ELP305 Design and Systems Lab

Dept of Electrical Engineering - IIT Delhi
Report for Experiment 2
Design of a Mule Bot
Submitted by Team G on 20 May 2021
For the period 29 April - 20 May 2021

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Authors

	Name	Responsibility
Lead Coordinator	Varun Desai	Leading the team
Activity Coordinators	Ishita Chawla	Documentation
	Kashish Arora	Documentation
	Himanshu Rajput	Documentation
	Rocktim Jyoti Das	Design
	Amenreet Singh Sodhi	Design
	Achint Aggarwal	Design
	Aravind Reddy	Enclosure
	Rithvik Iruganti	Enclosure
	Arshad Warsi	Electrical and Mechanical Specifications
	Jayant Choudhary	Electrical and Mechanical Specifications
Members	T Haokip	Documentation
	Kanishk Goyal	Documentation
	Pranjal Rai	Documentation
	Kamna Meena	Documentation
	Simran Rathore	Documentation
	Jeet Bansal	Documentation
	Harman Singh	Design
	Shubham Mittal	Design
	Sourav Kumar	Design
	Satyam Bohra	Design
	Mayank Gautam	Design
	Aditi Khandelwal	Design
	Rakshit Rao	Design
	Harsh Agarwal	Design
	Paritosh Singh	Design
	Chaitnya Shrivastava	Design
	Akarsh Sharma	Design
	Somanshu Singla	Design
	Ayesha Rafi	Enclosure
	Sanjeet Yadav	Enclosure
	Saurabh Raj	Enclosure
	Sarthak Pujari	Enclosure
	Ishan Agrawal	Enclosure
	Vyomesh	Enclosure
	Vineet Singh Yadav	Enclosure
	Ayush Garg	Electrical and Mechanical Specifications
	Shaurya Raj Singh	Electrical and Mechanical Specifications
	Abdul Basit Qureshi	Electrical and Mechanical Specifications
	Dhruv Anjaria	Electrical and Mechanical Specifications

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Team Name:	G
Approved for submission:	Varun Desai (LC) / 20 May 2021 / 17:00 hours
Contact for any correction/clarification:	Ishita Chawla / chawlaishita13@gmail.com / 8375883773
Submitted to:	Prof. Subrat Kar, Instructor, ELP305 Design and Systems Lab
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1 About This Document

1.1 Text Statistics

Number of sentences	800
Number of words	3500
Percentage of complex words	17.63%
Average number of words per sentences	3.39
Average number of syllables per word	1.64

1.2 Readability Indices

We generated these indices from the onlinetool [1].

1.3 Test Result

Your page has an average grade level of about 7. It should be easily understood by 12 to 13 year olds.

Description Index	**Value**	**Typical range and explanation**
Flesch Kincaid Reading Ease	60.3	Based on a 0-100 scale. A high score means the text is easier to read. Low scores suggest the text is complicated to understand. 206.835 - 1.015 x (words/sentences) - 84.6 x (syllables/words) A value between 60 and 80 should be easy for a 12 to 15 year old to understand.
Flesch Kincaid Grade level	5.8	Grade Level indicators – These equate the readability of the text to the US schools grade level system. Flesch Kincaid Grade Level _0.39 x (words/sentences) + 11.8 x (syllables/words) - 15.59
Gunning Fog Score	5.3	0.4 x ((words/sentences) + 100 x (complexWords/words))
SMOG Index	4.9	1.0430 x sqrt(30 x complexWords/sentences) + 3.1291
Coleman Liau Index*	13.5	5.89 x (characters/words) - 0.3 x (sentences/words) - 15.8
Automated Readability Index (ARI)	4	4.71 x (characters/words) + 0.5 x (words/sentences) - 21.43

2 Requirements

2.1 Electrical Requirements

The Mule Bot should meet the following electrical requirements:

1. A rechargeable battery with life of 4-5 hours (Average time spent by a person in a mall is 2-3 hours [2]).
2. A charging time of less than 8 hours(charging time should be less than the time between subsequent uses).
3. An auxiliary battery capable of running the trolley for a short duration in the event that the main battery discharges completely.
4. A GPS/ Infrared/ Bluetooth/ Radio waves/ IMU on person or Computer Vision based mechanism for the trolley to follow the shopper. The distance from the consumer should be kept around $0.5m$ (maximum $2m$).
5. A manual control override switch in case the trolley goes out of control.
6. An alarm system to address issues like low battery, the bot getting stuck, theft or lock on the lid of the basket which opens with some password/ fingerprint/ face recognition or speech recognition system.
7. It should have a sleep mode, which conserves battery during long periods of inactivity.

2.2 Mechanical Requirements

The Mule Bot should meet the following mechanical requirements:

1. It should not have sharp edges for user's safety.
2. It should be able to lift 40KG (+12KG tolerance) weight (as per the problem statement).
3. The size of the bot is close to that of a shopping cart. Dimensions: $400 \times 500 \times 400m^3$.
4. The base of the bot should be rectangular-shaped with four mecanum wheels and it should be able to travel in any direction.
5. It should be able to rotate, drag, move front, back and side-wise.
6. For better user experience it should be shockproof and should not make much noise.
7. An alternative mechanical mechanism to move it in case of electrical failure.
8. Braking mechanism to stop the bot.
9. Centre of gravity towards the lower side to prevent toppling while moving on elevated path like ramps.
10. It should have good suspension for steadiness and robustness.
11. For better maintenance it should be easily cleanable.
12. Bot's maximum speed: 7 km/hr (average walking speed of an adult man is 4-6 km/hr [3]).

