Mapping and Autonomous Navigation of an Indoor Environment in ROS Platform using Multiple Robots Equipped with LIDAR

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Abstract—This paper presents a comprehensive study on the development and implementation of a multi robot system for mapping and autonomous navigation within indoor environments, using the Robot Operating System (ROS) platform and LIDAR sensors. The ROS framework serves as the foundation for this endeavor, allowing seamless integration of sensor data, robot control, and high-level navigation algorithms. To realize Simultaneous Localization and Mapping (SLAM), we used a cartographer with ROS, ultimately enabling each robot to construct local maps of its surroundings. The paper discusses the mechanisms for merging these local maps into a coherent global map, emphasizing multi-robot SLAM techniques that facilitate collaborative mapping.
Keywords: Mapping, autonomous navigation, indoor environment, LIDAR, ROS (Robot Operating System), 2D mapping.

1. Introduction

The mapping and autonomous navigation within an interior environment includes the utilization of LIDAR (Light Detection and Ranging) technology and the ROS to generate a comprehensive depiction of the inside environment. This enables a robot to independently go through the mapped space. LIDAR is an advanced technological system that use laser beams to meticulously survey and identify various items inside a given environment. The process involves utilizing a laser emitter to gauge the spatial separation between items inside the environment, hence generating a two-dimensional representation of said environment. This technology is commonly used in robotics to help robots sense their surroundings and navigate through complex environments[1]. The mapping and autonomous navigation in an indoor environment using LIDAR and ROS are involved in path planning.

Once the path is planned, the robot can then navigate through the environment autonomously. This involves using various algorithms to control the robot's movements and ensure that it stays on the planned path. The robot will also need to be equipped with sensors to detect obstacles and avoid collisions.

Mapping is a concept that visualizes an indoor environment and data on a digital 2D map enabling solutions such as indoor positioning and navigation. Navigation involves the process of using the created map to plan a path for the robot to follow. This path planning is based on the accurate map of the environment that has been generated. The robot will then use this map to navigate through the environment autonomously, avoiding obstacles and following the planned path. Combining LIDAR technology and ROS, can create mapping and navigation systems for indoor robots. This technology has many potential applications, including manufacturing, logistics, and healthcare. For example, robots can be used to transport materials in a factory, guide patients in a hospital, or deliver goods in a warehouse.

The motivation for a project on mapping and autonomous navigation in an indoor environment using LIDAR and ROS[2] could be to develop a reliable and accurate system for navigating through complex indoor environments, such as factories, and hospitals. LIDAR and ROS could be to develop a robust and reliable system that can safely navigate through hazardous indoor environments, such as those encountered in disaster zones, mines, or industrial sites.

LIDAR technology can provide high-resolution 2D maps of the environment, while ROS can provide a flexible and customizable framework for controlling and integrating various sensors and actuators on a robot. The project aims to create a system that can autonomously navigate through indoor environments, detect obstacles, avoid collisions, and reach predefined locations. This system could be useful in various industrial and commercial applications, such as automating material handling, and Inventory management. Furthermore, the project could help advance the field of robotics and autonomous systems, which has potential applications in many fields, including manufacturing, logistics, healthcare, and transportation.

2. Related Works

The map building of unknown indoor environments is a crucial task in mobile robotics. Thrun[3] has used a multi-resolution algorithm to generate low-complex 3D models of indoor environments using laser range finders data where no odometry was available for mapping. The main limitation of multi-resolution planners with vehicle location-dependent decomposition is that they are prone to a lack of completeness in motion planning.

Rusdinar [4] try to solve the simultaneous localization and mapping (SLAM) problem in the mobile robot using the particle filter (PF). In his work he has used the LMS200Laser Range Finder (LRF) to recognize the landmarks like corner structures in the environment. The main drawback of this method is the requirement for more storage space for modeling large environments and it is time-consuming.

A. Rubinstein and T. Erez created a robot called LiTank which was used for tunnel mapping using only the LIDAR sensor without using GPS, odometry and other sensors [7]. The LIDAR mounted on the robot sends the mapping data to the computer in ground station. He runs the algorithms and process the data received from the LIDAR using computer on the ground station which is away from mapping environment. Depending on the map created and the robots position, the commands will be sent to the robot to control the robot movements. Since communication between robot and ground station is by Wi-Fi which is not suitable inside tunnel as the signal strength gets attenuated because of reflections in the tunnel.

Ryan W. Wolcott et al [8] have proposed a scan matching algorithm with Gaussian mixture maps to exploit the structure in the environment using 3D LIDAR in Automated Guided Vehicles.

In their work, Hemanth Malla and colleagues (Malla et al., 2015) successfully executed object-level mapping of an indoor environment by harnessing Radio Frequency Identification (RFID) technology. This innovative approach involved the deployment of RFID tags, RFID readers, and inertial navigation sensors (INS) to create detailed maps of objects within expansive indoor spaces.

