Autonomous Mapping Using Ros2 and Gazebo Harmonic

The domain of the Project:
ROS-2 , GAZEBO HARMONIC, SLAM

Under the guidance of:
Mr. Harish Pedakolimi (Mechanical & Robotics Engineer)

By
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Period of the project
August 2024 to February 2025

Declaration

The project titled “**Autonomous Mapping using ROS2 and Gazebo Harmonic**” has been mentored by **Mr. Harish Pedakolimi**, organized by SURE Trust, from August 2024 to February 2025, for the benefit of the educated unemployed rural youth for gaining hands-on experience in working on industry relevant projects that would take them closer to the prospective employer. I, Ms. Neha Thakur , hereby declare that I have solely worked on this project under the guidance of my mentor. This project has significantly enhanced my practical knowledge and skills in the domain.

Name

Ms. Neha Thakur

Signature

Mentor

Mr. Harish Pedakolimi
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1. Executive Summary

This project implements an autonomous mapping system using ROS2 and Gazebo Harmonic. The robot is equipped with LIDAR, IMU, and a camera for environment perception, enabling real-time mapping. The system integrates SLAM for localization and mapping, ensuring accurate and efficient autonomous navigation. By utilizing advanced sensor fusion techniques, the robot can generate highly detailed and precise maps of its surroundings, allowing it to navigate dynamically in both known and unknown environments.

To enhance its autonomous capabilities, the system incorporates intelligent path planning and obstacle avoidance mechanisms, making it robust for various real-world applications. Multiple testing scenarios, including different terrain types and dynamic obstacles, were executed to evaluate mapping precision, navigation performance, and the efficiency of implemented algorithms. The project demonstrates the effectiveness of integrating multiple sensors and SLAM-based localization to achieve an accurate and reliable autonomous mapping system in simulated environments.

2. Introduction

2.1 BACKGROUND AND CONTEXT OF THE PROJECT

Mapping and navigation are crucial in robotics, particularly for autonomous systems. This project focuses on leveraging ROS2 and Gazebo Harmonic for efficient mapping using multiple sensors
ROS2 (Robot Operating System 2) provides a robust framework for developing modular, scalable, and high-performance robotic applications. It enhances real-time capabilities, multi-robot communication, and simulation support, making it ideal for implementing autonomous navigation and mapping.
Mapping allows robots to build a representation of the environment, enabling localization and obstacle avoidance. *Simultaneous Localization and Mapping* (SLAM) is a widely *used technique that allows robots to construct maps while determining their own position within them*. ROS2 integrates various SLAM packages and tools like Nav2

2.2 PROBLEM STATEMENT

Autonomous mapping requires precise sensor fusion and localization techniques. This project aims to create a robust mapping system capable of handling different environments and obstacles in real-time.

2.3 SCOPE AND LIMITATIONS OF THE PROJECT

Scope:

- Development of an autonomous mapping framework:
  This includes the implementation of a system capable of generating real-time maps and localizing itself within an unknown environment using SLAM techniques.
- Integration of multiple sensors (LIDAR, IMU, Camera) for accurate mapping.:
  Ensuring accurate data collection and sensor fusion to enhance the mapping and navigation capabilities of the robot.
- Implementation of SLAM for environment perception.:
  Utilizing SLAM algorithms such as GMapping, Cartographer, and Nav2 for real-time map generation and localization.
- Implementation of multiple navigation strategies.:
  Incorporating both Waypoint Navigation and Navigation with SLAM to allow flexible movement in structured and unstructured environments.
- Development of a URDF and SDF File for Robot and Environment Modeling:

Creating a detailed Unified Robot Description Format (URDF) file to accurately simulate the robot’s physical structure, including its sensors and actuators in Gazebo Harmonic. Additionally, designing an SDF (Simulation Description Format) file to define custom simulation environments, including obstacles, terrains, and static/dynamic models to enhance the realism of the mapping process.

Limitations:

- Limited real-world testing due to simulation constraints.:
  The project is primarily tested in a simulated environment (Gazebo), which may not fully replicate real-world challenges such as unpredictable lighting conditions, terrain variations, and unforeseen obstacles.
- Computational limitations in complex environments.:
  High-resolution mapping and real-time SLAM processing require significant computational power, which may limit performance on resource-constrained robotic platforms.
- Sensor Noise and Calibration Issues: Variations in sensor readings due to noise, drift, and misalignment can impact the accuracy of mapping and navigation.
- Network Latency in Multi-Robot Implementations: If multiple robots are used, communication latency between agents may affect synchronization and overall mapping efficiency.

2.4 Innovation

The project introduces an optimized sensor fusion technique to improve mapping accuracy. It also integrates advanced navigation algorithms to enhance autonomous decision-making by incorporating both URDF-based robot modeling and SDF-based environmental simulations.

3. Project Objectives

3.1 Project Objectives and Expected Outcomes

1. Accurate Real-Time Mapping

- Implement a mapping system capable of generating real-time maps using LIDAR, IMU, and camera data.
- Expected Outcome**:** High-resolution maps with minimal drift and enhanced localization accuracy.

2. Robust Sensor Fusion

- Integrate data from LIDAR, IMU, and cameras to enhance mapping accuracy and robot perception.
- Expected Outcome: Improved data reliability and sensor redundancy to mitigate individual sensor limitations.

