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Design and Development of a Highly Efficient Autonomous Mobile Robot for Industrial Applications

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ABSTRACT: *The world of autonomous robots is experiencing rapid growth, transitioning from reliance on remote controllers to operating independently. These robots possess the capability to perform tasks autonomously, thereby significantly reducing the workload on humans, particularly for mundane and exhausting tasks. This research paper focuses on a specific category of autonomous robots known as Autonomous Mobile Robots (AMRs). The AMR discussed in this paper is constructed using a Raspberry Pi 3B+ with an embedded specialized chip, along with an Arduino Mega microcontroller. Additionally, it is equipped with various sensors and components enabling it to perceive its environment and navigate effectively. The current study has devised a methodology for constructing and operating this AMR, which includes the development of a specialized program for determining optimal routes to its destinations. Notably, this robot possesses the capability to dynamically generate maps of its surroundings as it traverses, thereby maintaining precise spatial awareness.*

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I. INTRODUCTION

The realm of autonomous robotics is witnessing a remarkable ascent. Previously reliant on remote control systems, these robots are now capable of functioning autonomously. Their ability to perform tasks independently offers substantial assistance to individuals engaged in arduous, hazardous, or time-sensitive occupations. For instance, they can undertake exploratory missions, tackle tasks deemed too risky for human intervention, or expedite processes requiring swift execution. Consequently, there is a reduction in the necessity for individuals to engage in monotonous or physically taxing labor. Furthermore, in certain scenarios, robots can assume roles unsuitable for human involvement, such as those in hazardous or extraterrestrial environments. The advancements in robotic technology are instrumental in expanding our exploration endeavors and fostering economic growth.

Autonomous Mobile Robots (AMRs), endowed with the capability to navigate independently, represent a category of mobile robots that operate devoid of human intervention. AMRs exhibit distinctive attributes including self-localization, orientation, and motion planning, all facilitated by information obtained from integrated sensors and control systems. Typically, AMRs are outfitted with a variety of sensors such as Lidar, cameras, tactile sensors, and infrared sensors to collect data from their surrounding environment. By employing data processing algorithms and control systems, AMRs can ascertain their position, generate maps, and identify obstacles to navigate around during movement. Furthermore, AMRs leverage the widely adopted Robot Operating System (ROS) environment for the execution of autonomous operations. ROS offers a plethora of software packages and tools aimed at facilitating the programming and control of autonomous robots [1].

Various factors are pivotal in enabling Autonomous Mobile Robots (AMRs) to attain autonomous functionality. These encompass mechanical precision, robust motor control algorithms, efficient navigation capabilities, and the incorporation of intelligent behaviors. AMRs are confronted with fundamental inquiries intrinsic to autonomous robotics, such as "Where am I?" and "How do I determine precise locations?" Addressing these queries necessitates solutions pertaining to localization, mapping, re-localization, and path planning. Furthermore, reactive behaviors are indispensable for ensuring safe and efficient operation. These encompass collision avoidance, target approach and tracking, and the capability to detect and classify moving objects. This research is dedicated to elucidating these critical facets of AMR development.

This paper presents the research and design of an Autonomous Mobile Robot (AMR) equipped with embedded computing and a LiDAR sensor for industrial applications. The study leverages the A1M8 LiDAR sensor alongside novel design methodologies and algorithms to endow the robot with the requisite capabilities for autonomous operation. Section 2 provides an introduction to the AMR and the A1M8 LiDAR sensor.

Section 3 delves into the control methods employed for autonomous navigation, focusing on the integration of various systems to facilitate map building and path planning. Finally, Section 4 presents the research findings, along with any relevant considerations and concluding remarks.

