Comparative Implementation of SLAM on Mobile Robotic Platforms using Ultrasonic and LiDAR Sensors

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Abstract—**This study explores the efficacy of Simultaneous Localization and Mapping (SLAM) on a two-wheeled mobile robotic platform, assessing the performance differentials when utilising Ultrasonic sensors versus LIDAR technology. An Inertial Measurement Unit (IMU) supplements odometry to furnish comprehensive data for navigation. The core objective is to determine whether SLAM's output remains consistent when implemented with either of the sensing modalities. The experiment involves navigating the robot along a predetermined closed path within a controlled environment to ensure uniformity in testing conditions. By comparing the spatial mapping and navigation data generated by each sensor type, the research aims to identify any discrepancies and assess the relative advantages or constraints of Ultrasonic and LIDAR sensors in a SLAM context. The outcomes are expected to provide insights into sensor selection for optimised robotic navigation and mapping in similar applications.**

Index Terms—**SLAM, ULTRASONIC, LIDAR, MOBILE ROBOT**

I. Introduction

The word 'robot' was first introduced in the real world in 1920 through the play 'Rossum's Universal Robots' written by the Czech Karel Capek [1]. Since then, The advent of mobile robotics has transformed a myriad of sectors, enabling the execution of tasks ranging from the mundane to the hazardous, altering the landscape of industries as diverse as agriculture, defence, and healthcare. The evolution of these autonomous agents has been significantly accelerated by the rapidly expanding field of microcomputers and embedded systems, leading to cost-effective yet sophisticated solutions tailored to a variety of applications [2]. The fundamentals of mobile robotics consist of the fields of locomotion, perception, cognition, and navigation [3].

Equipped with several sensors a Mobile Robot can investigate in a room or in an open area [4], as well as in industrial fields [5], [6]. The autonomous mobile robots that have been developed are equipped with obstacle avoidance features as one type of intelligent robots [7].The ability to detect walls and obstacles around them to predict collision-free paths automatically is the main feature of autonomous mobile robots [8]. Various sensors such as infrared and ultrasonic range finders, cameras and GPS are used to determine the obstacle free path and the exact position of the mobile robot [9]. However, these conventional sensors have limitations in terms of detection distance, spatial resolution, and processing complexity. As an instance, blanking intervals and angular uncertainty are limitations on the ultrasonic distance sensors [10].

This introduction serves as a preface to a detailed comparative study on the implementation of Simultaneous Localization and Mapping (SLAM) in mobile robotic platforms, contrasting the use of Ultrasonic and LIDAR sensors, while highlighting their respective benefits and limitations.

II. Literature Review

The increasing demand for self-driven systems has led to a notable rise in the use of sensors. These sophisticated devices are engineered to convert various physical parameters, such as temperature, pressure, humidity, velocity, and distance, into measurable electrical signals [11]. The selection of sensors is crucial and largely depends on the specific requirements of a project. A notable challenge arises when employing Ultrasonic Sensors (UsS). These sensors, which operate on sound waves, can encounter difficulties with materials like sponge and cotton, or with irregularly shaped objects [12]. Moreover, environmental factors like wind, heat, and humidity can also impact their effectiveness [13].Ultrasonic Sensors face numerous challenges, which have become a focus for many researchers. A recent study has explored their use in accurately positioning and identifying transparent objects, such as glass bottles. This research discusses a system that utilizes ultrasonic sound signals to perceive the location and shape of objects. This system is capable of determining the intended distance in both width and depth, in a step-by-step approach [13].

Since the inception of the laser in 1960, there has been a continuous pursuit of developing a novel ranging system utilising the transmission and reception of light, incorporating well-established principles from Radio Detection and Ranging (RADAR), and this innovative technique came to be known as LiDAR, an acronym for Light Detection and Ranging [24]. LiDAR has attracted developments in various forms such as opto-mechanical, electromechanical, micro-electromechanical systems (MEMS), and solid-state scanning [21]. This is due to its huge popularity in various applications such as navigation, robotics, remote sensing, and advanced driving assistance systems (ADAS). Despite the long history of usage of LiDAR in military and defence applications [22], LiDAR implementation FOR ADAS (Advanced Driver Assistance Systems) can be traced back to the DARPA Autonomous Vehicle Grand Challenges of 2004-2007 when a rotating LiDAR system was designed that scanned 360° and produced hi-resolution data out to more than 100 metres [23]. ADAS requires the automotive-grade LiDAR sensors to meet a wide variety of stringent requirements such as high range, sub-centimeter precision, low power consumption, low manufacturing cost and eye-safe signal transmission [24]. Other key requirements such as detection range, field of view, angular resolution, and laser safety, are analysed in [25]. In the study [26], the specifications for automotive LiDAR systems, determined through consultations with manufacturers, categorise them as short-range (20 m to 30 m) and long-range (up to 300 m) systems, with proposed angular resolutions of 1° for short-range LiDAR and between 0.1° and 0.15° for long-range LiDAR to enhance the delineation of distant objects. Studies such as [27,28] demonstrate the fusion of LiDAR data with that of the other sensors such as Global Positioning Systems (GPS) and Inertial Measurement Unit (IMU) to have a better estimate of the localization of vehicles.

