re-sizeable autonomous cleaning robot

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EXECUTIVE SUMMARY

Cleaning robots have advanced significantly in recent years, owing to increased market presence and the demand for improved cleaning performance. However, due to geometric restrictions of the platforms in relation to the cleaning stage, as well as furniture and architecture, most robots have difficulty covering the whole cleaning area. The robot developed in this project uses the on-board sensors which include ultrasonic sensors to detect obstacles and change the robot configuration accordingly and to navigate forward and backward and even sideways with the help of Mecanum wheels. Ball screw linear actuation mechanism has been used to change the length of the robot according to what it maps about the local terrain using the sensors. For this purpose, a precise CAD model has been designed with the decided parameters to bring down the cost of making the cleaning robot to the bare minimum while also optimizing its cleaning efficiency at the same time. A functional prototype has also been developed as a proof of concept and it has been compared with a simulation study done in CoppeliaSim software.

The robot consists of three separate compartments. The two side compartments slide in and out of the middle compartment with the help of Ball Screw Linear Actuators. This is the essence of the resizing system that has been developed. This enables the robot to increase its size when necessary to increase the swept area, and also decrease its size in order to reach more inaccessible areas. Having decided on the components required to ensure the optimal performance of the system, a CAD model has been developed to illustrate the design of the robot. Further, a Simulation study has been conducted to demonstrate the efficacy of the system. Since a Simulation environment comprises ideal scenarios, a Functional Prototype has also been developed as a proof of concept to the demonstrate and test the system in the real world. The design of the chassis of the robot posed several challenges, as the basic structure of the robot comprising three separate compartments came with its own set of challenges. The weight of the various components induced bending stresses on the chassis, and led to a loss of traction to the wheels. Hence, multiple iterations of the chassis had to be developed before satisfactory performance was achieved.

The Simulation study and the Functional Prototype, along with the various minor intricacies have been elaborated in this report.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Cleaning has always been an important and necessary aspect of human lives, and it has developed and changed over time. The need for completely automated floor cleaning robots has surged as a result of today's hectic lifestyle.

Automated floor cleaning robots are commonly employed in smart homes, residential, and office spaces to clean the floors.

According to a world market study, there is a strong demand for the application of these robots in domestic settings with fully automated functionalities and the least amount of human assistance, and while these robots still account for a small percentage of the global vacuum cleaner market, their recognition and implementation is growing at a rapid rate.

The robots are small and execute the cleaning operation without the need for human participation. These robots use motion planning algorithms to cover a large area while cleaning, such as spiral motion, backtracking spiral motion, boustrophedon motion (back and forth), and basic zig-zag motion patterns.

Even though fixed-configuration robots have sufficient path planning and motion skills, they may require more time and energy to complete the complicated task effectively than their changeable counterparts. As a result, building a re-sizeable robot that can increase the swept area in open spaces, and can reduce its size to reach more inaccessible areas, can make the task more efficient. This project focuses on the design and development of the same.

A functional prototype has been developed with the decided components as mentioned and exhaustive testing and simulations on the control mechanism have also been performed for introduction to the commercial market in the later stages.

Fig. 1.1 A Floor Cleaning Robot

1.2 LITERATURE REVIEW

Prassler et al. demonstrated almost how all commercial home cleaning robots are equipped with vacuum cleaners as their primary means of cleaning. Pool cleaning robots have also been developed. Some robots also have wet scrubbers to clean the floor (non-textile floor coverings), and some also clean carpets. Some industrial robots have sweepers along with vacuum cleaners. Duct cleaning robots with rotating brushes have also been developed. Sensors that are usually employed include Ultrasonic, LIDAR, IR, Cameras and Contact. Robots are navigated using dead reckoning, manually using a joystick, or even using magnetic markers to guide the way. Safety features include front bumpers that absorb impact shock. Robot road sweepers have also been developed for cleaning large open spaces. [1]

Endres et al. developed robots for cleaning purposes in the supermarkets. There are some special features in these robots, they consist of a retractable wing which is inserted in the right part of the robot. The use of this retractable wing allows the robot to get close to the objects and precisely cleans the floor without colliding with the obstacles. Also, the size of this wing can be adjusted according to the requirement it can be extended or reduced as needed. The main features of this robot were: To identify the obstacles properly for cleaning the environment, executing the plan properly, no need to install any additional part to localize the robot, a systematic skill to move around the obstacles for least energy consumption. [2]

Kushal et al. have worked on a cleaning robot ATMEGA 2560 which worked with two modes: automatic and manual. The hardware used were Arduino Mega 2560, Ultrasonic Sensor, DC Generated Motor, Vacuum Motor, L298n Dual H-Bridge Motor Driver, VL53LOX Laser TOF Sensor and Servo Motor. Since the robot has two modes, one of them is manual mode which is selected when the robot switch is high and allows the users to reach places which are not automatically detected by the robot. And for the autonomous mode there is an algorithm which is followed by the robot with path planning. There is also a water sprayer attached so that the robot can also be used for the moping purposes as for the convenience of the user. [3]

Sewan Kim et al. demonstrated the Roboking system integration in an autonomous cleaning robot. The purpose of this robot was the protection of the indoor cleaning environment while the robot is working. There are many different sensors and the functions which are integrated in this system. The robot uses a digital signal processor from Texas Instruments (320LF 2406A). It works on 40MHz frequency with 24 sensors performing the operations together gathering different signals from internal subsystems. Also, there are 14 ultrasonic sensors which are installed in the robot, where nine of them were used in the lower part to find the obstacles. And the others were used on the upper part so that the robot does not collide with the tall obstacles. For the Roboking mechanism, there are cliff detecting sensors which determine the upliftment of the robot and prevent the robot from falling down. [4]

Liu et al. developed a system that did not rely on mapping and global self-localization. It consists of three layers. The lowest layer contains the sensors and hardware, which include ultrasonic (13 pairs, 7 for the front and the rest for the sides), IR, encoders, DC motors, vacuum etc. The second layer is responsible for the behaviour of the robot, which include point turning, line following, wall following, side shifting, and obstacle rounding. The third layer is responsible for carrying out tasks, like environment learning, cleaning and homing. [5]

Mahmud Hasan et al. demonstrated the use of bumper contact sensors and cliff IR sensors. The path planning algorithms include Random walk, spiral, ‘S’-shaped path and wall follow. These four algorithms are cycled between until the entire area is covered. The motor specification is 2Amp/6VDC, 5500 rpm with 70:1 gearbox for the driving wheels. The side brush controlling motor specification is 0.5Amp/6VDC with a 30:1 gearbox. The vacuum motor is 5Amp/6VDC with 8000rpm (Cyclonic type dry vacuum is used). The battery used is 6V/4.5Ah lead-acid. The robot can operate for an hour. The battery takes 5-6 hours to charge. [6]

Joon et al. developed a combination of Lidar and camera. A manipulator arm containing the vacuum was attached to the mobile robot. The collector box has a volume of 378 cubic cm (10 cm × 6 cm × 6.3 cm). [7]

Shakhawat Hossen et al. discussed how LIDAR and GPS have been used for mapping and localization. IR proximity sensors and ultrasonic sensors were used for object detection. [8]

Gerstmayr-Hillen et al. discussed how an omnidirectional camera was used to generate panoramic images of the environment in order to map it, and hence guide and navigate the robot to cover a rectangular segment of the robot's workspace. The omnidirectional camera is used to simultaneously localize the robot and also map the environment. Hence, the camera carries out local visual homing and provides the data to generate a dense topological map. The robot is guided along parallel paths by controlling its distance from the previous lane. The distance is estimated using images from the camera and the robot's odometry. Only the robot's distance from the previous lane and its orientation are calculated. [9]

Karur et al. discussed various path planning algorithms. Dijkstra and A* algorithms are used for static environments, whereas D*RRT (Rapidly-Exploring Random Trees), Genetic, Ant Colony and Firefly algorithms are used for Dynamic environments. [10]

Dakulovic et al. demonstrated complete coverage of D* algorithm for path planning, using a combination of D* and PT algorithms. [11]

Lamini et al. demonstrated how GA (Genetic Algorithm) with improved crossover operators and fitness functions were employed to find optimal solutions. [12]

Amine Yakoubi et al. demonstrated that GA was used for path planning. Each gene represents the robot position and the chromosomes represent the mini-path. [13]

Liu et al. developed an algorithm for complete coverage path planning, which combines random path planning and local complete coverage path planning. Random path planning is very flexible for unstructured environments, but is inefficient. On the other hand, local complete coverage path planning generates a comb-like path to cover a relatively small area with high efficiency, but fails to do so in a larger area in an unstructured and dynamic environment. The proposed technique combined the benefits of both. 11 pairs of ultrasonic sensors were used, 7 for the front and the rest for the sides. [14]

Hofner et al. demonstrated path planning of a rectangular non-holonomic robot. Two changing manoeuvres were used to navigate the robot – U-Turn and Side-Shift. Based on the parameters of the robot and the environment, the path planning algorithm will choose the most appropriate path planning template such that the entire floor area is covered efficiently. Localization was done using ultrasonic sensors and dead-reckoning. Subgoals were determined in the vicinity of various pre-planned landmarks. Vehicle guidance was done by finding the specified start location and compensation of path errors. [15]

Ramalingam et al. developed an algorithm for detecting and classifying debris as solid and liquid spillage using CNN and SVM was developed. This helped the robot to avoid hard to clean debris, as robots are mostly unable to clean such debris and hence end up spreading them on the floor rather than cleaning it, thus also reducing their efficiency. [16]

Schmidt et al. developed an algorithm that has been developed to memorize uncleaned areas that couldn't be cleaned in the first sweep because of a temporary obstacle, and then come back to clean it after the remaining area has been cleaned. [17]

Parween et al. developed a self-reconfigurable robot called hTrihex has. It enables the robot to cover spaces that are generally missed or inaccessible by the usual circular shaped cleaning robots (like corners). This robot can configure itself into three different configurations based on the requirements, namely – Straight, Chevron and Closed. The sensors used onboard are encoders, LIDAR and IMU, along with a PID controller for implementing a closed-loop system. A differential drive has been implemented to steer the robot and hence control the heading. [18]

Parween et al. developed another similar self-reconfigurable robot is the hTetrakis. It consists of four equilateral triangles, and can change between three configurations namely – "I", "A", and "U" shapes. These configurations enable the robot to access convex and narrow corners that are generally inaccessible by the common circular shaped cleaning robots. [19]

Forlizzi et al. demonstrated that Mecanum wheels have their omnidirectional property that allow them to have excellent manoeuvrability and ability to move in a congested space. Congested spaces usually mean environments with static or dynamic obstacles or narrow areas respectively. Due to the Mecanum wheel's high manoeuvrability, it is ideal for outdoor applications like transportation purposes in warehouses, mining activities and even for military activities and indoor applications like autonomous robot cleaning that is the objective of this Capstone project. [20]

Laurena et al. developed and demonstrated control mechanism for actuating ball screw linear actuator. A ball screw linear actuator converts rotatory motion to linear motion. It has low friction and can withstand thrust loads. The programming and control system for the linear actuator was developed. [21]

Bhowmik et al. developed an algorithm for navigation of a cleaning robot by modifying the Dijkstra algorithm. A provision for backtracking and hill climbing were incorporated. This improved the performance of the Dijkstra algorithm. [22]

1.3 GAPS IN LITERATURE

After the exhaustive literature review it has been concluded that,

1. According to the literature review conducted, all the cleaning robots including the commercially available ones, are fixed in size and configuration.
2. A handful of self-reconfigurable robots have been developed. The objective of these robots is to cover hard-to-reach places, that conventional fixed configuration robots cannot.
3. Hence, the aim is to develop a re-sizeable robot that can increase its length to cover more area in a single sweep, and can also reduce its size to reach inaccessible areas.

1.4 BACKGROUND

The cleaning task is an essential one, and as a result, floor cleaning robots are gaining popularity. However, all the commercially available cleaning robots are of a fixed configuration. Hence, the cleaning task can be improved upon and made more efficient. A re-sizeable robot can help achieve the same.

1.5 POST/ RELATED WORK

Almost all the robots covered in the literature review are fixed in size and configuration. A handful of the cleaning robots reviewed are re-configurable. Re-configurable robots have the advantage of reaching inaccessible areas and hence lead to more efficient cleaning. A re-sizeable robot has similar advantages, along with the added benefit of increasing its size for a more efficient clean.

1.6 PROBLEM STATEMENT

Cleaning robots are available in a variety of sizes and can clean a specific area in a single sweep. However, the cleaning efficiency and effectiveness can be improved. In open places with little impediment, such as broad halls and living rooms, cleaning can be done quickly by sweeping a larger area in a single sweep. To address this problem, a re-sizeable cleaning robot is being developed that can extend its length, allowing it to cover a larger area in a single sweep, and can also reduce its size to reach inaccessible areas.

1.7 MOTIVATION

The motivation for the project was to reduce the amount of manual labour involved in cleaning an area and especially surfaces that are out of physical reach and to also reduce the amount of physical stress caused. The cleaning robot includes built-in sensors that can detect areas of home that require special attention and perform additional runs over them. High-traffic areas, such as hallways, entryways, mudrooms, and playrooms, will receive cleaning care. Due to the efficiency of the design and the sensors, the robot can work on any type of surface after receiving the necessary information from the surroundings.

1.8 CHALLENGES

The most challenging aspect has been the design of the chassis for the Functional Prototype. Having chosen sheet metal, the major problem that had arisen involved the bending of the chassis and subsequent loss of traction to the wheels. Choosing a thickness for the sheet involved creating a balance between rigidity and weight. Finally, an MS sheet of 1 mm thickness proved to be satisfactory.

Another noteworthy challenge has been the consideration of intricate details while developing the CAD model. Considering the complexity of the robot, several complications and challenges emerged during development.

1.9 ESSENCE OF YOUR APPROACH

The approach to the development of the robot involved defining a clear problem statement and designing the robot along with its functional architecture. Having done that, a detailed CAD model has been developed along with selection of the various components of the robot. Further, a Simulation study along with a Functional Prototype has been developed the demonstrate the effectiveness of the system.

1.10 STATEMENT OF ASSUMPTION

The robot has been developed assuming that standard elements such as LIDAR, Ultrasonic sensors and camera will work as expected and will not be affected by the re-sizing aspect of the robot. Although vacuum calculations have been conducted, it has been completely theoretical. Real life performance may vary, and hence it has been assumed that a vacuum pump of sufficient capacity will function satisfactorily, and will not fail in picking up dust particles despite the increase in the vacuum system orifice.