II. AN OVERVIEW OF AMRS

The concept of robots finds its roots in science fiction literature. However, their evolution from fictional constructs to tangible realities gained significant momentum between 1917 and 1921. During this period, the Čapek brothers, Joseph and Karel, authored stories that not only explored the concept of intelligent automation but also coined the term "robot," derived from the Czech word "robota" signifying servant or worker [2]. This literary foundation paved the way for the introduction of the first Automated Guided Vehicle (AGV) by Barret Electronics in 1953, marking a significant step towards the integration of robots into the real world [3]. Furthermore, the development of Unimate, the first industrial robot arm utilized on an assembly line by General Motors in 1958, solidified the transition of robots from the realm of science fiction to the domain of practical applications [3]. Since then, industrial robots have been developed and deployed to replace or assist humans in performing repetitive, monotonous, and hazardous manufacturing processes. Furthermore, the field of robotics has evolved to enable human-robot collaboration in tasks that are too complex to be fully automated or too costly to automate entirely. Collaborative robots (Cobots) have facilitated human-robot interaction (HRI) by allowing safe workspace sharing with human workers, in contrast to traditional industrial robot systems that require robots to be isolated from human co-workers to avoid accidents [4][5].

Industrial manipulator systems, including robots, can be integrated with mobile platforms such as Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) to streamline internal logistics and material transport within manufacturing facilities. However, AGVs have limitations compared to their AMR counterparts. AGVs heavily rely on infrastructural support for navigation, such as wires or magnets, which can restrict movement and potentially lead to entanglement within their predetermined paths [3]. In contrast, AMRs possess the capability to navigate freely within a designated operational space, adapting and making decisions based on real-time environmental dynamics. This inherent autonomy empowers AMRs to operate with decentralized control systems, enabling them to communicate and negotiate resource allocation and task distribution independently, either among themselves or with other devices within the environment. This fosters a dynamic response to incoming requests or changes, a capability absent in centralized AGV systems, which typically require an external control unit to make decisions and delegate tasks [6].

Technological advancements and high research interest in AMRs have enabled them to be applied not only in industrial applications but also in various other fields [7]. In agriculture, autonomous robots are used for activities such as planting and harvesting, irrigation, soil nutrient supply, pest detection, and more. In planetary exploration, space robots like Curiosity and Perseverance explore the planet Mars and conduct research on geology, chemical composition, atmosphere, and search for potential biological signs [8]. Some e-commerce companies, such as Amazon and Alibaba, utilize Reliable Mobile Robot Systems (RMFS) in their smart warehouses, where multiple mobile robots work together to transport products to picking stations, saving time, optimizing the picking process, and preventing errors caused by humans [9].

The utilization of AMRs transcends conventional warehousing practices, particularly within the e-commerce sector. Esteemed logistics entities such as DHL, FedEx, SF Express, Google, and UPS have discerned the substantial merits of AMR technology and are actively integrating it into multifaceted logistics operations. AMRs exhibit inherent flexibility, adaptability, and efficiency in executing material handling and transportation tasks, thereby cementing their status as indispensable assets within the contemporary milieu of automated logistics systems

III. DESIGN OF A NEW AMR MODEL

To enable autonomous operation, the hardware components designed for the robot include: a mechanical frame, a Lidar A1M8 sensor, a Raspberry Pi 3B+ embedded computer, an LM298 power amplifier module, an Arduino Mega 2560 microcontroller, a JBG 520 DC servo motor, and an LM298 power amplifier module.

Fig. 1 Module Raspberry Pi 3B+

Technical specifications: Raspberry Pi 3 Model B+ is the latest version in the Raspberry Pi 3 series. It features the Broadcom BCM2837B0, Cortex-A53 (ARMv8) SoC 64-bit processor running at 1.4GHz. It has 1GB LPDDR2 SDRAM for memory. The board supports wireless networking with IEEE 802.11.b/g/n/ac 2.4GHz and 5GHz, as well as Bluetooth 4.2 and BLE. It provides Gigabit Ethernet through a USB 2.0 port with a maximum speed of 300 Mbps.

The Raspberry Pi 3 Model B+ has a 40-pin GPIO header for expansion. It includes a full-size HDMI® port for display output. There are four USB 2.0 ports for connecting peripherals. The board has a CSI camera port for connecting a Raspberry Pi camera and a DSI display port for connecting a Raspberry Pi touchscreen display. It also features a 4-pole stereo audio output and a composite video port. A microSD card slot is available for loading the operating system and storing data. The board requires a 5V/2.5A DC power input. It also supports Power-over-Ethernet (PoE) with a separate PoE HAT (Power-over-Ethernet) module [10].

