Environmental Sensing using LiDAR Sensor with Simultaneous Localization and Mapping Method based on Robot Operating System

A. Trisanto, A.V. Nugraha, M. Taufik, E. Sitompul, N.S. Syafei, E. Supriyana, and ArjonTurnip

***Abstract*—This study proposes an environmental sensing system using the LiDAR method and Simultaneous Localization and Mapping based on a Robot Operating System using Raspberry Pi in real time for applications in an autonomous wheeled robot. Four types of experiments were conducted to test the proposed system. The sensor was proven to be able to measure the distance to surrounding objects with an average error percentage of 0.35%. The system can also create a two-dimensional scan map of a labyrinth-like test arena, with the highest and average errors percentage of 3.96% and 0.71%, respectively. The experiment also confirms that the surrounding material must be checked to ensure there are no reflective spherical objects such as mirrors or glass material as these objects cannot be detected accurately by LiDAR sensors. The proposed system demonstrates its ability to map the surrounding environment with high accuracy in real time. In addition, it is prospective to be implemented as autonomous robot navigation for certain environments.**

***Index Terms*—LiDAR, Autonomous, Medical Robot, Localization, Mapping, Communication.**

I. Introduction

THIS The COVID-19 pandemic makes people realize that direct contact should be avoided. For this purpose, robots that can move independently to transport goods need to be developed [1]. To move independently, a mobile robot requires the ability to sense and recognize the environment [2],[3]. One possible sensor is the light detection and ranging (LiDAR) sensor. LiDAR is a method used to determine distance or range by measuring the time required by a laser to reflect and return to the receiver. LiDAR sensors have several advantages over ultrasonic sensors such as a wider measurement range and the ability to create make 2-D and 3-D maps with suitable software support. However, to be applied to an autonomous wheeled robot, it is necessary to test its accuracy, precision, and sensitivity related to the type of material around it and conditions when LiDAR is used in real-time, etc.

In previous studies, ultrasonic sensors were developed to sense the surrounding environment with four integrated ultrasonic sensors able to measure distances between 0.7 m and 7 m [4]. Since a robot is required to move within repeated patterns, it requires not only a sensor system that can detect distance or range, but also markers and signs within its environment. So that the robot can map unfamiliar areas and respond faster to determine where it is currently located, LiDAR sensors are used. After a map of the surrounding environment is created, it becomes a reference for further movement of the robot. A robot that can move autonomously and automatically can be implemented in various useful applications such as a humanoid robot as a helper [5],[6] and preventive maintenance [7]. Furthermore, LiDAR sensors have been used for a wide variety of applications, including facial recognition [8], piping technology [9], agriculture, astronomy, etc. [10].

One of the methods of applying LiDAR as a sensor to create maps is the Simultaneous Localization and Mapping (SLAM) method [11]. The SLAM method is a method to estimate the shape of an environmental map around the sensor while estimating the position of the sensor that scans the created environmental map. SLAM is believed to be one of the fundamental things for robots to be able to move autonomously in an unfamiliar environment [12]. The use of Robot Operating System (ROS) software in robot development has the advantage of using a high level of language adaptation and being able to carry out complex instructions with limited programming knowledge [13]. Some studies that have been carried out using LiDAR and SLAM [14]. This includes the use of the Hector SLAM opensource library to model SLAM in a Robot Operating System (ROS) [15]. The mapping results produced by the SLAM method can represent a map of the environment being tested. [16], A two-dimensional (2-D) room mapping using LiDAR has been carried out [17].

In previous researches, environmental mapping using LiDAR sensors and computers was conducted in steady-state conditions [11]-[17]. In this research, environmental mapping was carried out using a LiDAR sensor and Raspberry Pi on moving electric-wheeled robots in real time and various materials around them to find out how accurate, precise, and sensitive they are when used in autonomous wheeled robots. For this reason, the accuracy, precision, and sensitivity of the LiDAR system will be tested in various conditions and materials. Furthermore, the system will generate a 2-D, real-time map, which is expected to be used in autonomous wheeled robot applications such as covid robots, among others.