1.11 ORGANIZATION OF THE REPORT

The various intricacies related to the development of the robot have been covered in the robot. The functional architecture, process flow charts, circuit diagrams and finalized components have been elaborated. Mathematical calculations related to the design and selection of components have been discussed. Finally, the Simulation study, Functional Prototype and Stress Analysis results have been showcased.

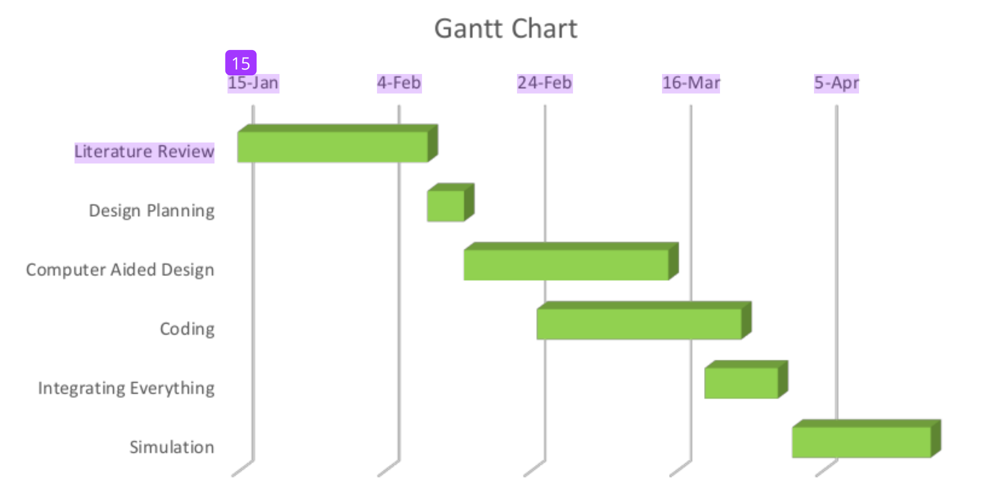
1.12 AIMS AND OBJECTIVES

1. To design a system that can change the length of the robot depending on the need and area that is currently being cleaned.
2. To integrate an actuation mechanism for changing the length.
3. To integrate object detection using camera and/or ultrasonic sensors.
4. To conduct a Simulation study.
5. To develop a Functional Prototype as a proof of concept.

CHAPTER 2

METHODOLOGY AND EXPERIMENTAL WORK

2.1 GANTT CHART (PHASES OF THE PROJECT)



	Simulation	Integrating Everything	Coding	Computer Aided Design	Design Planning	Literature Review
Start Date	1-Apr	20-Mar	25-Feb	15-Feb	10-Feb	15-Jan
Days to Complete	20	10	28	28	5	26

Fig. 2.1 Gantt Chart

2.2 MILESTONES IN THE PROJECT

1. Completion of Chassis Design
2. Development of CAD Design for Actuation Mechanism
3. Development of Path Planning Algorithm
4. Development of Object Detection Algorithm
5. Development of the control system to actuate the Ball Screw Linear Actuator used to change the size of the robot
6. Conduction of Simulation study
7. Development of Functional Prototype

2.3 FUNCTIONAL COMPONENTS

The theoretical design of the robot, as well as the basic components needed, have been finalised after extensive study and detecting gaps in the literature review, as well as recognising scope for improvement. The CAD model has been developed, based on the mathematical calculations and finalised components. The on-board sensors include LIDAR and camera to detect obstacles and change the robot configuration accordingly. The following steps include programming the robot's many functions like the ability to change its length according to the environment and conducting simulations like controlling the size of the robot and the ability of the robot to manoeuvre with the help of Mecanum wheels. The primary components that have been used are:

2.3.1 LIDAR – LIDAR (Light Detection and Ranging) is a remote sensing technique that measures ranges (varying distances) to the obstacle using light in the form of a pulsed laser.

The aim is to use RPLIDAR A1 which integrates the concept of SLAM (Simultaneous Localization and Mapping). RPLIDAR A1 is a laser triangulation range system that employs Slamtec's high-speed vision acquisition and processing hardware. The technology takes distance measurements at a rate of around 8000 times per second. RPLIDAR A1's core rotates clockwise to perform 360-degree omnidirectional laser range scanning for its surrounding surroundings and then build an outline map.

2.3.2 Mecanum Wheels – Mecanum wheels have their omnidirectional property that allow them to have excellent manoeuvrability and ability to move in a congested space. Congested spaces usually mean environments with static or dynamic obstacles, or with narrow areas.

The aim is to use a set of bush type aluminium Mecanum wheels with the following specifications:

i) Diameter: 60 x 31 mm (Diameter x Width)
ii) Body Material: Aluminium Alloy
iii) Roller Material: Hard Rubber
iv) Length of Roller: 30 mm

v) Net Weight: 93 gm (Each)
vi) Load Capacity: 3Kg/Wheel

2.3.3 Camera – The aim is to use a camera sensor for object detection so as to facilitate the cleaning robot to make its own autonomous decision. The objective is to use the Raspberry PI 5MP Camera Board Module. It will also enable a live video feed to be transmitted to any device via Wi-Fi or Bluetooth.

2.3.4 Raspberry Pi – The aim is to use Raspberry Pi 4 microprocessor as it is easier to integrate it with the SLAM based RPLIDAR A1 so as to facilitate smoother mapping of the terrain. Raspberry Pi 4 will be used specifically due to its high-performance 64-bit quad-core processor, 4 GB of RAM and dual display support with resolutions up to 4K via a pair of micro-HDMI ports.

2.3.5 Battery Pack – The aim is to use two 5000mAh 22.2V battery packs with maximum discharge current and maximum charging current as 15000 mA and 5000 mA respectively. Instead of using one big 10000mAh battery, the plan is to use two 5000mAh battery connected in parallel as the voltage remains constant and increase the duration for which it could power equipment. It's important to note that when charging batteries that are connected in parallel, the increased amp-hour capacity may require a longer charge time.

2.3.6 IMU – The aim is to use MPU9250 9-Axis Attitude Gyro Accelerator Magnetometer Sensor Module with a power supply of 3.3-5 V (DC) and dimensions 22 X 17 mm with 9 DOF modules.

2.3.7 Wheel Motor – The aim is to use a compact DC Motor with High Power Density and high efficiency. The following are its characteristics:

i) Input Voltage of 12 V (DC)
ii) No Load Speed = 9900 rpm
iii) Nominal Speed = 8050 rpm
iv) Maximum Output power = 6.64 W
v) Life (Typical) = 1000 hrs

2.3.8 Ball Screw Actuator – Ball screws are mechanical linear actuators made up of a screw shaft and a nut with a ball that rolls between helical grooves that correspond. Ball screws' main purpose is to transform rotational motion into linear motion. Ball nuts are used to transmit forces to a static or dynamic load with excellent precision, reproducibility, and accuracy. The rolling balls in the helical groove of ball screws are a unique feature that eliminates mechanical contact inside the screw assembly and replaces sliding friction with rolling friction. This technique reduces friction greatly, resulting in a very efficient power conversion. Screw efficiency is determined by their capacity to convert power used to exert rotating force into linear distance travelled.

The aim is to use ball screw linear actuators to control the size of the robot.

2.3.9 Chassis Material – A functional prototype was developed wherein mild steel sheet metal was used to construct the chassis. The reasons for using mild steel are its properties:

i) Cost Effective
ii) Weldable
iii) Ductile
iv) Can be carburised easily
v) Recyclable

2.4 WORK CARRIED OUT

1. Literature review has been completed.
2. Problem statement defined.
3. The primary components required to make the robot have been finalised.
4. The conceptual design of the robot, including the mechanism to change its size, has been developed.
5. The Functional Architecture has been developed.
6. Mathematical analysis required for the research has been conducted.
7. A detailed CAD Model has been developed.
8. Basic Simulation study has been completed.

9. A Functional Prototype has been developed.

2.5 FUNCTIONAL ARCHITECTURE

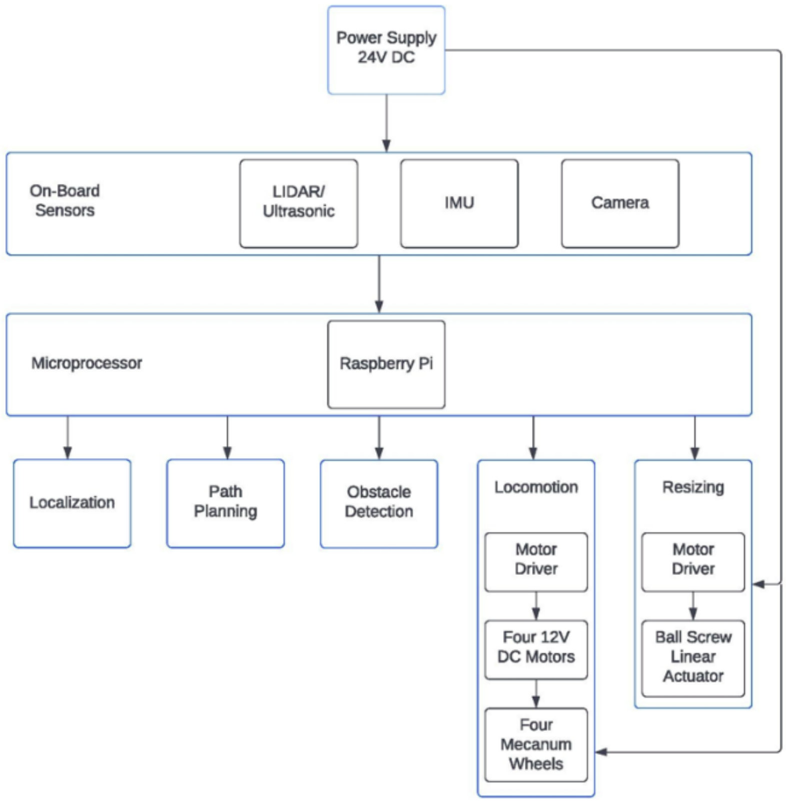


Fig. 2.2 Functional Architecture

The battery pack will power the on-board sensors, which include Ultrasonic sensors, IMU and Camera. These sensors will in turn provide input data to the Raspberry Pi, which is the microprocessor being used. The Raspberry Pi will in turn carry out and manage the various subsystems using the input data from the aforementioned sensors. The various subsystems include Localization, Path Planning, Obstacle Detection, Locomotion, and Resizing, as illustrated in Fig. 2.2.

The locomotion is carried out using four Mecanum Wheels connected to DC Motors, using a motor driver. Resizing is carried out using the Ball Screw Linear Actuator via another motor driver.

2.6 PROCESS FLOW CHART

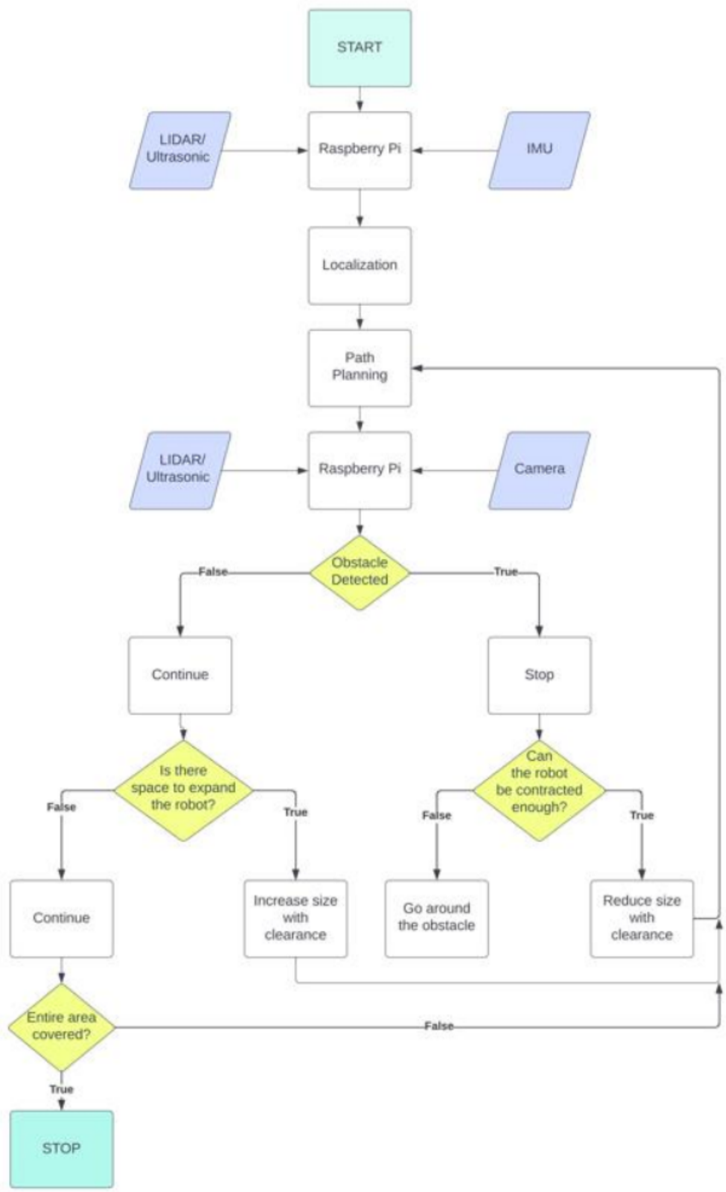


Fig. 2.3 The Robot's Process Flowchart

The robot will function based on a fixed set of logical decisions, as illustrated in Fig. 2.3, which will ensure efficient and reliable cleaning. In open spaces, the robot will try to increase is lengths as much as possible. In case there is an obstacle, it will first try to reduce its length so as to pass through the obstacle. If it is unable to do so, it will simply manoeuvre around the obstacle and continue cleaning.

