A blue rectangular sign with white text

Description automatically generated

##### **NIT6150**

##### **Advanced Project**

##### System Design and Approach

##### **2D SLAM-based Childcare Robot**

**Team Leader:** Mary Yazbek (s4674864)

**Team Members:** Meghna Meghna (s4683216)

John Machado (s4685542)

**Client:** Dr. Wenjie Ye  
VU Sydney

**Supervisor:** Dr. Wenjie Ye

VU Sydney

**Coordinator:** Dr. Wenjie Ye

College of Engineering and Science

Victoria University, Melbourne

Table of Contents

[Overview 3](#_Toc176196309)

[Human Factors and Privacy Preserving 5](#_Toc176196310)

[Ethical Issues 5](#_Toc176196311)

[References 6](#_Toc176196312)

# Introduction

Falls are the leading cause of home injuries among children, with approximately 8,000 children visiting emergency departments daily in the United States due to such accidents, as highlighted by the Centers for Disease Control and Prevention (CDC)[1]. Common hazards include stairs and windows, and the challenge of providing continuous supervision is significant for parents and kindergartens.

The field of service mobile robotics is rapidly advancing, offering significant benefits in household applications like vacuuming and gardening. These robots demonstrate substantial potential for assuming more complex household tasks, especially in environments where the Global Positioning System (GPS) is ineffective. This brings into play the technology of Simultaneous Localization and Mapping (SLAM), which enables robots to map their surroundings and pinpoint their locations without prior data, crucial in GPS-deficient indoor settings. SLAM is available in both 2D and 3D forms; 2D SLAM suffices for environments not requiring vertical mapping, whereas 3D SLAM, which includes height and depth, is valuable for navigating multi-level spaces or outdoor environments.

This project explores the integration of 2D SLAM technology with child supervision tasks within indoor settings such as schools and childcare centers, utilizing 2D LiDAR systems. This technology will not only enhance child safety by monitoring and preventing access to hazardous areas but also maintain privacy by avoiding the use of cameras. Given the rise of dual-income households and the increasing difficulty in continuous child supervision, this project aims to align technological solutions with modern family needs, focusing on navigating indoor environments accurately and preserving privacy.

The project's main objectives include developing an environmental map using SLAM, navigating effectively within this environment, and ensuring data privacy. The proposed SLAM robots will navigate and map environments in real-time, providing caregivers and parents a comprehensive view of the surroundings and ensuring children remain within safe zones. This approach is controlled to significantly reduce child injuries from common household hazards, marking a valuable advancement in the use of robotics for childcare and supervision. (don’t forget structure)

# Project Evaluation

## Implementation

1. **Hardware Configuration**

* **Robot Assembly**: The TurtleBot3 was assembled with essential components including motors, sensors, and control boards.
* **Remote PC Setup**: A Dell Windows laptop was utilized as the remote PC, interfacing with the robot via network connections.

1. **Software Setup and Customization**

* **Operating System and ROS Installation**: Oracle VM VirtualBox hosted Ubuntu 20.04, creating a stable environment for ROS Noetic, which supports comprehensive robot programming and management.
* **ROS Configuration**: Necessary ROS packages were installed to enable control and navigation of the TurtleBot3, such as the Gmapping package for SLAM and the teleoperation package for manual control via PC.

1. **Visualization and Simulation Tools**

* **RViz**: Employed for real-time visualization of the robot's perception data and state, RViz provides a dynamic interface to monitor and interact with the robot's sensors and navigation outputs.
* **Gazebo**: Used for simulating complex robot interactions and environments, Gazebo allows for pre-deployment testing and algorithm refinement without physical trials.

1. **Algorithms**

* **SLAM Implementation**: Gmapping, a ROS-based SLAM package, was used to generate a 2D grid map using data from LiDAR and IMU sensors.
* **Localization and Navigation**: After mapping, the Adaptive Monte Carlo Localization (AMCL) and navigation nodes (using Dijkstra's algorithm for global planning and Dynamic Window Approach for local planning) were deployed to enable autonomous robot navigation within the mapped environment.

