RRTM Assessment 2

Dissertation Proposal - March 2024

Dissertation Guide
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Contents

1 Description

Navigation and mapping of an autonomous mobile robot in a new environment is a challenge that will been countered in many situations. This project is related to work in a complex internal space containing many pieces of machinery. The aim is to develop a map of the entirety of the space and to enable the transfer of that map to various AMRs. In the first place the start will be using a simulation environment to produce a map of the space using a cad model and generating vehicle paths for later transfer to the AMR.

2 Title of the Dissertation and Introduction

Title:
SentryMax - Mapping and Navigation Guiding Through the Labyrinth of Machinery.

Introduction:
The emergence of Autonomous Mobile Robots (AMRs) has ushered in a new era of automation, offering industries unparalleled opportunities to enhance efficiency and productivity in internal logistics and monitoring operations. However, navigating complex internal environments poses a significant challenge for AMRs, characterized by intricate layouts and machinery. Traditional navigation methods often prove inadequate in such environments, leading to inefficiencies and safety concerns. Consequently, there is a critical need for innovative methodologies to enable AMRs to map and navigate these environments with precision and reliability.

Addressing this challenge requires a holistic approach that leverages cutting-edge technologies and computational techniques. Our proposed methodology aims to harness the power of Perception and Path Planning along with computer-aided design (CAD) and simulation environments to create detailed maps of internal layouts. By integrating advanced algorithms and sensor technologies, our solution empowers AMRs to autonomously navigate through complex environments, avoiding obstacles and ensuring safe interactions with machinery and human workers. Through this approach, we seek to optimize efficiency and safety in internal logistics and surveillance operations across diverse industries.

The implications of this research are profound and promise to revolutionize internal logistics and industrial automation. By empowering Autonomous Mobile Robots (AMRs) to seamlessly navigate complex internal environments, our methodology not only paves the way for enhanced operational efficiency and cost-effectiveness but also introduces significant scalability. Incorporating map transfer and fleet integration into the system further elevates its utility, allowing for seamless information exchange and coordinated operations among multiple AMRs. Ultimately, this innovation stands to redefine the future of indoor navigation, unlocking unprecedented opportunities for growth and innovation in the global marketplace.

3 Aim and Objective

Aim:

This dissertation project aims to develop and validate an advanced SLAM (Simultaneous Localization and Mapping) framework for Autonomous Mobile Robots (AMRs) to navigate efficiently in complex, machinery-dense environments. It focuses on integrating real-time data from LiDAR sensors and 3D depth cameras for dynamic adaptation, crafting robust algorithms to generate detailed maps transferable among AMRs for enhanced fleet collaboration. Through strategic design and simulation of realistic industrial environments, the research rigorously evaluates the SLAM system's robustness and efficiency across diverse operational scenarios, aspiring to significantly improve AMR navigation precision and safety while expanding their deployment potential in critical sectors like industrial surveillance, machine monitoring, and logistics, thereby driving forward the fields of robotics and automation.

Core Objectives:

1. **Simulation Environment Creation and AMR Teleoperation:** Familiarize with utilizing ROS, RViz, and Gazebo[1] to simulate and integrate AMR navigation within an existing complex environment, assessing AMR performance under teleoperation. [**?**, 1]

2. **Development of the SLAM Framework and LiDAR-Based Navigation:** Develop and validate an advanced SLAM framework for Autonomous Mobile Robots (AMRs) to efficiently navigate known custom created simulation worlds complex, machinery-dense environments using real-time data from LiDAR sensors and 3D depth cameras.

3. **Navigation in Unknown Environments:** Evaluate the AMRs' performance in simulation to adapt the developed algorithms, allowing them to autonomously navigate[2] and map out unfamiliar environments using Rapidly Exploring Random Tree (RRT) algorithms, and assess their adaptability and mapping accuracy.[3]

4. **Advanced Algorithm Optimization:** Enhance the efficiency and accuracy of the SLAM algorithms to minimize computational demands while maximizing mapping precision and unknown environmental understanding making it robust to dynamic environments.