There have been many different methods developed in recent decades to solve the computational problem of SLAM. Many types of sensors have been used to implement SLAM, such as cameras and LIDAR data [29]. GMapping [30][31] is one such approach that has been implemented in ROS (Robot Operating System)[32]. The GMapping ROS implementation is able to process range data from a laser scanner to create a map of its environment.

Item	Description
Size	240 (L) x 140 (W) x 180 (H) in mm
Weight	1.3 Kg
Power	10000 mAh Power Bank for Raspberry Pi, 4 x AA Battery for Motors
No. of Wheels	4
Steering Type	Differential
Type of Sensor	Ultra Sonic Sensor, Lidar
No of Sensor	2
Electronics	Raspberry Pi 4 Model b , 2x Arduino Uno, L298N Motor Driver, Stepper Motor, HC-SR04 Ultrasonic sensor

Fig. 1. Mobile Robot Description

III. Hardware

The mobile robot developed for this study serves as a testbed for comparing the navigational efficacy of advanced LiDAR systems with that of economical ultrasonic sensors. At the heart of its hardware configuration, the robot is equipped with a pair of driving wheels, each integrated with encoders for enhanced movement accuracy and feedback.Stability is provided by two strategically placed caster wheels, which support the structure and aid in maneuverability. However, during the development phase, the front caster wheel presented a significant challenge; its resistance to smooth pivoting was inadvertently influencing the robot's intended path. This mechanical constraint was critical, as it had the potential to skew the sensor comparison results. Overcoming this hurdle was paramount in ensuring that the robot's directional control remained unbiased and reliable for the sensor effectiveness trials.

A. Structure

The design was done in Solid works, the material used is 1/8 inch MDF plywood. The structure of our mobile robot is designed with simplicity and functionality in mind. It has a robust chassis that holds all the essential components together.

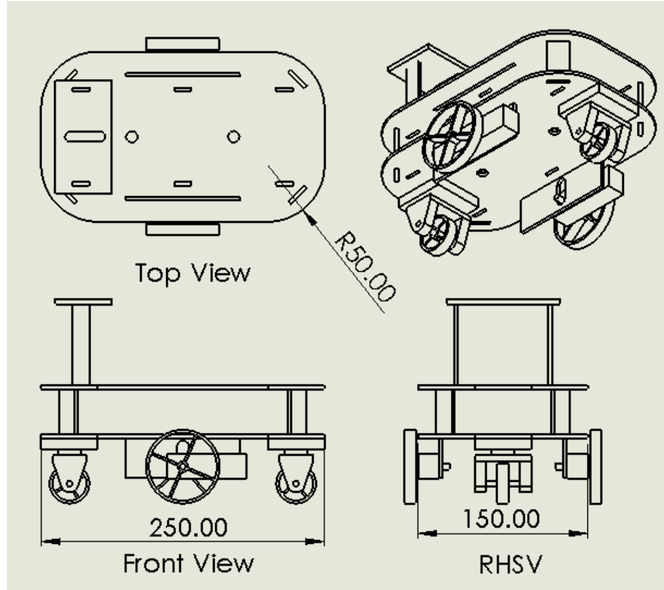

Fig. 2. Drawing Diagram

B. Electronics

a) LiDAR: LiDAR, which stands for Light Detection and Ranging, is a remote sensing technology that measures distances by illuminating a target with laser light and analyzing the reflected pulses. This sophisticated system operates on the principle of time-of-flight, where the LiDAR sensor emits laser beams toward the target, and the time it takes for the light to return is precisely measured. By calculating the round-trip time and knowing the speed of light, LiDAR determines the distance to the target with remarkable accuracy. Additionally, LiDAR sensors can scan the surrounding environment in multiple directions, generating a dense three-dimensional point cloud that represents the spatial characteristics of objects and surfaces. This wealth of data makes LiDAR an invaluable tool in various fields, including autonomous vehicles, environmental monitoring, and topographic mapping, offering unparalleled capabilities for high-precision and real-time spatial mapping.

