Ultrasonic Sensor Based 3D Mapping & Localization

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Abstract—**This article provides a basic level introduction to 3D mapping using sonar sensors and localization. It describes the methods used to construct a low-cost autonomous robot along with the hardware and software used as well as an insight to the background of autonomous robotic 3D mapping and localization. We have also given an overview to what the future prospects of the robot may hold in 3D based mapping.**

Keywords - Robotics; Autonomous Robots; 3D Mapping & Localization; Occupancy Grid; Ultrasonic Sensor; Bluetooth Module; Arduino;

I. INTRODUCTION

Robots are rapidly making their way from science fiction movies and books into our everyday lives. They can be found almost anywhere and everywhere starting from your local hospital to your home, and even the local coffee shop. These drastic improvements in the field of robotics have opened up new opportunities for making new discoveries and accomplishing tasks which were previously deemed to be impossible. The major fields of study that are contributing to robotics are electrical and mechanical engineering alongside with computer science. While electrical and mechanical engineering deals with the design, construction, and application of robots, computer systems deal with their control, sensory feedback and information processing. And with these three fields of study in unison robotics has lurched forward towards a brighter future. You can now see robot arms performing in hospitals, factories etc. as they minimize the margin for errors. They are also found in homes, shops and cafeterias where they do daily chores which were once done by humans, so basically robots can accomplish tasks both which humans can and cannot do.

This paper deals specifically with autonomous robots which use sensors (in this case ultrasonic sensors) to create a 3D map of their surroundings. Autonomous robot systems depend highly on their ability to recover durable spatial model of their surroundings from sensory information and use it in robot planning and control [1]. All these abilities enable the robot to make its own temporary decisions based on the data collected by the sensor. The data received from the sensors can be used to create a 2D/3D model for later use in different research programs and studies. Initially the sensors will be used for gathering data that will produce a 2D image of its surroundings. The robot can be used for mapping known as well as unknown indoor or outdoor locations based on its need.

II. BACKGROUND

Autonomous robotic mapping/explorations have led us to places well beyond our reach or places where human expeditions are too dangerous, technically challenging, too expensive or all three. The mars expedition of 2004 is one such example where human beings are not able to venture to. Even though humans are capable of building vehicles which can venture into the deepest parts of the oceans there are factors such as life threatening risks, operational costs and limited availability still that prevent them from doing so. Thus come in the autonomous robots that provide none of the life threatening risks that human expeditions hold. They are able to take and convey readings from their surroundings, which later once run through several algorithms, give a 3D image of their environment.

A. Simultaneous Localization and Mapping (SLAM)

In the past there have been a number of researches conducted on problems concerning robots mapping unknown environments one such problem is the simultaneous localization and mapping or better known as SLAM. The SLAM problem questions whether or not it is possible for a robot to map an unknown environment

while simultaneously localizing its position in this map [16]. Such ability would make a robot autonomous [18]. This wipes out the need for artificial infrastructures or prior knowledge about the environment.

In simpler words SLAM is the process by which a mobile robot can map its surroundings and use the same map to navigate without any prior knowledge of its environments [16]. The solutions to the SLAM problem have been a major break through in the field of robotics and artificial intelligence in over a decade.

The Kalman filter method is one of the methods than can be stretched out to solve the SLAM problem. There have been a few utilizations of this innovation in various distinctive situations, for example, indoors, underwater and outdoors. One of the principle issues with the SLAM calculation has been the computational necessities. It is understood that the time complexity of the SLAM calculation can be lessened to being the quantity of historic points in the guide. For long-term missions, the quantity of points of interest will increase and, in the end, PC assets won't be adequate to overhaul the guide continuously. This scaling issue emerges in light of the fact that every landmark is associated with every single other landmark. The relationship that shows up following the perception of another point of interest is gotten with a sensor mounted on the robot and in this way the landmark area error will be corresponded with the blunder in the robots surroundings and the errors in different landmarks on the map. This connection is of essential significance for the long haul joining of the calculation, and should be kept up for the full length of time of the mission. Leonard et al, tended to the computational issues by part the worldwide guide into various sub maps, each with their own particular vehicle track. They introduce an approximation strategy to address the upgrade of the covariance in the move between maps. Despite the fact that they display noteworthy trial results there is no confirmation of the consistency of the methodology or estimation of the conservatism of the covariance over-jumping technique [17].