In early days sonar was used to map the environment. The Burgard.W et al in [11] have mapped large scale environment using sonar .In this approach he has created small local maps by assuming odometry data is accurate and the Expectation-Maximization (EM) is then applied to estimate the position of these small local maps. Finally all the generated local maps are combined toget one global map using Bayes rule. The disadvantages of this sonar technology are that the range decreases with increasing of frequency of waves and can't give actual size of the objects.

3. Methodology

A. Mobile Robot Platform

It is a physical system providing foundation for development of mobile robot applications. It is typically a base moving in different directions, such as wheels, tracks, or legs with a controlling system allowing robot to navigate and interconnect with the environment. There are various applications supported by mobile robot platform such as surveillance, logistics, search and environmental monitoring. They can be either teleoperated by a human operator or programmed to move autonomously.Mobile Robot Platforms are designed for various applications related to indoor environments, while others are designs for outdoor environment. Since they provide a physical foundation for robot to move and interact with the environment, they become essential for the development of mobile robot applications. Choosing a mobile robot platform depends on the specified requirements of the application and the environment in which the robot is meant to move.

Here we used multiple mobile robot platform for Mapping and Autonomous Navigation in an indoor environment, which includes two tortoise bots which is a very simple and cost-effective ROS based robot with the capability of mapping and navigation. The core of tortoise bot is Raspberry pi 4 with a pre-installed ROS. This mobile robot platform supports Gazebo physics simulator, simulating robot algorithms while avoiding the risk of actually sending the robot to physical environment. It also allows to visualize the sensor data in RViz.

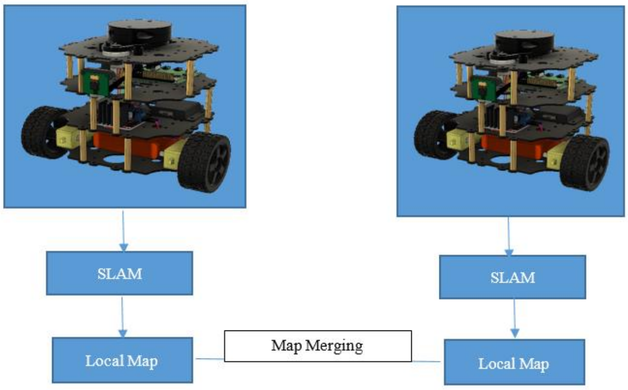


Figure 1. Experimental setup of Multi robot system Tortoise Bot

B. ROS system

ROS (Robot Operating System) is an open-source software system that is used for building robot applications with inbuilt set of software libraries and tools helping in development of robot software. ROS was released first in the year 2001 by the Stanford Artificial Intelligence Laboratory. Since than it became widely accepted and adopted in robotics community. ROS with its node-based architecture and messaging system helps enabling efficient communication between nodes, while its other features like tools for visualization and debugging helps with debugging and developing robot applications.

C. SLAM technology

The Cartographer algorithm is a typical SLAM algorithm based on graph optimization [3,4]. Highly optimized and non-iterative Cholesky matrix decompositions are used as the solver of the sparse linear system, and SPA (Sparse Pose Adjustment) is used to complete scan matching and loopback detection [5]. The filtering method has a large storage capacity and has updating efficiency problems. Therefore, it is difficult to be used in scenes with a large map scale [6]. The structure of Cartographer SLAM algorithm is simple and clear and the process is shown in Figure 2. The two tortoise bots are used here to develop a global occupancy grid map, where each robot implements cartographer SLAM individually to develop a local map. Then Map merging technique is used to combine individual maps into a coherent, global map that represents the entire environment. Map merging of two occupancy grid maps involves aligning their coordinate frames, matching resolutions, and fusing occupancy values[16] using union, intersection, or weighted averaging. Conflicts are resolved based on reliability, and map metadata is updated. Post-processing, visualization, and periodic updates ensure an accurate global map representation for multi-robot scenarios.

