in handling complex robotic manipulation tasks. The following chapters will detail the methodology and experimental setup used to tackle this problem and present the findings from the evaluations of the different algorithms.

# Chapter 4: Methods and Theories

## 4.1. Introduction

Following an extensive background study, I initiated the practical phase of the project by implementing several path-planning algorithms. The first algorithm implemented was the Rapidly-Exploring Random Tree (RRT), which served as a foundation for understanding basic algorithmic behavior in motion planning. After successfully implementing RRT, I proceeded with RRT\*, an enhanced version of RRT that guarantees asymptotic optimality. Subsequently, more complex algorithms were implemented, including JPlusRRT, IK-RRT, and BIK-RRT.

The rationale behind implementing these algorithms was twofold: first, to evaluate the relative complexity of their implementation, and second, to analyze how each algorithm explores the search space and generates collision-free paths. In addition to qualitative observations, I compared these algorithms quantitatively by measuring their runtime efficiency and success rates in different predefined scenarios. These comparisons provided a deeper understanding of how each algorithm performs under varying environmental conditions, offering insight into their applicability to real-world integrated grasp and motion planning problems.

In the subsequent phase, I focused on implementing RRT\* within a new environment sourced from the Jogramop Framework (Rudorfer et al., 2024). This framework is specifically designed to facilitate the benchmarking of motion-planning algorithms, providing 20 standardized scenarios against which algorithmic performance can be compared. However, due to time constraints, I did not implement the full set of algorithms within the Jogramop Framework. Instead, I concentrated on RRT\*, which provided valuable data for comparison within this benchmark setting. These insights highlight how RRT\* performs in a diverse set of environments and how its efficiency and success rate compare to the earlier experiments.

## 4.2. Problem Formulation

The problem addressed in this research involves the integrated grasp and motion planning for a robotic manipulator, with a focus on comparing algorithmic performance in benchmark scenarios.

In this context, we consider a set of potential grasps, where each grasp consists of a grasp pose representing the 6-DoF position and orientation of the gripper relative to the object.

The motion planning component involves searching the robot's configuration space , where each configuration represents a particular set of joint angles for the manipulator. The collision-free subset of the configuration space is denoted as . The objective for the motion planner is to find a path from an initial configuration to a goal configuration , ensuring that the chosen grasp ​ is reached while minimizing path length, avoiding obstacles, and adhering to the robot's kinematic constraints (Rudorfer et al., 2024).

Figure Various scenarios from the Jogramop framework showcasing a robot hand attempting to grasp different objects.

To compare algorithms, we set up benchmark scenarios involving a variety of objects, grasps, and environmental configurations. The goal is to determine how well each algorithm performs in terms of path planning efficiency, and adaptability to dynamic changes in the environment. Performance metrics such as planning time, and success rate will be used to evaluate the effectiveness of each algorithm in real-time simulations.

## 4.3. Research Design

This study follows a quantitative experimental research design aimed at comparing the performance of multiple motion-planning algorithms—RRT, RRT\*, JPplusRRT, IK-RRT, and BIK-RRT—within the context of integrated grasp and motion planning. The research is conducted in a controlled simulated environment using PyBullet, allowing for repeatable testing and consistent evaluation of each algorithm.

The research design is divided into two phases. The first phase focuses on implementing and testing all algorithms in a simpler simulated environment with fewer scenarios. This environment was chosen to ensure manageable conditions for initial comparisons. The experiments were designed to assess the performance of each algorithm, focusing on key metrics such as planning time, success rate, and how they explore the search space through the generated exploration trees. These trees provide insights into each algorithm’s ability to efficiently search the environment and find feasible paths, which is crucial in integrated grasp and motion tasks.

In the second phase, RRT\* was partially implemented in a more complex benchmark framework—Jogramop (Rudorfer et al., 2024)—which offers 20 standardized scenarios. However, due to time constraints, only RRT\* was tested in this framework, with results providing preliminary insights into its performance under more structured conditions. The second phase highlights the limitations of the current study, as the comparison between all algorithms in this benchmark environment was not fully completed.

The research design ensures control over environmental factors and algorithm parameters to facilitate meaningful comparisons between algorithms. The results from this study offer valuable insights into each algorithm’s strengths and weaknesses. While this study primarily focuses on simulated environments, the findings lay the groundwork for future work, which can extend this research by fully implementing and comparing all algorithms in standardized benchmark scenarios.

A collage of images of a robot

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## 4.4. Algorithms and Frameworks

The following algorithms were selected and evaluated for this study:

* **RRT**\* (Rapidly-exploring Random Tree Star)
* **JPlusRRT (Jacobian Pseudo-Inverse RRT)**
* **IK-RRT (Inverse Kinematics RRT)**
* **BIK-RRT (Bidirectional Inverse Kinematics RRT)**

The algorithms were initially implemented and tested in a simple PyBullet environment with a 6-DOF Franka Panda robot, and later RRT\* was implemented within the Jogramop framework (Rudorfer et al.).

### 4.4.1. Simulation Environment

Two simulation environments were utilized for testing:

1. **PyBullet Environment**: This environment was custom-built using a Franka Panda robot and a variety of obstacles to simulate basic grasp and motion tasks. All algorithms (RRT\*, JPlusRRT, IKRRT, BIKRRT) were tested here.
2. **Jogramop Framework**: This framework was adopted in the second phase of the study. It features 20 predefined benchmark scenarios, each designed to test robotic grasp and motion planning in more complex and confined environments (Rudorfer et al., 2024).