B. The Occupancy Grid Using MATLAB

Occupancy grids are one of the methods that can be used to represent a robot's surroundings as a discrete grid. The Occupancy Grid is a multi-dimensional (normally 2D alternately 3D) tessellation of space into cells, where every cell stores a probabilistic evaluation of its state [1, 9]. There are two different sorts of occupancy grids; the binary occupancy grid and the world and grid coordinates.

Binary Occupancy Grid

The binary occupancy grid returns true or false values to represent objects (obstacles) and free areas in the surroundings of the robot. It gives an overview of the robot's environment so that it is able to avoid obstacles and move around them.

World and Grid Coordinates

In MATLAB the user has the option to either use world or grid coordinates. World directions are utilized as a flat out direction outline with a fixed origin and have boundless resolution while indicating areas. Nonetheless, all areas are changed over to lattice areas as a result of data storage and resolution limits.

At the point when setting occupancy locations, you can enter the locations in either grid or world coordinates. Be that as it may, taking into account the limits of the grid, the areas are set to the nearest framework locations. Edges of the grid fit in with the lower left network area [4].

Grid coordinates define the actual resolution of the occupancy grid and the finite locations of obstacles. The origin of grid coordinates is in the top-left of the grid with the first location having a location of (1, 1). However, the location of the grid in world coordinates is defined by the property, Grid Location In World and specifies the bottom-left location of the grid. When creating a robotics Binary Occupancy Grid object, other properties such as XWorldLimits and YWorldLimits are defined by the input width, height, and resolution. The figure below shows a visual representation of these properties and the relation between world and grid coordinates [4].
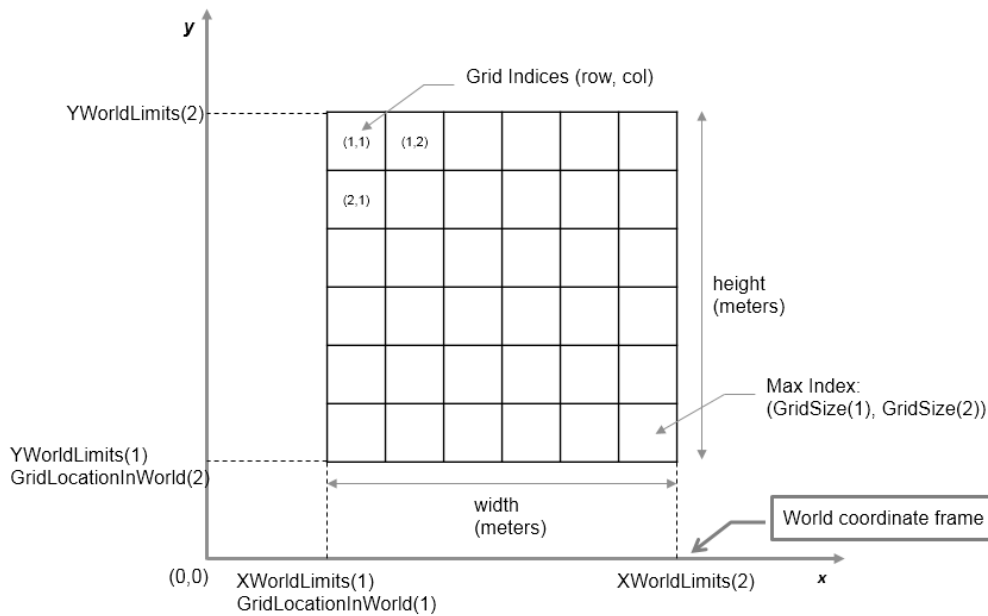
Figure 1.   The figure above shows a visual representation of these properties and the relation between world and grid coordinates [4].

Inflation of Coordinates

The inflate method is used to measure the dimensions of the robot and the obstacle locations are inflated accordingly so that it is able to create free spaces through which the robot can move through without hitting any object.

III.   UNIQUENESS AND MOTIVATION

Over the years there have been number of researches all of which specialized in environment mapping using robots, so what makes our work unique, something that is going to stand out among all of them?

