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AN INNOVATIVE APPROACH TO DEVELOPING A 3D VIRTUAL MAP CREATOR USING AN ULTRASONIC SENSOR ARRAY

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ABSTRACT

Humans shifted their focus toward robots when they realized that, with the increased complexity of built environments and the rapid advances in fields such as manufacturing and civil structures, robots could serve human development. This paper investigates the development of a mobile robot that uses ultrasonic sensors to obtain distance readings and utilizes those readings to draw 3D maps of its surroundings. The robot is designed to perform in narrow spaces and in rough terrain environments, such as underground piping structures or underground wiring networks. The wheeled platform is capable of maneuvering on rough surfaces guided by a specially designed obstacle navigation strategy using ultrasonic sensors. The mounting of the 3D mapping sensors is a new and innovative approach that resolves many of the problems encountered in previous proposed designs for 3D ultrasonic mappers. The 3D mapping sensors obtain data to create a 2D map and position localization data to create a 3D form. This paper presents the results obtained through extensive work on developing the vehicle and testing the control and 3D mapping algorithm.

Keywords: Localization; Mapping; Mobile robots; Ultrasonic sensors

1. INTRODUCTION

This paper presents the development of an ultrasonic sensor array capable of building a map of its environment as it travels through it. The ultrasonic sensors are arranged using an original approach to enable a robot to generate a 3D map of its surroundings based on three different perspectives: left, right and top. The authors also propose a novel method to construct a 3D map of the robot routing environment by abstracting the data from the invented sensory arrays.

In terms of biomedical imaging, Salles et al. (2017) estimated the velocity of mechanical waves (MW) produced by natural cardiac events such as aortic valve closure propagating along the left ventricle (LV) wall to visualize the propagation of MW in 3D and achieve a 3D elasticity map of the LV to inspect myocardial fibrosis. Pedrosa et al. (2016) provided an overview of the available ultrasound technology for cardiac chamber quantification in terms of volume and function and presented evidence for the value of these parameters when testing the effect of new cardiovascular therapies.

In the inspection of building structure, De La Haza et al. (2018) discussed the use of a recently developed instrument known as MIRA, which utilizes a patented phased array of dry point contact shear wave transducers to produce 2D and 3D tomography images of concrete structures. This

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new technology has allowed the operator to obtain in-situ, real-time test results.

Chen et al. (2016) proposed an indoor mapping suite prototype built upon a novel calibration method that calibrates the internal and external parameters of multiple RGB-D cameras. Three Kinect sensors are mounted on a rig with views in several directions to form a large field of vision. However, in terms of hardware, this prototype is bulkier and costly as it requires multiple RGB-D cameras, and the visual data, while satisfactory, are poor in depth data representation. The present authors' invention is smaller and simpler with less costly hardware as only ultrasonic sensors are required. Depth data representation is also better.

Wang and Niu (2018) used Open Street Map (OSM) data to integrate indoor and outdoor route planning for pedestrians. They focused on the interior connections of buildings and produced a data model that applies OSM primitives (nodes, ways, and relations) and tags to capture horizontal and vertical indoor components as well as connections between indoor and outdoor environments. However, the generated map is 2D, not 3D. The present authors' development generates a 3D map.

The approach presented in this paper specifically targets 3D mapping tasks for narrow or small spaces as well as geometrically irregular areas, such as tunnels or underground building structures for piping and underground wiring work. Therefore, the wheeled platform was chosen for the design because its wheel motion enables it to navigate a certain level of rough terrain. The 3D mapping robot is designed with a user-friendly interactive control system, which is achieved by providing the user with variable control features in a graphical user interface (GUI).

2. LITERATURE REVIEW

A review of the literature on the various attempts to create such a system showed that the majority of the robots operated with distance sensors focusing on either light detection and ranging (LiDAR), sonar, or ultrasonic sensors, while some researchers chose to utilize vision- and image-based mapping techniques. Sensor selection is considered the most common choice for several reasons, including its low cost and ease of use as well as the accuracy of the results (Zuff.Info, 2018).

The LiDAR sensors-based 3D mapper is usually used for robots that operate in open spaces with obstacles or features to be mapped that are located at a larger area compared with the environment in which the sonar and ultrasonic sensors are used. This utilization matches the main objective of LiDAR sensors since they are used as a surveying method. The sensors emit a pulsed laser light that hits a target and reflects back to the sensor. The reflected pulse is then measured and the distance between the target and the sensor is thus obtained (GeoSLAM, 2015).