2.7 CIRCUIT DIAGRAM

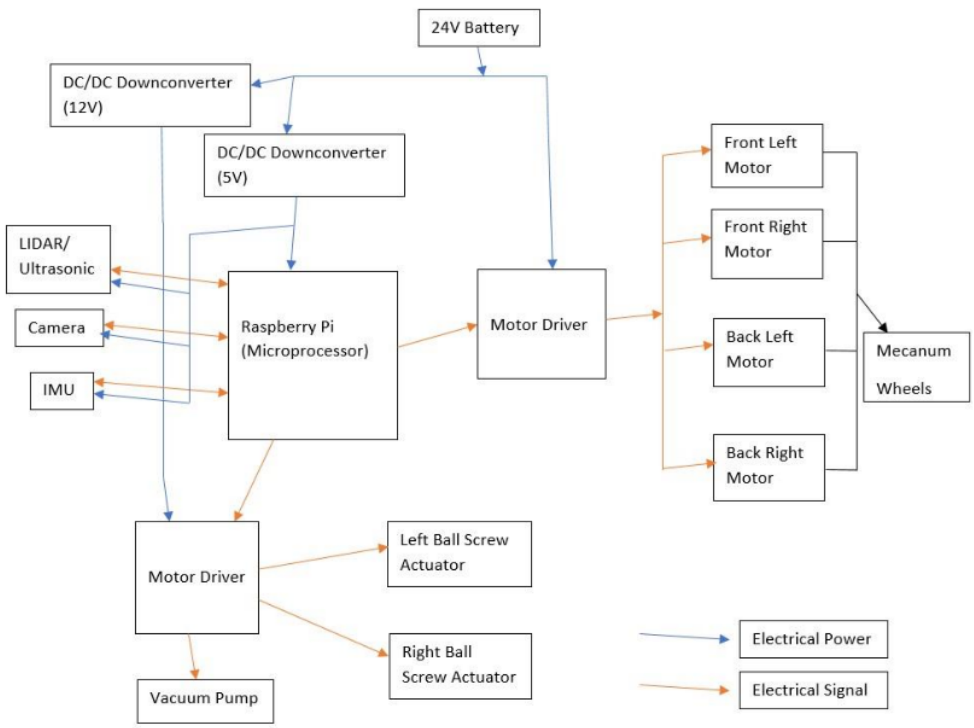


Fig. 2.4 Circuit Diagram

Fig. 2.4 illustrates the various electrical and logical connections between the various components. Logical connections are made between the Raspberry Pi and components, whereas electrical connection are made between the battery pack and components.

2.8 SIMULATION PROCESS FLOWCHART

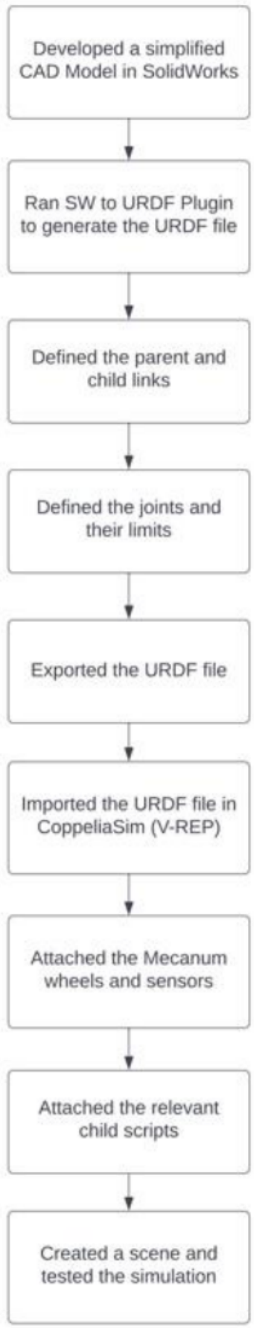


Fig. 2.5 Simulation Process Flowchart

The various steps involved in creating the Simulation study have been illustrated in Fig. 2.5. A simplified CAD model has been developed to ensure that the simulation goes smoothly. The CAD model has further been exported as a URDF file, and then imported into the simulation software. The simulation software chosen is CoppeliaSim (V-REP) because of its simplicity and familiarity with the software. Further, the joints and links have been defined, sensors integrated, and the scene set.

2.9 ULTRASONIC SENSOR CIRCUIT

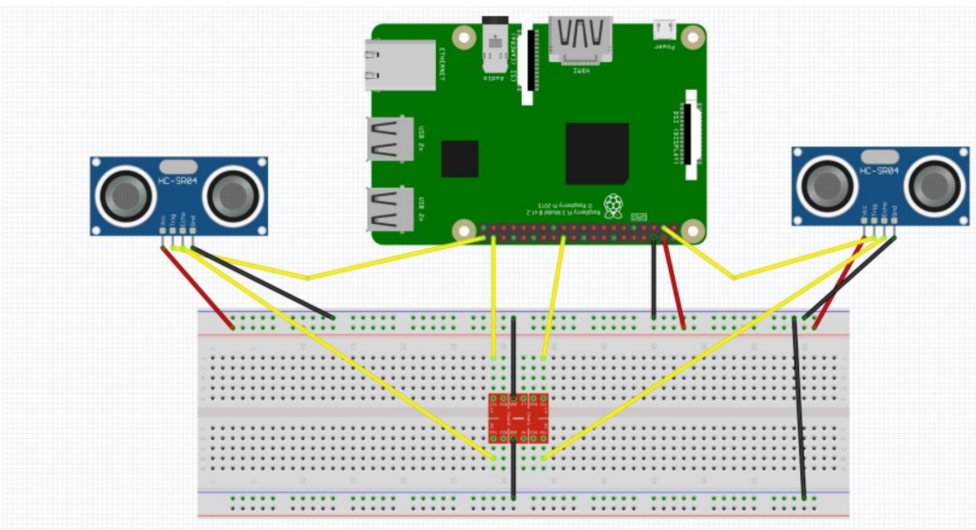


Fig. 2.6 Ultrasonic Sensor Circuit

Fig. 2.6 shows the various connections made between the Raspberry Pi and the HC-SR04 Ultrasonic sensors. The Ultrasonic sensors are powered via the +5V pins of the Raspberry Pi. The Grounds are made common. The TRIG pin of the sensor is set as an output pin, and is connected to one of the several GPIO pins of the Raspberry Pi. The ECHO pin of the sensor is set as an input pin. Since the HC-SR04 sensor functions on a 5V logic level, and the Raspberry Pi on a 3.3V logic level, connections have to be made via a 5V to 3.3V logic level shifter.

2.10 WHEEL MOTORS CIRCUIT

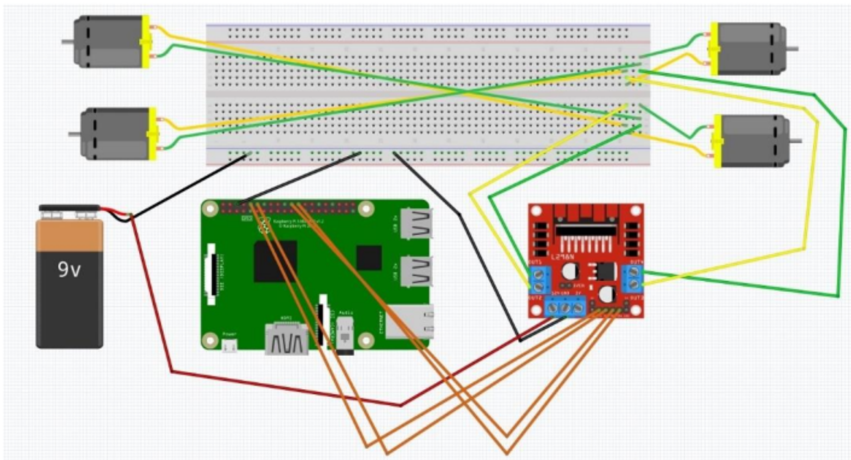


Fig. 2.7 Wheel Motors Circuit

Fig. 2.7 shows the connections between the Raspberry Pi, motors and the motor driver. Diagonally opposite motors, corresponding to the type A and type B Mecanum wheels respectively, are connected together. The positive and negative terminals are then connected to the OUT ports of the L298N motor driver. The motor driver is powered using a 12V battery via the +12V port. The Grounds are made common. Logical connections are made between the IN ports of the motor driver and the GPIO pins of the Raspberry Pi. The ENA and ENB pins of the motor driver can be used for PWM control, to control the speed of the motors.

2.11 LINEAR ACTUATOR CIRCUIT

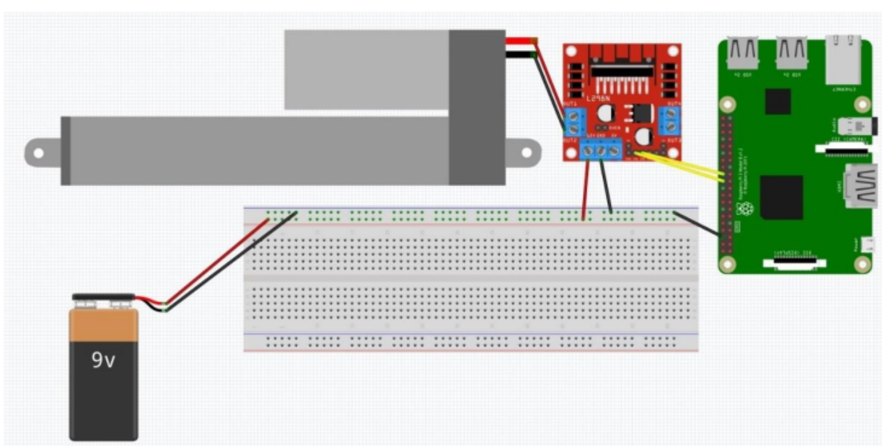


Fig. 2.8 Linear Actuator Circuit

Fig. 2.8 shows the connections between the Raspberry Pi, linear actuator and the motor driver. The positive and negative terminals of the linear actuator motor are connected to the OUT ports of the L298N motor driver. The motor driver is powered using a 12V battery via the +12V port. The Grounds are made common. Logical connections are made between the IN ports of the motor driver and the GPIO pins of the Raspberry Pi.

2.12 SENSOR CODING

<u>2.12.1 Ultrasonic Sensor:</u>

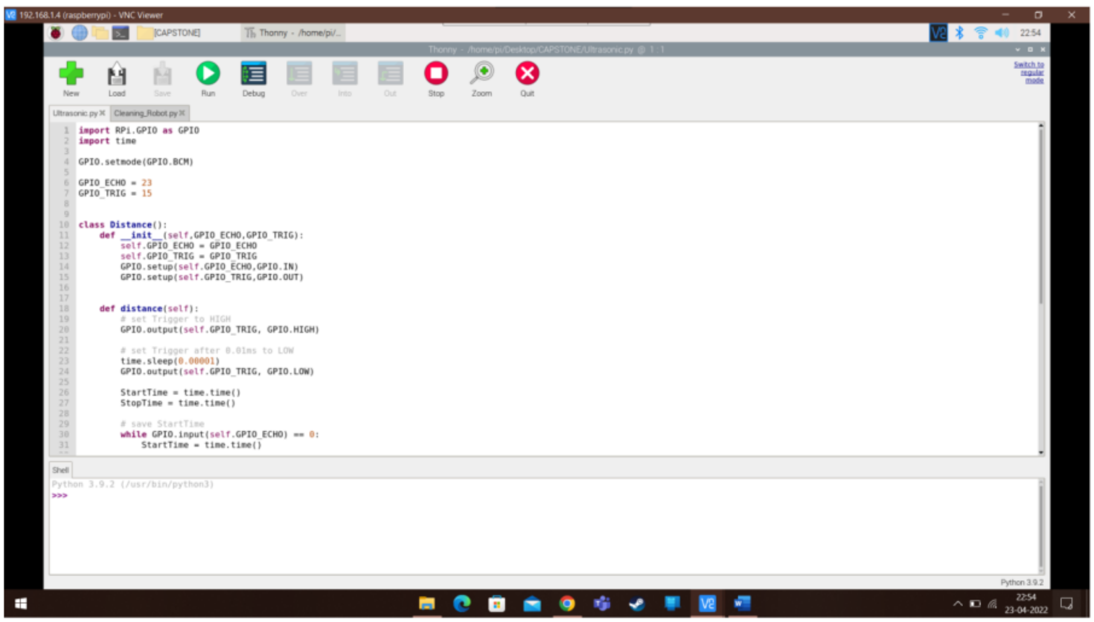


Fig. 2.9 Ultrasonic Sensor Code

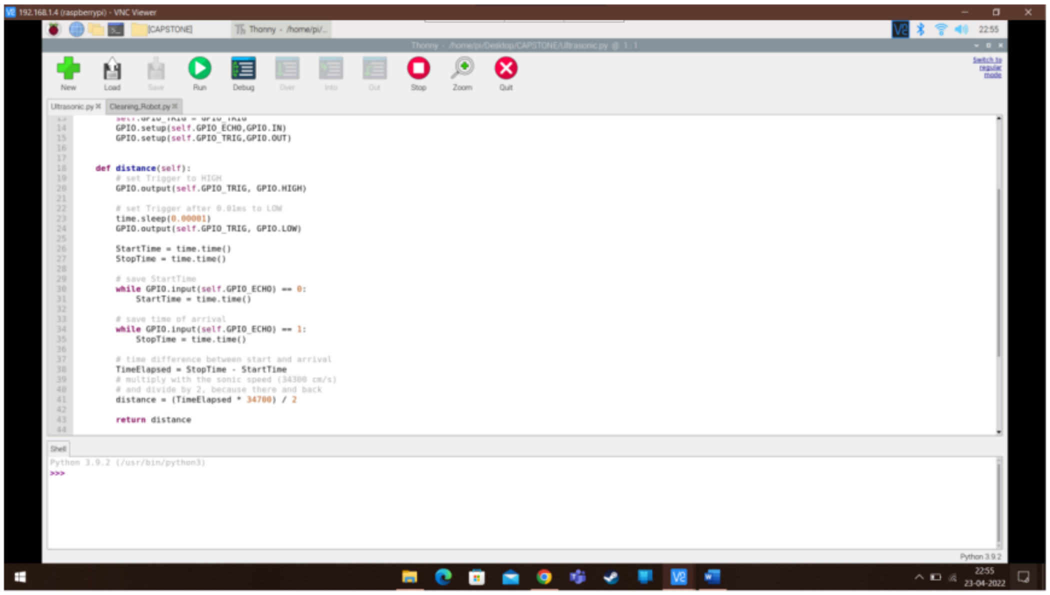


Fig. 2.10 Ultrasonic Sensor Code contd.

The operation of ultrasonic sensors is like that of radar sensors. The transmitter in a radar system produces radio waves (sound waves), which are electromagnetic waves that move through the air and return when they collide with an object in their path. The distance is then determined using the following simple formula,

Distance = Time x Speed

Time – amount of time taken by the sound wave to travel from the detected object to the receiver.

Speed – Sound wave speed. Most ultrasonic sensors consist of a trigger that transmits infrared sound waves and a receiver that records the reflected sound waves which is used for the basic purpose of object detection by the cleaning robot.