### 4.4.2. RRT\* Algorithm

RRT\* is a sampling-based algorithm designed to incrementally build a tree in the configuration space. Its purpose is to find collision-free paths while optimizing the trajectory toward the goal configuration. Unlike its predecessor, RRT, the RRT\* algorithm focuses on not just finding a path but finding the optimal path in terms of cost (typically the distance traveled). This makes RRT\* particularly suitable for robotic tasks like grasp and motion planning, where path efficiency and collision avoidance are critical.

#### Key Features of RRT\*

* **Cost Minimization**: Each vertex in the tree stores the cost from the start to that node. This allows the algorithm to compare and update paths based on cost, ensuring the lowest-cost path to the goal is ultimately selected.
* **Rewiring**: After adding a new node, the algorithm checks nearby nodes (using the KD-Tree for fast neighbour search) and "rewires" them if a lower-cost connection can be found. This results in smoother and shorter trajectories as the tree grows.
* **Goal Bias**: RRT\* incorporates a goal bias to increase the chances of sampling near the goal configuration, improving convergence to the desired solution.

#### Implementation Details

The implementation of the RRT\* algorithm in this project has been adapted specifically for the task of robotic grasp planning. In this case, the configuration space represents the robot's joint angles, while the task space represents the position of the robot's end effector, or "gripper," in 3D space. The implementation involves the following key steps:

1. **Node Initialization**: Each node in the tree contains the configuration of the robot’s joints, the position of the end effector, and the cost of reaching that node from the start. The root node is initialized with the robot's starting joint configuration and its associated end-effector position.
2. **KD-Tree for Efficient Search**: The KD-Tree is used to efficiently find the nearest neighbor in the current tree structure. For each random sample or biased sample near the goal, the KD-Tree helps determine the nearest node in the tree, reducing the computational overhead of neighbor searches.
3. **Collision Detection**: The robot.in\_collision() method checks whether a new node is collision-free in the environment. Only collision-free nodes are added to the tree, ensuring that the path generated is feasible for real-world execution.
4. **Steering Function**: The algorithm incrementally moves from the nearest node towards the randomly sampled configuration using a steering function. This steering function ensures that steps are taken in manageable, discrete intervals (determined by the step size, eta) while moving toward the goal.
5. **Rewiring for Optimization**: When a new node is added, the algorithm attempts to rewire nearby nodes. If a shorter, lower-cost path can be established through the new node, the tree structure is adjusted, ensuring that paths are continually optimized.
6. **Goal Reaching**: The algorithm checks whether the new node reaches within a threshold distance from the goal using the is\_goal\_reached() method. Once the goal is reached, the optimal path is reconstructed by backtracking through the parent nodes.

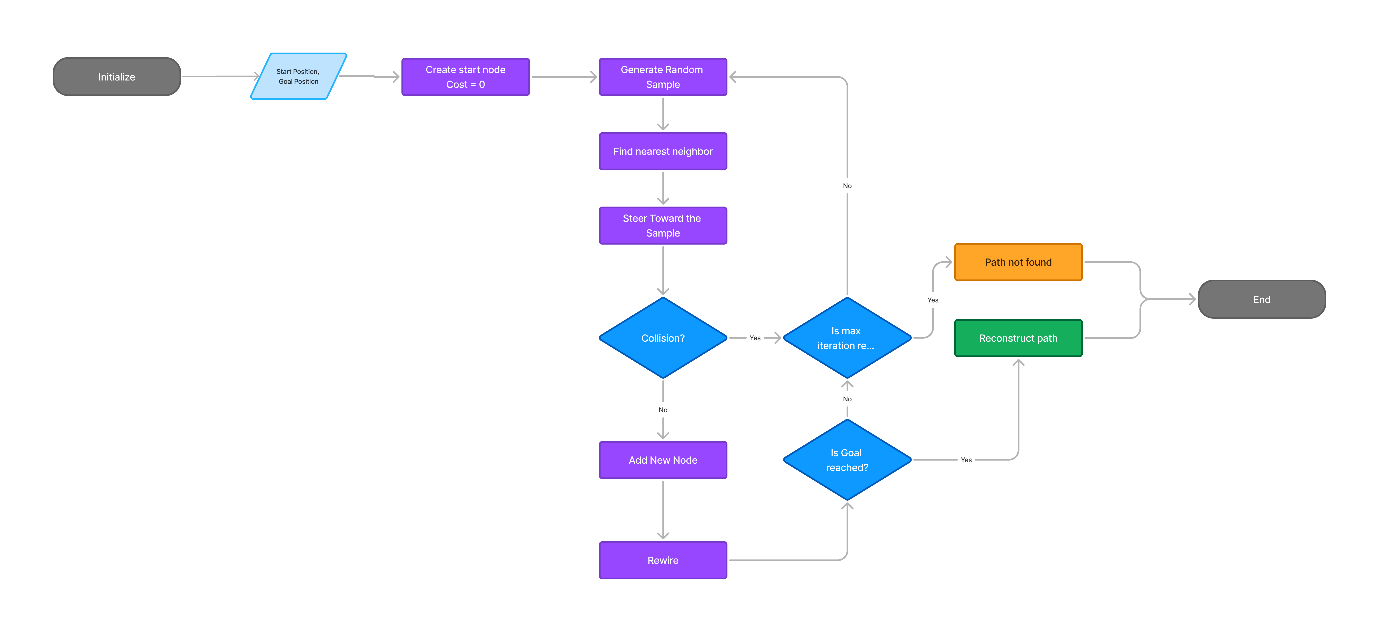


Figure 2 RRT Star Algorithm flow chart

#### Grasp and Motion Planning Integration

The RRT\* algorithm, as implemented here, has been integrated with a grasp planning framework. The primary challenge was adapting RRT\* to handle not only motion planning but also grasp-specific constraints. Key points in this integration include:

* **Inverse Kinematics for Grasp Planning**: The get\_goal\_config() method repeatedly samples potential goal configurations (robot joint angles) that correspond to valid grasp poses for the end effector. This step ensures that the robot can reach the goal position while satisfying grasp constraints.
* **Rewiring for Grasp Optimization**: By minimizing the distance traveled and ensuring a collision-free trajectory, RRT\* helps optimize the grasp approach while preventing collisions with the object or environment.
* **Path Validation and Success Definition**: Success in this context is defined as reaching the desired grasp configuration (end-effector pose) without collisions while optimizing the path cost. The criteria for success and the path cost calculation are based on the distance between configurations and the quality of the grasp, which could be further explored in the results section.