The methodology for the sensor usage in 3D mapping robots employs a hardware design. For example, the sensor is mounted on a rotating robotic arm. By operating the servo motor which connected to the robotic arm, the arm rotates between 180 degrees and 360 degrees. During this rotation, the sensor sends signals and collects the reflected pulse feedback to obtain readings for the 3D map plotting. However, this is not the only possible method, since LiDAR sensors collect a large number of data and combine them for an accurate result. Therefore, the sensor has been used in various and more creative methods, such as handheld sensor mounts similar to the version detailed in Farella (2016) or flying drone 3D mappers such as the one discussed in Atkinson (2018).

Sonar sensors are used for their cost efficiency. Overall, both sonar and ultrasonic sensors are very similar to each other; however, there exist slight differences between the two sensors. Sonar sensors employ sound navigation ranging, using the reflection of the acoustic frequencies sent by the sensor to measure the time interval between transmission and receipt (NASA, 2014).

Those acoustic sound wave frequencies range from ultrasonic to infrasonic, and the sensor can have several transmitters and receivers to execute the operation (Knight et al., 1981; Gubaidullin & Gafiyatov, 2018). Ultrasonic sensors are limited to the use of ultrasonic sound waves because the sensors measure the time interval to detect the presence of obstacles within their range even though the same methodology is used (Elfes, 1986). Another useful application of sonar wave is to detect and survey unknown environments. This utilization of autonomous robots is common and effective, working as a vision system to help the robot maneuver in the environment (Wilson, 2004).

Ultrasonic 3D mapping is considered a highly effective and useful method. This is based on several grounds of comparison, including the high accuracy of the sensors and their ability to map even the smallest details and surface contours.

The sensor position on a mobile robot to be used as a 3D mapper is a common cost-effective method for plotting. Munumer and Lerma (2015) proposed using one sonar sensor and placing the sensor on a servo motor so that the sensor could be rotated 180 degrees to collect the needed data points.

Ahmad et al. (2016) followed the same methodology but with a slight change in the rotation range of the servo motor and the choice of ultrasonic sensors.

Nakajima et al. (2017) merged two sets of data obtained from ultrasonic sensors to form a 3D map. The robot used in that study was a flying robot. The ultrasonic sensors were mounted on both the top and the bottom of the robot. The top sensor was fused with a servo motor to give the sensor a rotating range. The readings obtained by this sensor provided the data for a 2D map. The bottom sensor was used to indicate the data to be used as the third dimension points, and together with the top sensor data, a 3D map was made.

3. HARDWARE DESIGN APPROACH

A simple overall system is shown in Figure 1. The microcontroller is a central part of the integration between all of the robot's onboard equipment. The microcontroller is also necessary to perform all of the onboard computing for navigational purposes and to communicate with the main computer, which runs a GUI to plot the mapping data.

An array of ultrasonic sensors is used to collect mapping data as well as for navigational purposes. The microcontroller makes decisions on where to move next or to stop based on the data returned from the ultrasonic sensors.

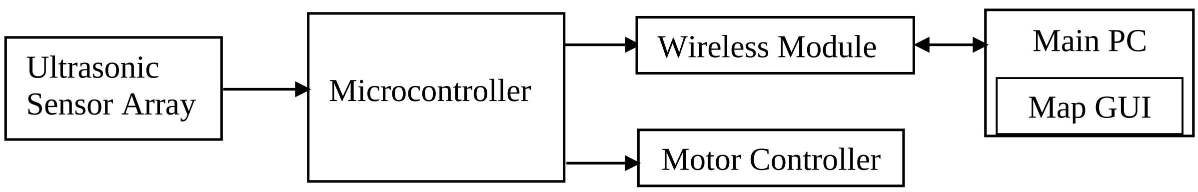


Figure 1 Overall system

3.1. The Robot Vehicle

Modified mobile cars or vehicular robot platforms have become common in robotics. Because of their size, cars offer a better option than standard robots as they can easily travel longer distances and have enough space to carry hardware components, such as control boards and sensors. Using cars has helped researchers and developers cover larger spaces in their experiments and tests. Therefore, two different types of automated vehicles, the wheeled mobile robots shown in Figure 2, were used for the development and testing of the 3D mapping robot.