2.12.2 Main Script:

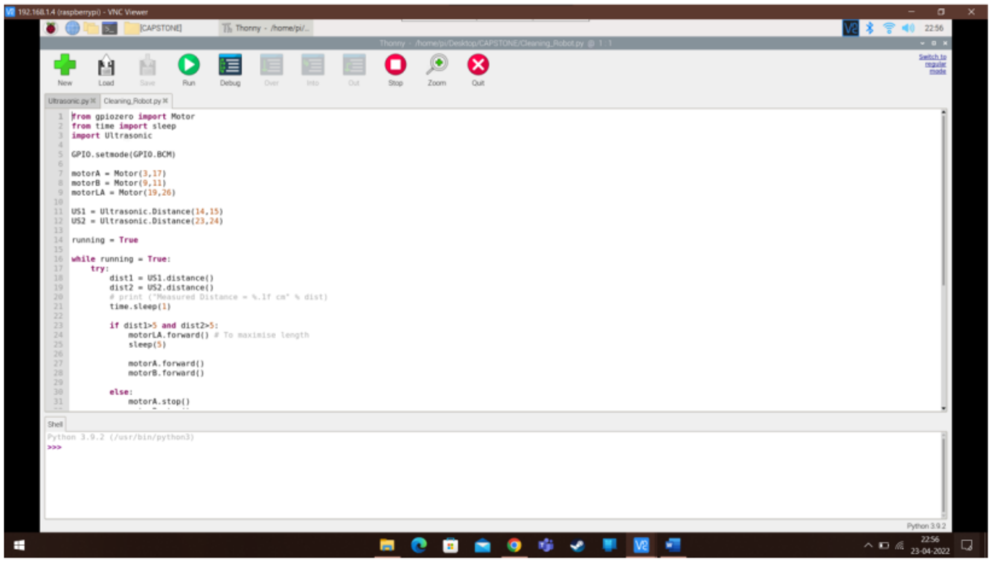


Fig. 2.11 Main Script

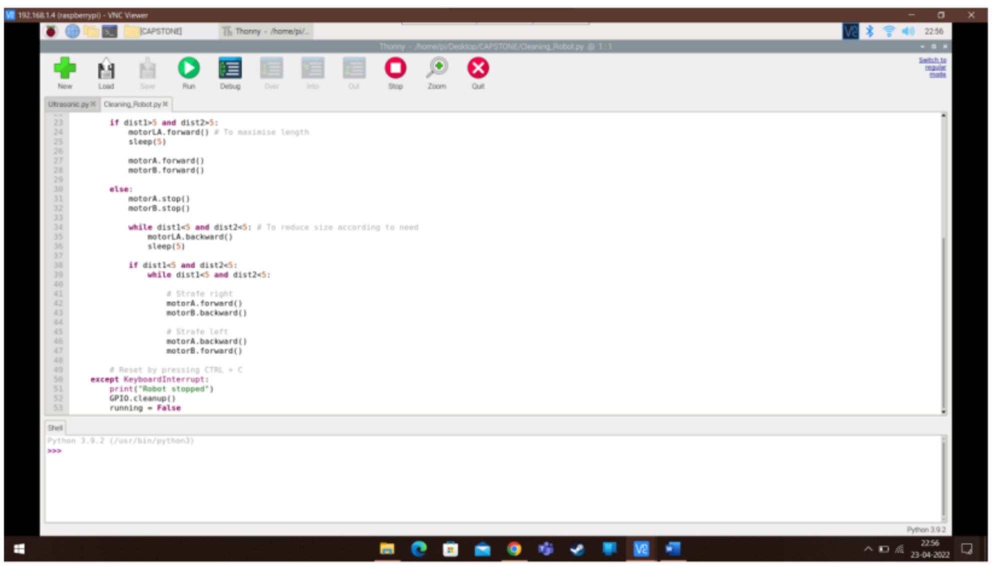


Fig. 2.12 Main Script contd.

The main script will run the robot. It will call the functions from the Ultrasonic file, and the Motor Class. It will then actuate the motors using the functions from the Motor Class, based on the inputs from the ultrasonic sensors.

2.13 DESIGN CALCULATIONS

2.13.1 Wheel Motor Torque Calculation for the 4 Mecanum Wheels:

Mass of Cleaning Robot = 9 kg
Radius of wheel = 0.03 m

$$\tau = \mu * M * g * R$$

1. Case 1 (Wooden Floor)

   Coefficient of Friction between hard rubber and wooden floor = 0.7
   Total Torque = 9*9.81*0.7*0.03 = 1.85409 Nm
   Individual Torque of each motor = 1.85409/4 = 0.4635225 Nm

2. Case 2 (Ceramic)

   Coefficient of Friction between hard rubber and ceramic tile = 0.32
   Total Torque = 9*9.81*0.32*0.03 = 0.847584 Nm
   Individual Torque of each motor = 0.847584/4 = 0.211896 Nm

3. Case 3 (Marble)

   Coefficient of Friction between hard rubber and marble tile = 0.25
   Total Torque = 9*9.81*0.25*0.03 = 0.662175 Nm
   Individual Torque of each motor = 0.662175/4 = 0.16554375 Nm

4. Case 4 (Smooth Concrete)

Coefficient of Friction between hard rubber and smooth concrete surface = 0.38

Total Torque = 9*9.81*0.38*0.03 = 1.006506 Nm

Individual Torque of each motor = 1.006506/4 = 0.2516265 Nm

5. Case 5 (Rough Concrete)

Coefficient of Friction between hard rubber and rough concrete surface = 0.62

Total Torque = 9*9.81*0.62*0.03 = 1.642194 Nm

Individual Torque of each motor = 1.642194/4 = 0.4105485 Nm

2.14 VACUUM SYSTEM CALCULATIONS

Taking D = 3 cm (1.1811 in), and L = 5 cm (1.9685 in)

Speed of pump, S_p = 49.3 CFM = 23.267 L/s

Now,

Conductance of the system,

$$C = \frac{78 * D^3}{L}$$

$$C = \frac{78 * 1.1811^3}{1.9685} = 65.2858\ L/s$$

$$\therefore C = 133.3327\ CFM$$

Therefore,

Effective pump speed, S

$$\frac{1}{S} = \frac{1}{S_P} + \frac{1}{C}$$

$$\frac{1}{S} = \frac{1}{23.267} + \frac{1}{133.3327}$$

$$\therefore \mathrm{S} = 19.81 \text{ CFM}$$

Now,

Velocity at orifice,

When robot is fully extended: A = 50 x 0.5 cm^2 = 0.0269098 ft^2

$$Q = Av$$

$$\therefore v = \frac{19.81}{0.0269098} = 736.163\ ft/min$$

$$v = \ 3.74 \text{ m/s}$$

When robot is at minimum extension: A = 30 x 0.5 cm^2 = 0.01614 ft^2

$$Q = Av$$

$$\therefore v = \frac{19.81}{0.01614} = 1227.385\ ft/min$$

$$v = 6.235 \text{ m/s}$$

2.15 BATTERY LIFE CALCULATIONS

2.15.1 Essential Components:

1. Units of Motors = 15*4 = 60 W
2. Vacuum Pump = 40 W
3. RPLIDAR A1 = 0.5 W
4. Camera = 7.5 W
5. Raspberry Pi 4 Model B = 25 W

Total Power Consumption by the essential components = 133 W

Rounded off to 135 W for ease of battery life calculations.

Battery type chosen is Lithium-ion

Battery Life = 240 Watt-Hour/135 W = 1.78 hours = 106.8 mins = 107 mins (Rounded off)

2.16 COMPONENTS

Table 2.1 List of Components

Component	Qty	Specs/Model Name	Dimensions	Weight	Price (Rs.)
LIDAR	1	RPLIDAR A1	98.5 x 70 x 60 mm	170 gm	8,549
Mecanum Wheels	4	45° in Tank Drive configuration, Load 3Kg/wheel	60 x 31 mm (Diameter x Width)	93 gm (per wheel)	5,549
Vacuum Pump	1	Nidec G10D	97 x 94 x 33 mm	180 gm	8,538
Dust box	1	With HEPA Filter	600 ml	87 gm	150
Battery pack	2	Orange 18650 Li-ion 5000mAh-6s-22.2v-3c 6S2P	160 x 100 x 50 mm (for 1)	770 gm (x2)	3,299 (x2)
Wheel Motor	4	Johnson Geared Motor (Grade B) 12 V DC	Ø 27 X 64 mm (for 1)	164 gm (x4)	384 (x4)
Motor Driver	2	L298N 2A Based Motor Driver Module	44 x 44 x 28 mm	25 gm (x2)	129 (x2)

Raspberry Pi	1	Raspberry Pi 4 Model B 4GB	85.6mm x 56.5mm	52 gm	5,149
Camera	1	Raspberry PI 5MP Camera Board Module	4 x 3 x 2 cm	10 gm	389
IMU		MPU9250 9-Axis Attitude Gyro Accelerator Magnetometer Sensor Module	25 x 15 x 3.5 mm	5 gm	749
Ball Screw Actuator	2	Linear Actuator Stroke Length 100MM,7mm/S,1500N,12V	210 x 74 x 36 mm	889 gm (x2)	3900 (x2)
DC/DC Converter	1	24V/12V to 5V 5A Power Module DC-DC XY-3606 Power Converter	63 x 27 x10 mm	22 gm	289
DC/DC Converter	1	A2412S-1WR2 Mornsun 24V to ±12V DC-DC Converter 1W Power Supply Module - Ultra Compact SIP Package	19.5 x 6 x 9.3 mm	2.4 gm	395
Ultrasonic Sensor	2	HC-SR04	5 x 4 x 3 cm	14gm (x2)	75 (x2)

1. <u>LIDAR Scanner:</u>

Fig. 2.13 RPLIDAR A1

RPLIDAR A1 has been chosen as it has been specifically designed for indoor robotic SLAM applications, and has been designed for the Raspberry Pi 4 Model B microprocessor, which is the microprocessor used in the robot.

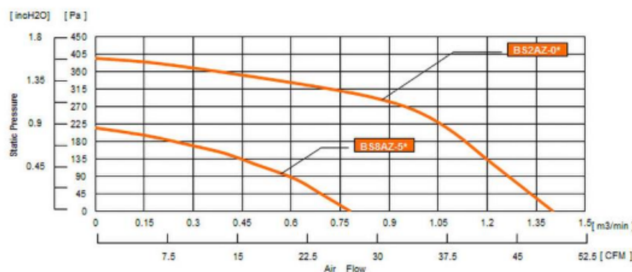
2. Mecanum Wheel:

i) Φ60 mm
ii) Load Capacity: 3Kg/Wheel
iii) Body Material: Al Alloy
iv) Length of Roller: 30 mm

Fig. 2.14 Mecanum Wheel

Mecanum wheels with 45° roller orientation have been chosen for the added manoeuvrability and degrees of freedom they provide, such as strafing and turning on the spot.

3. Vacuum Pump:



i) Model: Nidec G10D
ii) Rated speed: 5700 RPM
iii) Max. Airflow: 49.3 CFM
iv) Max. Static Pressure: 395 Pa
v) Rated Voltage: 12 V
vi) Rated Input: 38.4 W

Fig. 2.15 Vacuum Pump Characteristic

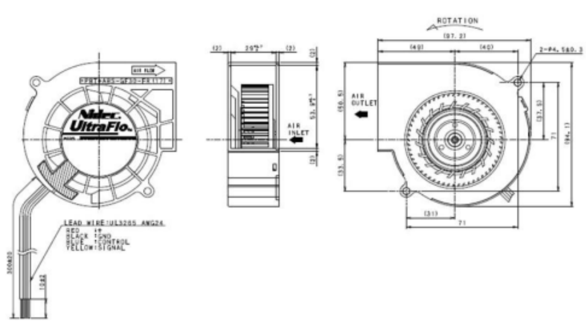


Fig. 2.16 Vacuum Pump **Fig. 2.17 Vacuum Pump Sketches**

The vacuum pump has been chosen on the basis of space available inside the robot, and the maximum discharge that it can provide, measured in CFM (Cubic Feet per Minute).

4. Battery Pack:

   i) Model: Orange 18650 Li-ion
   ii) Nominal Voltage: 22.2 V
   iii) Max. Charging Voltage: 25.2 V
   iv) Nominal Capacity: 5000 mAh
   v) Max. Discharge Current: 15 A

Fig. 2.18 Battery

A battery pack consisting of two 24V 5000 mAh batteries connected in parallel has been chosen for its excellent battery backup. Such a large battery pack is feasible because there is sufficient space inside the robot.

5. Wheel Motor:

   i) Johnson Geared Motor (Grade B)
   ii) Base Motor RPM: 18000
   iii) 500 RPM
   iv) Rated Torque: 0.1 Nm
   v) Stall Torque: 0.48 Nm
   vi) Nominal Voltage: 12 V
   vii) Operating Range: 6 – 18 V

Fig. 2.19 DC Motor

A geared DC motor with relatively high torque to meet the torque requirement as per the mathematical analysis has been chosen. Since it is a cleaning robot, high robot velocity is not a priority, hence 500 RPM is sufficient.

6. Motor Driver:

   i) Double H bridge Drive Chip: L298N 2A
   ii) Operating Voltage (VDC): 5~35
   iii) Peak Current (A): 2
   iv) Continuous Current (A): 0-36mA
   v) No. of Channels: 2
   vi) Can control up to 4 DC Motors

Fig. 2.20 Motor Driver

L298N Motor driver has been chosen since it is a very popular choice for robotics projects, and it also meets the design requirements of the robot. It can control up to 4 DC motors, has an inbuilt 5V regulator, and is very cost effective. The robot will use two of these motor drivers – one for the four-wheel motors, and one for the two ball screw actuator motors and the vacuum pump motor.

7. Raspberry Pi 4:

Raspberry Pi 4 Model B 4GB has been chosen because of the complexity of the robot and its various subsystems. A powerful microprocessor is needed to coordinate and execute all the various subsystems in real time.

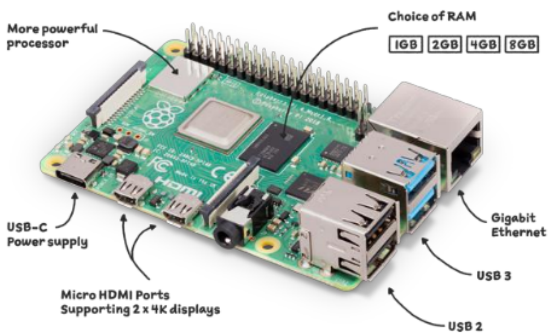


Fig. 2.21 Raspberry Pi 4

8. Camera:

i) Model: Raspberry Pi 4 Model B camera module
ii) Resolution: 5 MP
iii) Supported Video Formats: 1080p @ 30fps, 720p @ 60fps and 640x480p 60/90 video
iv) Fully compatible with Raspberry Pi 3/4

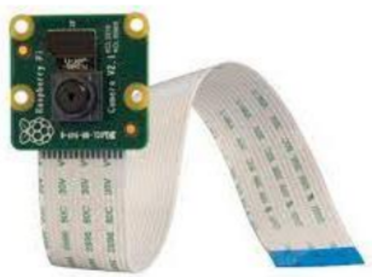


Fig. 2.22 Pi Camera

A Raspberry Pi 4 Model B camera module has been chosen because of its low cost, and compatibility and ease of integration with the Raspberry Pi 4 Model B microprocessor. A camera module is needed for object detection and to transmit a live video feed via Bluetooth/Wi-Fi.