The first thing that comes to mind when the word robot is heard is a very expensive smart machine that is able to complete tasks which are normally done by humans, and more. But the catch is the price of the robot. The reason behind them being so expensive is that their production cost is extremely high and when it comes to the case of 3D mapping and localization robots the costs are through the roof. This is one of the things that makes our robot stand out from the rest. The production cost is so low that two units can easily be made for $100 thus making the production cost of each robot roughly about $50.

Next not only will our robot collect data from its surroundings but it will also build a 3D map, which it will use in real time to move around thus making it autonomous. The user in real time will also receive the data retrieved by the robot in case it is needed for further research. The power of the robot will be provided by such means so that it is able to operate on its for a long period of time without the need for it to be charged frequently thus pushing off another possibility that could probably hinder its performance.

When we first got admitted into university our first computer course instructor was someone who had done his PHD on robotics, he talked with us about all the opportunities that the field of robotics held for computer science and engineering students. Later that semester we read about students from BRAC University making a robot that made it all the way to NASA. All these stories made us think that if they can do it so can we. And in our 4th semester we went and had a talk with our CSE course instructor who presented us with this research and enquired whether or not we were interested, it was an opportunity and guidance that we were looking for a long period of time and without any hesitation we took up his offer.

IV.   AIMS AND OBJECTIVES

The robot can be used in a number of fields starting from a mission to space to finding a clear path while on a hiking trip to exploring the deepest oceans. Due to a number of risk factors and constraints humans are not able to go down to deep ocean beds this is one instance where our robot can replace human requirements. One or more

units of the robot could be sent down to the ocean bed and be used to transmit back readings that can then be used to make a 3-Dimensional model to get an idea of what the surrounding area holds in store. The same can be said for outer space missions.

A. Search and Rescue Operations

Last year in Bangladesh in two similar separate incidents two children lost their lives only because no one was able to determine their positions and rescue them in time. These children had fallen down open manholes while playing and by the time anyone noticed it was already dark. In the dark the rescue team was not able to pinpoint the exact location of the children down the manholes and by the time they did it was too late and the rescue team brought out the bodies of the two deceased children. In a situation like this our robot could be suspended down the manhole and take readings that can be rendered into a 3-dimensional view pinpointing out the exact location of the victims, this can be achieved using a cell phone application. Once the positions of the victims are found a rescue team could be sent down to extract the victims.

Another scenario in which the robot can be used is during hiking trips and mountain climbing expeditions. In cases like these many a times people have to venture forward themselves and find out if there is a pathway available or not. Our robot can be sent forward in this case and with its capability to move around obstacles and send back readings with which a 3-D image can be rendered hikers can find out a pathway that they can use.

V. BASIC HARDWARE DESIGN

So far we have completed connecting the servo motor, ultrasonic sensor, bluetooth module and arduino together. Below is a detailed review of the hardware and how we have used it so far.
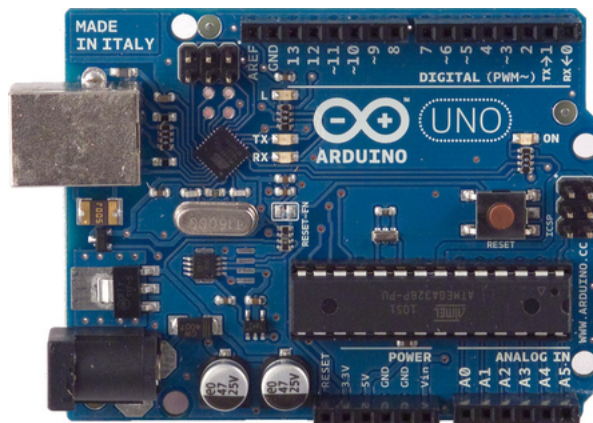
A. Arduino Uno

Figure 2. Arduino Uno Board [10].

The arduino UNO is a microcontroller board with 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. The Uno is the medium through which the sensor sends its readings back and forth and controls everything is else that goes on inside the bot. In simpler words it controls the bots actions.