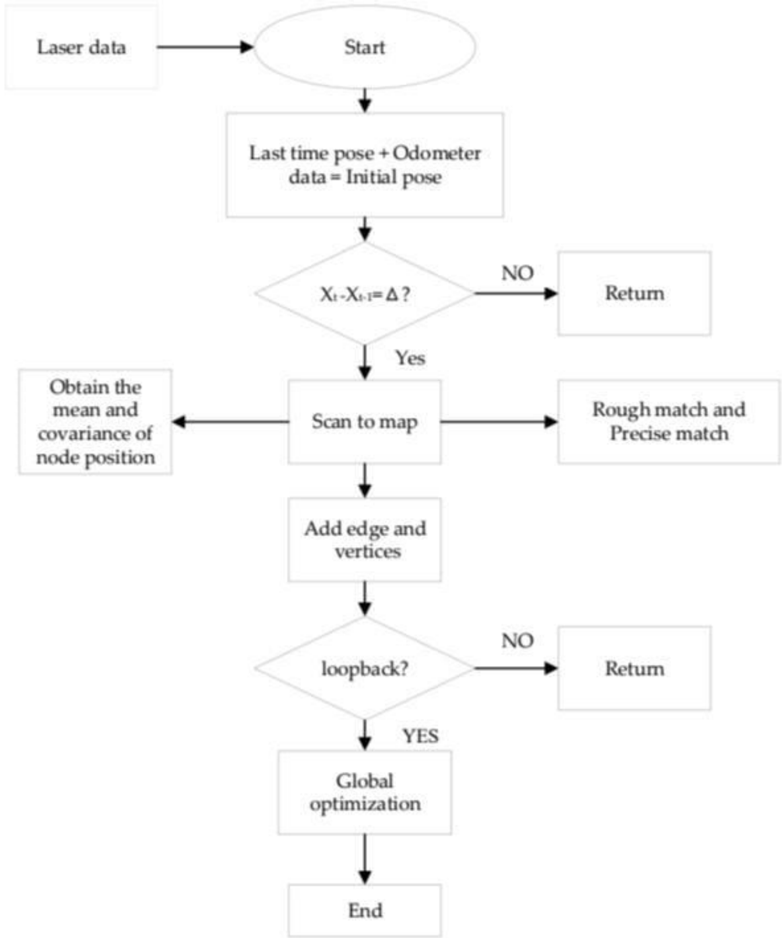


Figure 2. Cartographer SLAM flowchart

The Cartographer SLAM algorithm uses odometer data to assist positioning to get the initial position and pose. On the basis of this, the LIDAR scan data are matched with the surrounding map, called scan-to-map match. With the obtained LIDAR data, different angles are mapped in the coordinate system of the robot and an offset an offset value is driven to obtain the look up table. Along with it a multiple-resolution method is adopted improving the search efficiency. The front-end graph is constructed by scanning and matching the LIDAR data and loopback detection, it them transmits the constraints and poses to the back end for nonlinear optimization to update poses. The framework of the Cartographer SLAM is detailed in Figure 3.

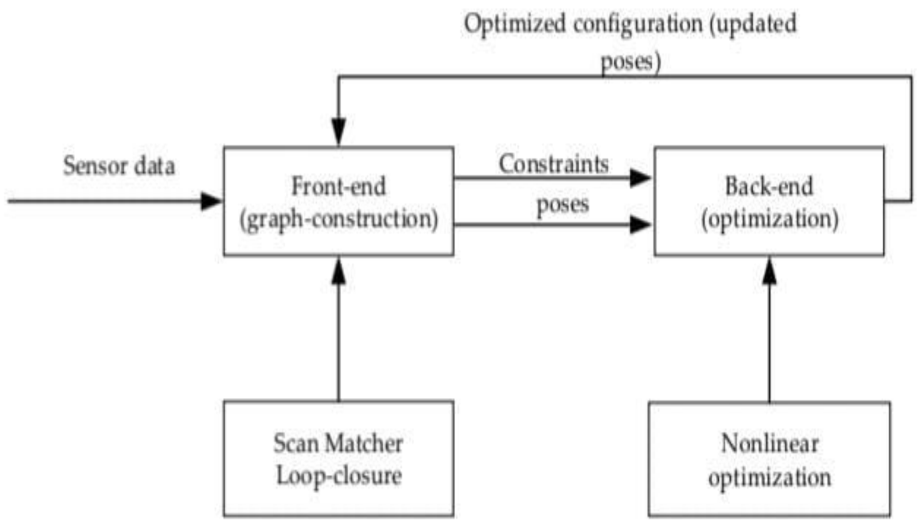


Figure 3. Framework of Cartographer SLAM

D. Description method of map

A map is a method used to depict the spatial characteristics of the environment in which a mobile robot operates. The implications on path planning in navigation are contingent upon the various modalities of map representation. There exists an inverse relationship between the level of detail in a map and the operational speed of path planning. This implies that as the level of detail in a map increases, the pace at which path planning operations are executed decreases. Similarly, path planning speed scales inversely with map detail. Several representations—grid, feature, topological, and direct—are available. Grid representation, favored for indoor robotics, is most suitable due to its appropriateness for indoor environments.