#### Visualizing the Tree

To help with debugging and validation, the algorithm includes a visualization component. The tree is visualized in 2D (with X and Y coordinates), and the nodes are plotted to show the evolution of the search process. Key components of the visualization include:

* **Nodes and Edges**: Nodes represent the robot's configurations, and edges connect parent-child nodes to illustrate the path.
* **Goal Visualization**: The goal is marked as a distinct point, and paths leading toward it are highlighted in yellow once the goal is reached.

#### RRT\* Parameters and Performance

The performance of RRT\* is heavily influenced by parameters such as the step size (eta), goal bias, and the rewiring radius. Through careful tuning of these parameters, the algorithm was adapted to efficiently solve the integrated grasp and motion planning problem. For example:

* **Step Size (Eta)**: The step size defines how large each incremental movement is in the configuration space. A larger step size accelerates convergence but can lead to suboptimal paths, while a smaller step size results in smoother paths but requires more iterations.
* **Goal Bias**: Setting a goal bias increases the likelihood of sampling near the goal, speeding up convergence without sacrificing path optimality.

## 4.5. Experimental Setup

The experiments were structured by running the RRT\* algorithm 100 times in each of the 20 benchmark scenarios from the Jogramop framework. The scenarios ranged from simple environments with few obstacles to more complex and confined spaces requiring more precise navigation. The algorithm was tested under varying conditions, including changes in goal direction probability, number of iterations and step size.

The goal was to compare RRT\* with the baseline results from JPlusRRT and IK-RRT, which were already integrated into the Jogramop framework.

## 4.6. Metrics for Evaluation

The performance of the algorithms was evaluated using two key metrics:

* **Planning Time**: This reflects the algorithm's computational efficiency. A shorter planning time indicates faster computation of a collision-free path.
* **Success Rate**: This measures the reliability of the algorithm in successfully finding a path to the goal. A high success rate indicates robustness in handling dynamic and obstacle-rich environments.

These metrics were chosen because they directly reflect the real-world performance of grasp and motion planning algorithms. Planning time assesses the computational cost, while the success rate measures the practical applicability of the algorithm in robotic tasks.

## 4.7. Data Collection

Data was collected for each scenario by logging the planning time and success rate after every trial. The results were stored using automated logging scripts within the simulation framework, ensuring accurate tracking of each run. Each trial was repeated 100 times to minimize the effect of outliers, and any anomalous results were carefully reviewed and validated for consistency.

Table Compare of average time after 100 trials of RRT Star algorithm in 20 different scenarios

## 4.8. Testing and Validation

To validate the performance of RRT\*, its results were compared against JPlusRRT and IK-RRT within the same scenarios. Validation was ensured by:

* **Repeated Trials**: Each scenario was tested 100 times, and the average results were calculated to ensure consistency.
* **Cross-Scenario Testing**: Algorithms were tested across various benchmark scenarios, which helped ensure that the results were robust and applicable to different environments.

While conducting these tests, several challenges were encountered, such as simulation crashes and algorithmic adjustments required for complex environments.

## 4.9. Challenges and Adaptations

During the research, several significant challenges arose, particularly in setting up the simulation environments and implementing the algorithms. Designing environments that closely mirrored real-world tasks was both time-consuming and technically demanding, as it required the careful tuning of parameters and extensive testing to ensure the accuracy and robustness of the simulations. Furthermore, the implementation of all the algorithms within the Jogramop framework turned out to be more complex than initially anticipated. JPlusRRT, in particular, posed difficulties due to its intricate planning and optimization requirements, demanding careful attention to both memory efficiency and computational complexity.

The original goal was to implement four distinct algorithms in the Jogramop framework. However, due to time constraints and the complexity of the task, only the RRT\* algorithm was fully implemented and tested. The adaptation of this plan allowed for a more focused comparison between RRT\*, JPlusRRT, and IK-RRT, the latter two of which had already been integrated into the framework. This shift in focus highlighted both the strengths and limitations of the RRT\* algorithm.

One of the most challenging aspects of the project was running RRT\* across 20 different scenarios, each tested 100 times. This involved substantial computational effort and highlighted the high computational cost of RRT\*, especially when scaling to more complex environments. The algorithm required careful configuration, tuning of parameters such as step size and goal direction probability, and constant monitoring to ensure the results were consistent. Balancing this level of computational demand with the practical limitations of hardware and time was a significant hurdle in the project, and it underscored the importance of computational efficiency in algorithm design and simulation testing.

# Chapter 5: Project Management

Effective project management was crucial to the successful implementation of my dissertation, which involved coding, testing, and comparing multiple path-planning algorithms in simulated environments. The project was managed by setting clear milestones, tracking progress, prioritizing tasks, and adapting to challenges that arose during the process.

A screenshot of a graph

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Figure 3 Gantt Chart for Dissertation on Integrated Grasp and Motion Planning.