5. **Dynamic Obstacle Detection and Avoidance:** Develop algorithms for real-time detection and avoidance of dynamic obstacles within the environment, ensuring safe and efficient navigation of AMRs in dynamic industrial settings.[4]

6. **Continuous Map Updating and Adaptive Path Planning:** Implement mechanisms for continuous map updating and refinement to accommodate environmental changes, alongside developing adaptive path planning algorithms for real-time trajectory adjustments based on environmental feedback. This ensures accurate and reliable navigation for AMRs in complex, dynamic environments.

7. **Inter-AMR Map Sharing and Communication:** Establish inter-AMR communication links for efficient map transfer and sharing, enhancing fleet collaboration and situational awareness.

Stretched Objectives:

1. **Integration, Real-World Testing, and Simulation Refinement:** Integrate SLAM with testing hardware for real-world validation. Conduct tests on AMR platforms in industrial settings, refining navigation through simulations.
2. **Enhanced Fleet Collaboration, Autonomous Mission Planning, and Scalable Map Integration:** Develop adaptive task allocation mechanisms and real-time adjustments for AMR fleets. Implement autonomous mission planning and scalable map integration for comprehensive facility mapping.
3. **Cross-Environmental Adaptability:** Expand SLAM's applicability beyond industrial settings to various environments, enhancing versatility and broader utility of AMRs.
4. **Autonomous Mission Planning:** Implement autonomous mission planning capabilities within AMRs for strategic decision-making based on environmental data and objectives, reducing human intervention.

4 Motivation

Why Monitoring Machinery is Essential ?

Monitoring machinery in industrial environments is indispensable for multiple reasons. It guarantees operational efficiency and equipment reliability, reduces downtime by forecasting failures before they occur, and bolsters worker safety through the early identification of hazardous conditions. Continuous monitoring enables the deployment of preventive maintenance strategies, substantially reducing repair costs and extending the machinery's lifespan. Furthermore, insights gained from monitoring data highlight critical areas for improvement. For example, Figure 1 indicates the maximum number of deaths due to heavy machinery, while Figure 2a shows that the majority of mishaps, 84.2%, occur during machinery operation, and 15.8% result from malfunctions. Additionally, 52% of machinery breakdowns Figure 2b are due to improper cleaning and maintenance, underscoring the importance of regular upkeep. These statistics fuel ongoing improvements in designs and performance optimization.[5] [6] [7]

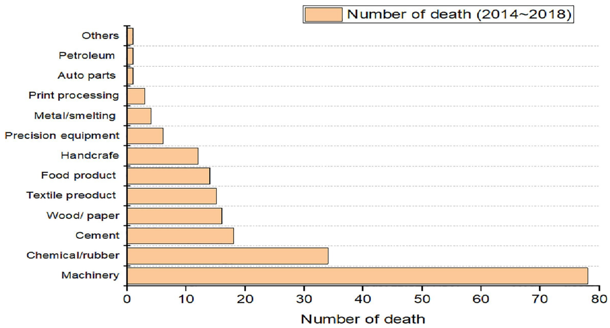
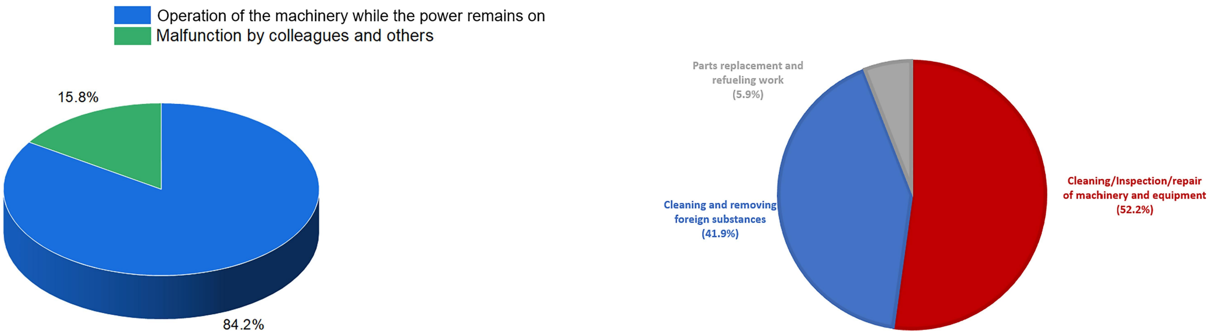