3. Implementation of Multiple Navigation Strategies

- Develop and test both Waypoint Navigation and SLAM-based navigation for different environments.
- Expected Outcome: Enhanced autonomous movement with optimized route planning and obstacle avoidance.

4. **Simulation and Realistic Environment Modeling**

- Design and integrate URDF and SDF models for accurate robot representation and environmental realism.
- Expected Outcome: Realistic simulation scenarios that closely resemble real-world conditions.

5. Performance Testing and Optimization

- Evaluate system performance in simulated environments under various conditions.
- Expected Outcome: Optimized system parameters ensuring stable and efficient mapping and navigation.

3.2 Deliverables

- **Functional ROS2-based Mapping and Navigation System:** A fully developed and tested autonomous mapping framework with SLAM and navigation capabilities.
- **URDF and SDF Files:** Complete models for the robot and environment to ensure realistic simulation in Gazebo Harmonic.
- **Demonstration photos:** Recorded tests and results showcasing the performance of the system in various environments.
- **Codebase and Documentation:** A well-documented code repository with setup instructions, implementation details, and usage guidelines.

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4. Methodology and Results

4.1 Methods/Technology Used

1. **Sensor Integration:** Implementing LIDAR, IMU, and camera for environmental perception.
2. **SLAM Implementation:** Utilizing ROS2-based SLAM techniques such as GMapping and Cartographer for real-time mapping.
3. **Navigation Strategies:** Implementing both waypoint-based and SLAM-based navigation.
4. **Simulation Environment:** Creating and testing mapping algorithms in Gazebo Harmonic before real-world deployment.
5. **URDF and SDF Modeling:** Designing and integrating custom robot models and simulation worlds.
6. **Performance Evaluation:** Conducting mapping accuracy, obstacle avoidance, and path optimization tests.

Tools Used

1. **ROS2 (Robot Operating System 2):** Core framework for robot control, navigation, and communication.
2. **Gazebo Harmonic:** High-fidelity simulation tool for developing and testing robot behavior.
3. **WSL (Windows Subsystem for Linux):** Running ROS2 and Gazebo Harmonic in a Linux-based environment on Windows.
4. **RViz2:** Visualization tool for mapping and sensor data representation.
5. **SLAM Toolbox:** Implementing localization and mapping techniques.
6. **Nav2 (Navigation Stack 2):** Enabling autonomous movement and path planning.
7. **Python & C++:** Primary programming languages for ROS2 node development.

4.2 SYSTEM ARCHITECTURE

The system architecture is designed to efficiently handle sensor data acquisition, processing, and navigation execution. It ensures smooth communication between different subsystems, providing a modular and scalable framework for real-time autonomous mapping and navigation.

1. **Robot Platform:**

A simulated robot in Gazebo with a URDF model definition, which is used within ROS2 to define the robot's kinematics, joints, and physical structure, ensuring proper control and visualization in Rviz2. Additionally, the SDF (Simulation Description Format) is utilized in Gazebo under the simulation environment section, providing a detailed

physics-based representation of the robot, including environmental interactions, sensor placements, and dynamics within the simulated world.
Equipped with LIDAR for distance measurement, IMU for orientation tracking, and a camera for visual perception, forming a comprehensive sensor suite.

2. **Sensor Data Processing Module:**

LIDAR: Captures 2D/3D point cloud data for obstacle detection and map generation.
IMU: Provides angular velocity, acceleration, and orientation estimation to enhance localization accuracy.
Camera: Enables visual feature extraction, object recognition, and environmental understanding, supplementing LIDAR and IMU data.
Sensor Fusion: Combines data from all sensors to reduce noise and improve mapping accuracy.

3. **ROS2 Communication Framework:**

Utilizes ROS2 nodes to separate and manage core functionalities such as perception, mapping, and navigation.
Topics and Services: Establish real-time communication between different ROS2 components, ensuring synchronized data flow.
Middleware (DDS): Enables efficient inter-process communication, allowing for distributed robot control and multi-agent collaboration.

4. **SLAM and Mapping Module:**

Implements SLAM techniques, specifically **Cartographer**, for generating real-time maps and performing accurate localization.
Pose Estimation: Determines the robot's position and orientation relative to its environment.
Map Representation: Maintains occupancy grids and point clouds for localization and path planning.

5. **Navigation and Path Planning Module:**

Nav2 Stack: Provides global and local path planning capabilities using algorithms like **Dijkstra's** and *A search**.
Obstacle Avoidance: Uses cost maps and dynamic re-planning to prevent collisions with static and moving obstacles.
Waypoint Navigation: Allows pre-defined waypoints for structured navigation.
SLAM-based Navigation: Dynamically explores and navigates through unknown environments.

6. **Simulation Environment:**

Gazebo Harmonic: Offers high-fidelity physics-based simulation for testing robot performance in different environments.
Custom World Files: Designed with realistic terrains, obstacles, and sensor placements to replicate real-world scenarios.

7. **WSL (Windows Subsystem for Linux):**

Provides a Linux-based development environment within Windows, enabling seamless execution of ROS2 and Gazebo Harmonic.
Facilitates cross-platform compatibility for integrating software and hardware components.