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II. THEORETICAL BASIS AND PROPOSED METHOD

A. LiDAR Method

Remote sensing can be defined as the process of detecting and monitoring to obtain information about an object or an area, by analyzing its electromagnetic reflected and emitted radiation at a distance. The difference between the emitted and the reflected radiation can be observed in the form of a pulsed approach, intensity modulation, phase modulation, or frequency modulation [18]. The sensors that can be used in remote sensing are, i.e., sonar, camera, or LiDAR.

LiDAR has the ability to measure a distance based on the Time-of-Flight (tof) principle. A laser is emitted on an object to be measured, then the time it takes for the laser reflection to return to the sensor is calculated. The distance between a LiDAR sensor and an object is determined by the time interval between emitting and receiving the light. Having its own source of energy or illumination, LiDAR belongs to the category of active sensors. No direct contact is required by a LiDAR in performing the detection. In the pulse approach technique, the distance measurement is calculated by multiplying the speed of light in the medium by the time it takes for light to reach the target. This is expressed by the following equation:

$$R = \frac{c}{2}(tof) \tag{1}$$

where R is the unit of distance from the sensor to the target, c is the speed of light in the medium (c = 3 × 108 m/s in vacuum), and tof is the time required by light to radiate and be reflected by the target to the receiver. Visually, the calculation in the tof pulse approach is shown in Fig.1.

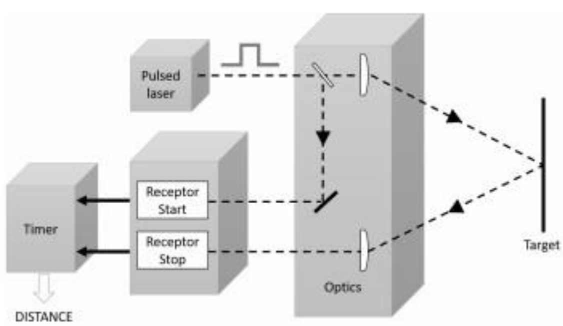

Fig.1. Calculation principle in pulse approach technique

Several strengths of LiDAR that can be mentioned are its high range of distances and measurement accuracy and its ability to measure three-dimensional structures. Besides, LiDAR can update the device quickly by taking the measurements in real-time and a combined structure can increase the coverage significantly [19]. Thus, LiDAR is suitable to be used in fast-moving tools or technologies. It also has a shorter wavelength when compared to sonar and radar, making it the best choice for measuring small objects.

On the other hand, some weaknesses of LiDAR are its relatively expensive price when compared to ultrasonic and IR sensors. Furthermore, it is unable to take measurements on objects that reflect light like a mirror [20].

B. RPLiDAR AIM8

RPLiDAR A1M8 (hereinafter shortly referred to as RPLiDAR) is a 360°-two-dimensional LiDAR laser scanner made by SLAMTEC. RPLiDAR A1M8 has a physical shape as shown in Fig.2 (a). This sensor can perform a 360° scan within a maximum distance of 6 meters from the sensor position. The results obtained by sensors can be used to make mapping, localization, and modeling of the environment or objects [21],[22]. The RPLiDAR sensor can measure objects in the range between 0.15 m and 6 m. The scanning frequency of the RPLiDAR in a single 360° scan is 5.5 Hz. An illustration is shown in Fig.2(b), about how the RPLiDAR works, depicting the positions of the sensor’s emitter and receiver.