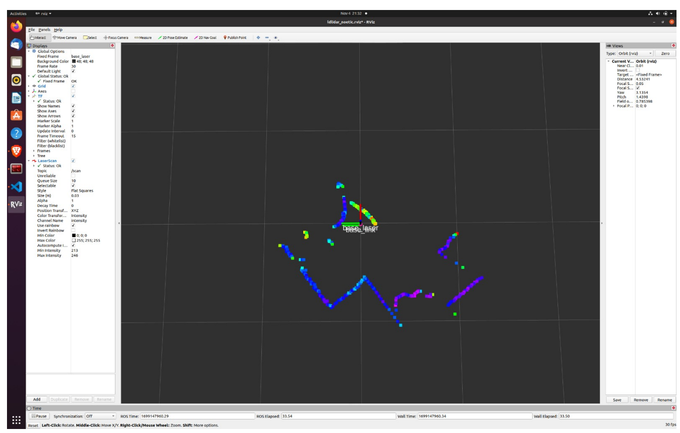

Fig. 3. Sample LiDAR output

b) SONAR: The HCSR04 is a cheap ultrasonic module popular among robotics enthusiasts. It provides an angular resolution of ... with a distance ranging of 2cm - 5m. Since our goal is to eradicate the LiDAR module and thereby reduce the cost factor incurred with the use of expensive sensorics in hobbyist projects, this HCSR04 module was deemed the perfect fit. The two transducers built on the sonar module are responsible for the sending and receiving of ultrasonic waves through the medium.

c) Stepper: The 28BYJ-48 Stepper Motor was controlled by the Arduino micro-controller board through the ULN2003 motor driver. The rotor shaft of the motor has 32 teeth, thus requiring 32 electrical pulses in sequences to be supplied to the stator. However, the stepper module has an internal gear reduction of 64:1, thereby requiring 64 revolutions of the rotor shaft to produce a single revolution at the output. Therefore, 2048 electrical sequential pulses have to be supplied to the rotor to be able to rotate the output shaft by an angle of 360°. This means that the angular resolution that can be achieved at the output is a staggering 0.176°.

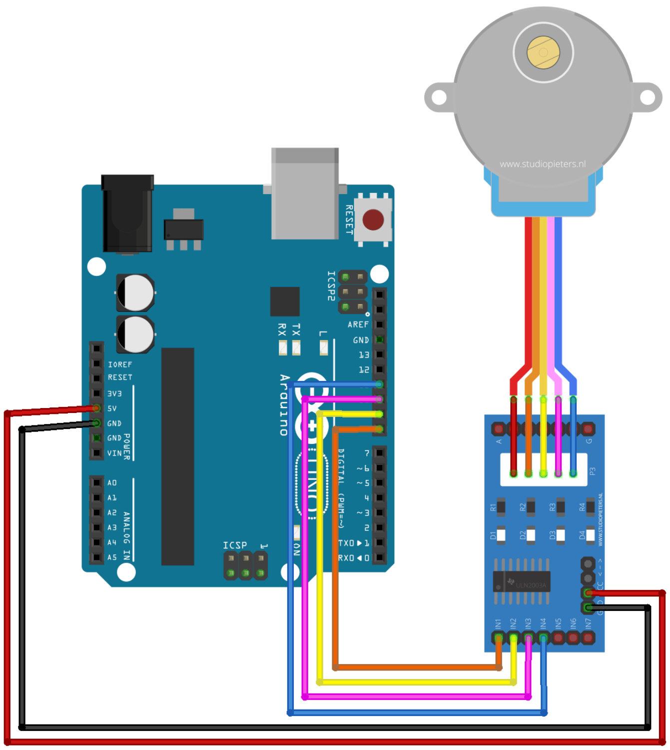

Fig. 4. Arduino Uno with 28BYJ-48 Stepper Motor and ULN2003 Driver

IV. Software

A. Stepper & SONAR

a) Rotation: However, the scope of this project required the sonar module, attached to the motor, to be rotated with angular steps of 2° each, which needed a combination of around 11 pulses to be supplied to the stator at a time. Additionally, the time delay between two consecutive steps was also of concern, but, since the sensor rate at 40 Hz outperforms the angular speed of the motor at 15 rpm, there was absolutely no need of waiting between steps to get the data from the sensor, thus allowing for faster sweeps. Each sweep of the sonar corresponds to a 180°rotation at the motor shaft in steps of 2° each, and then back to the home angular position at 0°, again, in steps of -2° each.