An automated car was used for the present study because the control of the vehicle can be easily interfaced directly with the microcontroller chip used for the project. The Arduino MEGA used in the study facilitated the development of important features in the GUI of the project, such as controlling the direction of the vehicle, its speed, and so on.

The first platform is a normal robotic car, shown on the right in Figure 2, consisting of four wheels attached each with a 6V DC motor. The motor on each side of the vehicle joined with a motor driver and addressed as one motor in the control system.

The set of ultrasonic sensors at the front of the vehicle serve as the obstacle detection system. The signals obtained from these sensors can detect whether there is an obstacle in front of the car and can measure the distance between the vehicle and that obstacle. This information allows the user to control the distance between the vehicle and the obstacle. For instance, the user can continue to draw the 3D map of the surroundings up to 2 cm from the obstacle, which can be reduced to the maximum close range, 400cm, of the ultrasonic sensor.

The second vehicle, shown on the left in Figure 2, operates with a similar strategy. There are only two main differences with the first vehicle. First, the second vehicle allows much more obstacle clearance and maneuvering capability over rough terrain than the first vehicle. Second, the driving motors in the second vehicle are a set of geared DC motors. This provides the vehicle with a higher torque and an increased load capacity of up to 3 kilograms.

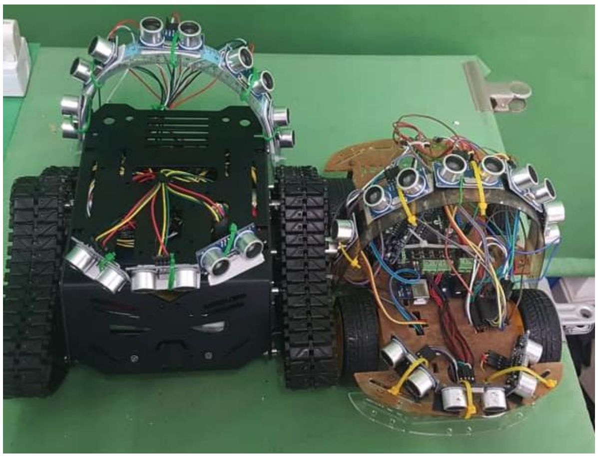


Figure 2 Two-wheeled platform used in the development of the robot

3.2. 3D Mapping Ultrasonic Sensor Mount

The design of the robot platform is a new approach to the arrangement of the ultrasonic sensors. The ultrasonic 3D mappers in the present design utilize one or two ultrasonic sensors. The sensors in previous designs are usually mounted on an arm with multiple degrees of freedom (DOF), while the arm in the present design rotates around its center to give the sensor access to the range required. For example, if the arm rotates half a rotation at a 180-degree angle, the sensor will be able to view only in this range (Ahmad et al., 2016).

When tested in real environments, the program still presents a few problems. For example, the x-axis can be any of the three sets of perpendicular axes in a 3D environment if the sensor is directed towards the x-axis. It must be mounted on a servo motor rotating mount to obtain a 2D map of the surroundings. This will require an additional controlling feature as well as energy to enable it. This naturally presents another problem as there must be a controlling interface linking with the time needed by the sensor to collect the signal of each point along the path of the robot for the area to be mapped. Most of the time, this can be achieved by allowing the user to pause the robot for as long as necessary to collect the required points for the 3D map drawing.

The operating time needed to finish the task depends on the complexity of the features in the surroundings and the operating time of the ultrasonic sensor on the rotating mount operated by a servo motor. Adding more sensors in the servo mount will not affect the operating speed since all of the sensors will be located at the same point on the rotating servo mount. The user must stop the car and rotate the servo to obtain the readings (Ahmad et al., 2016).

Hence, the innovative design of the 3D mapping robot was developed to solve the majority of the problems mentioned above. At the same time, it presents a greater level of operating quality in other respects, such as energy efficiency, since it does not need an additional servo motor, and a lighter weight.

The design presented for the ultrasonic sensors mount is in the shape of an arc or a semi-circle. Five ultrasonic sensors are mounted on the arc. A front view of the mount for the arrangement of the ultrasonic sensors on the arc is shown in Figure 3.