B. Ultrasonic Sensor HC-SR04

Most data by mapping robots are via sonar sensors, laser beams and cameras. Even though sonar technology is quite developed there a few fields where it is actually applied [2]. Some of the traditional places sonar is used are marine applications, camera autofocus and a few robotic applications that rely on sonar data to achieve their goals [2]. Ultrasound sensors are used in medical appliances one such example is ultra-sonogram, which helps create the image of an unborn baby.

The sensor HC-SR04 is basically what guides the bot and takes all the readings. It emits ultrasonic waves which hits an obstacle and reflects back to the sensor after which it calculates the distance between the bot and the obstacle. There are four pins on the sensor as visible in Figure 3, VCC, TRIG, ECHO and GND. Each of these pins are connected to the arduino board via jumper wires. The VCC pin is connected to the 5V volt power

supply, the TRIG and ECHO pins are connected to output and input pins respectively on the arduino board and the GND to one of the three ground connection pins on the board.
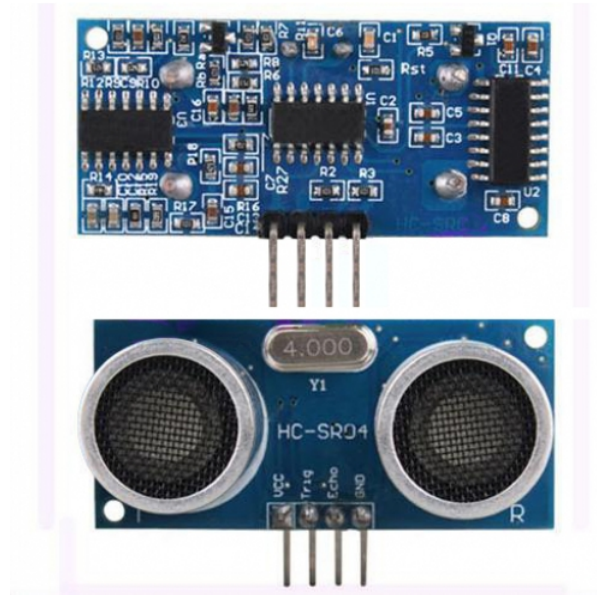

Figure 3. Ultrasonic Sensor HC-SR04 [9].

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Working Principles of Ultrasonic Sensor HC-SR04

The two circular structures placed on the sensors circuit board are the main parts of the module. These are the parts, which deal with sending out and receiving ultrasounds.

A short 10uS pulse is needed to the trigger input for the sensor to start the ranging; the module will start by sending out a burst of ultrasound sound at 40KHz and raise its echo. The range/distance of the sensor is calculated by the time taken of the reflection of the ultrasound to reach the sensor. In simpler words it is the time interval between the initial signal sent and the echo signal received by the sensor [11].

Advantages of Using the HC-SR04 Sensor [12]:

- Low cost.
- Can effectively provide distance to objects.
- Produces tractable amount of data for interpretation.

Disadvantages of Using the HC-SR04 Sensor [12]:

- Poorer discriminatory ability than vision
- Susceptible to noise/distortion
- Can produce erroneous data (reflections)

C. Tower Pro SG90 Servo Motor

Figure 4. SG90 Tower Pro Servo Motor [13].

The ultrasonic sensor is placed on the servo so that it can take a 180-degree reading of its surroundings. The servo has three wires coming out of it, of the three one is for power, one for grounding and another for input. However there are a couple of downsides of using the SG90 tower pro servo motor they are:

- The motor cannot take readings of surroundings of more than 180o
- The motor only moves horizontally and not vertically
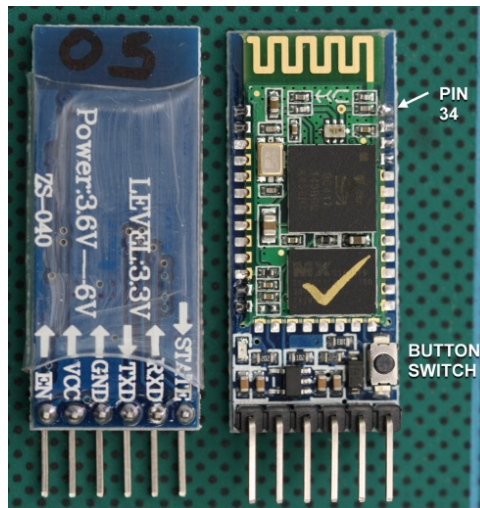
D. Bluetooth Module HC-05

Figure 5. Bluetooth Module HC-05 [14].