The grid representation approach involves the discretization of the environment, resulting in the division of the world into many grids of equal size. Various shades of gray are employed to depict the likelihood of a grid being occupied by barriers. The map that is produced is commonly referred to as the occupancy grid map. One advantage of this approach is its ease of construction and storage, which offers convenience for self-localization and course planning. However, a notable drawback is the somewhat complex maintenance required when operating in a large-scale environment. However, the interior service robot operates within a relatively confined and uncomplicated area. Therefore, utilizing a grid map is advantageous as it can effectively capture and store ample information without impeding the efficiency of the navigation algorithm. The grid map depicted in Figure 2 was constructed using two-dimensional LIDAR inside the experimental setting [4].

E. Navigation Algorithm

The previously mapped data is subsequently utilized by the navigation algorithm, facilitating the indoor robot's movement from its starting point to a designated destination. During this temporal interval, the precise location of the robot is ascertained based on the map that has been devised, adhering to the optimal trajectory as per the planned course of action, taking into account both the robot's current position and the predetermined goal position. Subsequently, the robot initiates its movement towards the designated target point in accordance with its preliminary path plan. Path planning can be categorized into two distinct techniques: global planning and local planning, which are differentiated based on the extent of their operational range.

Global planning: The system employs path planning algorithms, namely Dijkstra and A*, to build a high-level trajectory from the robot's present position to the intended target. The path planning algorithms consistently incorporate the robot's present location, intended goal, and the diverse barriers present in the environment to generate a path that is both secure and efficient within the given environment.

A graph-based approach called the Dijkstra algorithm is utilized to find the shortest path. The algorithm employs the breadth-first search strategy, progressively expanding from the initial node to the goal node in the vicinity, with the objective of determining an ideal path. Due to the absence of constraints and the extensive search range employed in the search process, the algorithm utilized by Dijkstra is deemed inefficient. On the other hand, the A* algorithm utilizes a heuristic search strategy and incorporates an evaluation mechanism, resulting in a significant enhancement in search efficiency [13]. The A* algorithm incorporates the concept of the father-child node relationship, which involves the use of two lists known as OPEN and CLOSE. The former data structure is responsible for storing the nodes that are yet to be treated, whereas the latter data structure is responsible for storing the nodes that have already been handled [15]. The evaluation function is formulated as,

$$f(n) = g(n) + h(n) \quad (1)$$

In this context, g(n) signifies the distance from the starting point to node n, while h(n) computes the node n's distance when moving horizontally or vertically towards the target point. Function f(n) denotes the current attachment node's location, determined by the algorithm after adding potential points, starting from the initial point, to the open list. The algorithm then selects the node with the smallest value, aiding in finding the most efficient route from the initial location to the desired destination. Figure 4 illustrates the A* algorithm.

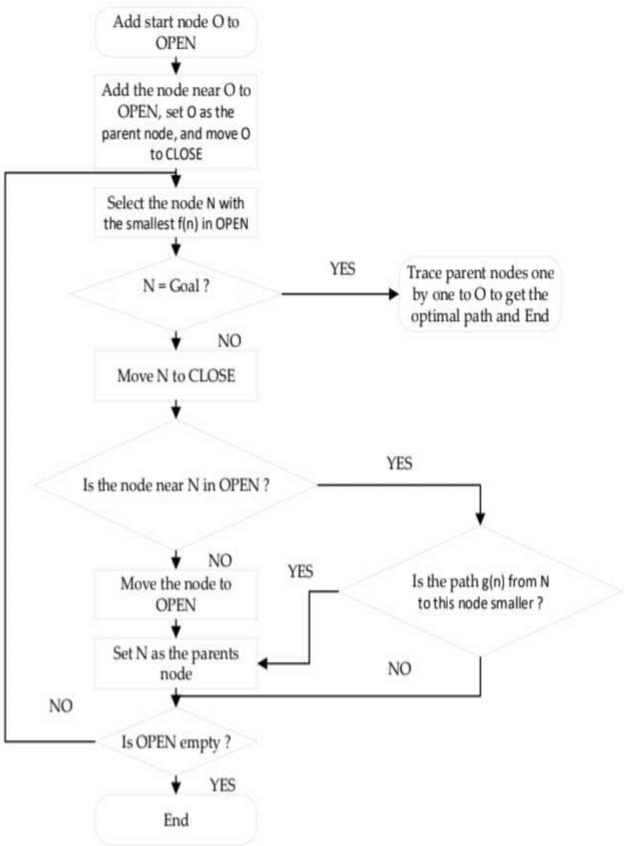


Figure 4. Flowchart of A* algorithm

Local planning: The DWA algorithm is selected for local path planning, which takes into account the robot's kinematics and environment constraints to generate a safe and feasible trajectory. With the help of the current state and sensor data of the robot, DWA algorithm generates the best trajectory selecting the most feasible one based on a cost function.