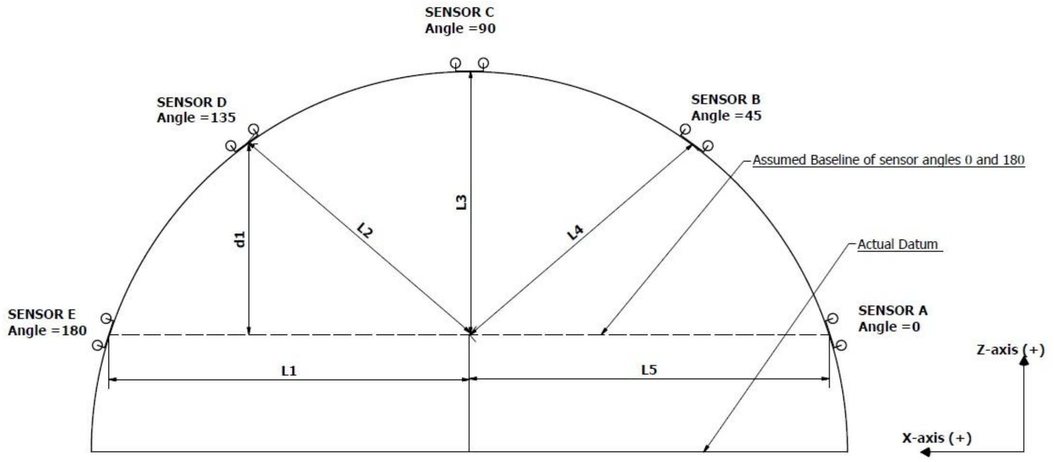


Figure 3 The 3D mapping ultrasonic sensor mount

Each of the sensors lie on a plane of x-z axes with coordinates based on the assumed baseline to the actual datum.

The general format of the sensor coordinates is:

Sensor N :(x-axis coordinate, z-axis coordinate)

The coordinates of each of the sensors are:

Sensor A: (-L5, 0)
Sensor B: (-L4 Cos 45, L4 Sin 45+d1)
Sensor C: (0, L3)
Sensor D: (L2 Cos 135, L2 Sin 135+d1)
Sensor E: (L1, 0)

The missing third axis is the y-axis. It represents the position of the robot on its forward motion track. It can be seen in Figure 4.

For each point on the y-axis referred to as position *n*, the value of *n* starts at 0. When the robot reaches the first point, the robot is stopped and *n* is equal to 1. The encoded counter reaches a new position after 200 milliseconds have elapsed.

So, the coordinates for each sensor on the three axes become:

Sensor N: (x-axis coordinate, y-axis coordinate, z-axis coordinate)

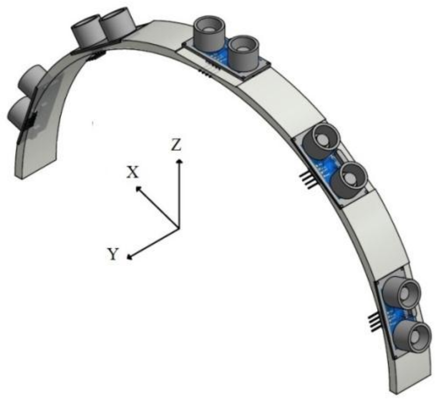


Figure 4 Auxiliary view of the arced sensor mount

The coordinates for each of the sensors at position 1(P1) along the y-axis will be:

Sensor A: (-L5, P1, P0)
Sensor B: (-L4 Cos 45, P1, L4 Sin 45+d1)
Sensor C: (0, P1, L3)
Sensor D: (L2 Cos 135, P1, L2 Sin 135+d1)
Sensor E: (L1, P1, 0)

The two geared motors are connected to one motor driver circuit in this robot platform. The three ultrasonic sensors from the front row are connected to the Arduino board. Sensor R is on the right side, sensor L is on the left side, and sensor M is in the front center of the wheeled platform between the other two sensors.

The other five sensors are mounted on the arc and are connected directly to the Arduino. The Arduino is connected to an XBee, a wireless communication device that can communicate the data to another XBee connected to the computer. The communication process between the various components of the robot is shown in Figure 5. The list of the components used in this robot design is shown in Table 1.