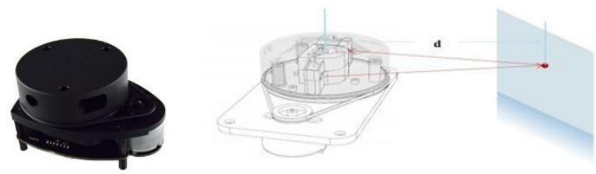

Fig.2. The LiDAR sensor (a) the physical shape; (b) The emitter and the receiver of the sensor

C. Raspberry Pi 4B

The Raspberry Pi 4B is a mini-computer manufactured by the Raspberry Pi Foundation. Raspberry Pi 4B can carry out a calculation process and/or data processing equivalent to a mini-computer. Raspberry Pi can operate by using the Linux Ubuntu 20.04 operating system [23]. Its specifications meet the minimum requirement for real-time mapping and it is compatible with the selected robot operating system (ROS) software. Therefore, the Raspberry Pi 4B was chosen in this research as the central processing unit.

D. Robot Operating System (ROS)

Robot Operating System or ROS is a framework for writing code or creating software for robots. ROS is a set of tools, libraries, and conventions that aim to simplify the process of creating robotic behavior on various robotic platforms. Nowadays, ROS has become a standard in robot programming [24][25]. Even though it is called a robot operating system, ROS actually runs on top of another operating system, such as Ubuntu, Windows, or Mac OS. The programming languages used by ROS are Python and C++ programming languages and are available in various versions. It is an open-source middleware which means that this ROS software will continue to grow along with a large number of users, as a bridge between the basic operating systems and the application running on them. The basic concept of ROS itself is to enable writing commands in a software environment. The commands are then collected in a processing center called ROSCORE. A ROS has Nodes and Topic features. Nodes are command associations in the form of a script or software that functions to perform a calculation or work. The resulting information obtained from the processing of Nodes is referred to as a Topic.

The process of putting information from some type of standard information into a specific Topic is called publish. All

Nodes can access the information contained in the Topic for a computational process or work which called subscribe. The block diagram of the basic concepts of ROS shown in Fig.3. By applying the working concepts, ROS is believed to be able to facilitate the process of making complex commands for robots [26].

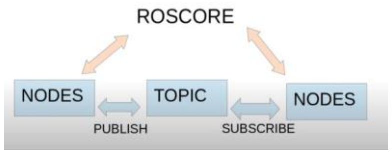

Fig.3. The concept of the Robot Operating System

E. Slam Method

The Simultaneous Localization and Mapping (SLAM) method is a method to estimate the shape of an environmental map around the sensor while estimating the position of the sensor that scans the created environmental map itself. SLAM in this day and age is believed to be one of the fundamental things for robots to be able to move autonomously in an unfamiliar environment [27],[28].

SLAM is divided into two parts, namely the front-end and the back-end. In the front-end, there is a process of data retrieval by sensors. This data is then converted into a middle-class data representation so that it can be used in the algorithm. In the back-end, there is a process of retrieving data from the middle class in the front-end. This data is then processed to produce solutions to problems such as where certain objects are in an environment or where the position of the device is, within the map created. In this study, the SLAM library used was Hector SLAM [29],[30].

Hector SLAM or Hector mapping is a library that contains a Simultaneous Localization and Mapping approach that can be used without odometry and can also be used on surfaces where the robot may roll or have pitch motion. This method takes advantage of the high mixing rate of modern LiDAR systems and provides an estimate of the 2D pose at the scanning speed of the sensor according to the sensor used. The systematic modeling of mapping using the Hector SLAM library is shown in Fig.4. depicts the flowchart of the proposed system.

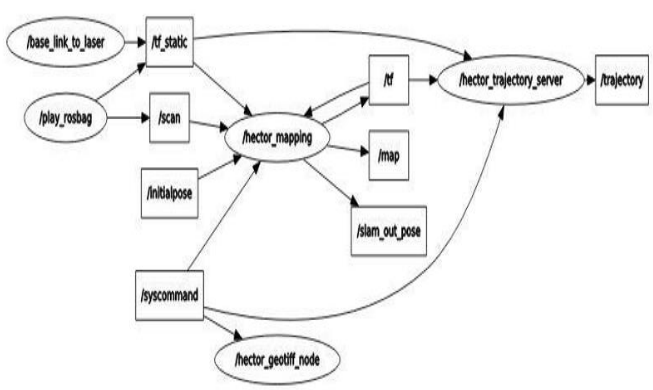

Fig.4. Systematic modeling of mapping with the SLAM method using the Hector SLAM library in ROS