b) Data Acquisition & Processing: The timer in the module then calculates the time duration between the two instants of trigger and echo. The distance is calculated by dividing the duration by twice of the speed of sound in air. This distance is paired with the angle at whcih it was recorded and stored in memory as an angle-distance pair, which is ready for further processing. The range of values recorded as distances may be filtered and also mapped to be inbound to a prescribed range of distance values, which may decided appropriately in consideration with the actual range of the sensor module.

c) Data Conversion: The distance converted raw data pair, i.e., the distance and the angle at which it was recorded must be converted to a 'Laserscan' message in order to be used by ROS. ROSwiki provides documentation for the LaserScan message with definition of the fields contained in the message type. The message once converted is then to be published by the Arduino module over 'rosserial' to a prescribed topic running under the ROS master node. 'rosserial' is a library that enables serial communication between a variety of peripherals and ROS. This enabled us to use the Arduino Uno module for communication with the Raspberry Pi using the constituent library named as 'rosserial_arduino'. However, the converted LaserScan message was causing the Arduino Uno module to run out of memory due when the message was being sent through serial. This may be attributed to the small serial buffer of the Uno module. Upon consideration, it was decided that the raw angle and distance pairs would be sent over to the RPi over ROS, after which we could utilise the RPi's computational power to convert it to a LaserScan message and then use it for visualization and further processing.

B. IMU

We originally planned to use a VN-100 IMU to measure the vehicle's odometry. Since the VN-100 measures linear acceleration, angular velocity, and yaw angle, we would be able to determine the vehicle's current position, a key value for implementing SLAM. We wrote code for doing this, but ran into issues with the accelerometer data. Ideally, when the car was completely still, we would read 0 acceleration in the x and y axes. However, our IMU would read consistent amounts of acceleration, which in turn made our odometry measurements unusable, as the car would appear to be constantly moving around the map even when still.

We suspect that this issue is likely due to the impacts of gravity and improper calibration of the IMUs. Ideally, gravity should only impact the z axis, but we suspect it was partially impacting the x and y axes, resulting in consistent acceleration in those axes.

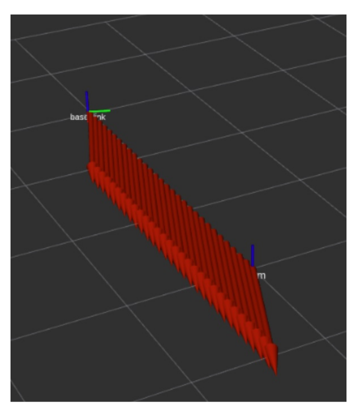

Fig. 5. IMU drift in stationary condition

Due to these measurement issues, we decided to switch to using encoders on our wheels to determine the vehicle's odometry.

C. Encoders

A rotary encoder is a device that is used to keep track of the number of rotations of a rotating shaft. The encoder can detect the change in angle of the rotating shaft. The encoder used in this case is a non-contact encoder that makes use of principle of change in inductance.

One of the outputs of the encoder provides the direction of rotation while the other is attached to an interrupt pin of the Arduino which will either increase or decrease the tick number depending on the direction output. The Arduino runs a Publisher that publishes the left wheel and right wheel tick values as Int16 values.

The change in the value of ticks per second is then determined and the wheel velocity is measured using this data. On getting the wheel velocity, the odometry of the robot can be derived from this data.

D. Differential Drive

The experiment makes use of a simple two-wheeled differential drive setup. It has two active wheels powered by a motor each. There are two passive caster wheels to maintain balance. It is a simple setup used in favour of simplicity and minimum number of actuators that has full 3 degree-of-freedom.

Differential drive works on the basis of turning due to difference in wheel velocities. To turn left, the left wheel is made to spin slower than the right wheel. Similarly, to turn right, the right wheel is made to spin slowly.