The velocity vectors (v, ω) where v represents linear velocity while ω represents angular velocity satisfying the certain conditions are sampled. To predict the robot's trajectory, we utilize the velocity vector of a sample point and employ solutions for both forward and inverse kinematics of the robot. Ultimately, by employing a suitable cost function, the score for the projected trajectory is determined, and thereafter, the robot's movement is governed by the ideal velocity vector that has been selected. The cost function associated with the Dynamic Window Approach (DWA) is expressed as follows:

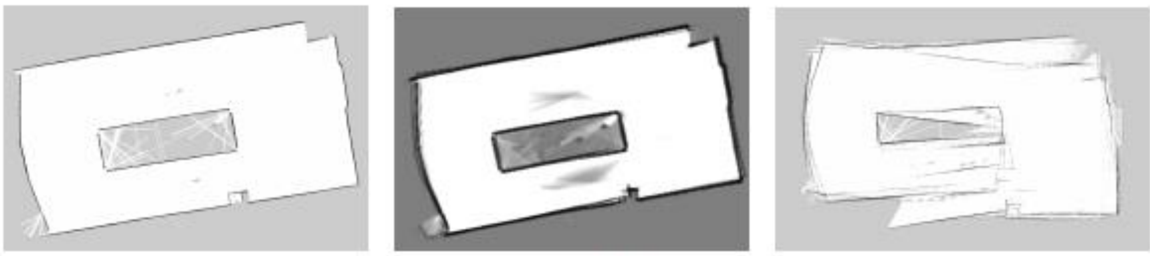
$$G(v,\omega)=\alpha * CostObstacle + \beta * CostPath + \lambda * CostGoal \quad (2)$$

The variable "CostObstacle" represents obstacle distances on the track, while "CostPath" signifies the shortest distance to a local reference path, and "CostGoal" represents the range to the path's end. Weights α, β, and λ adjust these factors. These parameters enable robot movement adaptation to the environment. Common robot challenges include location, destination, and pathfinding, addressed through mapping and autonomous navigation. Figure 4 depicts the solution's flowchart.

4. RESULTS

For validating robot mapping and navigation, we selected the Gazebo simulation platform as our experimental environment. Gazebo provides a user-friendly graphical interface, allowing users to visually experience the virtual environment and monitor the robot's behavior and interactions within it. It also helps for analyzing the data generated during simulation, with the help of various tools. It checks the performance of the control algorithms or the accuracy of the sensor data.

Initially to validate the mapping, the methods such as Gmapping[18], Cartographer, and Hector slam methods were implemented on single robot equipped with LIDAR. To generate the map, the robot is driven manually in the environment. All the mapping methods were implemented on the same environment. The results of the methods has been shown in the Figure 5.



(a) (b) (c)

Figure 5. Occupancy grid maps (a) Gmapping, (b) Cartographer (c) Hector SLAM constructed by SLAM algorithms

The tests that were presented show that almost in all scenarios Google Cartographer constructs maps with the smallest error relative to the precise ground truth. This algorithm is robust enough for the different types of mobile robot movements.

To assess the mapping accuracy of the Cartographer algorithm, we conducted simulation experiments within the Gazebo platform on Ubuntu 18.04 and ROS Melodic systems. Our study involved three robots navigating indoor environments, utilizing the tortoisebot virtual robot model. The simulation incorporated simulated sensor data, including Lidar and odometer information. These simulations were executed on a laptop computer equipped with an Intel i5-11400H processor and 8 GB RAM memory. We meticulously designed the simulation environment to mimic realistic physical characteristics, ensuring it serves as a dependable reference for real-world applications. Figure 6 illustrates the environment modeling within the Gazebo simulation platform.