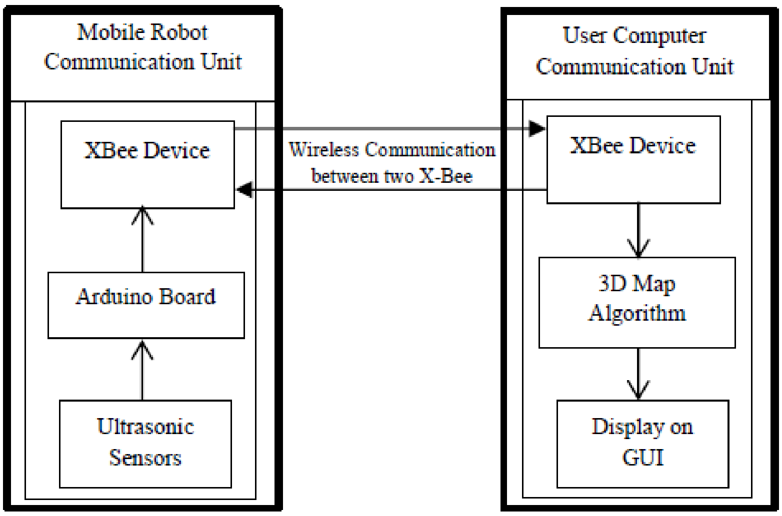


Figure 5 Block diagram of the data communication

Table 1 List of components

Component	Quantity
Devastator Tank Mobile Robot Platform (Metal DC Gear Motor)	1
Arduino MEGA 2560	1
SKXBee (XBee)	2
L298N Motor Driver	1
HC-SR04 Ultrasonic Sensor	8

4. CONTROL ALGORITHM

4.1. Robot Control

The car moves based on the range of speed selected by the user. This can be achieved with a simple torque control algorithm that keeps the range in the desired speed through the motor driver control. The user can select the motor speed through the GUI.

Once the speed range is selected and the start button is pressed, the car will begin to move. The car will not move continuously; it stops for a few milliseconds at a time to collect data using the ultrasonic sensor mounts on the robot. The front three sensors (Left, Middle and Right) will record signals and communicate with the Arduino to detect any possible obstacles.

There are four possible scenarios based on the detections. In the first scenario, the right-side sensor detects an object and the robot will turn left to avoid that obstacle following the program instructions. This obstacle-avoiding strategy is to ensure the safety of the robot. It is set by default and the user has no control over it. In the second scenario, the left-side sensor detects an obstacle and the vehicle will turn right to avoid it. In the third scenario, both the right- and left-side sensors detect an obstacle simultaneously and the reading of the middle sensor will determine whether the path ahead is clear of obstacles or not. If it is clear, the robot will continue to move forward. If it is not clear, the robot will stop forward motion and that means dead end. In the fourth scenario, all the sensors detect an obstacle simultaneously, which the program will interpret as a dead end and stop the robot's forward motion.

Even though the navigation strategy mentioned above is set by default, the user can still determine a value for the minimum distance between the obstacle and the robot at which the default navigation algorithm is activated.

4.2. 3D Mapping

For the mapping data, the x and z coordinates data are obtained from the five ultrasonic sensors mounted on the arc and the values for the y coordinates are obtained from the position of the robot on its forward track.

Once the car starts moving, the five ultrasonic sensors mounted on the arc start detecting the x and z values and the counter starts incrementing the counter numbers for the y values. The ultrasonic sensor records time values, and those values are substituted in Equation 1 to obtain the measure of the distance.

$$\text{Distance} = (\text{Speed} \times \text{Time}) / 2 \qquad (1)$$

This calculation is performed by certain portions of the code in Arduino. The distance values obtained are then encoded and sent to the XBee, which in turn sends it to the receiving XBee attached to the computer. When the second XBee receives the data to plot the 3D map, all the features will be displayed on the GUI developed through C# as well as within the same program flow.

5. RESULTS AND DISCUSSION

The finalized design of the robot is shown in Figure 6. After the different parts and electronic components were fully assembled, the vehicle was tested to ensure smooth motion. The testing was done while focusing on the results of the motor driver control as well as the obstacle navigation system.