The system uses Lidar A1M8 sensor. This type of sensor employs filters and sensitive detectors to collect and measure the reflection time of the laser beam. Based on the reflection time, the sensor calculates the distance from the sensor to the object. By scanning the laser beam at various angles, the Lidar A1M8 sensor generates a three-dimensional image (point cloud) of the surrounding environment. This image allows for the determination of the position and shape of objects within the scanning range.

Fig. 2 The A1M8 Lidar sensor

DESIGN OF THE MECHANICAL STRUCTURE

The objective of designing the autonomous vehicle is to create a simple, symmetrical, and easy-to-control vehicle. To achieve this, the research team utilizes basic geometric shapes with a symmetrical structure, enabling easy maneuverability of the vehicle. The vehicle in the project is designed with two layers: the first layer houses the control circuitry, drivers for the vehicle, and the embedded computer. The second layer is dedicated to the placement of the lifting frame and the Lidar sensor. Figure 3 represents the mechanical structure of the proposed AMR.

Fig. 3 The mechanical design of the vehicle

DESIGN OF THE EMBEDDED PROGRAM

The autonomous vehicle is designed to receive control signals from the ROS operating system. The received signals include the linear velocity v and angular velocity ω. The task of the embedded program is to control the autonomous mobile robot (AMR) to execute the desired actions based on these velocities.

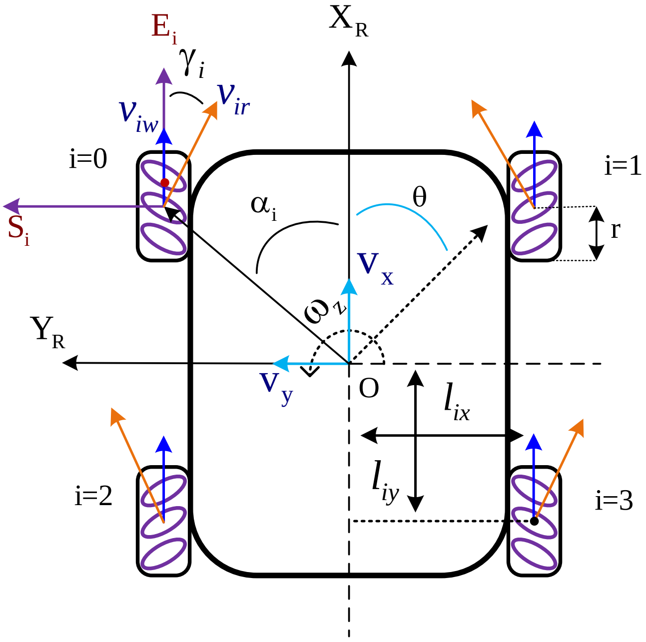

Fig. 4 The wheel configuration and posture of the vehicle

From the received velocity information, it is necessary to convert it into the desired linear velocity and angular velocity, using commands sent from the software to ensure that the vehicle's center velocity matches the required velocity. With a mecanum wheel configuration consisting of four wheels with symmetric centers, we utilize a multi-drive differential system. This system operates by generating rotational forces for each individual wheel in the same direction as conventional wheels. However, the difference is that the multi-drive differential system has the ability to slide freely in a different direction [13].

The individual angular velocities of each wheel are as follows:

$$\begin{cases} \omega_1 = \dfrac{1}{r}(v_x - v_y - (l_x - l_y)\omega), \\ \omega_2 = \dfrac{1}{r}(v_x + v_y + (l_x + l_y)\omega), \\ \omega_3 = \dfrac{1}{r}(v_x + v_y - (l_x + l_y)\omega), \\ \omega_4 = \dfrac{1}{r}(v_x - v_y + (l_x + l_y)\omega), \end{cases}$$

Where:

- vx and vy represent the translational velocities along the x-axis and y-axis, respectively.
- lf denotes half of the front wheelbase.
- lr represents half of the distance between the front and rear wheels.
- ω signifies the angular velocity.
- vl and vr correspond to the rotational speeds of the left and right wheels, respectively.
- R refers to the radius of the wheels.