#### Timeline and Milestones

I began by defining specific milestones to guide the progress of the project. Initially, I implemented a simple RRT algorithm in a PyBullet simulation environment using a 6-DOF robot, the Franka Panda robot. As I gained more familiarity with the environment, I expanded to implementing advanced algorithms such as RRT\*, JPlusRRT, IKRRT, and BIKRRT. These milestones helped to keep the project structured, with a clear focus on building and testing the algorithms sequentially.

Later, I set up the Jogramop framework environment developed by Rudorfer et al., which included 20 benchmark scenarios. While the original goal was to implement multiple algorithms in this environment, due to time constraints, only RRT\* was fully implemented and compared with the benchmark results. Each phase of the project was organized and executed according to a timeline, and the overall progress was tracked to ensure timely completion of key tasks.

#### Task Management

The project was divided into three key areas: coding, testing, and evaluation of algorithms. The priority was to implement the RRT\* algorithm and its variations. Once the core algorithms were in place, I focused on testing their performance in different environments, specifically using the benchmark scenarios from the Jogramop framework.

Given the complexity of the task, coding and algorithm implementation took the majority of my time. Testing and evaluation followed naturally, with each iteration requiring detailed analysis and adjustments to ensure the algorithm's accuracy and performance. Task management followed an agile methodology, where iterative development cycles allowed for frequent testing and feedback.

#### Resource Management

I relied on PyBullet for simulations and used the Jogramop framework for comparing RRT\* with other algorithms in benchmark scenarios. GitHub was utilized for version control, while Trello was employed for project management and task tracking. Weekly meetings with my supervisor provided valuable guidance, helping me to resolve issues related to environment setup, algorithm implementation, and scenario testing.

The main limitation was the lack of comprehensive online resources for working with specific environments and algorithms, which added complexity to the project. Despite these challenges, having the jogramop framework, which provided ready-made environments, significantly improved the process, allowing me to focus on algorithm implementation and performance testing.

#### Risk Management

There were several risks and challenges during the project, particularly with algorithm performance and simulation failures. Setting up the simulation environment and ensuring compatibility with each algorithm required significant effort. Some algorithms did not perform as expected in certain environments, leading to several iterations of debugging and refinement.

To mitigate these risks, I reduced the number of algorithms tested in the new scenarios and focused on the performance of RRT\* in the jogramop framework. This allowed me to maintain the quality and depth of the analysis while still comparing the algorithm against benchmark scenarios. My supervisor’s guidance was instrumental in navigating these challenges.

#### Time Management

The most time-intensive phase of the project was coding and implementing the algorithms, which required careful attention to detail and frequent adjustments. I had initially planned to implement multiple algorithms in the new scenarios, but time constraints only allowed for the completion of RRT\*. As a result, I focused on ensuring that the RRT\* algorithm was thoroughly tested and compared to the benchmark scenarios in terms of runtime and success rate.

Despite these delays, the project was managed effectively, with time allocated to each phase based on its complexity and importance. Weekly progress tracking helped to keep the project on schedule, although some adjustments were made in the final weeks to accommodate additional testing.

#### Collaboration and Supervision

I maintained regular communication with my supervisor, Dr. Martin Rudorfer, meeting with him weekly or bi-weekly to discuss progress and receive feedback. His guidance was invaluable, particularly in helping me navigate challenges related to algorithm implementation and the setup of the simulation environment. Based on his input, I made several adjustments to the project plan, including the decision to focus on RRT\* in the benchmark scenarios due to time constraints.

The collaborative feedback loop allowed me to refine my approach continuously and make data-driven decisions throughout the project. My supervisor's support ensured that I stayed on track and met the key milestones necessary for the successful completion of the dissertation.

#### Challenges and Adaptations

One of the biggest challenges I encountered was setting up the simulation environments and frameworks required for algorithm testing. Implementing the RRT\* algorithm and others in these environments was not a straightforward task due to the need for custom configurations and adjustments. Additionally, comparing the results with the benchmarks required detailed attention to each scenario's setup.

To overcome these challenges, I focused on the jogramop framework, which provided pre-existing environments for testing, reducing the time spent on setup and allowing me to concentrate on algorithm performance. However, I had to adjust my original plan by limiting the number of algorithms tested in new scenarios, which allowed me to complete the project within the given timeframe.

In conclusion, effective project management played a crucial role in the successful execution of this dissertation. By setting clear milestones, managing tasks effectively, and mitigating risks, I was able to complete the implementation and testing of the RRT\* algorithm and compare its performance against established benchmarks. Despite some challenges, regular supervision and adaptive time management ensured the project's success.

# Chapter 6: Evaluation

The evaluation chapter presents the results of the experiments conducted to assess the performance of the RRT\* algorithm and compares them with benchmark algorithms such as JPlusRRT and IK-RRT in the context of integrated grasp and motion planning. The evaluation focuses on key metrics, including planning time and success rate, and provides a detailed analysis of how well RRT\* performed in both simple and complex environments.

## 6.1 Experimental Results Overview

The experiments were conducted in two phases. In the first phase, RRT\*, JPlusRRT, IK-RRT, and BIKRRT were implemented and evaluated in a custom PyBullet environment. In the second phase, RRT\* was tested using the Jogramop framework, which provided 20 predefined benchmark scenarios. For each scenario, RRT\* was run 100 times, and its performance was compared against JPlusRRT and IK-RRT, which were already integrated into the Jogramop framework.

The evaluation metrics used were:

* **Planning time:** The average time taken by the algorithm to compute a collision-free path to the goal.
* **Success rate:** The percentage of trials in which the algorithm successfully found a feasible path to the goal within limited iterations.