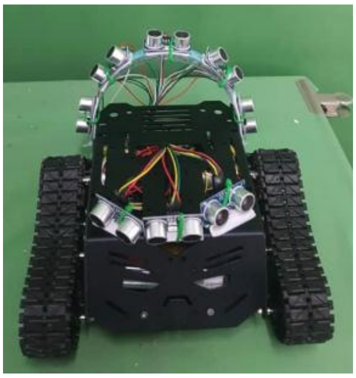


Figure 6 The final vehicle design

A GUI was created based on the C# code along with the utilization of the Helix Toolkit, which contains a 3D map development library. The GUI is shown in Figure 7. The function of the GUI feature is to draw 3D maps and to complete the tests listed below the figure according to the control algorithm.

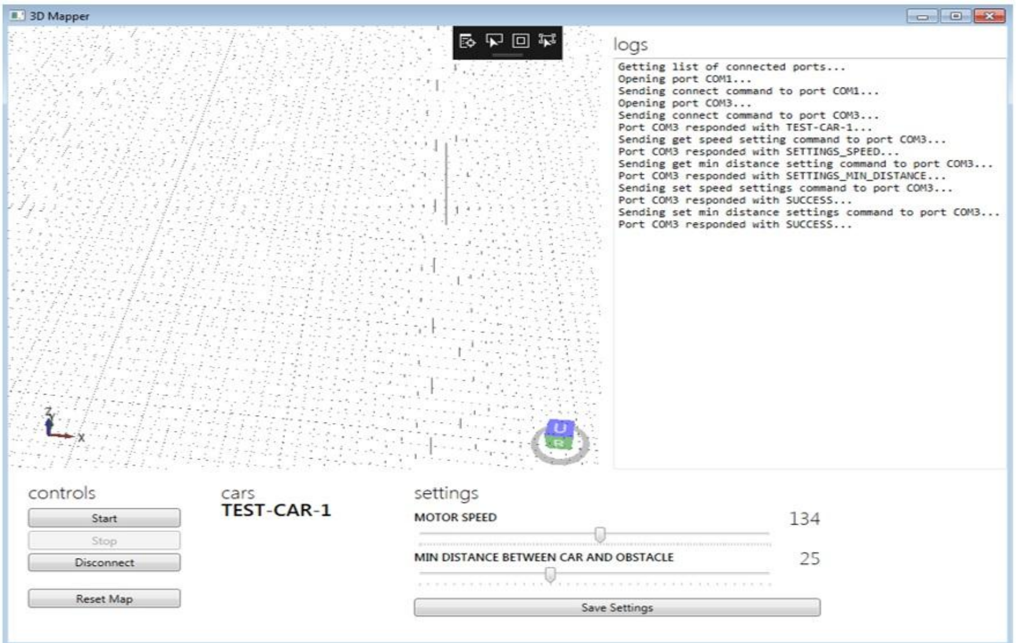


Figure 7 Finalized GUI

Test 1: The robot’s start and stop buttons are connected to the computer GUI, which identifies a successful communication between the two XBee boards.

Test 2: The speed control feature must send direct commands to the computer XBee so that it can communicate the order to the Arduino XBee, which in turn should slow down or increase the speed of the vehicle through the motor driver.

Test 3: The ‘minimum distance to obstacle’ feature enables the user to set the distance between the car and any obstacle at which the default obstacle navigation strategy will be activated in the car.

Test 4: A rectangular box, similar to the one shown in Figure 8, is used as the testing environment for the 3D map.