To fulfill the control problem of the AMR, a flowchart representing working principle for the major motor of the vehicle is plotted in Fig. 5.

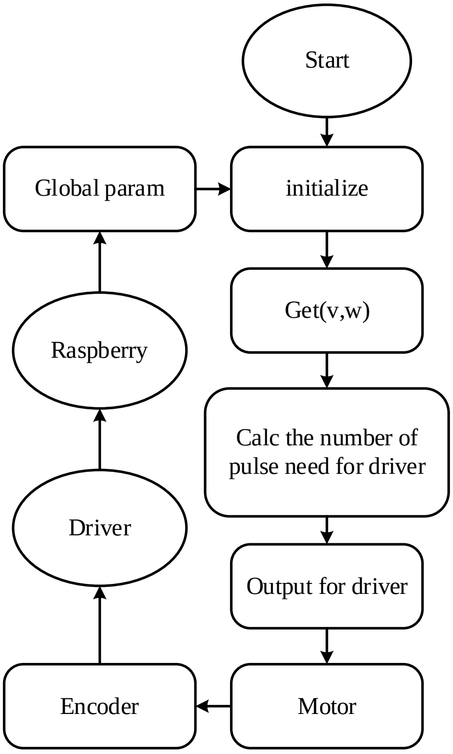

Fig. 5 The control algorithm diagram for motor control

The microcontroller operates in a cyclical manner. Following each Timer cycle, it retrieves velocity values (v, ω) from designated global variables. Based on these values, the microcontroller calculates the required pulse count for both the left and right motors. These calculated pulse signals are then transmitted to the motor controller for actuation. If an encoder is incorporated into the system, it transmits feedback signals back to the pulse calculation module. This feedback loop ensures the accuracy of the motor's pulse output. During operation, the system can receive new signals from the Raspberry Pi via the USB connection. Upon receiving a complete data frame (indicated by the USB buffer reaching a specific byte count), an interrupt is triggered. This interrupt allows the processor to access the data frame from the buffer and subsequently calculate the corresponding velocity values. Finally, these calculated velocity values are updated within the global variables.

IV. EXPERIMENT RESULTS AND DISCUSSIONS

In order to assess the effectiveness of the research and the accuracy of the robot's performance, a series of controlled experiments were conducted within a designated indoor environment. This environment consisted of a specific area with a tiled floor, replicating terrain suitable for the robot's design. Moreover, the research team strategically introduced obstacles to simulate real-world operating conditions. To minimize the impact of extraneous factors on the test results, the robot was systematically restarted and maneuvered along a predefined trajectory at a constant velocity during each experimental trial.