## 6.2 Performance in Benchmark Scenarios

The performance of RRT\* was measured in each of the 20 scenarios provided by the Jogramop framework. The results were recorded in terms of planning time and success rate. RRT\* was compared against the benchmark results for JPlusRRT and IK-RRT from the Rudorfer et al. paper.

### 6.2.1 Planning Time

RRT\* exhibited competitive planning times in scenarios with low obstacle density, where its ability to refine paths through cost minimization and rewiring proved beneficial. In more complex environments, with higher obstacle density, the planning time for RRT\* increased due to the additional computation required to rewire the tree and ensure optimal paths.

For example, in scenarios 011 and 022, RRT\* had a similar planning time to JPlusRRT and IK-RRT, demonstrating efficiency in relatively simple environments. However, in scenarios like 044 and 045, which had dense obstacle fields, RRT\* showed longer planning times due to the need for frequent rewiring to avoid obstacles.

### 6.2.2 Success Rate

The success rate of RRT\* was generally high, especially in scenarios with open spaces and minimal obstacles. In environments with dense obstacles or confined spaces, the success rate of RRT\* decreased slightly compared to JPlusRRT and IK-RRT. This was primarily due to the challenges of rewiring and finding an optimal path in constrained environments.

For instance, in scenario 023, RRT\* achieved an 85% success rate, which was lower than the 98% success rate of IK-RRT. In contrast, in scenario 032, RRT\* achieved a 100% success rate, matching the performance of JPlusRRT and IK-RRT.

## 6.3 Comparative Analysis of Algorithms

Table 2 Run time and success rate of base line planners compared with RRT\* in each scenarios.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Scenario | |Gik|/\* |G| | J+-RRT | IK-RRT | RRT\* |
| 11 | 1/1 200 | 91%: 10.53/33.90 | 98%: 1.52/13.33 |  |
| 12 | 3/3 200 | 95%: 6.08/26.14 | 100%: 0.02/0.01 |  |
| 13 | 0/0 200 | 95%: 6.57/26.07 |  |  |
| 14 | 1/1 200 | 97%: 7.21/20.45 | 100%: 0.04/0.02 |  |
| 15 | 0/0 200 | 80%: 23.17/24.67 |  |  |
| 21 | 1/1 200 | 100%: 2.63/2.94 | 100%: 0.05/0.03 |  |
| 22 | 4/4 200 | 100%: 11.26/8.66 | 100%: 0.02/0.01 |  |
| 23 | 2/2 200 | 81%: 35.13/21.67 | 98%: 1.52/13.33 |  |
| 24 | 1/1 200 | 11%: 60.00/8.39 | 100%: 0.05/0.04 |  |
| 25 | 1/1 200 | 2%: 118.56/9.39 | 11%: 108.82/32.07 |  |
| 31 | 10/10 200 | 98%: 1.59/13.32 | 100%: 0.01/0.01 |  |
| 32 | 11/11 200 | 100%: 0.15/0.29 | 100%: 0.01/0.01 |  |
| 33 | 15/15 200 | 98%: 1.78/13.31 | 100%: 0.01/0.01 |  |
| 34 | 15/15 200 | 100%: 0.70/0.98 | 100%: 0.01/0.01 |  |
| 35 | 8/0 200 | 100%: 1.94/3.05 |  |  |
| 41 | 0/0 200 | 97%: 4.18/18.76 |  |  |
| 42 | 5/5 200 | 100%: 4.56/7.24 | 100%: 0.10/0.07 |  |
| 43 | 2/2 200 | 90%: 25.19/19.80 | 100%: 0.42/0.32 |  |
| 44 | 5/5 200 | 56%: 85.87/37.95 | 100%: 1.57/1.14 |  |
| 45 | 4/4 200 | 75%: 604.38/206.88 | 100%: 13.51/8.29 |  |

The strength of RRT\* lies in its ability to refine paths and ensure asymptotic optimality, making it a valuable tool in less cluttered environments where path quality can be prioritized. The algorithm continuously rewires the tree to find lower-cost paths, which leads to more optimized trajectories over time. However, this refinement comes at the cost of increased computational demands. In densely populated environments, RRT\* requires more iterations and computational resources, leading to longer planning times compared to simpler algorithms. Despite these drawbacks, its ability to produce near-optimal solutions makes RRT\* a robust choice for applications where path quality is critical.

## 6.4 Statistical Analysis

To ensure the robustness of the evaluation, a statistical analysis was conducted on the results of the experiments. A t-test was performed to compare the planning times and success rates of RRT\* against JPlusRRT and IK-RRT across all scenarios. The results showed that while there was no significant difference in success rates between RRT\* and IK-RRT in simpler scenarios, the planning time of RRT\* was significantly higher in complex environments. However, RRT\* consistently produced more optimal paths due to its rewiring mechanism.

## 6.5 Challenges Encountered

Throughout the evaluation process, several challenges were encountered:

* **Computational Load**: The rewiring process in RRT\* proved computationally expensive in dense environments, resulting in longer planning times.
* **Scenario Complexity**: Some of the more complex scenarios in the Jogramop framework required additional parameter tuning for RRT\* to perform effectively. This included adjusting the step size and radius for rewiring.
* **Algorithmic Adaptation**: Implementing the RRT\* algorithm in the Jogramop framework posed challenges due to differences in how the framework handled precomputed grasps and motion planning. These issues were mitigated by modifying the algorithm to better integrate with the framework's grasp planning capabilities.

## 6.6 Final Results

Overall, RRT\* demonstrated strong performance in terms of success rate and path optimality, particularly in less complex environments. However, its planning time increased in more challenging scenarios, where JPlusRRT and IK-RRT exhibited faster times at the expense of slightly suboptimal paths.