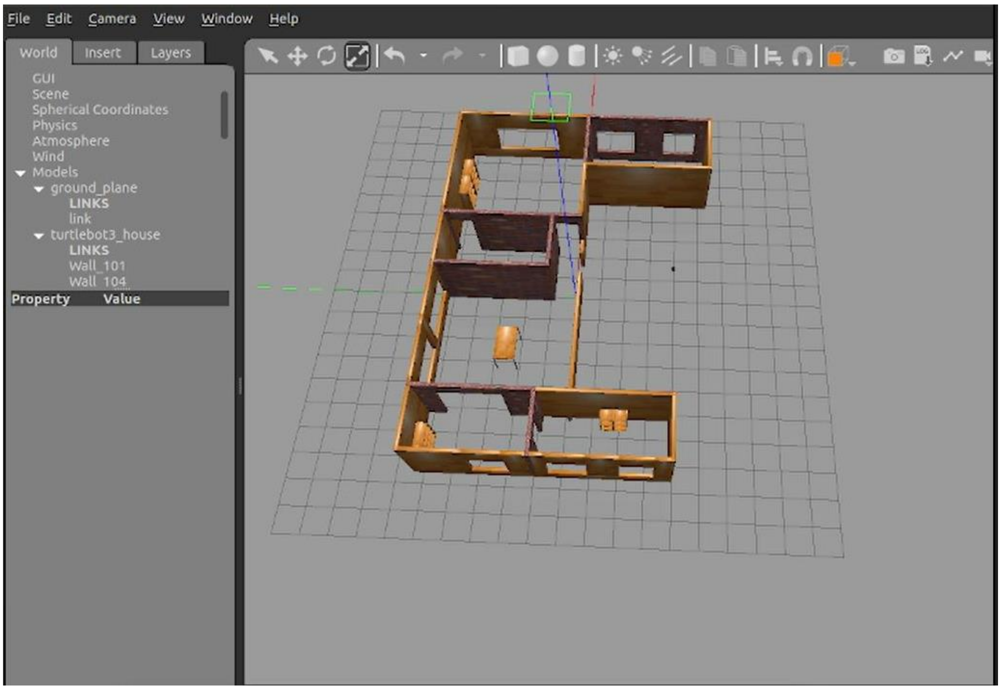


Figure 6. Environment setup to carry out exploration using Multi robot system.

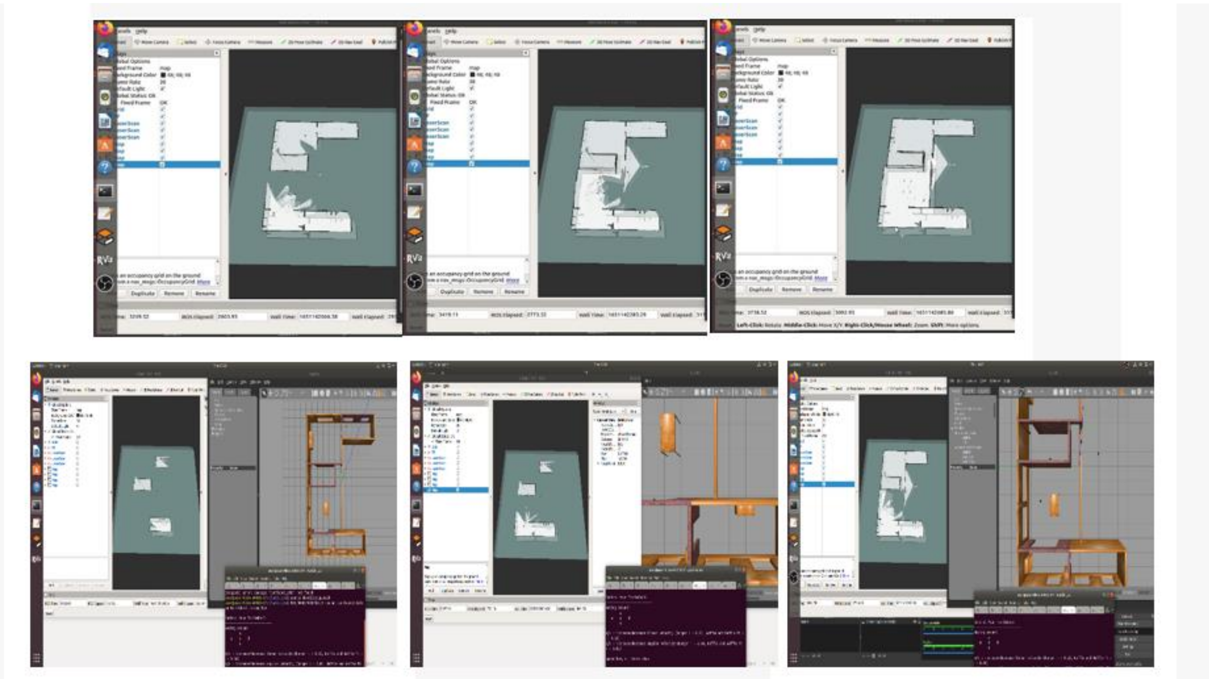


Figure 7. Simulation results of three robots exploring the given environment and developing the global map through merging process.