Figure 1: Number of Deaths due to Heavy Machinery



(a) Accident causes involving machinery

(b) Maintenance breakdown

Figure 2: Overview of industrial machinery safety

Why Advanced SLAM for AMRs in Industrial Environments ?

Advanced SLAM is vital for Autonomous Mobile Robots (AMRs) in industrial settings, facilitating autonomous navigation in unknown spaces. Its sophistication is crucial due to the dynamic and intricate nature of industrial environments, where obstacles and layouts change frequently. By accurately mapping surroundings and real-time self-localization, advanced SLAM ensures safe and efficient navigation around people, products, and machinery. The global autonomous mobile robots market is projected to grow at a compound annual growth rate of 15.5% from 2023 to 2030, reaching USD 9.56 billion by 2030.3

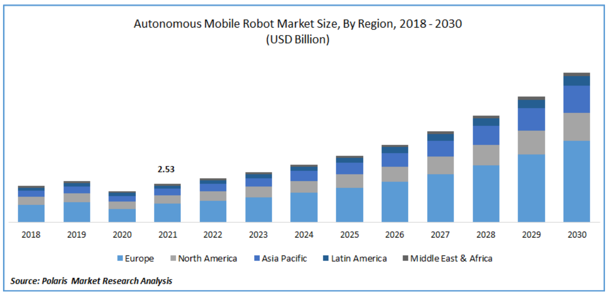


Figure 3: Predicted Growth of AMRs in Industrial Environments

What makes this method challenging?

Implementing advanced SLAM in industrial environments, as noted by [8], Navigating and mapping in dense environment with moving obstacles, the need for precise safety measures, and the heavy computational load for real-time processing. Integration complexities with multiple sensors like LiDAR and cameras further compound these challenges.[9].

What is the importance of map transfer and its wide applications?

Map transfer helps in sharing of spatial data and maps between AMRs, allowing them to collaborate more effectively and navigate shared spaces more efficiently. This capability is crucial for operations where multiple robots work together, just as in our machine dense enviornment. Map transfer enables one robot to benefit from the mapping work already completed by another, reducing redundancy and saving time. Further applications include enhanced fleet management, where robots can dynamically reassign tasks based on their location and the current state of the environment, and more complex collaborative tasks that require spatial awareness among multiple agents

Why Ethical and Social Considerations are Essential for Deployment?

When deploying Autonomous Mobile Robots in workplaces, it's essential to think about the bigger picture. This means considering how the technology affects jobs and making sure there are plans to help workers adapt. We should also protect employees' privacy, especially when robots are constantly monitoring work areas. Plus, it's important to create safe ways for people and robots to work together. Tackling these ethical and social issues shows a commitment to using technology in a thoughtful and inclusive way.[10]

Why is it both novel and challenging?

The concept of map transfer and the development of advanced SLAM technologies for AMRs are relatively new and present significant technical challenges. Designing systems that can accurately and reliably map complex environments in real time, while also being robust to changes in those environments, requires advanced computational algorithms and significant processing power. Additionally, ensuring the generated maps are interpretable by the systems for map transfer and sharing between different types of AMRs adds another layer of complexity. These challenges are compounded by the need for these systems to operate safely and efficiently in environments where humans and machines coexist.

5 Literature Review

1. **Mapping and Navigation Techniques for Autonomous Mobile Robots (AMRs)**

   Autonomous Mobile Robots (AMRs) are pivotal in revolutionizing task execution in dynamic and complex environments[2]. Their autonomy hinges on the ability to navigate and map their surroundings through Simultaneous Localization and Mapping (SLAM). Early methods like Extended Kalman Filters (EKF-SLAM) used sensor data to iteratively update maps and robot positions, setting a foundational framework [4, 11, 12]. Advances have introduced Graph SLAM and Particle Filters, enhancing data uncertainty management and marking SLAM evolution [13, 4].