1. **Testing**

* **Simulation Phase:** Experiments commenced in a simulated Gazebo environment, specifically a house setting, to align closely with real-world conditions. Using the *turtlebot3\_gazebo turtlebot3\_house.launch* command, we simulated the robot navigating through this environment. The teleoperation node was used for manual control to optimize map accuracy via strategic path planning.
* **Real-World Testing:** The transition to real-world tests in an apartment setting involved using the gmapping SLAM node to generate a 2D map. Various velocities were tested, with optimal mapping occurring at 0.1 m/s to avoid redundant path overlaps. This meticulous mapping strategy was essential for producing the most accurate maps possible, depicted in subsequent figures.
* **Measurement and Accuracy Assessment:** Physical measurements of key objects were compared with their dimensions on the generated 2D maps to calculate mapping accuracy using RMSE, which showed a 5.45% error rate. This quantitative analysis underscores the potential and limitations of the current SLAM implementation.
* **Autonomous Navigation Testing:** With the map established, autonomous navigation tests were conducted. The robot's localization accuracy was crucial for effective navigation, ensuring it avoided obstacles dynamically and reached predetermined destinations safely.

### **Outputs**

A screenshot of a computer game

Description automatically generated A floor plan of a house

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Figure 1: Simulated Environment in Gazebo vs Mapped Output

A white and black drawing of a person

Description automatically generated A white rectangular object with black lines

Description automatically generated

Figure 2: Poor Real World Mapped Environments

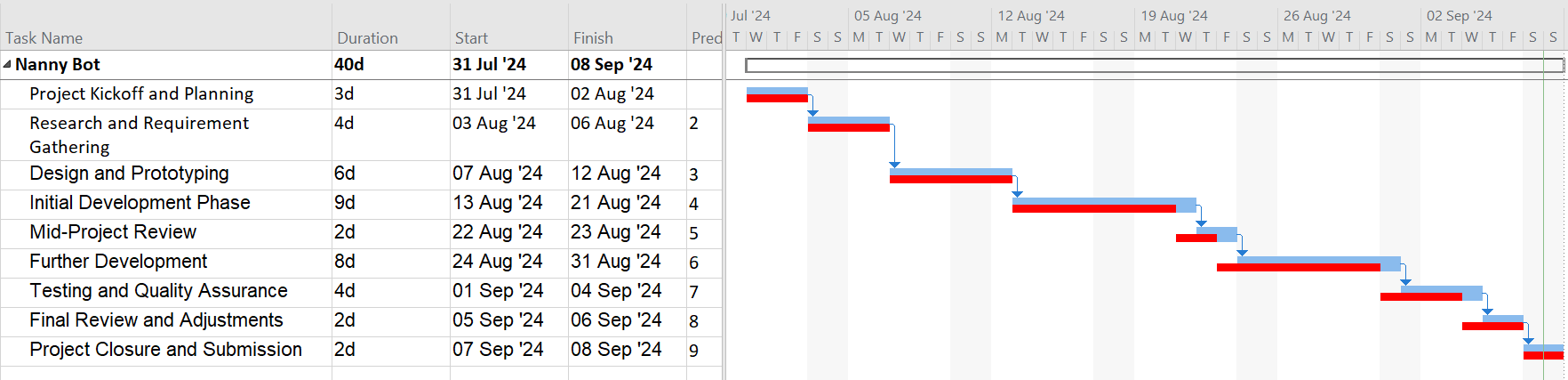
A drawing of a rectangular object

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Figure 3: Improved Real World Mapped Environments

## Schedule

In the project report, the Gantt chart has been updated to reflect actual task durations compared to the original schedule. Notably, the "Initial Development Phase" required an additional day to complete, extending from the planned 8 days to 9 days. Consequently, the "Final Review and Adjustments" phase was compressed from 3 days to 2 days to adhere to the project's deadline. This adjustment ensured that the project closure remained on track for the scheduled completion date of September 8th, as visually represented in the Gantt chart with actual durations in blue and planned dates in red.



## Challenges and Solutions

1. **Challenge: Inaccurate Mapping at Higher Speeds**

* **Solution:** Reduced the operational speed of the robot.
* **Justification:** Initial tests at higher speeds resulted in maps that lacked detail and accuracy, as the robot's sensors had insufficient time to accurately scan and process environmental data. By reducing the robot’s speed to 0.1 m/s, the sensors could capture more detailed information, resulting in significantly improved map fidelity. This slower speed allowed for better data integration and fewer errors in the SLAM process.