This architecture ensures that all subsystems work cohesively, allowing the robot to perceive its environment, localize itself, plan paths, and navigate autonomously in dynamic surroundings.

4.3 World File Creation

A customized simulation world is created in Gazebo, incorporating real-world elements such as:

- Static obstacles
- Dynamic objects (e.g., moving pedestrians)
- Landmark-based navigation points

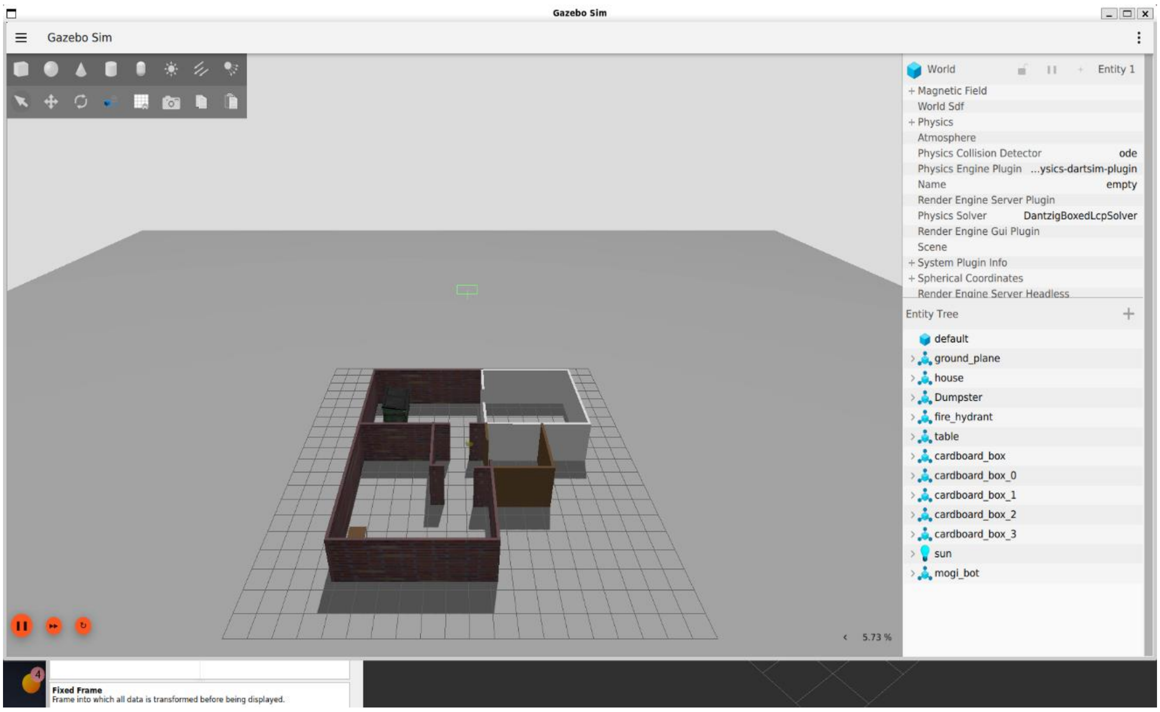

*Fig 1: **World** file*

This Gazebo simulation world represents an enclosed structure with multiple rooms, surrounded by walls constructed from brick-textured materials. The environment contains various objects that contribute to a realistic and interactive simulation space.

4.4 URDF File Creation

A URDF (Unified Robot Description Format) file is created to define the robot's structure, including:

- Link and joint definitions.
- Sensor placements.
- Actuator configurations.
- Visualization and collision properties for accurate simulation in Gazebo.

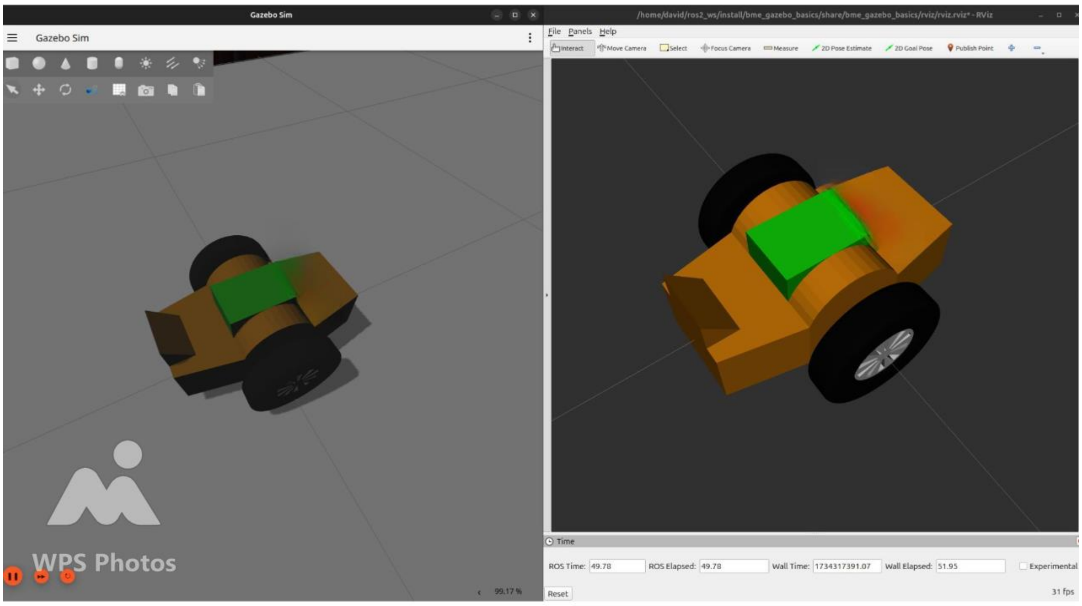

*Fig 2: **URDF** file*

This is a **wheeled robot** simulation designed using **URDF (Unified Robot Description Format)** and visualized in **Gazebo and RViz**. The robot appears to be a simple autonomous vehicle with a minimalistic design, suitable for simulation and testing in **ROS 2**.