   In mapping techniques, Occupancy Grid Mapping, a grid-based approach, differentiates occupied from free spaces using binary representation [12]. Feature-based mapping, on the other hand, leverages environmental features for navigation, using extraction techniques like SIFT and FPFH to improve accuracy [14, 15].

   An additional dimension to the realm of autonomous navigation is the application of Rapidly-exploring Random Trees (RRT) for path planning. RRT is a highly efficient algorithm that swiftly explores space by growing a tree rooted at the initial state and expanding towards random samples from the search space. This approach has proven to be particularly effective in complex, high-dimensional spaces and dynamic environments where traditional methods fall short. The inclusion of RRT path planning complements SLAM by providing a robust solution for real-time navigation in unknown or changing landscapes, thereby significantly enhancing the operational autonomy of AMRs [16, 17, 3].

2. **Integration of LiDAR and 3D Depth Cameras for Mapping and Navigation**

   The advancement of Autonomous Mobile Robots (AMRs) in navigating complex environments is largely attributable to the integration of sophisticated sensory technologies. LiDAR sensors and 3D depth cameras have emerged as pivotal in enhancing environmental perception. LiDAR, which gauges the return time of emitted laser beams, coupled with the depth information from 3D cameras, affords AMRs a comprehensive geometric and semantic view of their surroundings. This synergy is instrumental in bolstering advanced Simultaneous Localization and Mapping (SLAM) processes, allowing for more precise localization and mapping efforts. The effectiveness of this integration is exemplified in algorithms like LOAM (Lidar Odometry and Mapping) and LeGO-LOAM, which are designed to optimize both efficiency and accuracy in real-time environmental mapping and robot positioning [18, 19].

   AMRs are navigation methodologies such as the Rapidly-exploring Random Trees (RRT) algorithm[3]. RRT enhances path planning in unpredictable environments by efficiently exploring large spaces and identifying viable navigation paths. This algorithm, alongside its variants like RRT* and RRT-Connect, provides a framework for AMRs to navigate effectively, even in settings with complex obstacles and constraints [16, 17].

   Techniques such as Dynamic Window Approach (DWA) for obstacle avoidance and Vector Field Histograms (VFH) for steering control further enrich the navigational strategies available to AMRs. These methods enable AMRs to dynamically adjust their paths in real-time, responding adeptly to changing environments and ensuring safe and efficient operation [20, 21].

3. **Applications of AMRs in Surveillance and Machine Monitoring**

   In industrial settings, AMRs serve crucial roles in surveillance and machine monitoring, boosting safety and efficiency. These robots navigate and survey areas autonomously, using behavior-based monitoring and anomaly detection to pinpoint security threats and mechanical faults [22, 23]. Predictive maintenance models showcase AMRs' potential in failure prevention, facilitating uninterrupted operations [24].

   Moreover, the integration of predictive maintenance models further enhances the effectiveness of AMRs in ensuring continuous operations and minimizing downtime [24, 23]. By leveraging machine learning algorithms and historical maintenance data collected by AMRs, predictive maintenance models can forecast equipment failures before they occur, enabling proactive maintenance interventions to be undertaken. This proactive approach not only reduces the likelihood of unexpected equipment breakdowns but also optimizes maintenance scheduling and resource allocation.

   The deployment of AMRs in industrial surveillance and machine monitoring represents a paradigm shift in operational practices, offering unparalleled capabilities in terms of efficiency, accuracy, and safety. As research and development efforts continue to advance, further refinements in sensor technologies, data analytics algorithms, and predictive maintenance strategies are anticipated, paving the way for even greater integration of AMRs in industrial automation and maintenance workflows.