1. **Challenge: Map Degradation from Repeated Area Coverage**

* **Solution:** Developed a strategic mapping route prior to deployment.
* **Justification:** Previous mapping sessions where the robot covered the same area multiple times led to redundant data collection and confused map outputs. By designing a specific route that efficiently covered all necessary areas without overlap, the system could generate more consistent and reliable maps. This approach minimized the gathering of excessive data points from the same location, thereby optimizing the SLAM algorithm's performance and enhancing the overall quality of the environmental mapping.

1. **Challenge: Localization Errors Leading to Navigation Failures**

* **Solution:** Utilize the Adaptive Monte Carlo Localization (AMCL) algorithm with an increased number of particles to improve accuracy. Additionally, implementing a sensor fusion approach that combines data from LiDAR, IMU, and cameras can enhance localization precision.
* **Justification:** Sensor fusion techniques have been proven to improve localization accuracy in robotics by integrating multiple data sources, reducing the likelihood of navigation errors.

## Strengths and Limitations

### Strengths

1. **Effective 2D Mapping**: The use of a 2D LiDAR sensor with ROS Gmapping has proven effective in generating accurate maps of indoor environments, which is critical for reliable navigation.
2. **Accurate Localization**: The implementation of the Adaptive Monte Carlo Localization (AMCL) algorithm ensures precise self-localization within the mapped environment, which is essential for accurate navigation and obstacle avoidance.
3. **Real-time Navigation and Obstacle Avoidance**: The integration of global and local planners, such as DWA, allows the robot to navigate in real-time while effectively avoiding obstacles, ensuring safe movement through dynamic environments.
4. **Simulated and Real-world Testing**: The combination of Gazebo simulations with real-world experiments provides a robust validation of the robot’s performance, enhancing the reliability of the results and ensuring the system is well-tested before deployment.
5. **User-friendly Setup**: The use of ROS and tools like Rviz for visualization makes the system accessible to developers, allowing for easier setup, control, and customization of the robot's operations.
6. **Cost-effectiveness**: Utilizing a 2D LiDAR sensor instead of more complex 3D sensors reduces costs while still providing sufficient data for effective navigation and mapping in indoor environments.

### Limitations

1. **Limited Environmental Awareness**: The reliance on 2D LiDAR sensors limits the robot's ability to perceive and navigate complex 3D environments, potentially reducing its effectiveness in areas with varying floor levels or overhead obstacles.
2. **Inconsistent Mapping in Real-world Conditions**: The accuracy of the mapping can be compromised by factors such as inconsistent speeds, wheel slippage, or inadequate traversal of certain areas, leading to potential errors in navigation.
3. **Restricted Obstacle Detection**: The current system’s ability to detect and avoid smaller or moving obstacles, particularly in real-time, may be insufficient in dynamic environments where quick adjustments are necessary.
4. **Limited Interaction Capabilities**: The robot’s interaction with users, particularly children, is limited to navigation and obstacle avoidance, lacking more advanced human-robot interaction features such as voice recognition or gesture commands.
5. **Energy Efficiency Concerns**: The system's operational time may be limited by battery life, necessitating frequent recharging, which could reduce its practicality for continuous monitoring or guidance tasks.

## Future Improvements:

1. **Integration of Advanced Sensors**: Incorporating depth cameras or more sophisticated LiDAR could enhance obstacle detection and environment mapping, providing a richer data set for navigation algorithms.
2. **Machine Learning Implementation**: Applying machine learning, particularly reinforcement learning, could improve the robot's path planning and adaptability in dynamic environments, making navigation more robust.
3. **Expansion to Larger Settings**: Tailoring the system for use in larger environments like kindergartens and public play areas, where the dynamics are more complex.
4. **Energy Efficiency**: Improving the robot’s battery life and operational efficiency to ensure longer periods of uninterrupted service, essential for continuous monitoring tasks.

## Lessons Learned:

1. **Importance of Testing Environments**: Simulated environments are invaluable but must closely mimic real-world conditions to ensure the system's effectiveness and reliability.
2. **Adaptability of Speed and Path Planning**: Adjustments in navigation speed and pre-planning routes proved crucial for optimizing mapping quality, highlighting the need for flexible system parameters.
3. **Privacy by Design**: The positive reception of the privacy-focused features (using LiDAR instead of cameras) reinforced the importance of considering user privacy in the design of assistive technology.