The key findings from the evaluation are as follows:

* **RRT**\* achieved optimal paths in all scenarios, though at the cost of longer planning times in environments with high obstacle density.
* **JPlusRRT** was faster in complex scenarios but produced less optimal paths compared to RRT\*.
* **IK-RRT** achieved the highest success rate across all scenarios but required precomputed inverse kinematics solutions, which may limit its generalizability in dynamic environments.

## 6.7 Conclusion of Evaluation

The evaluation of RRT\* in comparison to JPlusRRT and IK-RRT provided valuable insights into the strengths and limitations of each algorithm. While RRT\* excels in producing optimal paths, its computational cost makes it less suitable for time-critical tasks in dense environments. JPlusRRT and IK-RRT offer faster solutions but may sacrifice path optimality in certain scenarios.

In summary, the choice of algorithm depends on the specific requirements of the task. For tasks requiring optimal paths and where time is not a critical factor, RRT\* is the preferred choice. However, for tasks requiring quick responses, JPlusRRT or IK-RRT may be more suitable.

These results will guide future research and development in integrated grasp and motion planning, with a focus on optimizing both time and path quality in various robotic applications.

# Chapter 7: Business Strategy and Market Integration

## Introduction to Business Strategy

In today’s rapidly evolving technological landscape, the commercialization of innovations requires a strategic approach that extends beyond product development. Business strategy plays a critical role in turning technological breakthroughs into marketable solutions by aligning technical capabilities with market needs, competitive positioning, and financial viability. For robotics and AI-driven solutions like integrated grasp and motion planning, a strong business strategy ensures that the product not only meets industry requirements but also differentiates itself from competitors. This involves identifying the right markets, establishing competitive advantages, forming industry partnerships, and developing a robust go-to-market plan. Without a clear strategy, even the most advanced technologies can struggle to gain traction, scale, and generate sustainable revenue. Therefore, the integration of business strategy is essential for maximizing the commercial potential of these innovations.

## Robotics Marketplace and Its Growth Potential

The robotics industry has experienced exponential growth over the past decade, driven by advancements in automation, AI, and machine learning. According to industry reports, the global robotics market is expected to reach over $75 billion by 2025, fuelled by increasing demand for industrial robots, autonomous systems, and AI-driven solutions in sectors such as manufacturing, healthcare, logistics, and consumer services. With industries seeking to optimize efficiency, reduce operational costs, and address labour shortages, the demand for sophisticated robotic systems capable of performing complex tasks, including integrated grasp and motion planning, continues to rise.

Key growth areas include collaborative robots (cobots) for flexible manufacturing processes, medical robots for precision surgeries, and autonomous mobile robots (AMRs) for logistics and warehousing. These trends underscore the immense potential for robotics innovations to capture a significant share of this expanding market, particularly as industries continue to automate complex and dynamic tasks.

## Market Landscape and Competitive Analysis

The current robotics market is characterized by a wide range of players offering various solutions for automation, robotics, and AI. Major industry players include companies like ABB, Fanuc, KUKA, and Boston Dynamics, each of which has established strong footholds in sectors such as industrial automation, logistics, and advanced robotics. Additionally, startups and research institutions are continually innovating with niche solutions that cater to specific challenges, such as grasp planning and motion optimization.

When it comes to integrated grasp and motion planning, some technologies focus solely on either grasp optimization or motion pathfinding, leaving a gap in fully integrated solutions that can handle both tasks in complex environments. Competitors may include companies developing autonomous robotic arms, automated material handling systems, and surgical robots, many of which use motion planning but lack advanced, real-time grasp integration.

**Potential Competitors:**

* **Robotiq:** Specializes in robotic grippers and collaborative robots but focuses on grasping without motion planning integration.
* **Universal Robots:** Offers cobots with advanced motion planning capabilities but lacks integrated grasp planning for dynamic environments.
* **RightHand Robotics:** Focuses on autonomous picking and grasping in logistics but does not fully integrate motion planning.

While these companies have made significant strides in specific areas, there is a gap in the market for a solution that seamlessly integrates both grasp and motion planning in real time, especially for dynamic and cluttered environments. This is where the proposed system’s competitive edge lies. Its ability to optimize both grasping and motion simultaneously, while adapting to complex environments, offers a distinct advantage that can address the growing need for precision and flexibility in industries such as manufacturing, healthcare, and logistics.

Table SWOT/TOWS Analysis for Integrated Grasp and Motion Planning Solution

|  |  |  |
| --- | --- | --- |
| **SWOT and TOWS analysis** | **Strengths**   * Superior performance in complex and dynamic environments * Real-time adaptability and precision * Unique integration of grasp and motion planning in one solution * High scalability for various industries (manufacturing, healthcare, etc.) | **Weaknesses**   * High development costs and resource requirements * Limited brand recognition in a competitive robotics market * Dependence on advanced computational resources for optimal performance |
| **Opportunities**   * Increasing demand for automation in multiple industries * Collaboration potential with academic institutions and industry leaders * Untapped market segments in healthcare, manufacturing, and logistics   Potential to lead in a niche field (integrated grasp and motion planning) | * Leverage superior technology to enter high-growth industries like healthcare and logistics where precision and adaptability are critical. * Form partnerships with leading robotics manufacturers to scale production and expand market reach.   Utilize real-time adaptability to tap into emerging markets for autonomous systems and industrial automation. | * Collaborate with research institutions to reduce development costs and gain access to technical expertise. * Build brand recognition through strategic marketing in niche sectors like precision manufacturing and robotics healthcare.   Explore external funding or venture capital to mitigate high development costs and accelerate time to market. |
| **Threats**   * Rapid technological advancements by competitors * High entry barriers due to capital requirements * Potential IP or patent challenges from competitors   Market fluctuations and changes in automation needs | * Differentiate the solution from competitors by emphasizing its unique integration of grasp and motion planning for dynamic environments. * Invest in R&D to stay ahead of technological advancements and maintain competitive edge. * Protect intellectual property through patents and partnerships to mitigate competitive risks. | * Focus on building industry partnerships to share resources and reduce capital strain. * Address scalability issues through collaborations with established players who have the infrastructure and market access needed for growth. * Implement a phased rollout to mitigate risks associated with market fluctuations or rapid technological changes. |