The Bluetooth module used in the research to receive data on an android device is the HC-05. The module operates at a frequency/baud of 9600. It has six pins coming out which are as the following:

- State: The state pin is not connected with any input or output pin in the Arduino. It just determines, which state the module, is currently in i.e. whether or not it is connected with a device.
- RXD & TXD: These two pins are connected with the RX and TX pins on the arduino respectively. These are the pins that are responsible for receiving and sending data via the module. The TXD

and RXD pins however cannot withstand a voltage of more than 3.3V and if supplied with more there is a chance that the module might get damaged. This however is only applicable if they are connected to any other pin than the TX and RX pins on the arduino. If they are, then a voltage divider has to be used in order to rule out the risk of damaging the module.

- GND: The GND (Ground) pin is connected to the GND pin on the arduino board.
- VCC: The VCC pin is the one that is connected to the power supply. The module can withstand a voltage from a minimum supply of 3.6V to a maximum of 6V, however it will also function properly if connected with a 3.3V supply. A 3.3V supply was used in this research as the TXD and RXD cannot withstand more than that. Thus the VCC pin is connected to the 3.3V pin on the arduino.
- EN: The EN pin is not connected to any pins on the arduino.

The HC-05 module has two modes the slave and the master mode. The slave mode depicts that it can only transmit data to and from devices nothing more nothing less. The master mode depicts that it can send data and commands as well as receive them. In this research the module was used as a slave thus it only sends the data collected by the sonar sensor to the device that it is connected to.

Working Principles of the Bluetooth Module HC-05

Previously data collected by the ultrasonic sensor would be viewed on the serial monitor of the arduino. However after installing the Bluetooth module in the processing unit the data can be viewed on any device with the help of a Bluetooth terminal. In this we use an application called *Bluetooth terminal* to meet our specific needs. As the module is used in its slave mode it will only be able to send data from the arduino to the connected device. Now instead of sending the data to the serial monitor of the arduino the data is sent via Bluetooth to the connected device. The pairing of the module is explained in details in later sections of the paper.

Advantages of Using the Bluetooth Module HC-05:

- Cheap and readily available.
- Data transfer mode is easier.
- Does not heat up if used for a longer period of time.

Disadvantages of Using the Bluetooth Module HC-05:

- Range within which it can be used is small.

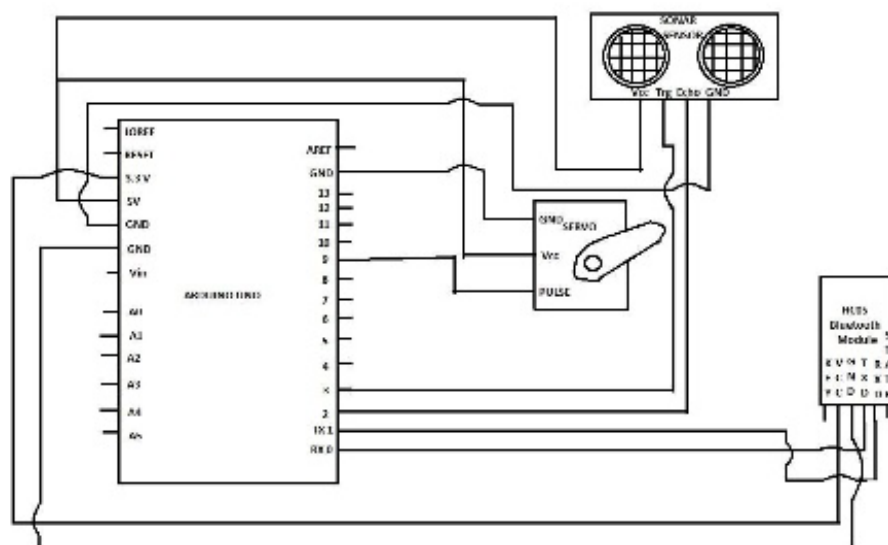## VI. METHODOLOGY AND CIRCUIT SETUP

Figure 6.   Schematic Diagram of Circuit Setup

Components:

- Arduino UNO board – 1 Piece
- USB power cable – 1 Piece
- Servo Motor Tower Pro SG90 – 1 Piece
- Ultrasonic Sensor HC-SR04 – 1 Piece
- Bluetooth Module HC-05 – 1 Piece
- Bread Board – 1 Piece
- Connecting Wires – As many needed

Both the servo motor and the ultrasonic sensor are connected to the arduino uno board via wires and a bread board. The pins of the sensor are connected to the breadboard via female jumper wires and from there more wires connect them to the arduino board, the same is said for the servo motor. Here is how the connections go:

For Ultrasonic Sensor HC-SR04 – Arduino Uno Board via Breadboard:

- VCC – 5V power supply pin
- GND – GND (ground) pin
- TRIG – Output pin 3
- ECHO – Input pin 2

For Servo motor – Arduino Uno Board via Breadboard

- Power Source Wire – 5V power source pin
- GND Wire – GND (ground) pin
- Input Wire – Input / Output pin 9

Bluetooth Module HC-05 – Arduino Uno Board via Breadboard

- STATE - Not connected.
- TXD – TX pin
- RXD – RX pin
- GND – GND (ground) pin
- VCC – 3.3V power source pin
- EN – Not connected

As the sonar sensor and the servo both had to be connected to the 5V power supply pin on the arduino. A wire was used to connect the pin to the bread board and from there the servo and sensor were connected in a parallel way so that both had a supply of 5V.
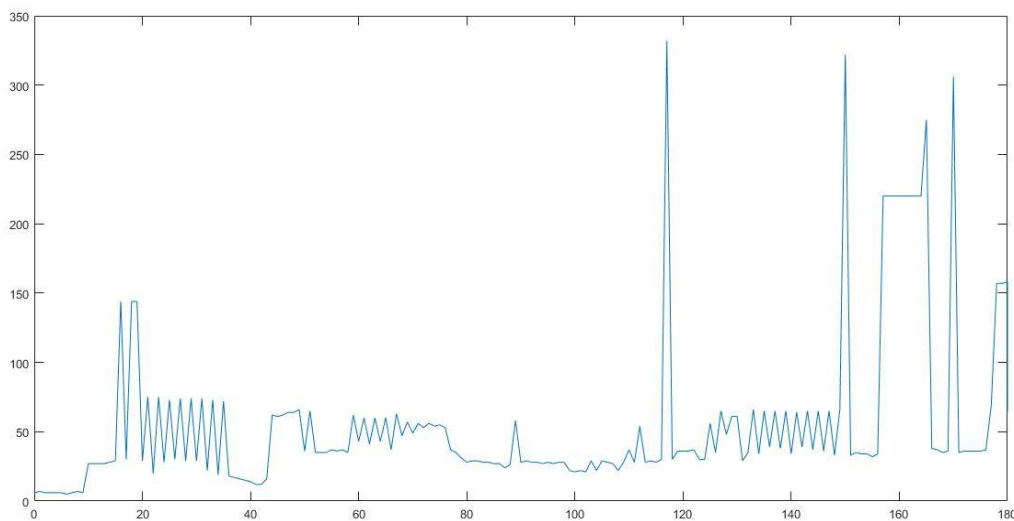

Figure 7.   Graph obtained from the data collected by the ultrasonic sensor

VII. STEPS TO CONNECT BLUETOOTH MODULE HC-05 TO AN ANDROID/BLUETOOTH DEVICE

After setting up the circuit the last step is to connect to the Bluetooth module so that the data collected by the ultrasonic sensor can be viewed on an android device. When not connected the led on the module blinks every second or so and once connected it blinks every two seconds. The connection to the module has to be made in the same way every other Bluetooth device is connected to. By default it is discoverable and once found by the android device it has to be chosen from the list and a passcode (default 1234) has to be entered. That is all that has to be done to create a connection between the module and an android device.