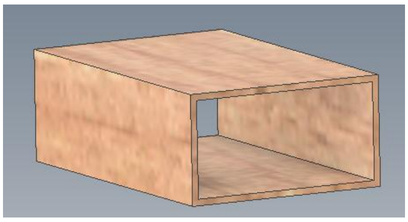
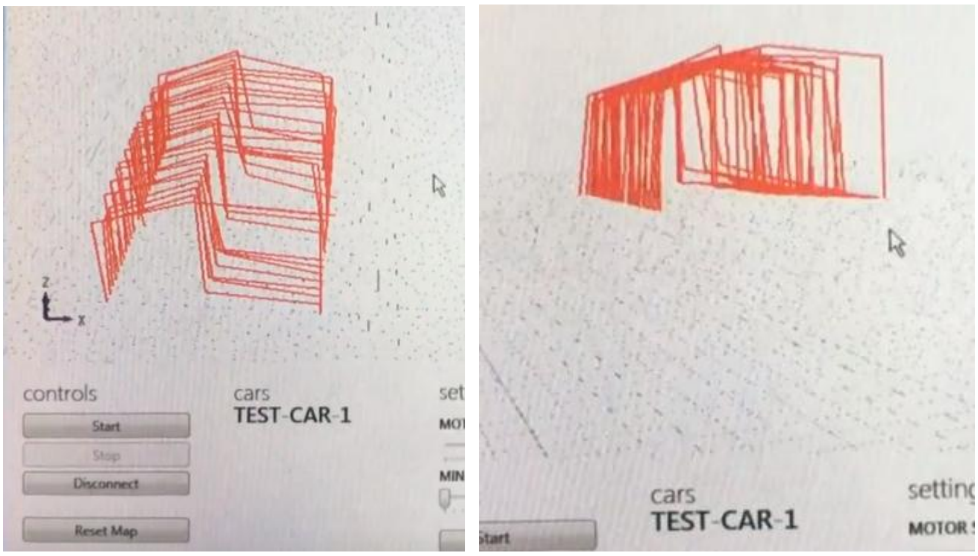


Figure 8 Testing environment

Once the start button was pressed at Test 1, the car started forward, indicating a successful connection between the two XBee devices. The GUI displayed the logs obtained from the code flow and the 3D map was plotted one point at a time, with each point forming after 200 milliseconds.

The distance crossed during the 200 milliseconds varied according to the selected motor speed at Test 2. If the speed was high, the distance between the first and the second position on the y-axis increased because more distance was crossed during the 200 milliseconds and vice versa. These results proved the validity of the speed selection feature.

After the speed selection feature test was successfully completed, a simple change of the minimum distance to obstacle showcased the success of that feature at Test 3For the mapping accuracy test at Test 4, the obtained 3D map of the paper box in auxiliary left side view and front view is shown in Figure 9. The opposite side auxiliary view is shown in Figure 10. Both the GUI and the code plotted followed the correct format, but there is still some error percentage in the experiment.



(a) (b)

Figure 9 (a) Front view; (b) Left side view of the plotted 3D map

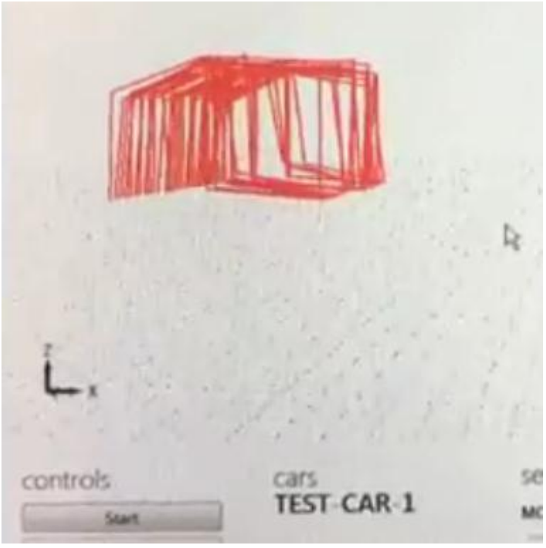


Figure 10 Right side view of the plotted 3D map

It can be seen that the map cannot be formatted exactly in the real physical condition of the space because of the motor speed and ultrasonic sensor quality. The final outcome obtained after inspection and a few runs of the vehicle show that the errors can be fixed through proper usage of noise filters and the addition of more ultrasonic sensors.

6. CONCLUSION

The approach presented in this paper solves several problems related to the commonly used servo motor-based robotic arm, which held one or two ultrasonic sensors that rotate a minimum of 180 degrees to obtain the desired map. The design arranged the sensor to cover the full 180 degrees by adapting a half-circular pattern and enables the mobile robot to collect data for the 3D map without having to be paused. The test results showed that the mobile robot navigation strategy functions as desired for the selected operating environment. The results for the 3D mapping capabilities of the robot show the expected outcome even though they may seem a relatively inaccurate interpretation of the testing environment. The problem of the accuracy of the results can be corrected by incorporating a noise-filtering algorithm such as the Kalman filter or by utilizing sonar sensors, which provide more accurate results than ultrasonic sensors.

7. ACKNOWLEDGEMENT

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