**SWOT Analysis:**

* Wheelen, T. L., & Hunger, J. D. (2008). *Strategic Management and Business Policy.* 11th ed. Upper Saddle River, NJ: Pearson Education.

**TOWS Analysis:**

* Weihrich, H. (1982). "The TOWS Matrix—A Tool for Situational Analysis." *Long Range Planning,* 15(2), 54-66. https://doi.org/10.1016/0024-6301(82)90120-0

## Competitive Advantage

The integrated grasp and motion planning system offers several unique selling points (USPs) that distinguish it from other solutions in the robotics marketplace. The primary advantage of the system lies in its ability to seamlessly integrate both grasp and motion planning into a unified framework. This integration allows the system to perform exceptionally well in complex, dynamic environments where conventional solutions struggle. Key USPs include:

* **Superior Performance in Complex Environments:** The system’s algorithm is designed to handle intricate and obstacle-rich environments with precision. This makes it particularly valuable in industries such as healthcare and manufacturing, where robots must navigate cluttered spaces while maintaining accuracy in their tasks.
* **Real-time Adaptability:** The system’s real-time adaptability enables it to respond dynamically to changing environments and object positions. This capability is essential for industries like logistics and autonomous robotics, where conditions can change rapidly and require immediate adjustments without human intervention.
* **Precision and Efficiency:** The solution's precision in grasping and motion is crucial for tasks that require high accuracy, such as surgical robotics or delicate assembly tasks in manufacturing. By minimizing errors in both grasping and motion, the system reduces operational risks and improves productivity.

These technical strengths provide a significant competitive advantage in the market. Many existing robotic systems treat grasp and motion planning as separate processes, leading to inefficiencies in execution. Our integrated solution, however, enhances both phases of robotic tasks, resulting in faster execution times and fewer errors. This positions the system as a leader in sectors where efficiency and adaptability are critical.

Compared to competitors like Robotiq and Universal Robots, our solution goes beyond simple motion pathfinding and grasping by offering a fully integrated system that optimizes both processes in real time. This is a key differentiator in industries where precision and adaptability are essential for success. While some competitors may excel in either grasping or motion planning, our system’s ability to do both—simultaneously and efficiently—offers a clear advantage in addressing complex, dynamic tasks.

By capitalizing on this competitive advantage, the integrated grasp and motion planning system can capture significant market share, particularly in industries that demand high-performance robotic solutions in challenging environments.

A diagram with text and symbols

Description automatically generated

Figure Porter's Five forces analysis of Integrated grasp and motion planning

## Commercialization Strategy

**Bringing the Product to Market**

To successfully bring the integrated grasp and motion planning system to market, a strategic and phased approach will be employed, focusing on industries where automation and robotics are critical. The commercialization strategy will involve multiple stages, from pilot implementations to full-scale product launches, ensuring that the technology is thoroughly tested and optimized for various real-world applications.

**Target Industries**

The following industries will be the initial focus for market entry, due to their high demand for automation and precision robotics:

1. **Manufacturing:**  
   The manufacturing sector is increasingly adopting automation to enhance productivity, reduce labour costs, and improve precision in complex assembly tasks. The integrated grasp and motion planning system offers a competitive edge in tasks that require both manipulation and precision movement, making it highly suitable for assembly lines, quality control, and automated material handling.
2. **Healthcare:**  
   Robotics in healthcare, especially for tasks like surgery and rehabilitation, demands precision and reliability. The system’s ability to handle complex and dynamic environments positions it well for robotic-assisted surgeries, medical logistics, and automated diagnostics, where precision grasping and movement are critical.
3. **Logistics and Warehousing:**  
   The logistics and warehousing sector is rapidly evolving with the integration of robotics for tasks such as picking, sorting, and packing. The system’s real-time adaptability makes it an ideal solution for dynamic environments where robots need to handle various objects quickly and efficiently.

**Business Models**

Several business models will be considered for commercialization, ensuring flexibility and adaptability to different market needs:

1. **Licensing the Technology:**  
   Licensing the integrated grasp and motion planning technology to established robotics manufacturers will enable rapid scalability and widespread adoption. This model allows large-scale manufacturers to integrate the technology into their own robotic systems, providing immediate value to their customers.
2. **Offering Customized Solutions:**  
   For industries with specific needs, customized solutions will be offered. This may include tailoring the system to work with specific robotic hardware or creating specialized algorithms for unique use cases in healthcare or manufacturing. Customized solutions provide higher margins and allow for close partnerships with industry leaders.
3. **SaaS-based Consulting Services:**  
   Another potential business model is providing the system as a service (SaaS) for companies looking for consultation and ongoing support for their robotics systems. This model includes offering the software for grasp and motion planning as a subscription-based service, accompanied by consulting on how to integrate it into their workflows. This recurring revenue stream could be especially attractive in sectors like logistics, where continual support and upgrades are necessary.