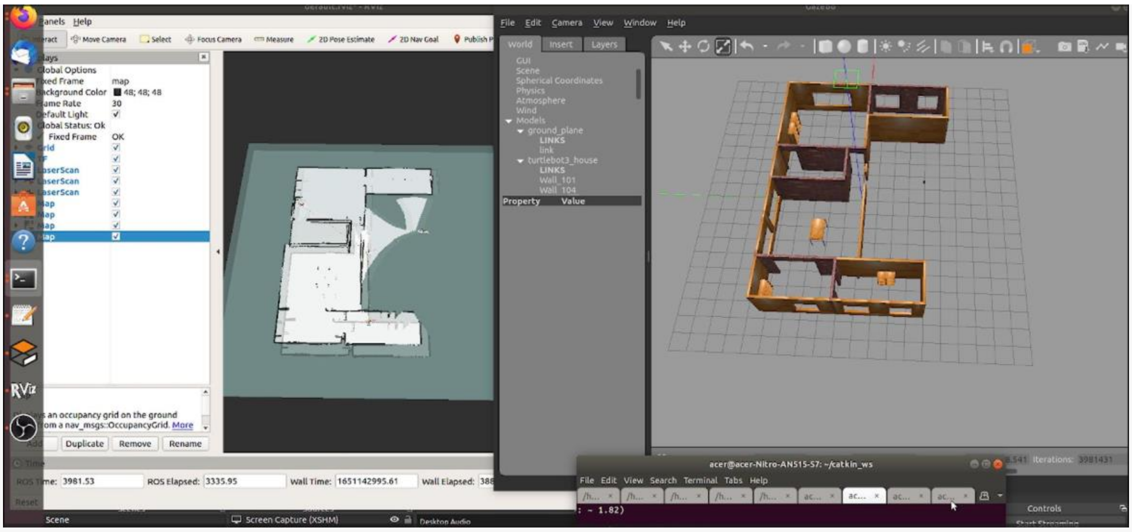
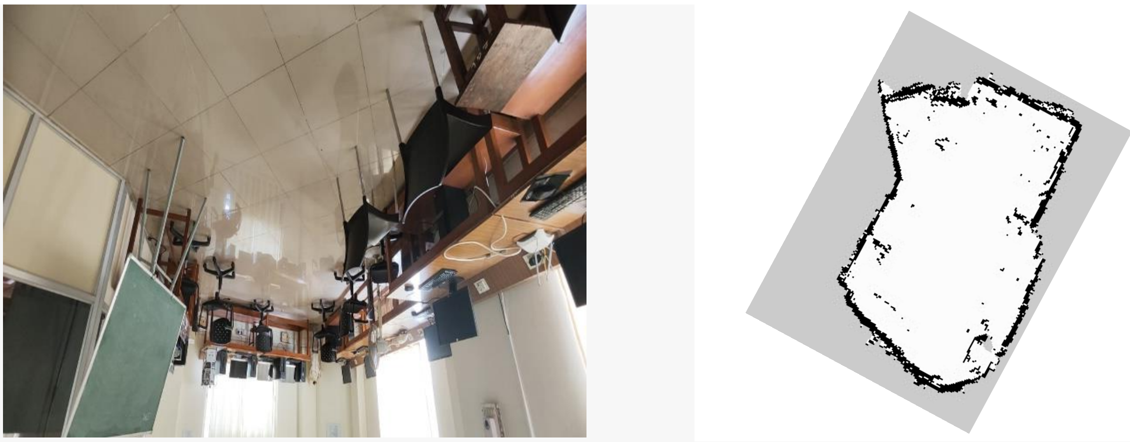


Figure 8. Global map of the environment setup

The simulation has been carried out in the real physical experimental setup involves two robots, which work together to perform cooperative autonomous exploration tasks. Where each robot implements Gmapping algorithm to build the map as shown in Figure 9 and 10 , and update the merged map through the updating formula of an occupancy grid map by multiple robots as shown in Figure 11. The merging process and the status has been shown in Figure 12, which validates that merging process has been successfully done.



(a) Real Scenario Lab office 1 environment (b) Constructed Map

Figure 9. Results of map generated by robot1

(a) Real Scenario Lab office 2 environment

(b) Constructed Map

Figure 10. Results of map generated by robot2

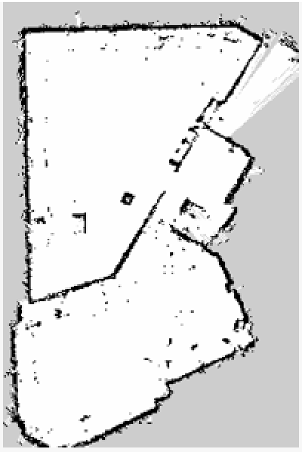
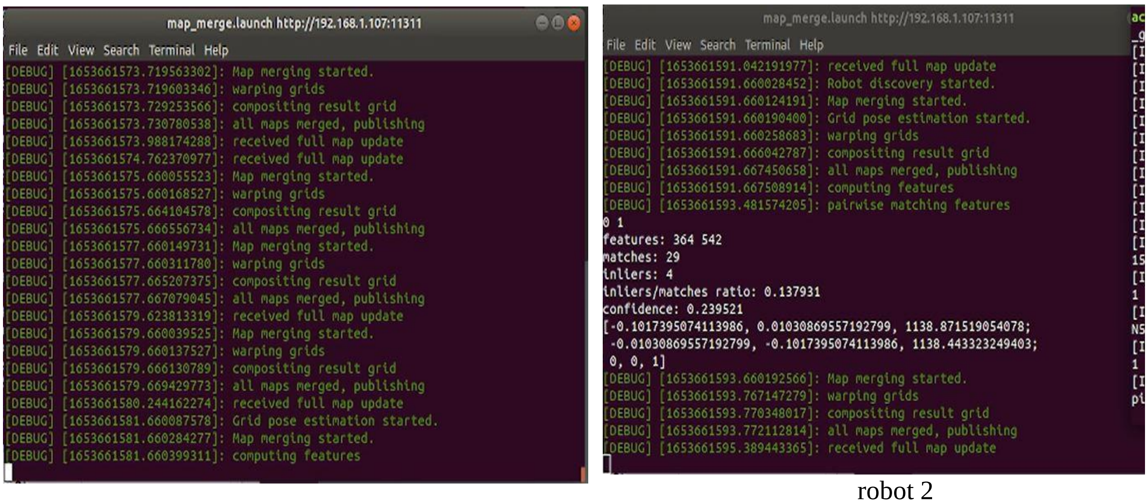