## Ethical Issues

Creating a childcare robot is exciting, but it comes with important ethical questions. First, we need to protect privacy. The robot will collect some data, so we’ll make sure it’s encrypted and let parents and staff know how it’s used and stored. Being open about this builds trust.

It’s also important that everyone understands and agrees to the robot being in the daycare. We’ll clearly explain what the robot does and how it helps keep kids safe, so everyone feels comfortable with it. We need to be honest about what the robot does and how it benefits the children. Transparency builds trust and reassures everyone that the robot is there to help, not to replace caregivers. If something goes wrong, like a malfunction, we’ll have clear roles and responsibilities to address issues quickly. And while some might worry about job security, the robot is designed to assist, not replace, human caregivers.

## Human Factors and Privacy Preserving

When developing the 2D SLAM-based childcare robot, it’s crucial that the system is easy for daycare staff to use with minimal training. Our goal is a user-friendly design that fits smoothly into daily routines.

A key challenge is ensuring the robot’s interface isn’t too complex, which could lead to frustration and mistakes. To avoid this, we’re focusing on a simple, clear design with easy-to-recognize icons and prompts, making the robot intuitive to use. While the design will be straightforward, some training will still be provided, including tutorials and hands-on sessions to ensure everyone is comfortable with the robot. We’ll also set up a feedback system so staff can share their experiences, helping us make improvements based on real-world use. Prototyping and user testing will help catch any usability issues early, and simplified controls will make the robot easy for all staff to operate. After deployment, ongoing feedback will guide further refinements to keep the system responsive to daycare needs.

Privacy is also a top priority. The robot uses LiDAR sensors instead of cameras to avoid capturing personal images, greatly reducing privacy risks. We’ll implement strong data protection measures, like encryption, to ensure that any collected data is securely stored and only accessible to authorized personnel.

By prioritizing ease of use, intuitive design, and privacy protection, we aim to develop a childcare robot that seamlessly integrates into daycare operations, is easy to adopt, effective in its role, and trusted by all users.

# Conclusion

This report delves into the development and testing of a LiDAR-equipped mobile robot aimed at enhancing child safety within confined spaces. Reflecting on the achievements, the project successfully implemented SLAM technology for robust navigation and precise obstacle avoidance, all while ensuring the privacy of household environments. However, challenges such as the system’s scalability in varying home layouts emerged as limitations. Future work will focus on incorporating advanced sensors and machine learning algorithms to refine the robot's adaptability and expand its application to broader environments like daycares. The next steps include addressing dynamic obstacle navigation, enhancing human-robot interactions, and improving energy efficiency for sustained operations.

# Project Documentation

## Workload application

|  |  |
| --- | --- |
| **Proposal** |  |
| Introduction | Mary |
| Background and client profile | Mary |
| Purpose and objective | Mary |
| Scope and Exclusion | Meghna |
| Assumptions and constraint | Meghna |
| Schedule | John |
| Budget | John |
| Resources, roles, and responsibility | John |

|  |  |
| --- | --- |
| **System Analysis and Design** |  |
| System development approach | Meghna |
| Functional requirements | Mary |
| Use case diagram | Meghna |
| User testing | ALL |
| Limitations (performance review) | ALL |
| Non-Functional Requirements (ethics and professional) | Meghna |
| Cultural and political requirements | Meghna |
| Legal and licensing requirements | Meghna |
| Look and feel and portability | Meghna |
| Maintainability and support requirements | Meghna |
| Operational requirements | Meghna |
| Performance requirements | Meghna |
| Security issues | Meghna |
| Usability and humanity requirements | Meghna |
| System Navigation and Interface | Mary |
| Project Management | John |
| Cost Estimate | John |
| Schedule | John |
| WBS | Mary |
| Activities List | Mary |
| Gantt Chart | Mary |
| Considerations and Issues | Mary |
| Human Factors and Privacy Preserving | John |
| Risk and Issue Mitigation | John |

|  |  |
| --- | --- |
| **Final System Delivery and Evaluation (Finish product)** | |
| Overview | Meghna |
| System product and features |  |
| Project Documentation | Mary |
| Strength and Limitations |  |
| Future Improvements |  |
| Lesson Learned |  |
| Challenges and proposed solutions |  |
| Implementation |  |
| Human Factors and Privacy Preserving |  |
| Professional Ethics |  |
| Conclusions |  |
| Infographics |  |