F. The Research Method

This research was conducted in the Laboratory of Electrical Engineering Department of the Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Indonesia. The tools that we are using in this research are the Raspberry Pi 4B as the central processing unit for real-time mapping because the specifications meet the minimum operating limits for real-time mapping and have an operating system compatible with the software to be used, and the RPLidar A1M8 type as a LiDAR sensor for the environmental sensing sensor. The software used in this research is the ROS and the Hector SLAM package. To get an environmental map that uses a LiDAR sensor and Raspberry Pi microcontroller, we carry out several stages of data processing, as shown in Fig.5. In this research, mapping was made by LiDAR sensors placed on wheeled robots while in motion and under various conditions. The measurement process was carried out in several stages as shown in Fig.6.

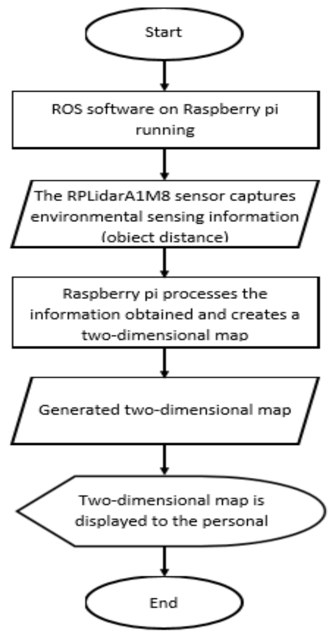

Fig.5. The Flowchart of Mapping Process

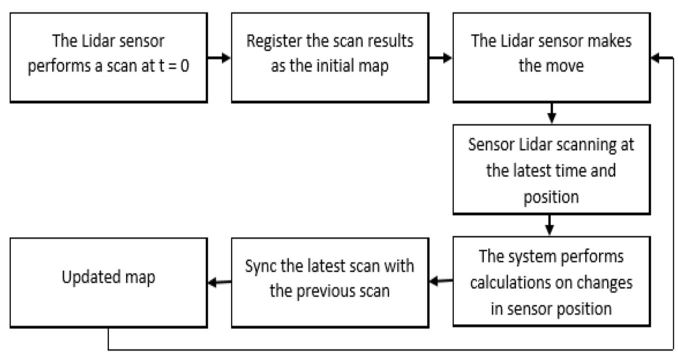

Fig.6. The Measurement Process

G. Experimental Setup

The experiment arena has a dimension of 240 cm × 240 cm × 30 cm. The experiment arena is made of four plywood boards with a length of 240 cm and a height of 30 cm. The plywood board is combined into a box-shaped space as shown in Fig.7.

Data collection is planned for four experiments. In the first experiment, the detection ability of the LiDAR sensor will be

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measured against objects stored arbitrarily in the experiment arena, shown in Fig.8. In the second and third experiments, the accuracy and precision of measurements will be tested at a various distance and on various materials as shown in Fig.9.(a) paper material and (b) glass material. Finally, in the fourth experiment, the 2-D mapping will be carried out for a labyrinth-like arena shown in Fig.10.

Data from the results of measurements taken are then observed and analyzed the percentage of error by comparing the true data from manual measurement and the data from the RPLiDAR as the test equipment.

Fig.7. The experiment arena

Fig.8. The arrangement of the randomly placed objects

(a) (b)

Fig.9. Accuracy and precision measurements at various distances and materials (a). Paper, (b). Glass