4.5 Sensor Integration

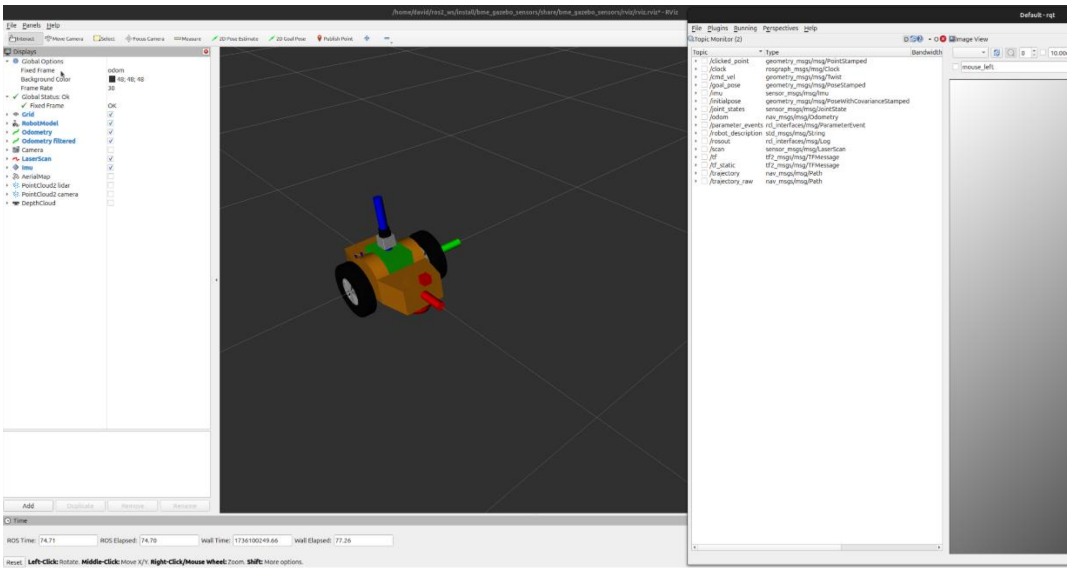

*Fig 3 : Visualized **camera Integrated** on robot as Gray colour box*

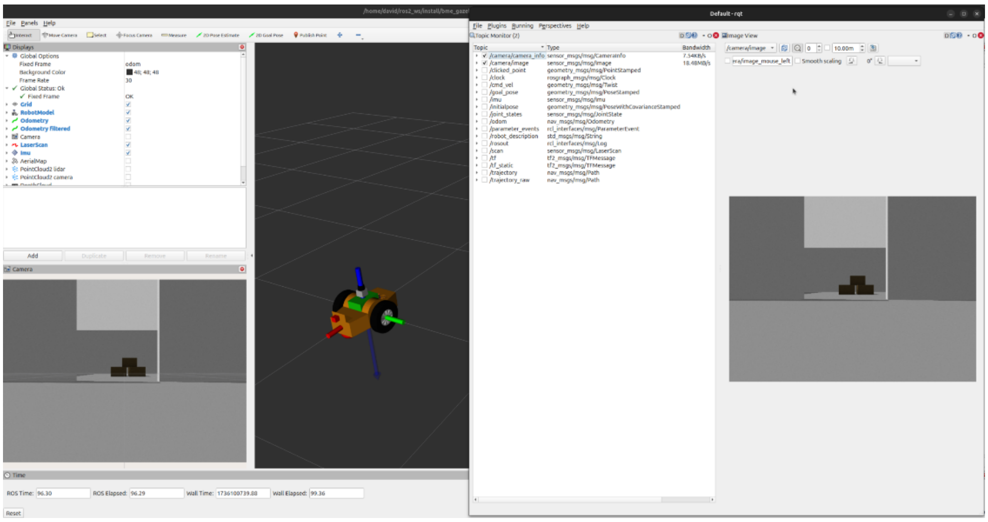

Fig 4: camera ***working***

Which means when we insert our robot in world file camera is working fine means it shows the path which needed while mapping and navigating our robot