9. IMU:

i) Model: MPU9250
ii) Accelerometer, Gyroscope & Magnetometer
iii) 9 DOF Modules
iv) Power Supply: DC3.3V-5V
v) Chip: MPU9250
vi) Gyro range: ± 250 500 1000 2000 °/s
vii) Acceleration range: ± 2 ± 4 ± 8 ± 16g
viii) Magnetic field range: ± 4800uT

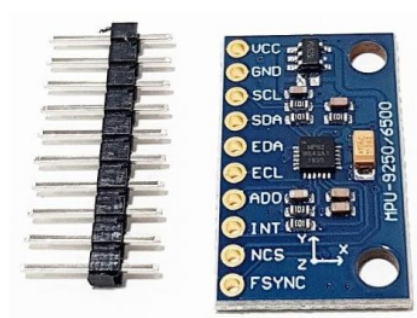


Fig. 2.23 IMU

An IMU module has been chosen to fulfil the localization needs of the robot. It has 9DOF and is cost effective.

10. Ball Screw Actuator:

Fig. 2.24 Ball Screw Actuator

i) Stroke Length: 100 mm
ii) 7 mm/s
iii) Permanent magnet DC motor drive: Voltage 12VDC
iv) Self-Locking Force: 1500N
v) Aluminium frame and extension tube
vi) Long life: A service life of more than 50000 times

Ball screw linear actuators have been chosen to facilitate the extension and retraction of the robot. The stroke length perfectly matches the project needs, frictional losses are minimal, and controlling it is relatively easy because of DC motors.

11. DC/DC Converters:

Fig. 2.25 DC/DC Converters

i) Working voltage: DC 9V–36V
ii) Output voltage: 5.2V/5A/25W

i) 24V to 12V DC -DC Converter
ii) High efficiency of up to 80%

DC/DC converters have been chosen since the robot uses a 24V battery pack. The first DC/DC converted reduces the voltage to 5V for the Raspberry Pi and the on-board sensors. The second one reduces the voltage to 12V for the ball screw actuators and the vacuum pump.

12. Ultrasonic Sensor:

i) Operating Voltage: 5V
ii) Sonar Sensing Range: 2-400 cm
iii) Max. Sensing Range: 450 cm
iv) Frequency: 40 kHz

Fig. 2.26 HC-SR04 Ultrasonic Sensor

Ultrasonic sensor has been chosen as a range sensor as they are cost effective and reliable and can be used for obstacle detection.

2.17 DESIGN PROTOTYPE (REVIEW 1)

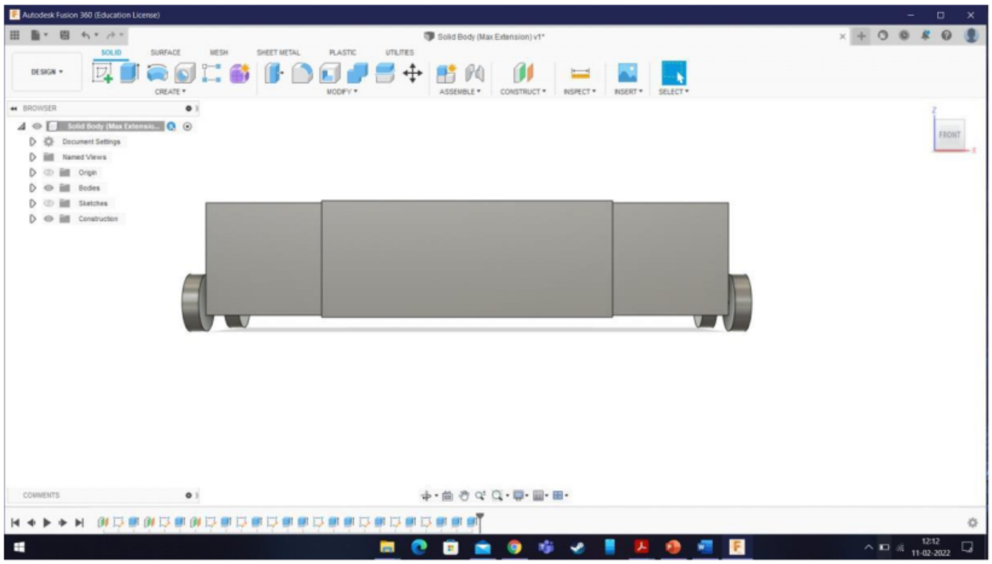


Fig. 2.27 Front View (Design Prototype)

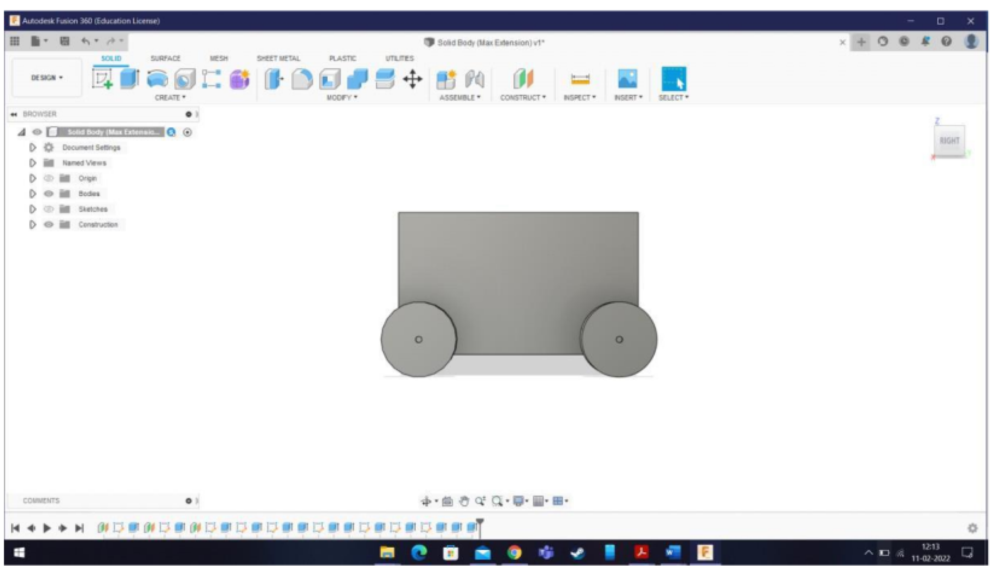


Fig. 2.28 Side View (Design Prototype)

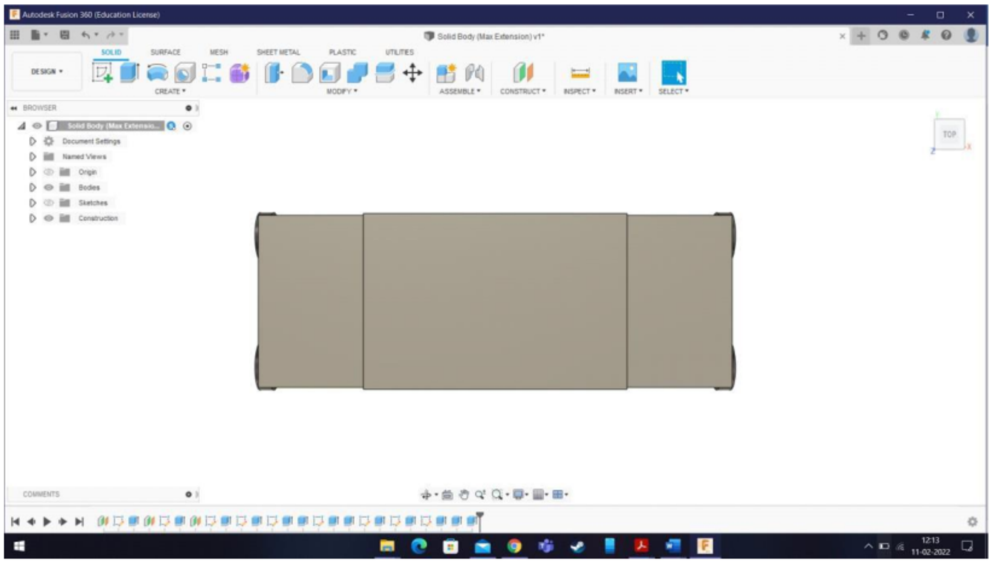


Fig. 2.29 Top View (Design Prototype)

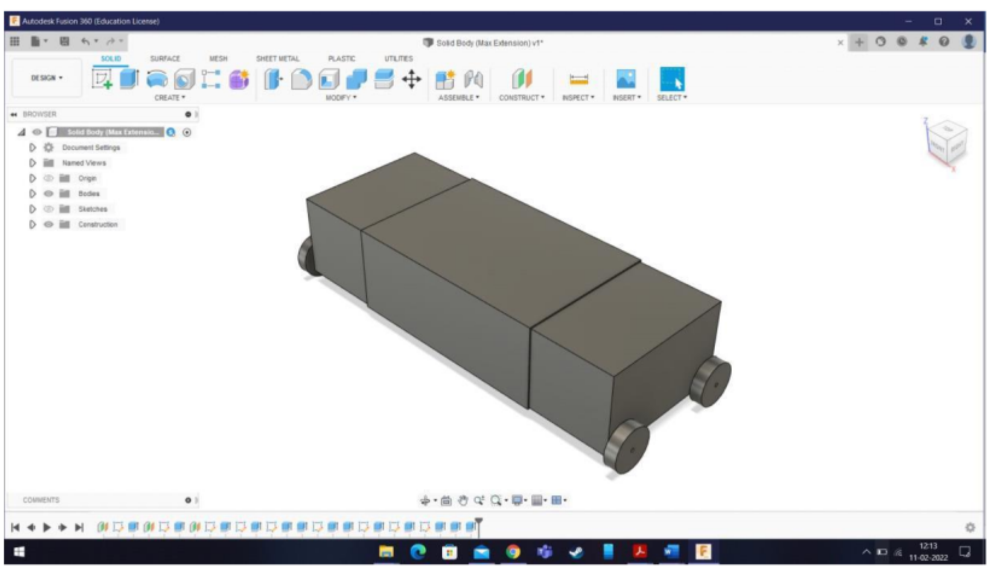


Fig. 2.30 Isometric View (Design Prototype)

2.18 CAD DESIGN

The robot comprises three hollow cuboid compartments that overlap and can linearly actuate with the help of the ball screw mechanism. The vacuum system comprises a set of rigid concentric pipes, and there will be a slit along the length of the pipe which will make the vacuum opening. The ends of these pipes will be attached to the walls of the robot on both sides. Hence, whenever the pipes will move further away from each other the slit opening will also increase making it more efficient to collect dust. These pipes will be connected to a storage compartment via a connecting pipe.

Increasing the area of the vacuum opening will reduce the suction power so to overcome this problem a motor will be inserted which will adjust the suction power based on the largest opening. For example, when the robot is fully extended it will be powerful enough to absorb dust at the largest opening and when the opening size reduces i.e., when the robot contracts, the vacuum motor voltage will automatically be reduced using a buck converter in order to maintain a constant suction pressure.