Only pairing with the module is not enough to receive data on an android device, a third party software is required to do so. In this case the application Bluetooth term was used. It is readily available on the Google play store. Any other Bluetooth terminal software can also be used.
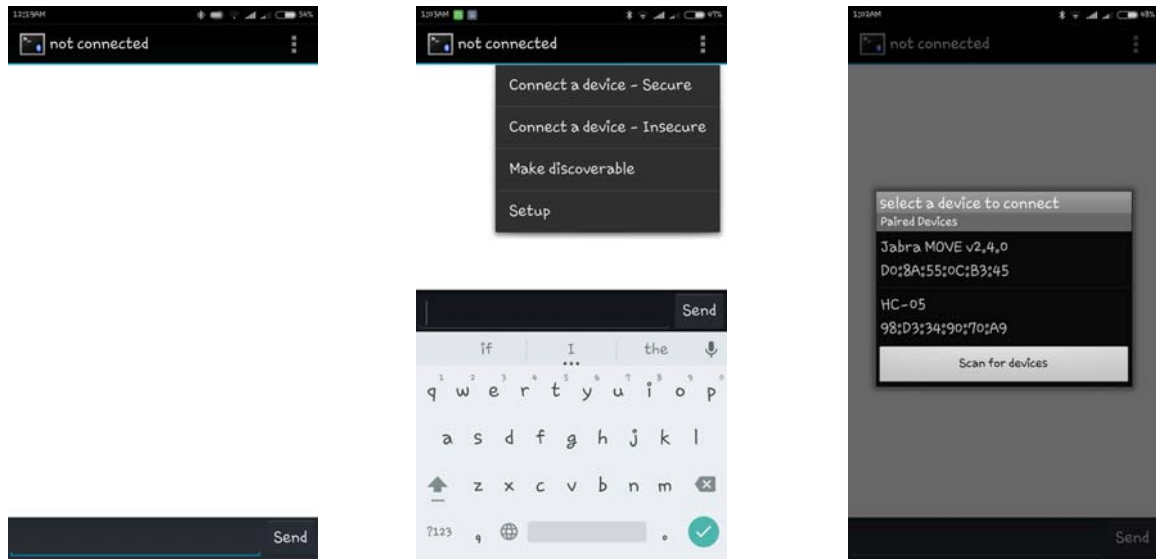

Figure 8.   Bluetooth term before connection, choosing connection type and choosing device from paired device list.

As the module was previously paired with the phone it will appear in the list of paired devices and the next step to be completed is simply to select it from that list.

Figure 9.   Data collected by sensor received on a bluetooth enabled device (android) via bluetooth module HC-05

Once connected a letter has to be sent to the module in order to receive any data back.

VIII. FUTURE PROSPECTIVE

The project is in its initial phase at the moment and only a processing unit has been developed which is able to take readings horizontally. Future prospectives include 3D mapping of the robots environment (currently only 2D is being done), improving the Bluetooth design so that it can operate over a wider range, creating a full unit so that the robot is able to move around and take readings both vertically as well as horizontally on its own.

At the moment only one servo motor is being used with the ultrasonic sensor. A servo is only able to rotate 180 degrees horizontally starting from position 0, thus the readings obtained by the ultrasonic sensor gives us a view of the horizontal environment of the robot. However vertical readings can also be taken, to do so all that has to be done is that two servos have to be connected together; one horizontally while the other is connected vertically. It will be somewhat like the one in Figure 10.

Figure 10. Servo mount for taking horizontal and vertical readings [15].

The initial servo will have to be placed on the bottom of the mount on its side this will allow the upper portion of the mount to move vertically, the secondary servo will then be placed on the upper portion of the mount in an upright position so that it is able to take readings horizontally. Thus combining the two sets of readings obtained we will be able to create a 3D view of the robots environment. Summarizing the whole concept the initial servo will move the sensor vertically and the secondary servo will move the sensor horizontally.