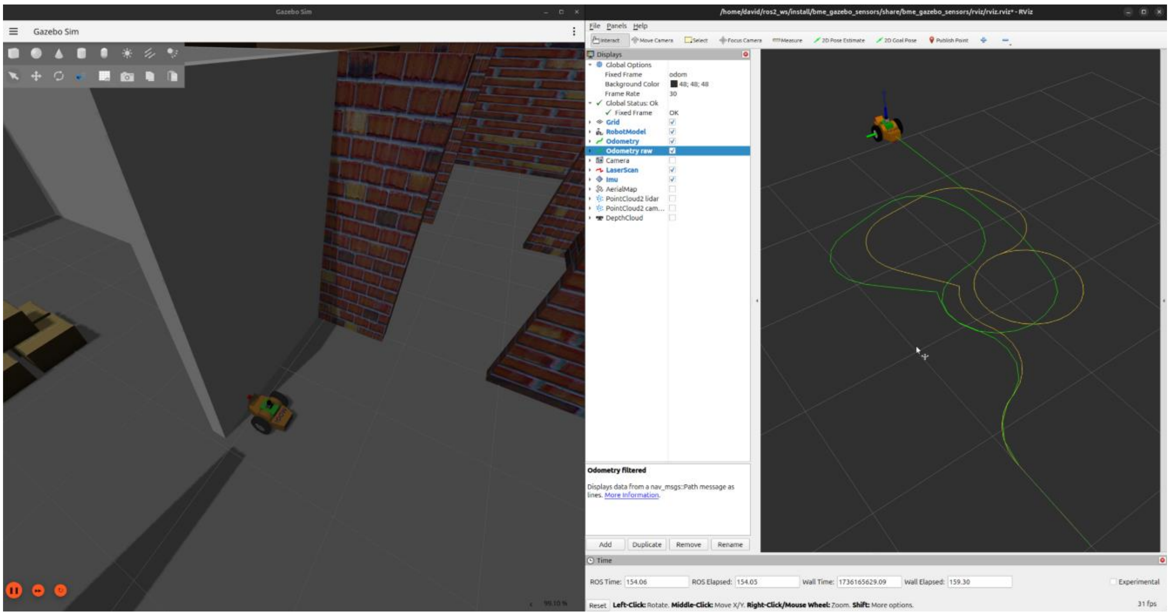

Fig 5.: show ***odometry***

Odometry is used in robotics to estimate a robot's position and orientation over time based on motion data. In the provided image, odometry data is being visualized in **RViz**, where the green and yellow lines represent the estimated path of the robot as it moves within the **Gazebo** simulation.

- The **Gazebo simulation (left side)** shows the robot navigating a virtual environment with obstacles.

- The **RViz visualization (right side)** plots the real-time odometry path in two colors, likely representing raw and filtered odometry data.
- The robot's movement and estimated trajectory can be analyzed to improve motion planning and localization

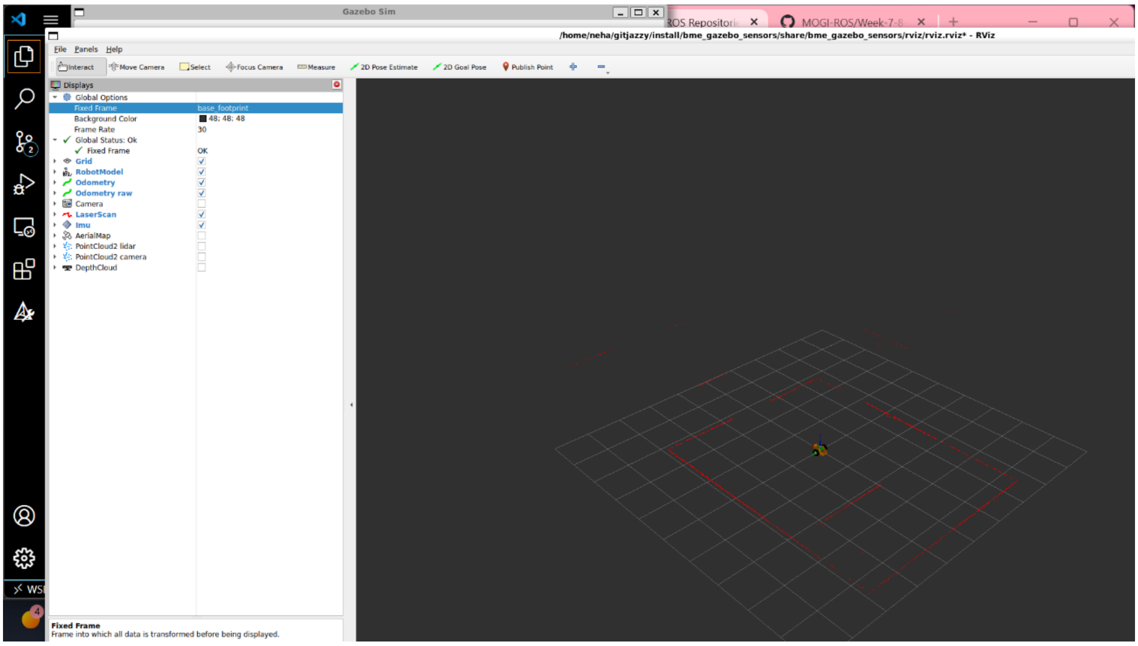

*Fig 6: **LiDAR and IMU** integration on robot*

This image shows a **Gazebo** simulation with **RViz**, where **LiDAR** (red points and lines) is detecting obstacles and mapping the environment. The **IMU** sensor is enabled to provide orientation and motion data, helping stabilize the robot's movement. LiDAR is used for obstacle detection and SLAM, while IMU aids in position estimation and motion tracking.