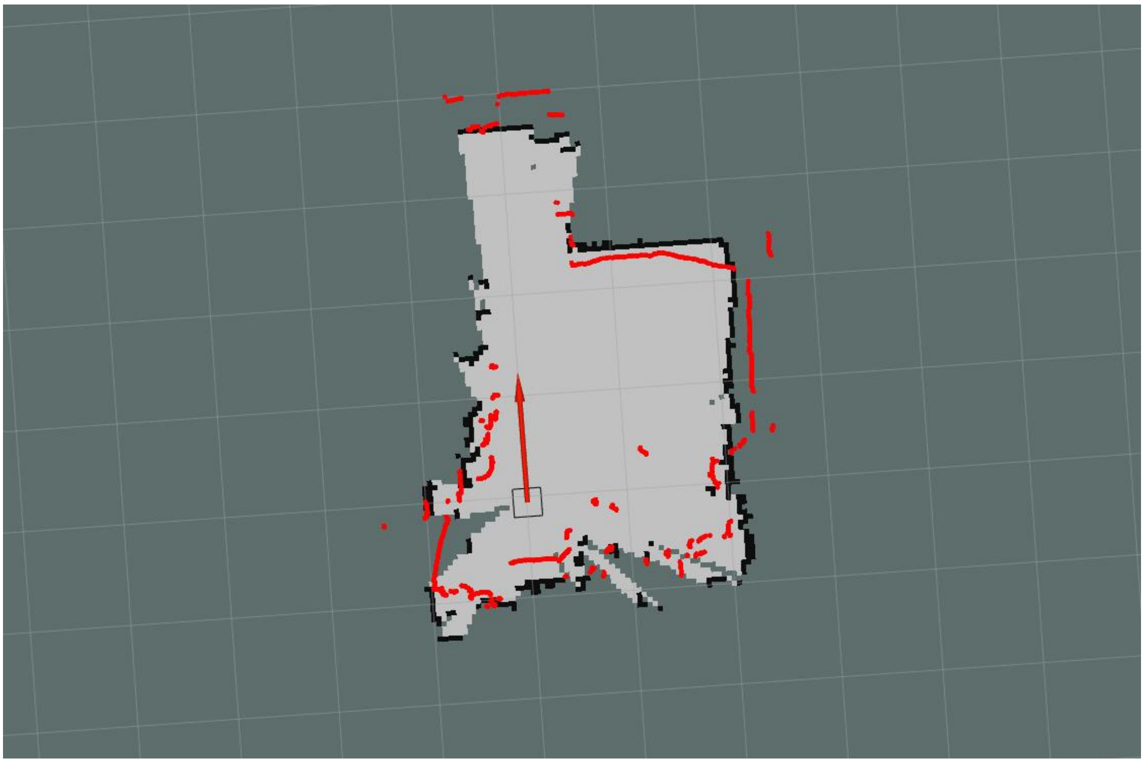

Fig. 6 The AMR robot scans for signal alignment with the constructed 2D map

Figure 6 illustrates the data utilized by the robot for localization. Black areas represent the projections of obstacles onto the map's 2D plane, while red lines depict laser scans exceeding a specific ground height extracted from the LiDAR data. The Adaptive Monte Carlo Localization (AMCL) algorithm employs a map generated during the robot's mapping process for localization. Upon initialization, AMCL establishes a particle filter with pre-defined parameters. The initial particle set within the filter is concentrated at the origin (0, 0, 0) unless otherwise specified. These configuration parameters can be tailored within the Navigation section of the robot's software. Particles within the filter are generated based on sensor data and assigned corresponding weights. Subsequently, a resampling process occurs, retaining particles with higher weights and discarding those with lower weights. The robot's current position is estimated based on the particle possessing the highest weight.

This process iterates continuously whenever new sensor data becomes available. This continuous loop refines the robot's localization accuracy and updates the map within the database. Figure 7 depicts the particle sampling process during map initialization. The red arrows in Fig. 7 represent the initial particle distribution. Following the resampling process, the particles tend to converge towards the robot's actual position. In essence, even if the robot rotates in place for an extended period, the particles will converge upon the most likely location. The red arrows ultimately represent the range of possible robot poses on the map.