4. **Challenges and Future Directions**

   Despite significant progress, deploying AMRs in real-world scenarios faces challenges like adaptability to dynamic environments, scalability, and real-time processing. Future research aims to tackle these through more efficient SLAM algorithms, incorporating deep learning for better environmental interaction, and exploring collaborative multi-robot systems for task efficiency [25, 26]. Ethical and regulatory issues concerning privacy and safety will also be central to AMRs' broader acceptance.

6 Impact Assessment

In this research, we delve into reshaping how AMRs function in the dynamic industrial landscape to enhance navigation and monitoring alongside inter-AMR communication amidst heavy machinery. We also target for smoother cooperation between robots and humans, setting improved standards in workplace safety. This segment on risk assessments explores how such redefined roles can lead to improved safety and efficiency. We'll dive into risk assessments to understand how AMRs can enhance both safety and productivity:

(+): Potential Benificial; (-): Potential Risky; (/): Uncertain

1. **Enhancing Workplace Safety (+):** By deploying AMRs for tasks in high-risk areas and machine monitoring, the number of individuals exposed to potential harm is reduced, resulting in a notable decrease in workplace incidents. OSHA (Occupational Safety and Health Administration)[27] underscores the imperative for ongoing workplace safety enhancements, as evidenced by the staggering report of over 2.8 million nonfatal workplace injuries and illnesses in 2019 alone.

2. **Efficiency and Productivity (+):**

   (a) Uninterrupted Production: In the future factory, all machinery operates continuously, driven by timely monitoring by AMRs tirelessly working to ensure the safety of the machines. This relentless workflow has the potential to revolutionize productivity metrics.[6, 7]

   (b) Agile Operations: With the ability to map unknown spaces and swiftly share insights, AMRs can adapt as rapidly as the industrial landscape changes. This ensures they remain aligned with the latest layout modifications, enhancing efficiency and productivity.

3. **Technological Leap (+):**

   (a) Pushing Boundaries in SLAM Technology: This research isn't just another notch in the belt of robotics; it's may be a potential milestone in SLAM technology, paving the way for AMRs that can master the maze of complex environments.

   (b) Collective Intelligence: By developing the method of map sharing, this research not only enhances individual robot efficiency but also focuses on forming a network of shared multi-agent intelligent AMR fleets that amplify collective intelligent task in the dynamic industries.

4. **Environmental Considerations (/):** The increase in deployment of Autonomous Mobile Robots (AMRs) poses an energy dilemma while they may increase energy usage initially, their potential to streamline operations offers hope for overall efficiency gains. However, the sustainability of materials and manufacturing processes is a critical concern. This could be addressed by Regulatory bodies for recycling of the robot components. Balancing energy consumption with material sustainability is key to navigating the environmental impact of deployment.

5. **Economic Waves (+/-):** Using AMRs to automate tasks can really trim operational costs—think cutting down on labor costs, insurance, and more, making our expenses leaner as time goes on. But as AMRs step in, some jobs are going to change or even become unnecessary. That's why it's crucial to have solid retraining programs in place. We've got to help the workers transition into new tech-focused careers so everyone can keep moving forward together as technology advances.

6. **Ethical and Social Dynamics (/):** As we dive into automation, ensuring everyone has equal access to new job opportunities and the necessary training. It's about maintaining fairness so that nobody is left behind in the changing landscape. And as we get deeper into using AMRs and advanced SLAM tech, We need to conisder the implications of how strong our industrial systems are against things like tech glitches or cyber attacks.

7. **Legal and Regulatory Pathways (/):** The advent of AMRs calls for a unified approach to safety protocols, data security, and operational standards by international governments, industries and establishment of regulatory bodies ensuring these innovations enrich society equitably. In an era where AMRs map and memorize every nook, ensuring the privacy and security of this data is non-negotiable, demanding stringent legal safeguards and encryption measures.

7 Risk Register

Risk Register and Mitigation Strategies

Identifying and devising contingency mitigation's for potential risks occurring during research is critical. These potential risks, elaborated in Figure 4, aid in raising awareness of issues during the execution phase and devising possible solutions. Addressing these risks proactively not only helps during execution but also assists in deciding the importance of each task.