4.6 Mapped A Robot

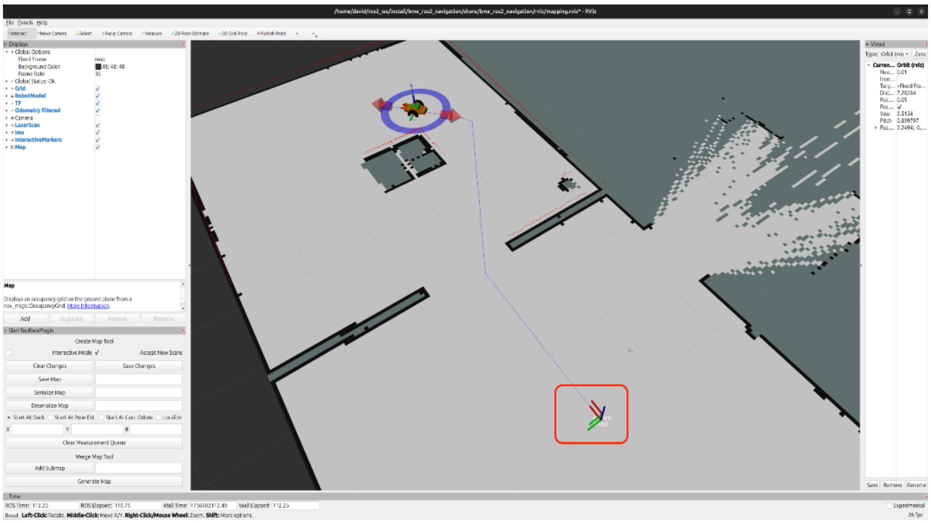

*Fig 7 : **Mapping** of robot*

This image shows the SLAM (Simultaneous Localization and Mapping) **process in** ROS 2**, where a robot is actively mapping an indoor environment using** LiDAR and odometry data**. The** occupancy grid **(gray and black regions) represents the mapped area, with black indicating obstacles and gray showing explored free space. The** robot's trajectory **is depicted as a blue line, showing its movement path. The** red arrows **around the robot indicate detected obstacles from the** LiDAR sensor**. The lower right section (inside the red box) represents the** map frame**, which serves as the global reference for localization. This visualization in** RViz **demonstrates how the robot builds an accurate map while localizing itself in real time.**

4.7 Navigation with SLAM

Navigation in robotics is the overall process that enables a robot to move from one location to another in a safe, efficient, and autonomous manner. It typically involves:

1. Knowing where the robot is (localization or SLAM),
2. Knowing where it needs to go (a goal pose or waypoint),
3. Planning a path to reach that goal (path planning), and
4. Moving along that path while avoiding dynamic and static obstacles (motion control and obstacle avoidance).

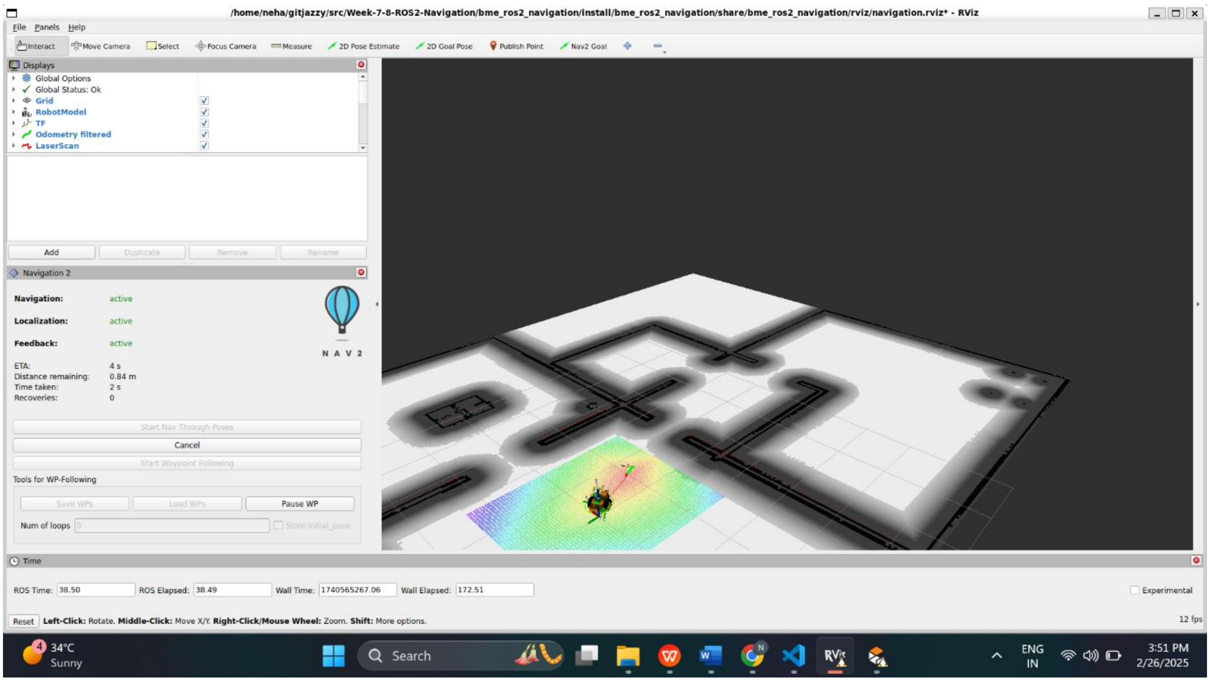

Fig 8: Before receiving any **obstacle**

As soon as the pose goal is received the navigation stack plans a global path to the goal and the controller ensures locally that the robot follows the global path while it avoids dynamic obstacles. The controller calculates a cost map around the robot that determines the ideal trajectory of the robot. If there aren't any obstacles around the robot this cost map weighs the global plan.