1. <u>Main Box:</u>

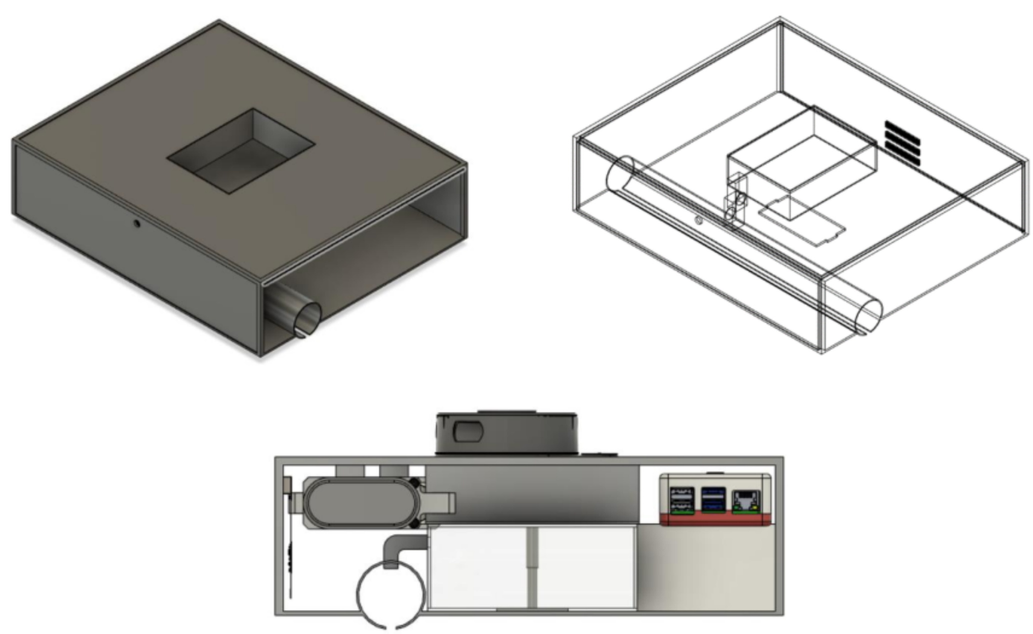


Fig. 2.31 Main Box

2. Left Box:

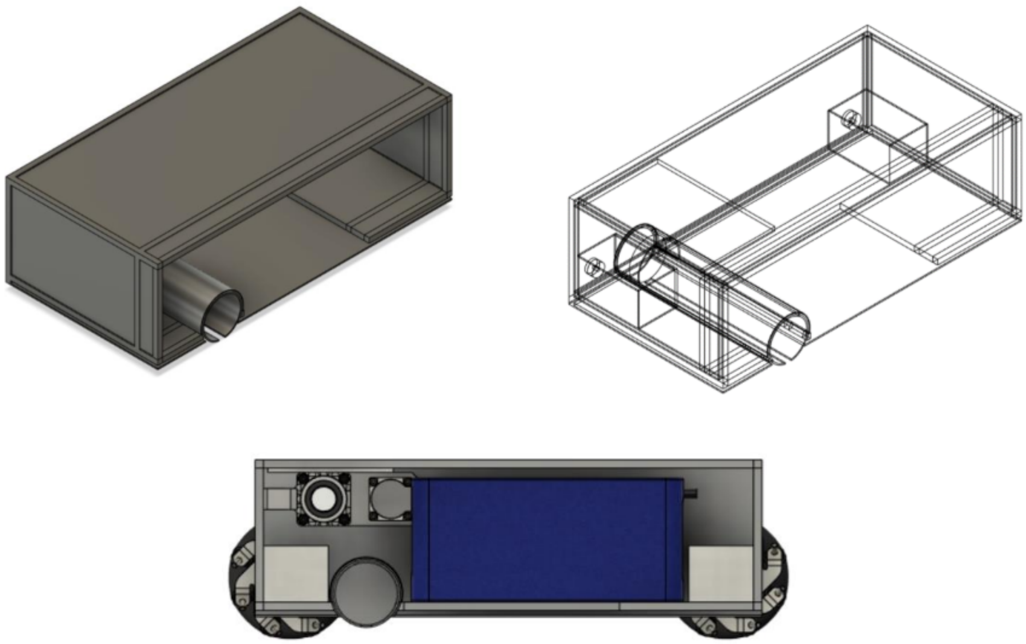
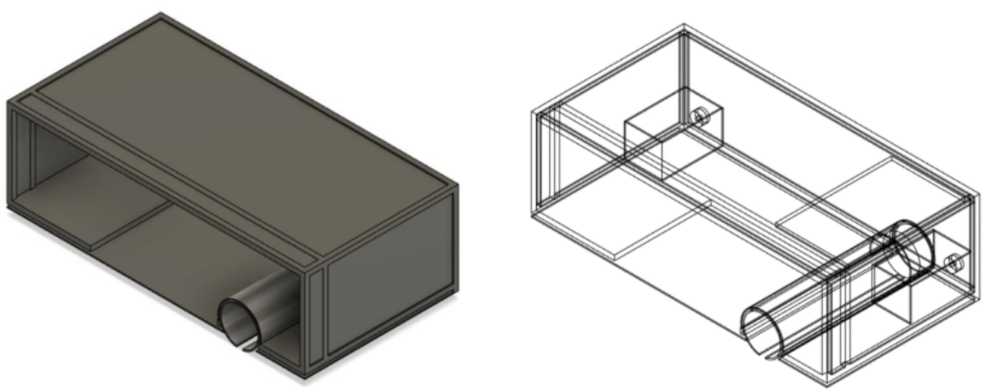


Fig. 2.32 Left Box

3. Right Box:



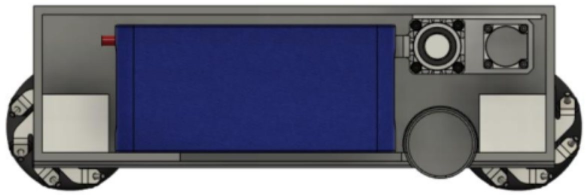


Fig. 2.33 Right Box

4. <u>LIDAR Scanner:</u>

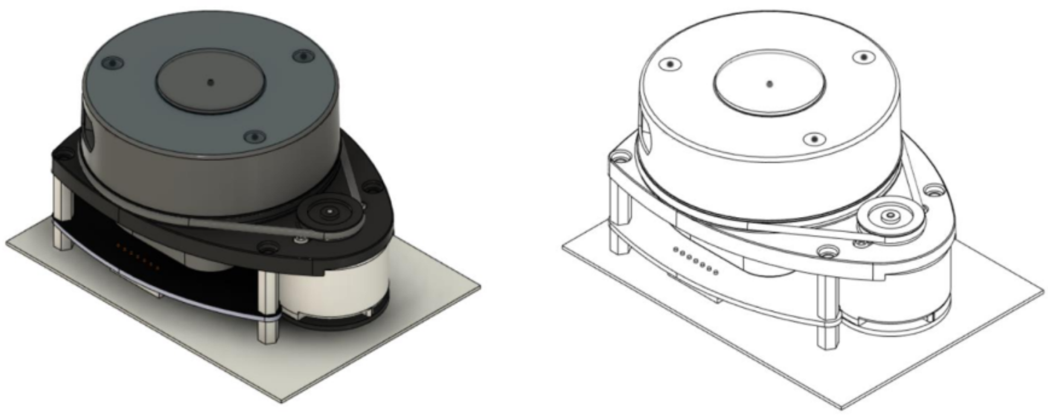


Fig. 2.34 LIDAR CAD Model

5. <u>Mecanum Wheel:</u>

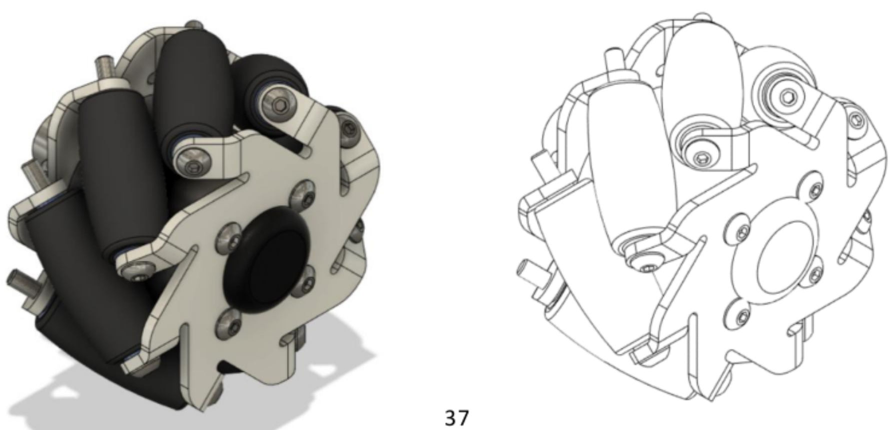


Fig. 2.35 Mecanum Wheel CAD Model

6. Vacuum Pump:

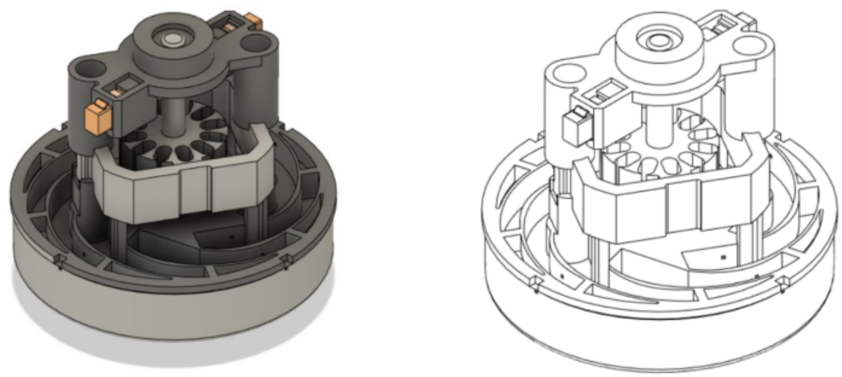


Fig. 2.36 Vacuum Pump CAD Model

7. Battery Pack:

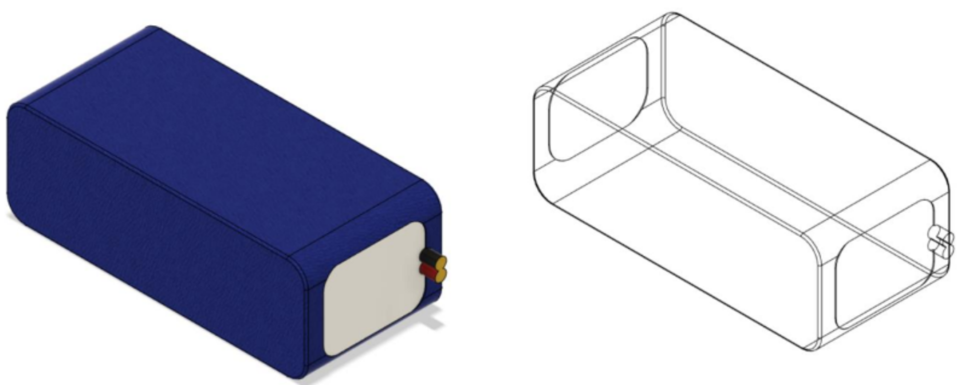


Fig. 2.37 Battery CAD Model

8. Wheel DC Motor:

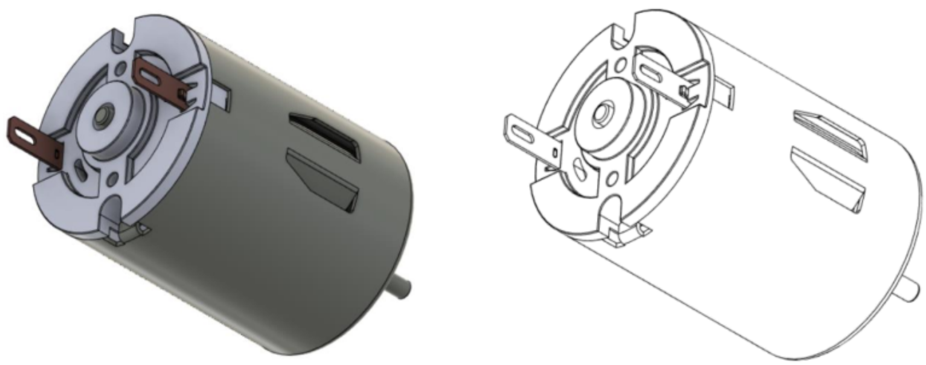


Fig. 2.38 DC Motor CAD Model

9. Raspberry Pi 4:

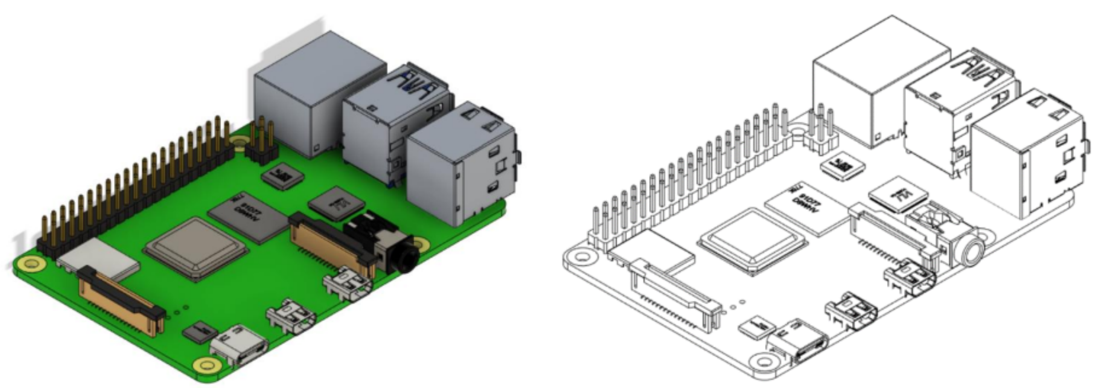


Fig. 2.39 Raspberry Pi 4 CAD Model

10) Camera

Fig. 2.40 Pi Camera CAD Model

11) <u>Ball Screw Actuator:</u>

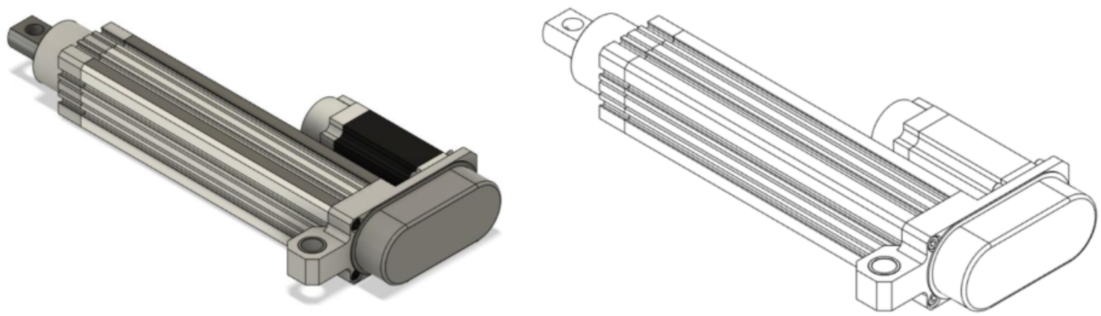


Fig. 2.41 Ball Screw Actuator CAD Model

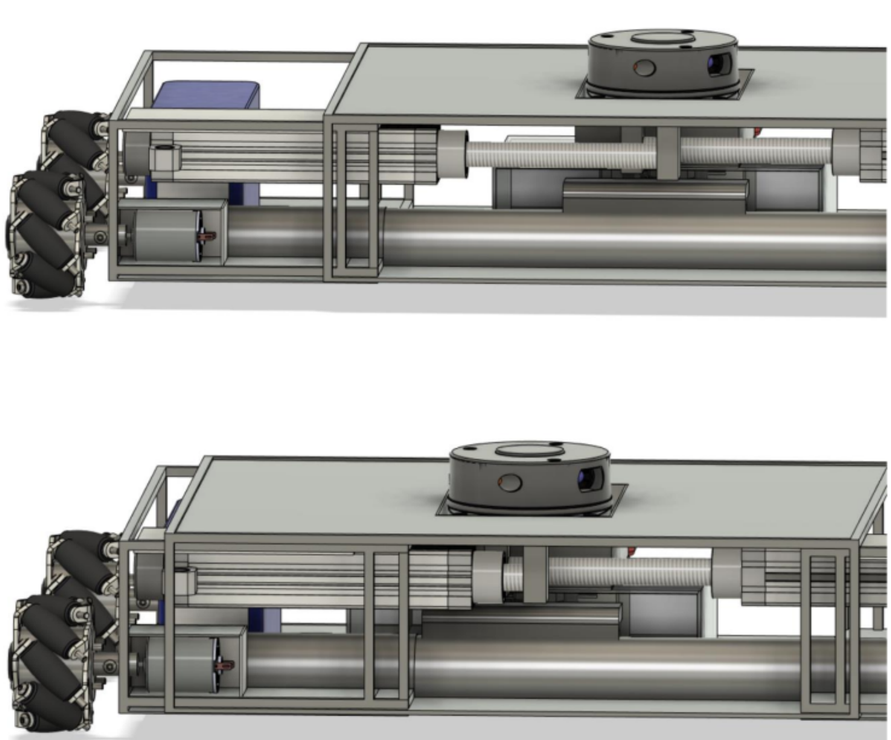


Fig. 2.42 Ball Screw Actuation Mechanism

2.19 FINAL MODEL

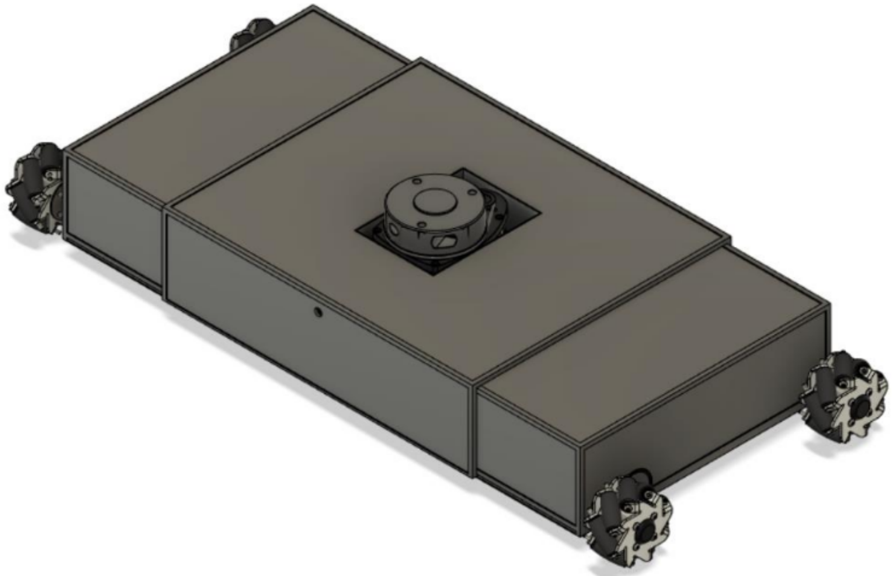


Fig. 2.43 Isometric View (CAD)