The second phase would be making the whole structure for the robot. We have already made a 3D model of how it may look like once finished.
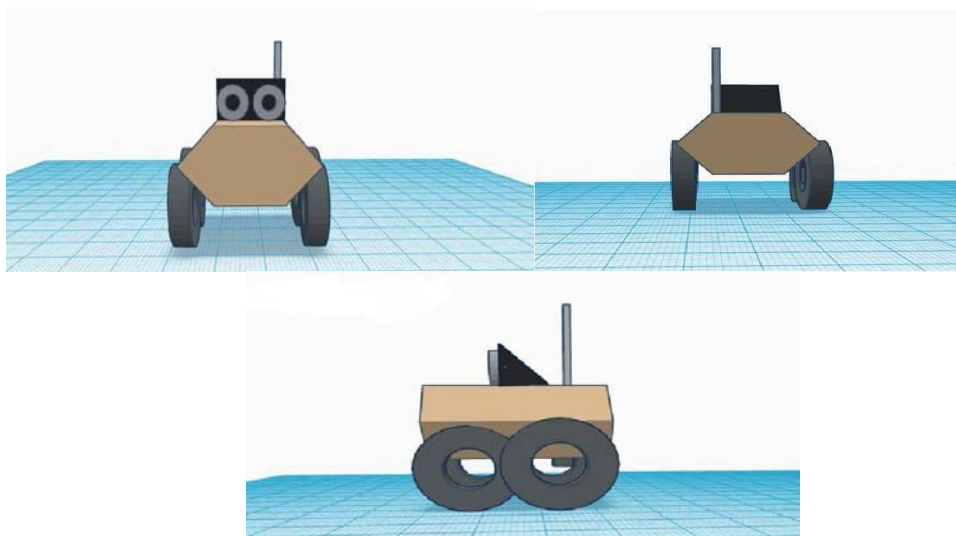

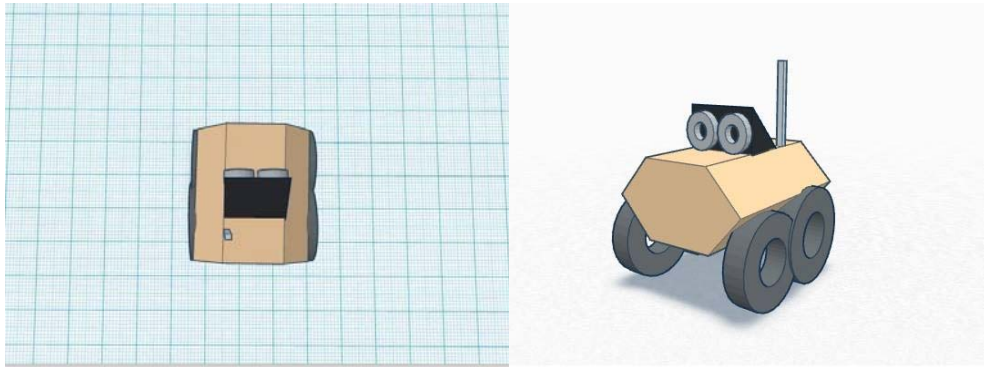Figure 11. Front, Rear and Side Views Respectively.

Figure 12. Aerial and Angular Front Views Respectively.

Figure 11 and Figure 12 showcase the front, rear, side, aerial and angular front views of the robot respectively. The unit will be made of some very simple and light components so that it is able to travel into and out of tight spots, it will be able to venture into places where its weight will not be an issue. First thing that will be taken into account while constructing the robot is its size, it will not be bigger than small cell phone box reason being once is so that it is able to travel into tight spaces where human beings are not able to go. The tires of the unit will be all terrain tires so they are able to go basically anywhere, whether that be up a up a mountain or down rabbit holes. The material that the main structure will be made of will be a waterproof material completely sealed shut so that water has no entry point. The entire processing unit i.e. the arduino, bread-board, servo motors, Bluetooth module etc; so that water can in no way can get inside the robot. The position of the ultrasonic sensor however might be changed instead of placing it on top of the robot it might be placed in front so that it able to take vertical readings. Placing the sensor on top of the model might prevent it from doing so. Last but not least an antennae may be used to increase the Bluetooth connection range of the robot.

IX. CONCLUSION

For more than over a decade there has been numerous researchers from various reputed institutions have conducted studies regarding 3D mapping and localization using ultrasonic sensors and autonomous robots. Since then the concerned field has seen immense development, numerous robot units have been developed and tested in the field successfully. Even though we have only completed the 2-dimensional mapping phase of the project we intend to complete the 3-dimensional phase soon enough. The processing unit of the robot currently only takes horizontal readings, which allows us to create the 2D image of the environment however as soon as we develop the mount for the vertical readings we will be able to create 3D images. Soon enough the first prototype will be completed and will be able to operate in real-life instances. This paper is simply documents the initial phase of the research, as further progress is made more documentation will be done.

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