If obstacles are detected around the robot those can be visualized as a cost map

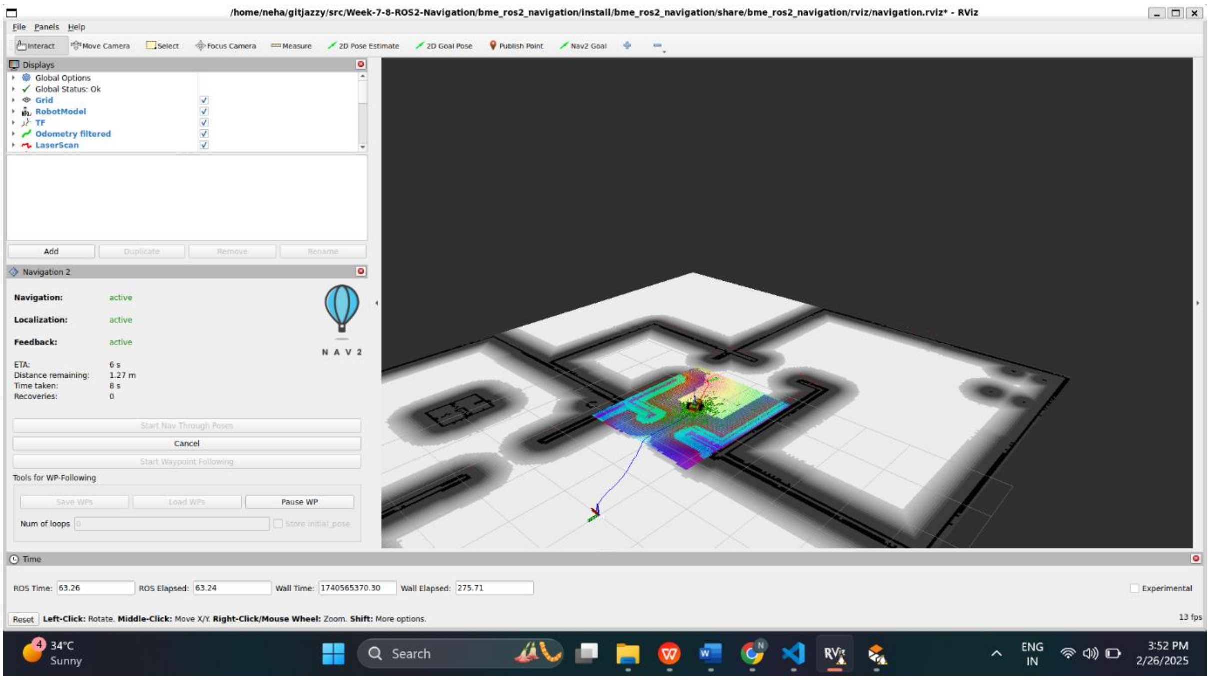

Fig 8: After detecting an obstacle used a **cost Map**

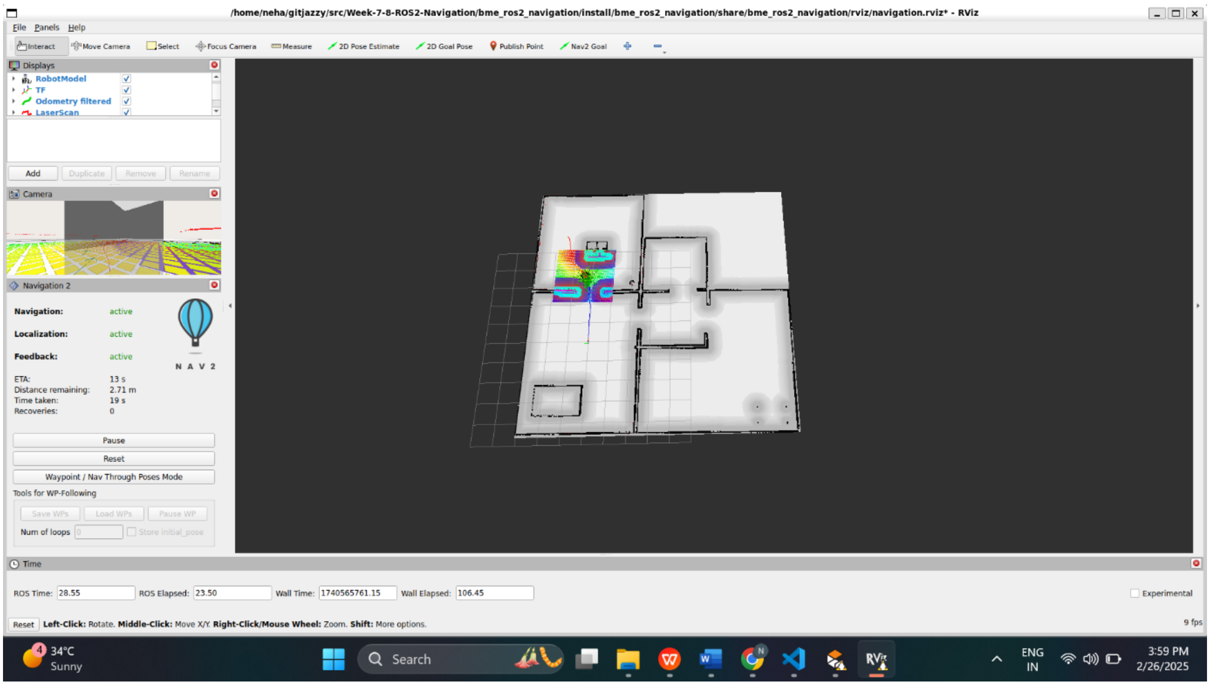

Fig 9: detecting an **obstacle**

Detected obstacle or object will be Shown in mapped and also visible through camera.

5. Learning and Reflection

5.1 Learning:

1. **Project Planning & Execution**
   - Understanding the importance of structured project planning.
   - Learning to break down tasks into manageable milestones.
   - Ensuring timely execution and tracking progress.
2. **Stakeholder Collaboration**
   - Effective communication with team members and external stakeholders.
   - Understanding different perspectives and integrating feedback.
   - Building partnerships for successful project outcomes.
3. **Technical Skills Development**
   - Gaining expertise in mapping technologies and software tools.
   - Implementing data collection and analysis methodologies.
   - Learning to troubleshoot technical challenges in the project.
4. **Problem-Solving & Adaptability**
   - Addressing unforeseen challenges with creative solutions.
   - Adapting to changing project requirements and constraints.
   - Enhancing critical thinking and decision-making skills.
5. **Resource Management**
   - Optimizing available resources for efficient project execution.
   - Learning cost-effective ways to achieve project objectives.
   - Managing time effectively to meet deadlines.
6. **Data Accuracy & Quality Control**
   - Ensuring data integrity in mapping and documentation.
   - Learning validation techniques to maintain high-quality standards.
   - Understanding the impact of inaccurate data on project outcomes.

5.2 Reflection:

1. **Impact of Effective Planning**
   - Reflecting on how well planning contributed to project success.
   - Identifying areas where planning could be improved.
   - Understanding the importance of contingency plans.
2. **Collaboration Strengths & Weaknesses**
   - Evaluating team dynamics and communication effectiveness.
   - Identifying strengths in teamwork and areas for improvement.
   - Recognizing the role of leadership in project execution.
3. **Personal Growth & Skill Enhancement**
   - Assessing personal contributions to the project.
   - Identifying new skills learned and areas for further improvement.
   - Reflecting on how the experience aligns with future career goals.

4. **Challenges Faced & Lessons Learned**
   - Documenting the biggest challenges encountered.
   - Analyzing how those challenges were tackled.
   - Extracting key takeaways for future projects.