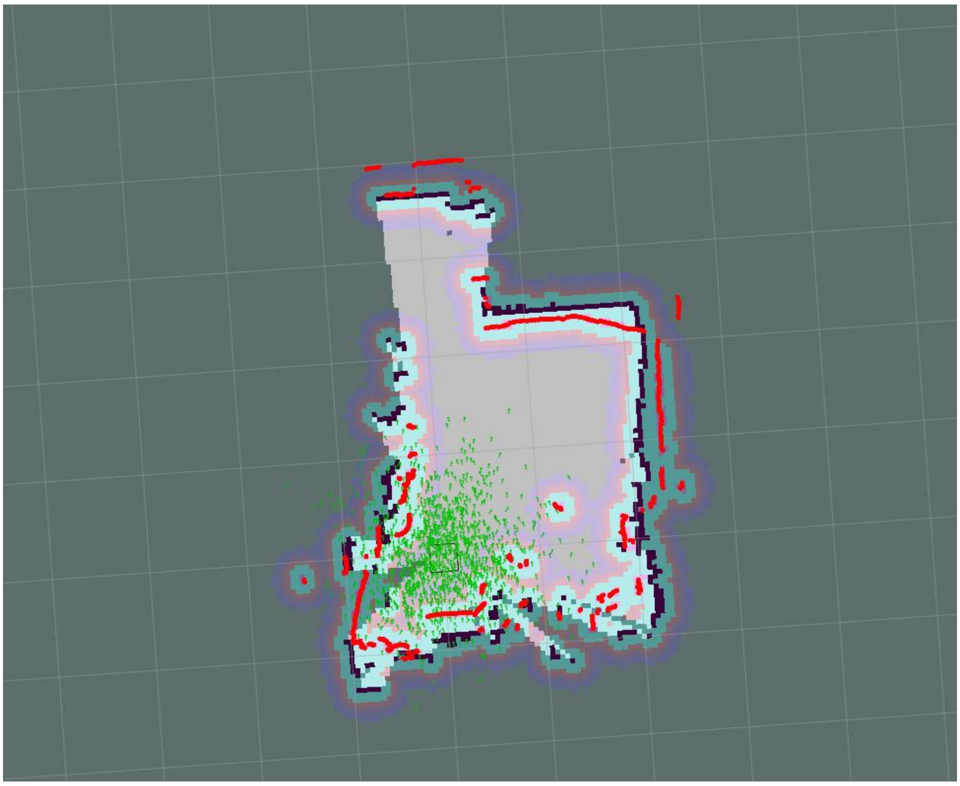

Fig. 7 The Robot utilizes an AMCL filter for localization

Path planning and initiating robot movement towards the goal shown in Fig. 8.

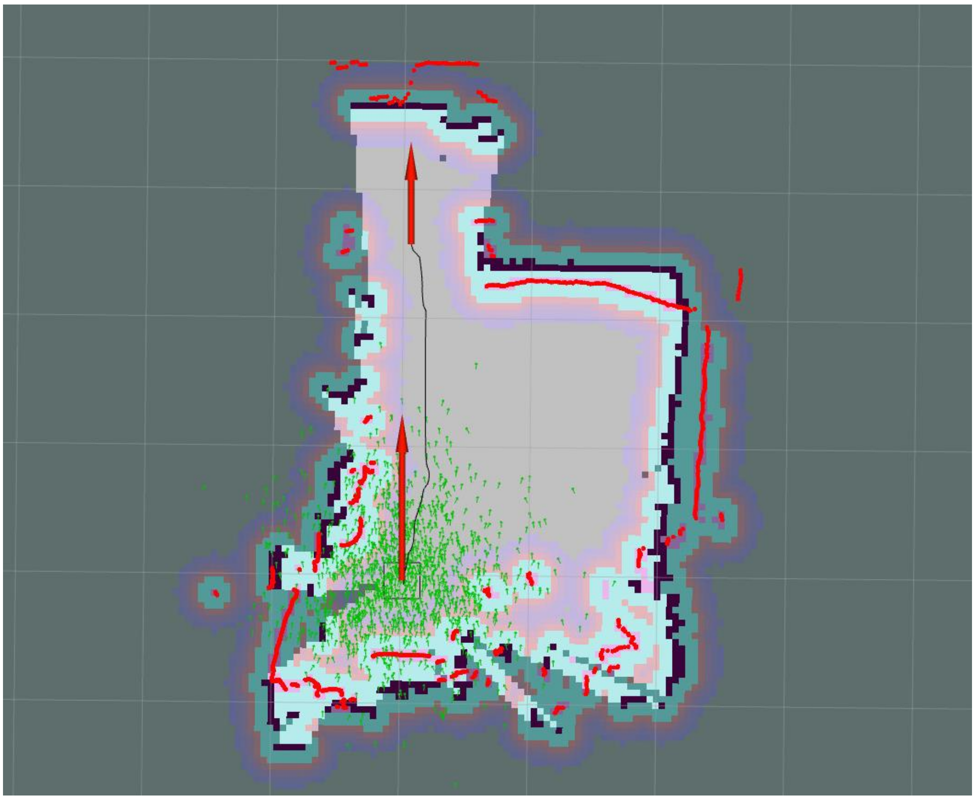

Fig. 8 Robot path planning

Moving towards the destination point following the pre-determined path.