The inverse kinematics for deriving the wheel velocities can be derived from the following equation,

$$\Omega_{left} = (V_b - d * \Omega_B)/a$$

$$\Omega_{right} = (V_b + d * \Omega_B)/a$$

where

$$V_b = Linear\ velocity\ of\ thebot,$$

$$\Omega_b = Angular\ velocity\ of\ thebot,$$

$$d = Wheelbase\ of\ the\ bot,$$

$$a = Radius\ of\ the\ wheel.$$

The above inverse kinematics is incorporated in an Arduino script which runs a ROS Subscriber to receive commands from the /cmd_vel topic where the commands are given in form of std_msgs/Twist message.

V. Results

The goal of this project is to compare the performance of LiDAR against the performance of the Ultrasonic sensor in mapping. As mentioned before to provide a one-on-one comparison between the two different methodologies of mapping, the mapping algorithm chosen in both cases are the same to avoid the effects of other affects. This makes sure that the difference in the output is caused sorely due to the different sensing methodologies.

a) LiDAR: The map was succesfully generated using the LiDAR sensor by slowly looping the bot around the corridor a few times. The bot profited from the localization algorithm as it received incorrect odometry readings from the encoder due to slippage of the wheels on a smooth floor on multiple occasions during it's mapping phase. This added a bit of noise in the map but the resulting map was still satisfactory.

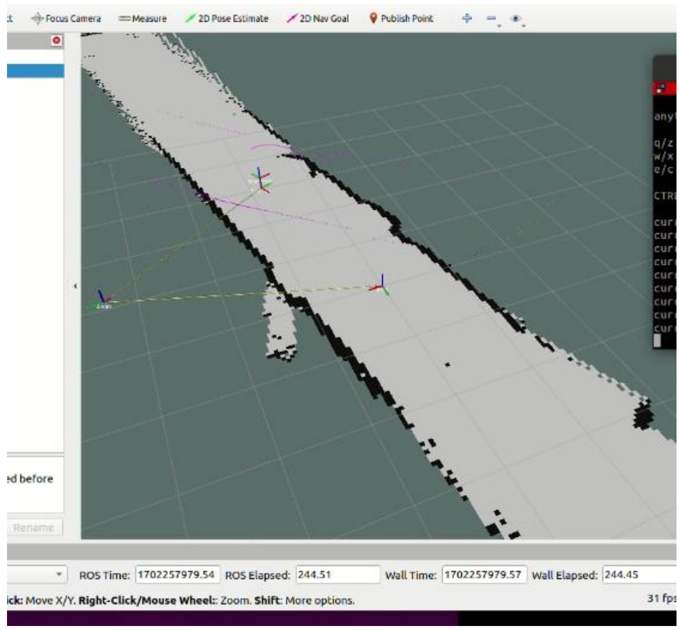

Fig. 6. Map generated using LiDAR

b) Ultrasonic: Initially, The data returned by the ultrasonic sensor was noticed to be erroneous. When facing a straight wall, the data returned took an arc shape in contrast to the expected straight line of the wall. One of the possible reason for this error could be the source of reflection of the sound wave being different from the obstacle in line of sight. Since sound waves propagate in waves, the sound waves gets reflected off of a neared object in the cone of propagation.The initial maximum range was set to 1.5 meters, on dropping the range to 0.5 meters, the data received was found to be significantly similar to the characteristic of the wall.

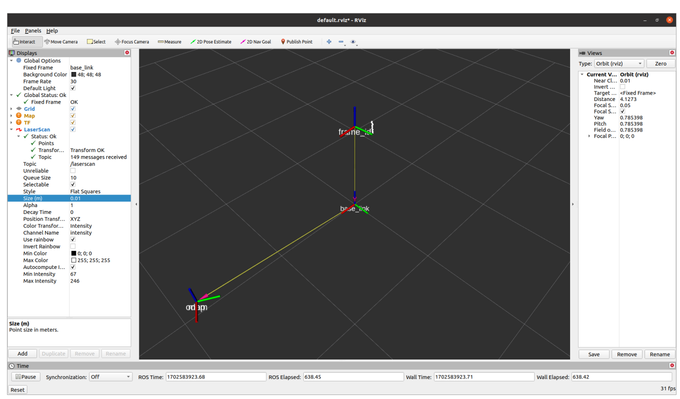

Fig. 7. Corrected output of the sensor

Unfortunately, the sample rate of the spinning ultrasonic sensor was too low to implement a practical SLAM algorithm.

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