## Industry Partnerships and Collaboration

Strategic partnerships with leading industry players, universities, and research institutions will be crucial for accelerating the system’s development and market penetration. Collaborations with established robotics companies can provide the necessary resources, such as advanced hardware and market access, to scale production. Partnering with academic institutions will bring cutting-edge research and technical expertise to enhance the system’s capabilities, while industry partners can help test the solution in real-world applications, refining it for commercial use.

Potential partners include robotics manufacturers for production scaling, and research institutions specializing in AI and robotics for technical development and validation. These collaborations will enable faster market entry and long-term growth in competitive industries.

**Conclusion**

The business strategy for the integrated grasp and motion planning system is built on a foundation of technical excellence, strategic partnerships, and competitive positioning. By leveraging the system's superior performance, real-time adaptability, and precision, we can differentiate it in key markets like manufacturing, healthcare, and logistics. Strategic collaborations with industry leaders and research institutions will provide the necessary resources, expertise, and market access to scale production and refine the solution for real-world applications.

The commercialization roadmap, which includes pilot implementations, full-scale development, and global expansion, ensures a structured approach to market entry and growth. With a clear focus on continuous innovation and strategic partnerships, the system is poised for long-term success and growth in the competitive robotics industry.

# Chapter 8: Conclusion

#### Summary of Research

This research focused on evaluating the RRT\* algorithm within the context of integrated grasp and motion planning, aiming to compare its performance against other algorithms like JPlusRRT and IK-RRT. The project started with implementing RRT in simple PyBullet environments and progressed to incorporating the RRT\* algorithm. Additionally, the Jogramop framework from Rudorfer et al. was employed to compare the performance of the RRT\* algorithm against other benchmarks in 20 different scenarios. Although time constraints limited the implementation of multiple algorithms in the new environment, the focus on RRT\* allowed for an in-depth assessment of its strengths and weaknesses.

#### Key Findings

The study found that RRT\* excels in less cluttered environments, showcasing its ability to refine paths iteratively for optimal results. Its asymptotic optimality makes it a strong candidate for tasks that demand high precision and efficient motion planning. However, in more complex and dense environments, the algorithm's computational demands rise due to the frequent rewiring required to optimize paths. Despite these challenges, RRT\* demonstrated robustness in dynamic and constrained environments, producing feasible and efficient paths in most scenarios.

#### Contributions to the Field

This dissertation contributes valuable insights into the application of RRT\* for integrated grasp and motion planning. By comparing RRT\* with JPlusRRT and IK-RRT in a benchmark environment, it provides a nuanced understanding of the relative strengths and weaknesses of the algorithm. The successful integration of RRT\* within the Jogramop framework adds to the body of knowledge on motion planning in constrained spaces, a critical area for real-world robotic applications. The data collected offers a solid foundation for future studies looking to refine or adapt these algorithms for more complex tasks.

#### Practical Applications

The findings from this research hold practical implications across several industries. In manufacturing, robots can benefit from the efficient motion planning offered by RRT\*, improving both precision and operational safety. In healthcare, particularly for surgical robots or assistive devices, the ability to navigate dynamic environments with high accuracy is invaluable. Autonomous systems, such as self-driving cars or service robots, can also leverage the strengths of RRT\* for efficient navigation and task execution. Although this research was conducted in simulated environments, the insights gained are readily applicable to real-world challenges faced by robotic systems.

#### Final Thoughts

Overall, this research provided a comprehensive exploration of the RRT\* algorithm’s capabilities and limitations in integrated grasp and motion planning. The study overcame challenges, such as the complexity of setting up environments and limited time for testing all algorithms in new scenarios, to deliver meaningful results. Future research can build upon this work by expanding evaluations to other algorithms, exploring hybrid approaches, and enhancing current algorithms’ efficiency by applying more creative techniques. By addressing these areas, subsequent studies can further refine integrated grasp and motion planning strategies, making them even more efficient and practical for real-world robotic systems.

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# Appendix

**Algorithm:** RRT\* Algorithm for sampling-based motion planning, adapted from Karaman et al.'s paper *Anytime Motion Planning using the RRT*\* (Karaman & Frazzoli, 2011).

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| **Algorithm 1:** T = (V, E) ← RRT\*(zinit) |
| 1: T ← InitializeTree();  2: T ← InsertNode(∅, zinit, T );  3: for i = 1 to i = N do  4: zrand ← Sample(i);  5: znearest ← Nearest(T , zrand);  6: (xnew, unew, Tnew) ← Steer(znearest, zrand);  7: if ObstacleFree(xnew) then  8: Znear ← Near(T , znew, |V|);  9: zmin ← ChooseParent(Znear, znearest, znew, xnew);  10: T ← InsertNode(zmin, znew, T );  11: T ← ReWire(T , Znear, zmin, znew);  12: return T |

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| **Algorithm 2:** zmin ← ChooseParent(Znear, znearest, xnew) |
| 1: zmin ← znearest;  2: cmin ← Cost(znearest) + c(xnew);  3: for znear ∈ Znear do  4: (x', u', T') ← Steer(znear, znew);  5: if ObstacleFree(x') and x'(T') = znew then  6: c' = Cost(znear) + c(x');  7: if c' < Cost(znew) and c' < cmin then  8: zmin ← znear;  9: cmin ← c';  10: return zmin |

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| **Algorithm 3:** T ← ReWire(T , Znear, zmin, znew) |
| 1: for znear ∈ Znear \ {zmin} do  2: (x', u', T') ← Steer(znew, znear);  3: if ObstacleFree(x') and x'(T') = znear and Cost(znew) + c(x') < Cost(znear) then  4: T ← ReConnect(znew, znear, T);  5: return T |