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| --- | --- |
| **Oral presentations** | |
| Project overview | Mary |
| Problems | Mary |
| Objective and the scope | Meghna |
| Solutions | Meghna |
| Performance review and limitations | John |
| Profession ethics, human factors and privacy preserving | John |

## Meeting Minutes

|  |  |
| --- | --- |
| MEETING MINUTES 1 | |
| Meeting Date: | August 5th 2024, 12:00 PM |
| Meeting Minutes Admin: | Mary Yazbek |
| In Attendance: | Mary, John, Meghna |
| Meeting Agenda: | The team attended the advanced project class to receive guidance from the supervisor (Wenjie Ye). |
| Meeting Resolution: | * Established a group chat to use as a communication platform. * Created a shared folder on both drive and GitHub to store all project materials. * Got more clarity on the direction of the project. * Agreed on conducting a weekly meeting (and more if needed). |

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| MEETING MINUTES 2 | |
| Meeting Date: | August 18th 2024, 4:00 PM |
| Meeting Minutes Admin: | Mary Yazbek |
| In Attendance: | Mary, John, Meghna |
| Meeting Agenda: | * Objective: To compile all research and data required to commence the technical implementation phase. * Discussion Points: * Review of data collected to date. * Identification of any gaps in information. * Finalization of resources and preparation for technical development. |
| Meeting Resolution: | The team has unanimously agreed to proceed with gathering all necessary findings essential for the initiation of the technical implementation phase of the project. This includes finalizing the collection of all relevant data and ensuring that all resources are aligned and prepared for the commencement of technical development. |

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| MEETING MINUTES 3 | |
| Meeting Date: | August 18th 2024, 4:00 PM |
| Meeting Minutes Admin: | Mary Yazbek |
| In Attendance: | Mary, John, Meghna |
| Meeting Agenda: | 1. **Implementation Kickoff**  * Objective: Officially begin the technical implementation phase. * Discussion Points:   + Final review and approval of the implementation plan.   + Establishment of timelines and milestones for the technical tasks.  1. **Resource Allocation**  * Discussion on the distribution and assignment of resources and personnel to ensure smooth project progression. |
| Meeting Resolution: | The team resolves to officially commence the technical implementation phase, approve the final implementation plan, and allocate necessary resources as outlined in the discussions. This also includes adopting updated risk management strategies to mitigate identified risks effectively. |

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| MEETING MINUTES 4 | |
| Meeting Date: | August 29th 2024, 6:00 PM |
| Meeting Minutes Admin: | Mary Yazbek |
| In Attendance: | Mary, John, Meghna |
| Meeting Agenda: | 1. **Progress Review**  * **Objective**: Evaluate the early results and progress of the technical implementation phase. * **Discussion Points**:   + Present completed tasks and milestones.   + Identify any deviations from the timeline and strategies for realignment.  1. **Quality Control and Testing**  * Discuss protocols for ongoing quality assurance and schedule the initial system testing. |
|  | The team commits to approving the progress report, adjusting based on identified deviations, and continuing with established quality control. |

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| MEETING MINUTES 5 | |
| Meeting Date: | September 5th 2024, 4:00 PM |
| Meeting Minutes Admin: | Mary Yazbek |
| In Attendance: | Mary, John, Meghna |
| Meeting Agenda: | 1. **Final Project Review**  * Objective: To conduct a comprehensive evaluation of the entire project. * Discussion Points: * Overview of project outcomes versus initial goals. * Review of all deliverables and confirmation of completion.  1. **Lessons Learned**  * Discussion on the insights gained and challenges faced throughout the project. * Recommendations for future projects based on these lessons.  1. **Project Closure**  * Finalize all documentation. * Officially close the project and release resources. |
|  | The team resolves to approve the project completion, noting that all objectives have been satisfactorily met and deliverables are complete. The team agrees to document the lessons learned for future reference and formally closes the project, releasing all allocated resources. |

## Git

*https://github.com/maryyaz/NIT6150/tree/main*

# References

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