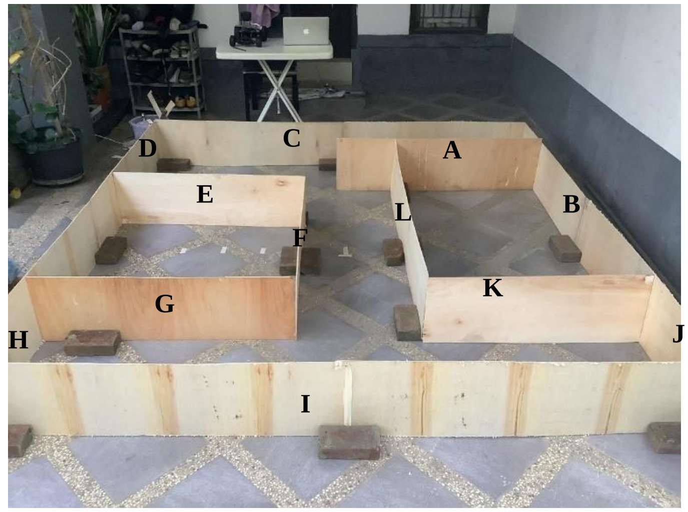
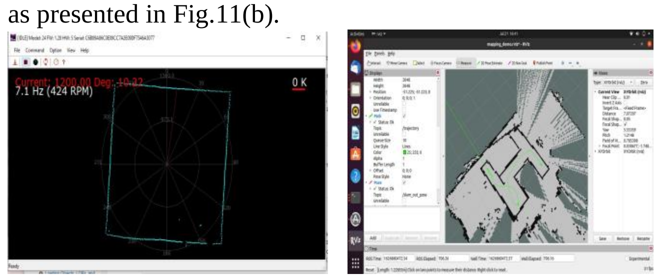


Fig.10. The arrangement of the labyrinth-like arena

H. Software Tools

Two software were used to build the overall system in this research as shown in Fig.11. The first is for measuring the distance of objects and visualizing the scan results by using the RPLiDAR, as shown in Fig.11(a) The second is for executing the Robot Operating System (ROS) and Hector SLAM package, as presented in Fig.11(b).



(a) (b)

Fig.11. Software Tools for the LiDAR experiment: (a) The software used for operating the RPLiDAR; (b) The display of the Rviz visualization tool of the ROS

III. Results and Discussions

A. Hardware Construction

Hardware construction covers all the requirements to compile the RPLiDAR environmental sensing systems. The hardware system consists of two parts, the first is the environmental sensing unit, consisting of the LiDAR sensor, a Raspberry Pi, and the power supply put on an electric wheeled robot, and the overall system is shown in Fig.12.

The RPLiDAR sensor is connected to the Raspberry Pi by using a USB cable and a UART bridge. Raspberry Pi 4B requires a power source with a voltage of 5V 3A using a USB type C connection. For this purpose, a power bank with a power capacity of 10000mAh is used. The overall dimension of the system is 21 cm long, 26 cm wide, and 20 cm high.

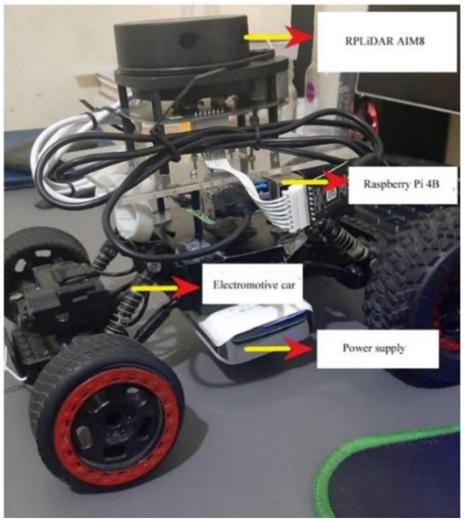


Fig.12. The environmental sensing unit is installed on the electric wheeled robot

B. *Distance measurement of randomly placed objects*

In the first experiment, the objects used were several small boxes that were placed arbitrarily around the LiDAR sensors, which is initially placed at the center of the experiment arena. The RPLiDAR sensor has a free line of sight to all the objects. The experiment results are summarized on Table I. The visualization of the measurement results of the LiDAR sensor after a 360° scanning can be seen in Fig.11(b).