Fig. 2.44 Front View (CAD)

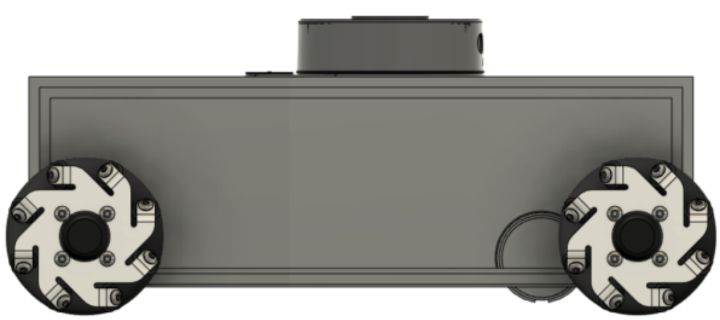


Fig. 2.45 Side View (CAD)

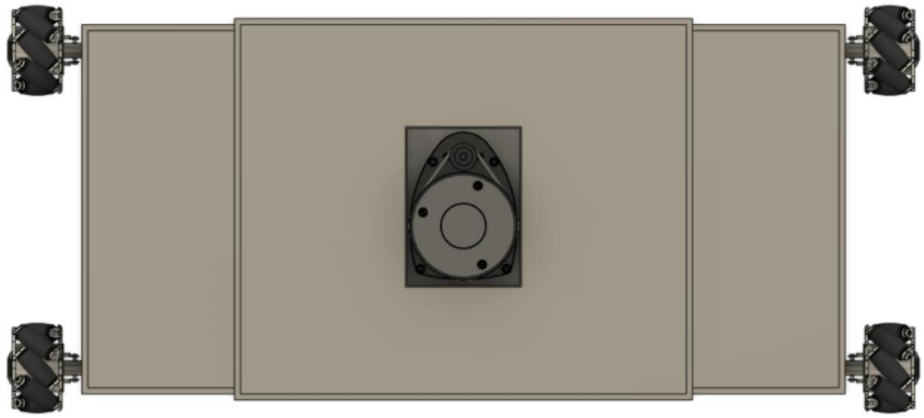


Fig. 2.46 Top View (CAD)

Fig. 2.47 Bottom View (CAD)

Fig. 2.48 Back View (CAD)

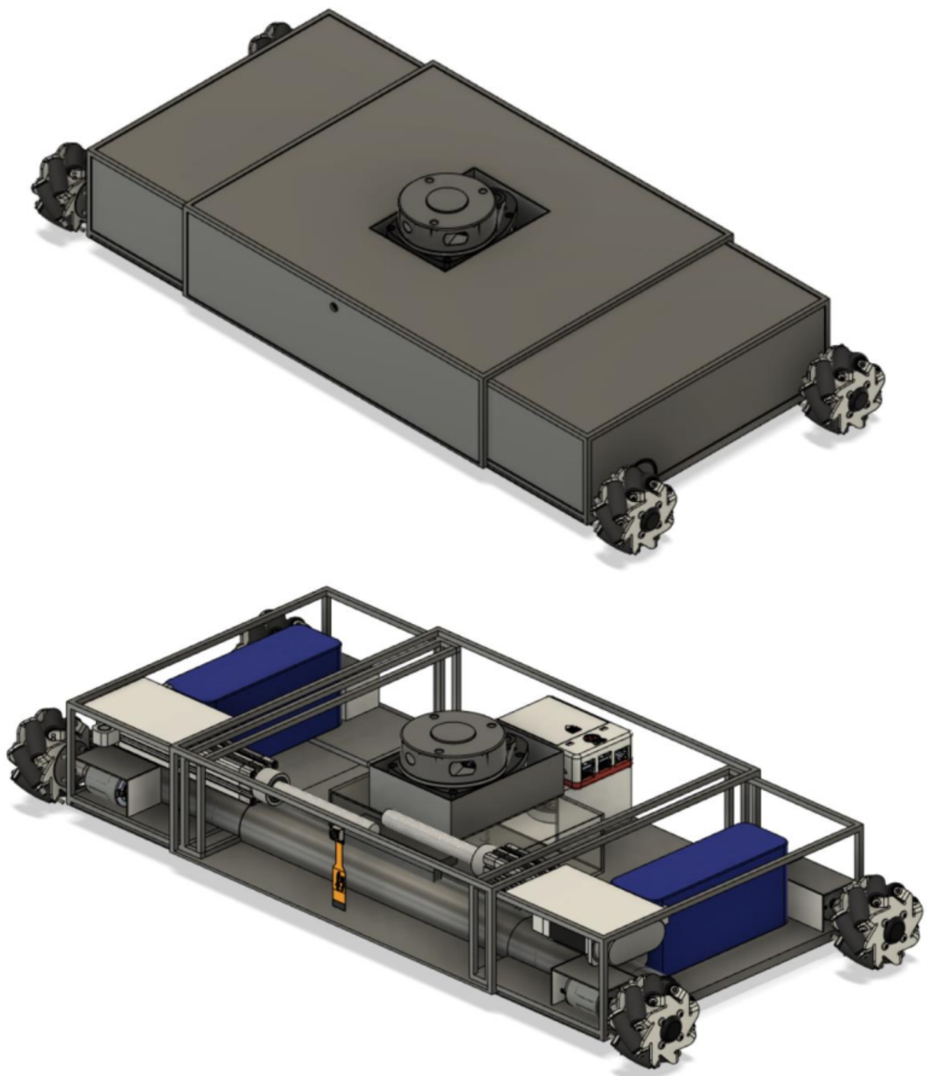


Fig. 2.49 Maximum Length (CAD)

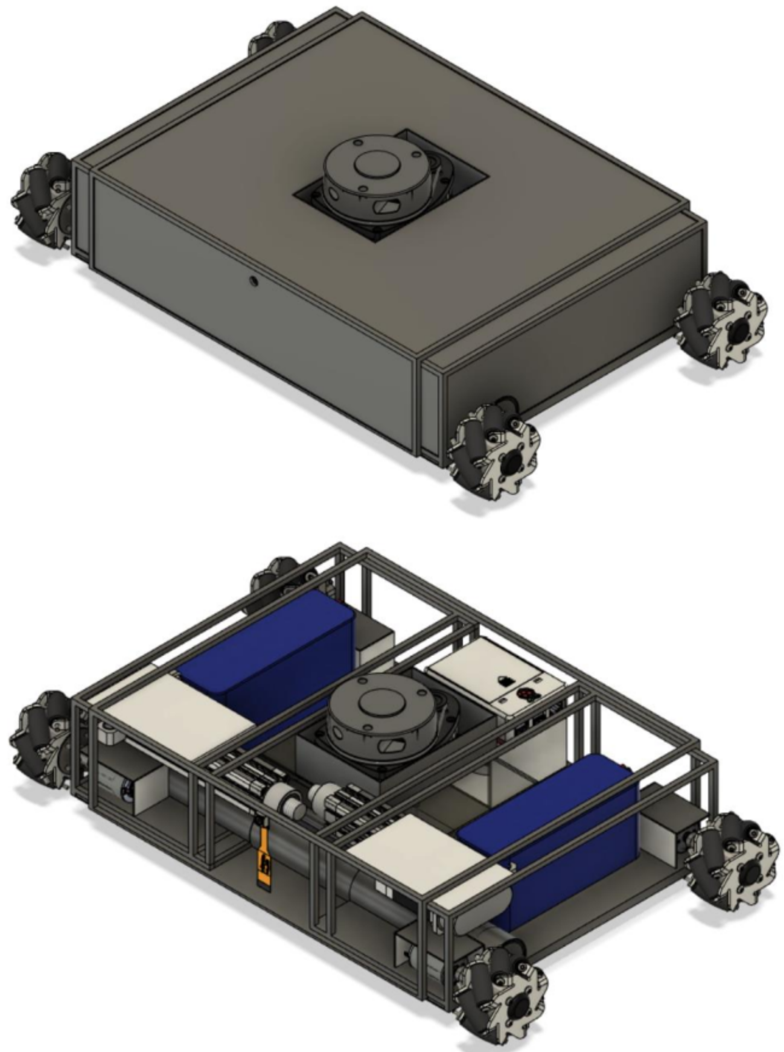


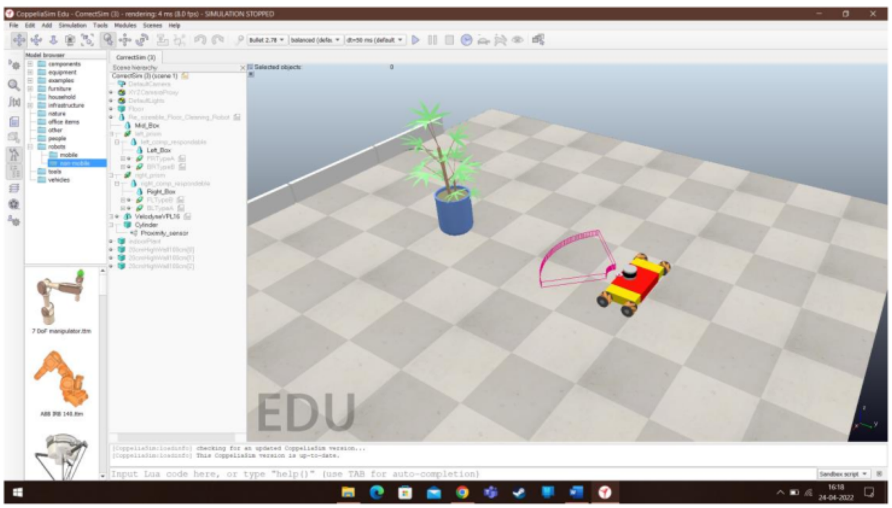
Fig. 2.50 Minimum Length (CAD)

CHAPTER 3

RESULTS AND DISCUSSION

3.1 SIMULATION

A simulation study has been created to demonstrate and analyse the efficacy and effectiveness of the system. A simplified CAD model has been developed to ensure that the simulation goes smoothly. The CAD model has further been exported as a URDF file, and then imported into the simulation software. The simulation software chosen is CoppeliaSim (V-REP) because of its simplicity and familiarity with the software. Further, the joints and links have been defined, sensors integrated, and the scene set. The robot can move and also change its size effectively.



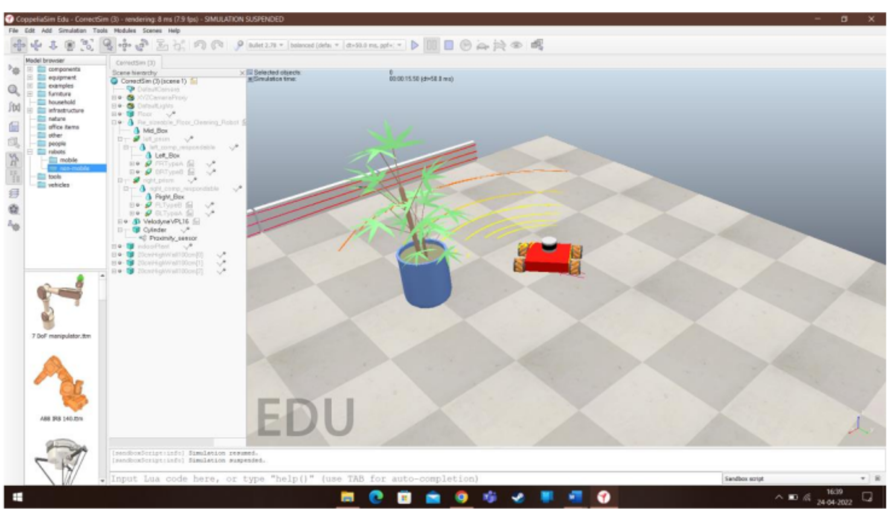


Fig. 3.1 Simulation

As demonstrated in Fig. 3.1, the robot can detect and avoid obstacles effectively.