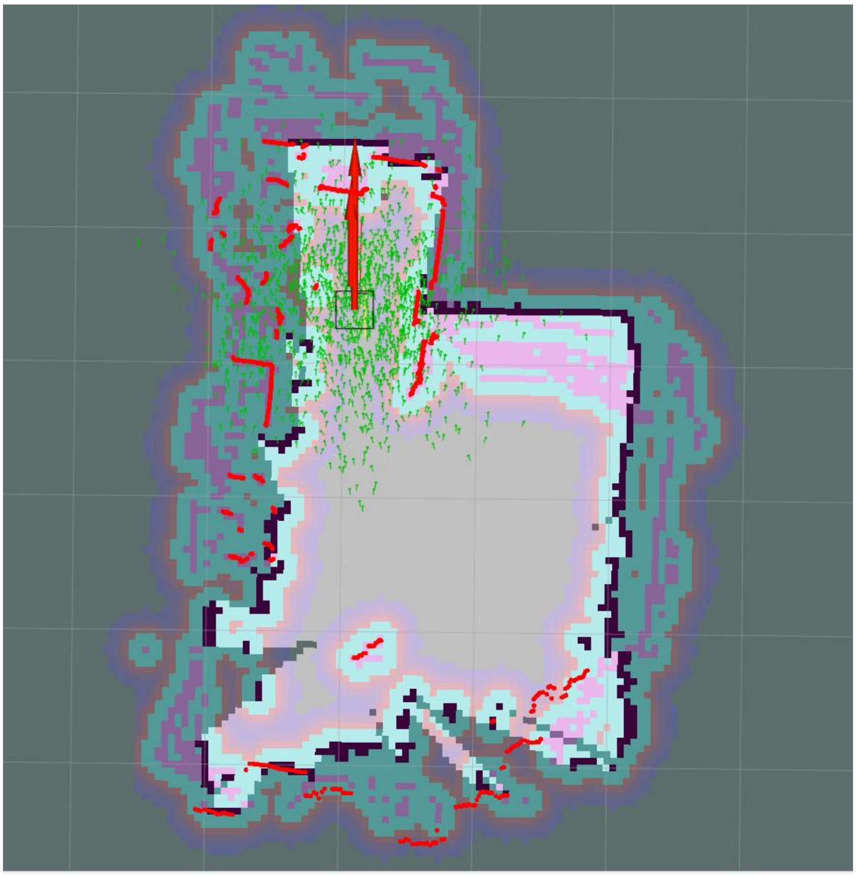

Fig. 9 The ARM robot follows the planned path and reaches the destination

In Fig. 9, it is shown that the robot has reached the predetermined end position. The robot has moved close to the desired destination according to the given path plan. However, there is still a slight deviation between the robot's position and the target destination, and during the movement, the robot exhibits some instability.

V. CONCLUSION AND FUTURE WORK

The analytical, simulation, and discursive components of this investigation have yielded significant findings regarding the implementation of control algorithms for robots operating within the Robot Operating System (ROS) framework. The study successfully utilized LiDAR sensors to equip the autonomous vehicle with robust mapping and stable navigation capabilities. Moreover, the research identified time-variant controller parameters dependent on desired linear and angular velocities. This optimization ensures the stability of the autonomous vehicle during various trajectory maneuvers. Additionally, the integration of an embedded computer within the autonomous vehicle effectively reduced its physical footprint and enhanced operational flexibility.

These current research outcomes establish a critical foundation and framework for the ongoing development and performance optimization of autonomous vehicles. Future endeavors will focus on comprehensively refining the system and ensuring its stable operation across a broader range of environmental conditions.

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