TABLE I
EXPERIMENT RESULTS FOR RANDOMLY PLACED OBJECTS

Object	Real distance (cm)	Measurement result (cm)	Difference (cm)	Error (%)
A	74.2	74.1	0.1	0.13
B	46	45.5	0.5	1.09
C	95.2	95.1	0.1	0.11
D	95.6	95.7	0.1	0.10
E	71.7	71.5	0.2	0.28
F	85.5	85.7	0.2	0.23
G	125.5	124.8	0.7	0.56
H	49.7	49.6	0.1	0.20
I	85	84.6	0.4	0.47
		Average	0.267	0.35

Based on the experiment results, it is found that the range of the percentage of measurement errors is between 0.11% to 1.09% with an average error percentage of 0.35%. This very small error can be achieved because the RPLiDAR records the measurement data every 0.3° to 1°. Errors in the manual measurement may easily occur because the accuracy of a ruler is only 0.5 mm. According to the RPLiDAR sensor datasheet, the percentage of measurement error on the LiDAR sensor is 1% of the distance measured. Judging from the data generated in this test, the measurement error is less than 1% of the distance measured. Thus, the error in this magnitude is acceptable. The 360° measurement test using this LiDAR sensor is appropriate and achieves a fairly high degree of accuracy as shown in Fig.13.

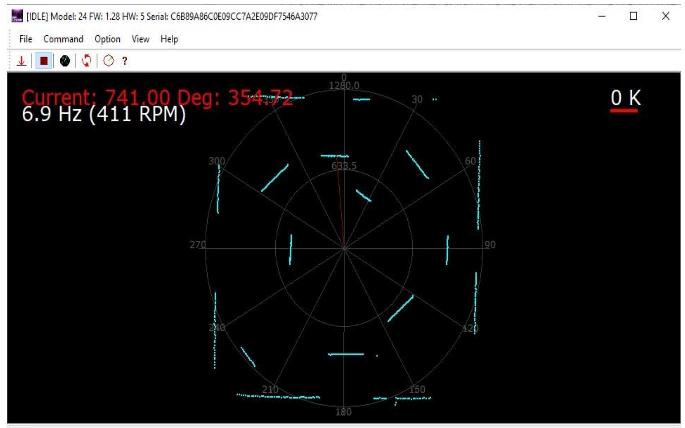


Fig.13. Visualization of 360° scanning test with RPLiDAR A1M8 measurement software.

C. *Distance measurement of an object with a predetermined distance*

In this test, the object used was a box placed in the positions of 20 cm, 40 cm, 60 cm, and 80 cm from the RPLiDAR sensor. This experiment aims to see the level of accuracy of the RPLiDAR sensor to measure its distance to objects with predetermined values. As in the previous experiment, the distance recorded by the sensor will be compared with the distance measured manually by using a ruler. Then, the measurement error percentage can be calculated and presented. The errors are below 0.5%, proving the high accuracy of the sensor, shown on Table II.

TABLE II
EXPERIMENT RESULTS FOR PREDETERMINED DISTANCES (PAPER BOX)

Real distance (cm)	Minimum and Maximum deviation (cm)	Average error (%)
20	–0.2, +0.1	0.50
40	–0.2, +0.2	0.30
60	0, +0.1	0.13
80	0, +0.4	0.18

D. *Distance measurement of a mirror (spherically reflective)*

In this test, the object used is a flat mirror. Objects are laid out at the same predetermined distances as set in the previous tests. The objective of this test is to examine the level of accuracy of the RPLiDAR sensor in sensing a spherically reflective object, which in this case is a flat mirror. The distance measured by the sensor will be compared with the one measured manually by using a ruler as shown in Table III.

TABLE III
EXPERIMENT RESULTS FOR PREDETERMINED DISTANCES (MIRROR)

Real dimension (cm)	Measurement result (cm)	Difference (cm)	Error (%)
20	164.6	144.6	723
40	208.4	168.4	421
60	247.4	187.4	312
80	0	80.0	100

Based on the data obtained in the test, the average error percentage is large, which is 389 %. This shows that the measurement of the distance from the RPLiDAR sensor to the mirror is very inaccurate and it can be said that the sensor has failed. This test is not carried out repeatedly due to the high percentage of errors. This test concludes the inability of the RPLiDAR to detect the position of spherically reflective surfaces.