Risk ID	Task	Risk	Likelihood	Impact	Mitigation Strategies	Risk Level
1	Simulation Environment Setup	Inaccurate representation of the real-world environment in the simulation	Low	Medium	Thoroughly validate Gazebo enviornent and CAD models and environmental parameters before integration. Conduct iterative testing and validation throughout the setup process. Utilize reference materials and expert consultation for accurate representation.	Medium
		Technical challenges in integrating CAD models into the simulation environment	Low	Medium Low	Allocate sufficient time for troubleshooting and debugging. Engage with the simulation software community for support and guidance. Develop contingency plans for alternative integration approaches.	Medium Low
2	Mapping Algorithm Development	Algorithm performance may not meet the desired accuracy and efficiency standards	Medium High	High	Conduct comprehensive benchmarking and validation against ground truth data. Implement algorithm optimization techniques to improve performance. Plan for iterative refinement based on feedback and testing results.	High
		Limited availability of sensor data for mapping algorithm development	Low	Medium Low	Explore alternative sensor options Intergation options or data augmentation techniques.	Low
3	Path Planning Algorithm Development	Complexity of the environment may lead to suboptimal path planning solutions	Medium Low	Meidum High	Implement advanced path planning algorithms capable of handling complex environments. Conduct thorough testing and validation in diverse scenarios. Incorporate dynamic re-planning mechanisms to adapt to changing conditions.	Medium High
		Inadequate consideration of heavy machinery dynamics in path planning algorithms	Meidum Low	Meidum	Collaborate with Guide to understand the behavior of heavy machinery. Incorporate realistic dynamics models and constraints into path planning algorithms. Conduct extensive simulation testing to validate the performance of the algorithms.	Meidum
4	Dynamic Obstacle Detection and Avoidance	Difficulty in accurately detecting dynamic obstacles in real-time	Meidum	Medium Low	Implement robust sensor fusion techniques to improve obstacle detection accuracy. Develop algorithms capable of predicting the future motion of dynamic obstacles. Integrate reactive and proactive avoidance strategies to ensure safe navigation.	Medium
		Computational complexity may impact real-time performance of obstacle detection and avoidance algorithms	Medium Low	Meidum High	Optimize algorithm efficiency through parallelization and simulation acceleration. Prioritize critical tasks and allocate computational resources accordingly. Conduct thorough performance profiling and testing to identify and address bottlenecks.	Medium High
5	Intra-AMR Map Transfer	Improper mapping and storing may lead to misscommunicatons	Medium High	Medium	Establish clear guidelines and protocols for mapping and storing data. Conduct extensivevalidation of the map transfer mechanisms under various enviorment and network conditions. Develop backup and recovery procedures to mitigate data loss risks.	Medium High
		Compatibility issues between different AMR platforms may hinder seamless map transfer	Medium High	High	Standardize data formats and protocols to ensure interoperability across different platforms. Establish compatibility testing procedures to identify and resolve compatibility issues early. Maintain open communication channels with AMR manufacturers to address compatibility concerns.	High

Figure 4: Risk Register Table

Heat Map: Heat maps can be utilized to enhance the visualization of the risks involved throughout the research study and to grasp the significance of each task as we progress. This understanding can be leveraged when creating a timeline see Figure **??** and allocating significant duration's to high-impact tasks.