5. **Sustainability & Long-Term Impact**
   - Evaluating the project's impact on stakeholders.
   - Considering how the project can be sustained or improved over time.
   - Identifying potential future developments based on current findings.

6. Conclusion and Future Scope

6.1 Achievements:

- Successfully developed an autonomous mapping system using ROS2 and Gazebo Harmonic
- Improved localization accuracy through effective sensor fusion techniques
- Enhanced navigation capabilities by implementing both waypoint navigation and SLAM
- Created structured URDF and SDF files for accurate robot and environment simulation
- Demonstrated the effectiveness of the system in various simulated environments
- Optimized path planning and obstacle avoidance using the Nav2 stack

6.2 Future Enhancements:

- Integration of machine learning algorithms for adaptive navigation in dynamic environments
- Deployment of the system on a real-world robotic platform for practical testing and validation
- Enhancement of sensor accuracy and data processing for improved mapping performance
- Implementation of multi-robot collaboration for faster and more efficient mapping of large areas
- Development of a user-friendly interface for real-time monitoring and control of the mapping process
- Integration with cloud-based services for remote monitoring and data analysis
- Incorporation of semantic mapping to identify and classify objects within the environment
- Exploration of 3D mapping techniques for more comprehensive environmental representation
- Implementation of energy-efficient navigation strategies to optimize battery life in real-world scenarios
- This project has laid a strong foundation for autonomous mapping using ROS2 and Gazebo Harmonic. The achievements demonstrate the potential of this approach in creating efficient and accurate mapping systems. The integration of multiple sensors, advanced navigation

strategies, and robust simulation techniques has resulted in a versatile and reliable autonomous mapping solution.

- Future enhancements will focus on improving the system's adaptability, real-world performance, and user interaction. The integration of machine learning and multi-robot collaboration holds promise for tackling more complex and larger-scale mapping tasks. As the field of robotics continues to evolve, this project serves as a stepping stone towards more advanced applications in areas such as search and rescue, industrial automation, and space exploration.

7.References

- ROS2 Documentation
- Gazebo Harmonic Official Guide
- SLAM and Navigation Research Papers
- GIT-HUB Repositories