E. 2-D Mapping of Labyrinth-Like Arena

In this test, the RPLiDAR environmental sensing system is deployed to create a 2-D map of a labyrinth-like arena as shown in Fig.10. The output of the scan is a 2-dimensional map that will be displayed in the RViz visualization tool. In Fig.10, the mapping process starts from point H at one corner of the arena, Then the sensing system moves through all points I, F, and C, along the corridor. The mapping movement ends at the diagonally opposite corner, point B. The sensing system is moved by manually controlling the electric wheeled robot. The 2-D mapping result of the interior of the arena is shown in Fig.14. The green line indicates the path of the sensing system.

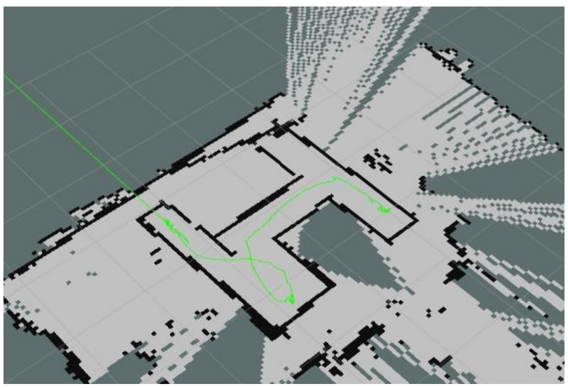


Fig.14. The mapping result in Rviz visualization software

The mapping image obtained is considerably good. It shows the shape of the labyrinth-like arena from the interior corridor. One thing that needs to be improved is that the image still contains so many black dots that should actually not be mapped. This can be traced back to being caused by some shocks that occur during the movement.

The wall ends from the mapping results are now located and the length of the wall segments can be determined. The lengths obtained by the sensing system are now compared with the lengths obtained from the manual measurements. The results are presented in Table IV. The percentage of error range between 0.00% and 3.96%, with an average of 0.71%. This shows that the length of the wall segments can be determined from the resulting map with a high level of accuracy. It can be concluded that the sensing system can create an accurate 2-D mapping, which later on can be used to help an autonomous robot to identify its surrounding, localize its own position, and move to a certain destination.

TABLE IV
THE COMPARISON OF THE LENGTH OF THE WALL SEGMENTS

Wall segment	Real dimension (cm)	Measurement result (cm)	Difference (cm)	Error (%)
A	122.4	122.8	0.4	0.33
B	39	39.5	0.5	1.28
C	240.5	241.5	1.0	0.42
D	87.8	87.5	0.3	0.34
E	100.5	100.5	0	0.00
F	100.9	100.7	0.2	0.20
G	100.8	100.5	0.3	0.30
H	50.8	50.2	0.6	1.18
I	240	241.1	1.1	0.46
J	50.2	50.2	0	0.00
K	80.8	84	3.2	3.96
L	150.5	150.4	0.1	0.07
		Average	0.642	0.71

IV. CONCLUSION

This objective of the research to design and construct an environmental sensing system using LiDAR sensors with the SLAM method based on the Robot Operating System is successfully achieved. The sensing system is tested to measure the distance of objects with paper surfaces and obtains an average accuracy of 0.35 %. A direct comparison of detecting objects from predetermined distances shows that the LiDAR sensor cannot be used to detect objects with a spherically reflective surface such as mirrors or glasses.

The system is successfully used to create a 2-D map of a labyrinth-like arena in real-time with an error percentage of 3.96 % highest and 0.71 % average. The filtering process needs to be embedded to encompass the negative effects of shocks during the mapping movements. The system demonstrates its ability to map the surrounding environment with high accuracy and real time. In addition, it is prospective to be implemented as autonomous robot navigation for certain environments.

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