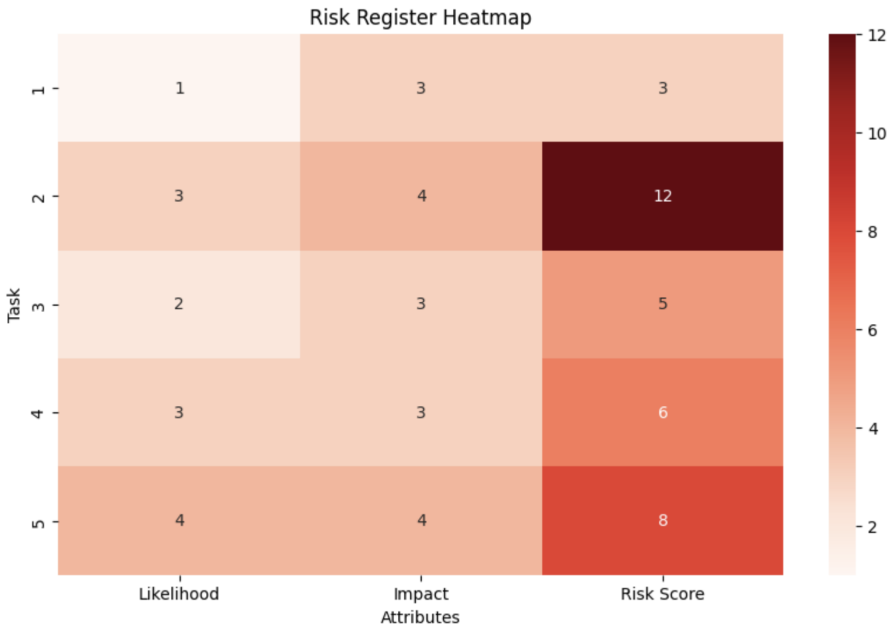


Figure 5: Risk Register Heat Map

By incorporating heat maps into the planning process, we can prioritize tasks effectively, ensuring that adequate time and resources are allocated to mitigate potential risks and address critical aspects of the research.

8 Timeline

Planning a timeline is crucial for the execution of research. Figures 6 and 7 utilize insights from core objectives and risk assessment to prioritize tasks and schedule them chronologically for efficient completion of the report.

No	Task	Start Date	End Date	Days
Task 1	Simulation Enviorment Creation and AMR Teleoperation (Weeks 1-3)			
	Environment Design in Ros	Monday, 27 May 2024	Sunday, 2 June 2024	6
	Sensor Integration in simulation	Sunday, 2 June 2024	Thursday, 6 June 2024	4
	Robot Modeling in Ros	Thursday, 6 June 2024	Wednesday, 12 June 2024	6
	Teleoperation Interface for simulation	Thursday, 13 June 2024	Monday, 17 June 2024	4
	Testing and Validation	Monday, 17 June 2024	Thursday, 20 June 2024	3
Task 2	Dynamic obstacal detection and avoidance and Mapping (Weeks 3-6)			
	Dynamic world modeling	Thursday, 20 June 2024	Saturday, 22 June 2024	2
	Dynamic Obstacle Detection and avoidance	Saturday, 22 June 2024	Friday, 28 June 2024	6
	Mapping and path planning	Monday, 1 July 2024	Sunday, 7 July 2024	6
	Local, Global, and spatial map	Sunday, 7 July 2024	Friday, 12 July 2024	5
	Implement map fusion techniques	Friday, 12 July 2024	Friday, 19 July 2024	7
Task 3	Navigation in Unknown Enviornment with heavy machines (Weeks 6-9)			
	World Modeling with Machinery Integration	Saturday, 20 July 2024	Wednesday, 24 July 2024	4
	Robot Model Integration	Wednesday, 24 July 2024	Monday, 29 July 2024	5
	Navigation Algorithm Implementation	Tuesday, 30 July 2024	Sunday, 4 August 2024	5
	Algorithm Optimization for autonomous navigation	Sunday, 4 August 2024	Saturday, 10 August 2024	6
Task 4	Intra AMR Map transfer (Weeks 9-12)			
	Map Representation and generation	Saturday, 10 August 2024	Tuesday, 13 August 2024	3
	Map Fusion and Synchronization	Tuesday, 13 August 2024	Saturday, 17 August 2024	4
	Map standardization and Communication Protocols	Saturday, 17 August 2024	Thursday, 22 August 2024	5
	Map Update and Maintenance:	Thursday, 22 August 2024	Friday, 23 August 2024	1
Task 5	Writing the Dissertation Report			
	Writting report Task by Task	Monday, 27 May 2024	Wednesday, 28 August 2024	93
	Report Review and Feedback	Wednesday, 28 August 2024	Tuesday, 3 September 2024	6
	Final Submission	Thursday, 5 September 2024	Thursday, 5 September 2024	0

Figure 6: Dissertation timeline

A Gantt chart serves as a powerful tool for visualizing the timeline of a research study. It effectively maps out the phases, tasks, and milestones within a project, providing a clear and concise overview of the research's progression and deadlines.