Figure 11. Merged global map of robot1 and



robot 2

Figure 12. Mapmerging process illustration through terminal

Once the global map is generated, it's been shared among the robots for autonomous navigation. Each robot then uses the global map generated in the multi-robot system to independently navigate to the destination. The global map generated as shown in Figure 11 is then used by each bot to navigate autonomously to the target location. The 2D pos estimate button in the Rviz tool is used initially to locate the robot, which internally runs the AMCL algorithm to know where it is inside the map. The target is set by using a 2D nav goal key, which intern uses the A* path planning algorithms to plan the route from the starting point to the target destination as shown in Figure 13.

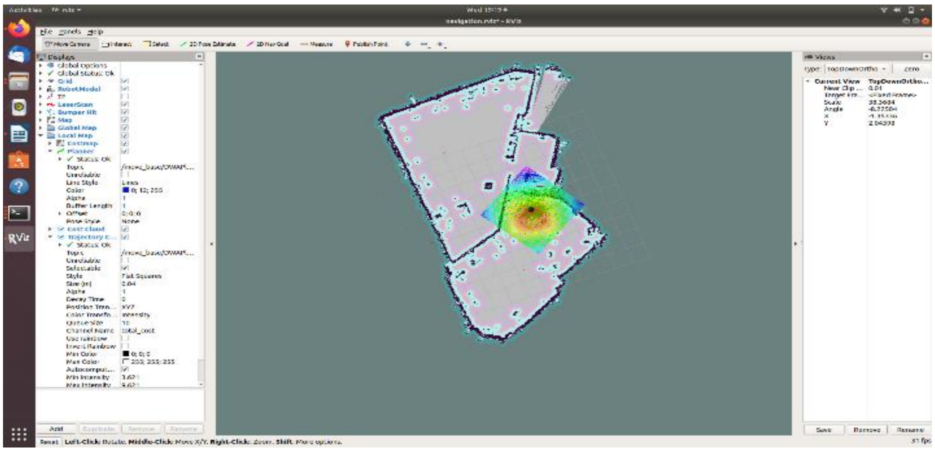


Figure 13. Autonomous Navigation of the robot through the generated map

5. Conclusion And Future Work

A. Conclusion

The work reveals that an efficient and safe solution for navigation through unknown indoor environment can be provided by mapping and autonomous navigation using LIDAR and ROS. With the help of LIDAR sensor an accurate 2D map of the indoor environment that are processed by ROS algorithms can be generated followed by the autonomous navigation. The system that had been described here is tested providing promising results in obstacle detection and avoidance. With the help of LIDAR and ROS we were opened to new possibilities for navigation in complex environment. The system has a wide range of potential applications in many different fields such as industrial automation, surveillance, and many more. The system's autonomously navigating ability can also provide valuable assistance in emergency situations, where human intervention may be limited or difficult. A further more development and testing of the proposed system can enhance its capabilities with the increase in its potential applications.

B. Future Work

There are several different methods to improve the mapping and navigation system in indoor environment using LIDAR and ROS for future works. It involves incorporating various other sensors such as cameras and inertial measurement units (IMU's), which can help in improving the performance of the system by providing additional information about the environment. This method can enhance the system's ability to detect and avoid obstacles by improving navigation efficiently. The next step is to extend the system to operate in outdoor environments that can be achieved by incorporating various sensors and different algorithms designs especially for outdoor environment. The system can also be optimized for real-time operation that can be done by implementing various parallel processing techniques and algorithms enhancing system's ability to operate I dynamic environment and handle real-time changes in the environment. Lastly, integrating system with machine learning algorithm can enhance the ability of system to recognize different types of obstacles and environment.

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