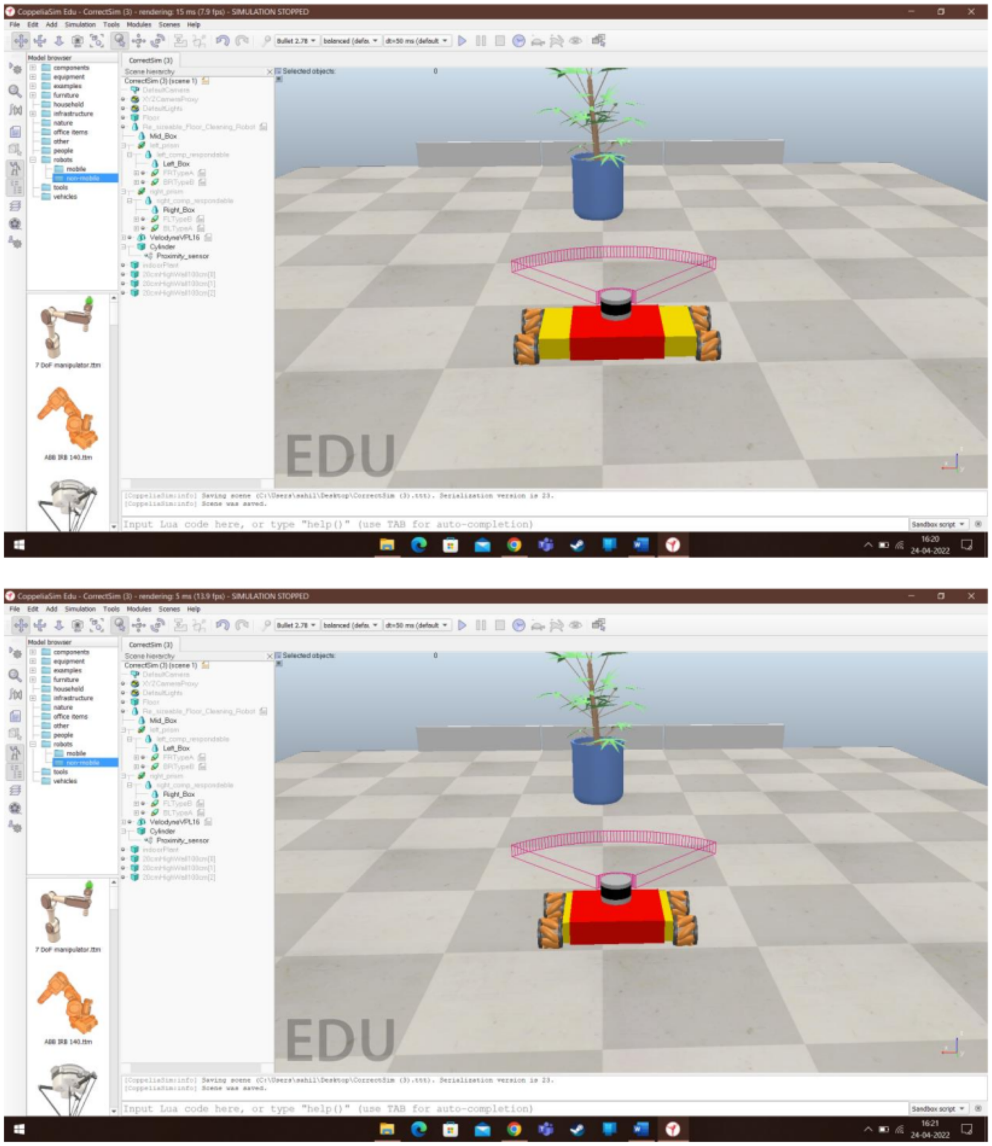


Fig. 3.2 Length Actuation (Simulation): Fully Extended (Top) and Fully Retracted (Bottom)

Fig 3.2 demonstrates the actuation mechanism that changes the size of the robot. It basically consists of two prismatic joints on either side.

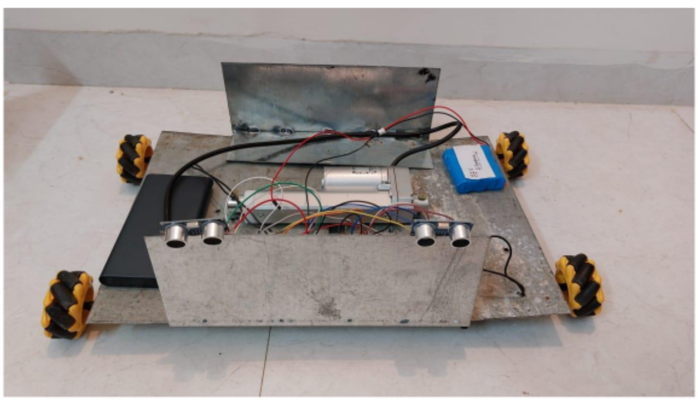
3.2 FUNCTIONAL PROTOTYPE

A functional prototype has been developed to demonstrate the performance of the system in the real world. The design was modified to simplify the model and reduce costs at the same time, ensuring that the critical components and concepts of the robot are not affected.

The chassis has been designed using Mild Steel sheets. MS sheet was chosen because of its relatively low cost, high strength and easy availability and machinability. Two ultrasonic sensors have been used for obstacle detection.

Table 3.1 Properties of MS

Properties	Values
Young's Modulus	200 GPa
Poission's ratio	0.31
Density	7750 Kg/m^3
Tensile Yield Strength	320 MPa
Tensile Ultimate Strength	400 MPa



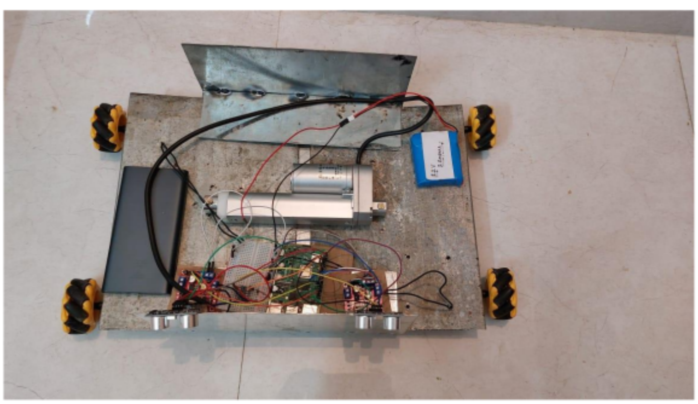


Fig. 3.3 Functional Prototype (Fully Retracted)

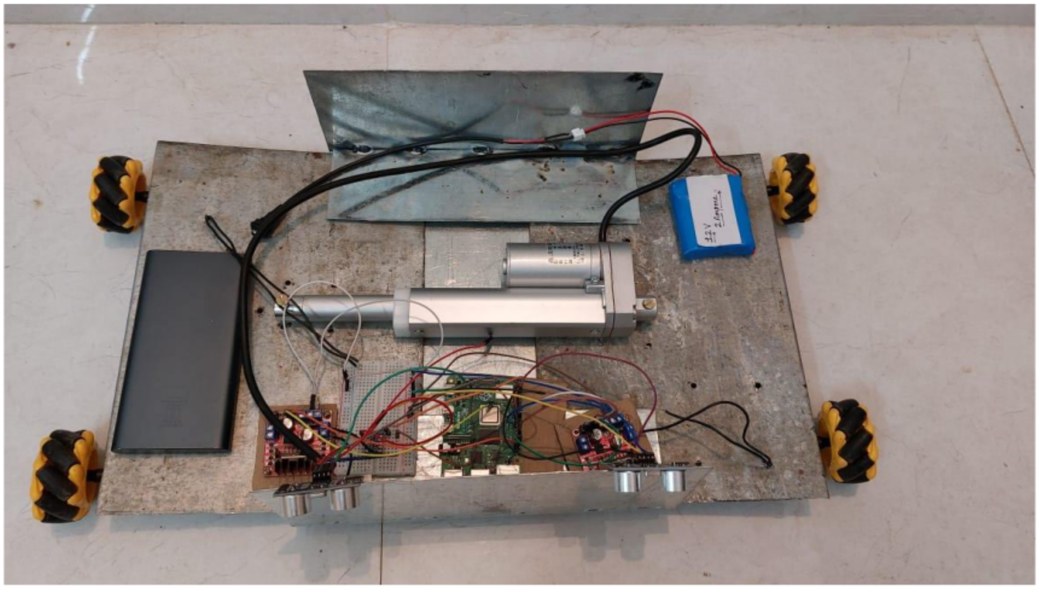


Fig. 3.4 Functional Prototype (Fully Extended)

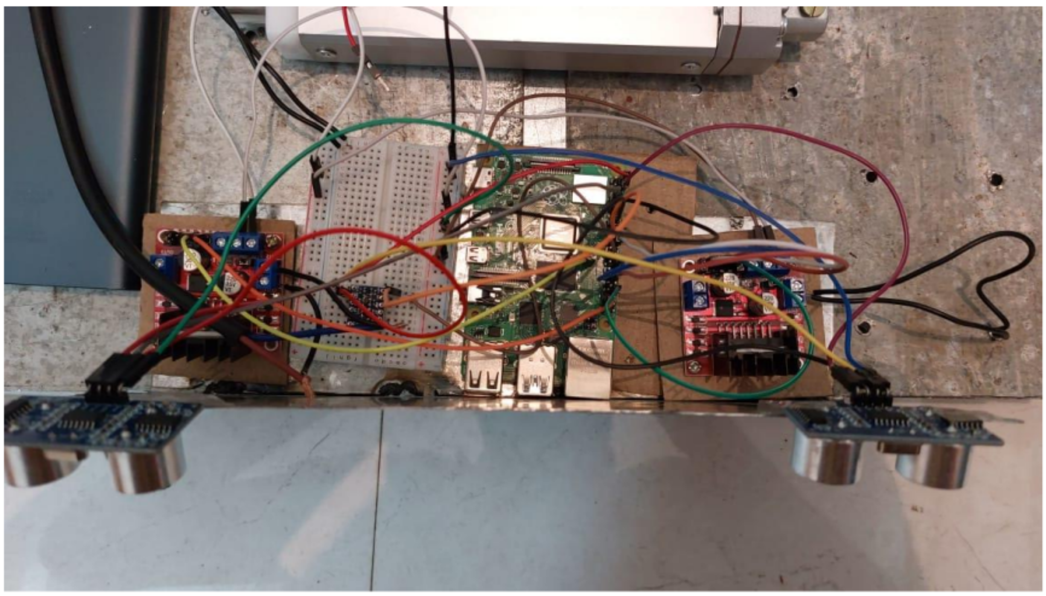


Fig. 3.5 Functional Prototype (Circuit)

The components include a linear actuator, two motor drivers, four motors and Mecanum Wheels, two Ultrasonic sensors, a Raspberry Pi 4, a bread board, a 5V battery and a 12V battery.

3.3 STRESS ANALYSIS

A static stress analysis has been conducted on the MS sheet used to make the chassis of the robot. The applied load is 20N. Two studies have been created - one when the robot is fully retracted, and another when it is fully extended.

The analysis results show that the Factor of Safety is 15, hence the chassis will not fail. The maximum displacement is 0.3745 mm, which is at the middle box chassis. Further, the maximum stress induced is 14.75 MPa.

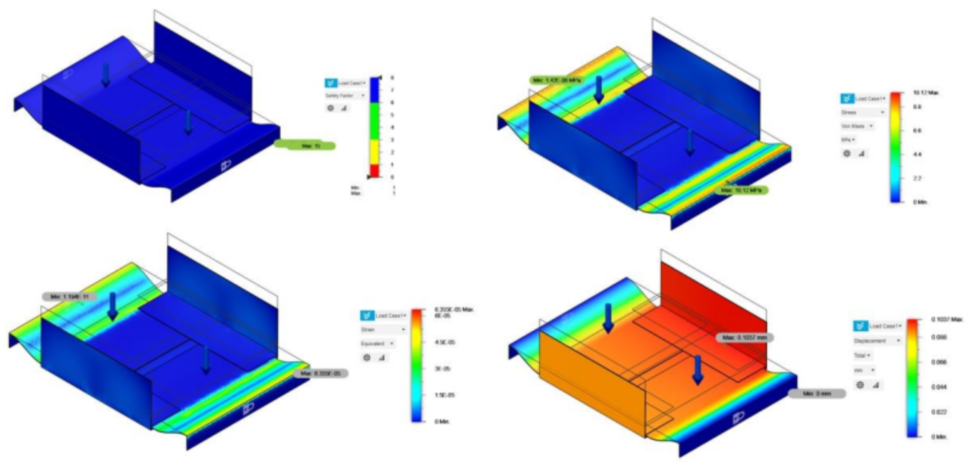


Fig. 3.6 Stress Analysis (Fully Retracted)

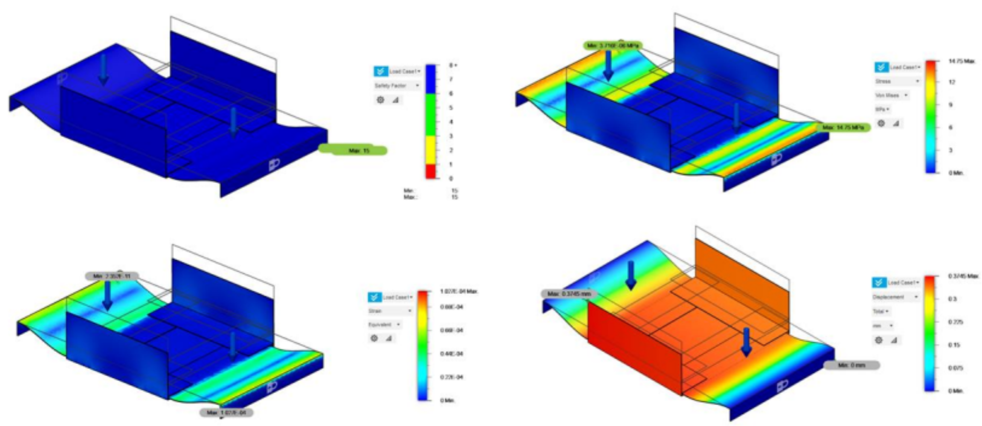


Fig. 3.7 Stress Analysis (Fully Extended)

CHAPTER 4

CONCLUSIONS

A simulation study has been demonstrated to verify the efficacy of the system. Further, a functional prototype has been developed as a proof of concept to test the system in the real world. A static stress analysis has been conducted to determine the factor of safety of the chassis, which is the main load bearing element of the robot. Since the chassis is made of MS sheet, the weight of components will introduce stresses and bending. The stress analysis as well as the model developed prove that bending and subsequent failure are not a problem. Future work will involve integrating SLAM using LIDAR, for more efficient and systematic cleaning.

A Simulation environment has extremely ideal conditions, and there are no stresses induced on the robot. However, in the real world, there are several factors such as weight of components and friction that affect the performance of the robot. As a result, several iterations were required to attain a chassis that was performing well. Earlier iterations of the functional prototype suffered from bending of the chassis and loss of traction to the wheels. Having identified the problem areas, necessary modifications were made to the chassis to ensure compliance. After several iterations, a chassis was finally developed that functioned well. Such complications are not faced in a Simulation study, hence developing a functional prototype is of utmost importance, and has its own set of challenges.

A static stress analysis has been conducted on the MS sheet used to make the chassis of the robot. The applied load is 20N. Two studies have been created - one when the robot is fully retracted, and another when it is fully extended.

The analysis results show that the Factor of Safety is 15, hence the chassis will not fail. The maximum displacement is 0.3745 mm, which is at the middle box chassis. Further, the maximum stress induced is 14.75 MPa.

After exhaustive testing and checking for the efficacy of the cleaning robot, it has been concluded that the robot is economically viable and feasible and its design flexibility make it a value for money product if properly commercialized.

re-sizeable autonomous cleaning robot

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