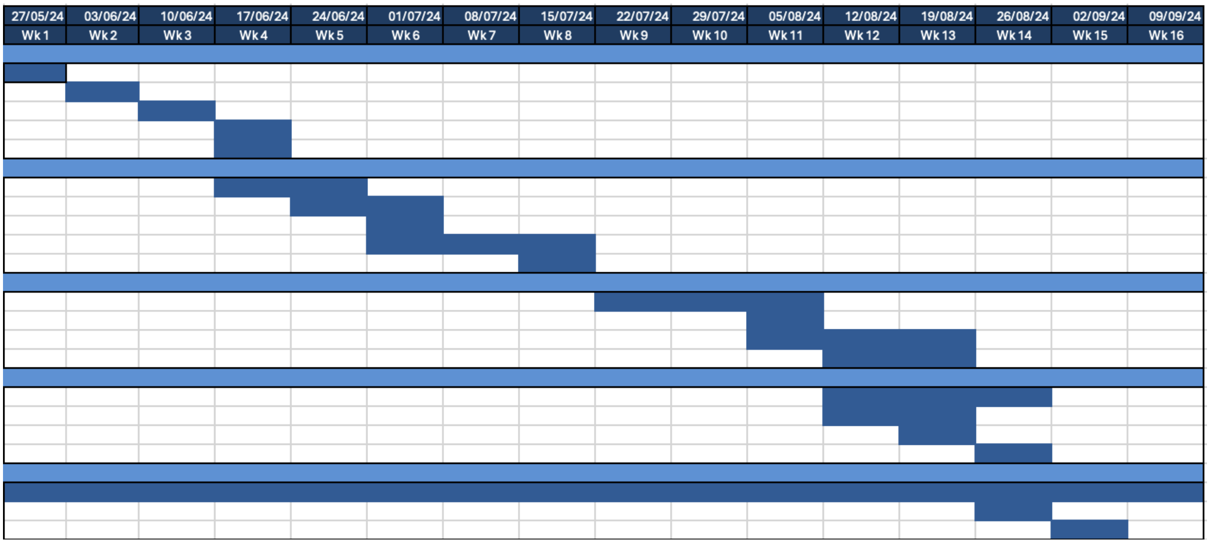


Figure 7: Gantt Chart for timeline

9 Appendix: Sustainability Assessment

This research in development of a SLAM framework for Autonomous Mobile Robots (AMRs), focusing on examining key aspects like energy consumption, electronic waste, and the carbon footprint associated with manufacturing, this study offers thoughtful strategies to mitigate ecological impact. This sustainability assessment shows how much one should consider about the environment while designing robotics and automation.

Potentially Unsustainable element	Likelihood of Unsustainable effect (5 = very likely, 1 = very unlikely)	Severity of this effect (5 = very severe, 1 = very low severity)	Proposed Mitigation Strategy
Energy Consumption	4	4	Optimize algorithm efficiency to reduce computational power requirements. Employ energy-efficient hardware where possible.
Electronic Waste	3	4	Design systems with modularity in mind to extend the lifespan of electronic components. Implement recycling programs for outdated or unusable hardware.
Resource Intensive Simulation	3	3	Utilize cloud computing resources to distribute simulation loads efficiently. Opt for green hosting solutions where feasible.
Carbon Footprint from Equipment Manufacturing	2	5	Source materials and components from suppliers committed to sustainable practices. Aim for a circular economy model by reusing or recycling parts.
Data Storage and Management	2	2	Implement data minimization strategies. Use energy-efficient storage solutions and consider the environmental impact of data centers.

Figure 8: Sustainability Assessment

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