2.3 Functional Requirements

The bot should meet the following usage requirements:

1. It should not follow the shopper into clustered spaces.
2. It should adjust its position and distance according to the surroundings (obstacles, other people and other mule bots etc.).
3. It can be tracked through a smartphone.
4. The bot should not always be 0.5m from the shopper, i.e. it should be able to figure out when the shopper is coming to fill the trolley.

5. A follow on/ off feature when going into small/ big shops.
6. Phone/ watch/ ring that can remotely control the bot.
7. A setting which allows user to customize minimum distance.
8. It should be able to find its way back to the user (i.e., should not lose the user at turns).

3 Design Mockup

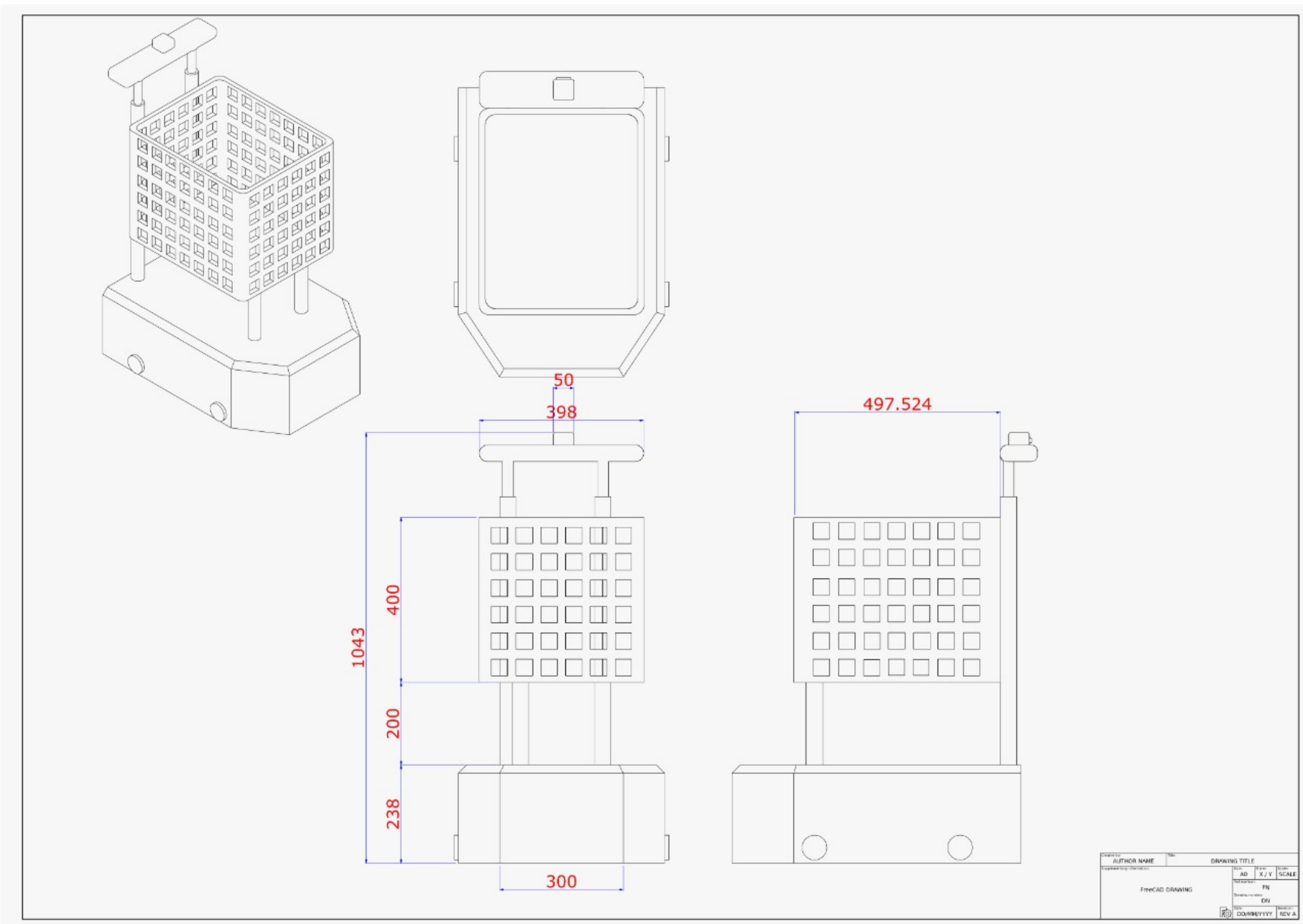


Figure 1: Mockup

4 Hardware Level Specification and Description

4.1 Body

4.1.1 Trolly Dimensions

The dimensions of the trolley are to be $800 \times 485 \times 975$mm. The mockup model shown in the Figure 1 is effectively a cuboid having a length of $800mm$, a breadth of $485mm$ and a height of $975mm$.

Diameter	$152mm$ (6 inch)
Width	89
Rollers	8
Plates	2
Body material	Stainless Steel
Roller material	Rubber
Spacer material	Aluminium
Length of roller	$77mm$
Net weight	$2.3kg$
Load capacity	$50kg$

Table 1: Mecnaum wheel specifications

4.1.2 4 Wheel Mecnum Design

This (6 inch) 152mm Stainless Steel Mecanum wheel right should work with other 3 Mecanum wheels. Each wheel is comprised of 8 rollers,these rollers have an axis of rotation at 45° to the plat of the wheel in a plane parallel to the axis of rotation of the wheel. The wheel is a heavy duty wheel itself, they are sold in assembled units with two thick stainless steel plates. The rollers are made of black rubber. The stainless steel body mecanum wheels of load capacity is higher than aluminum mecanum wheel.The technical details [4] are as follows:

4.1.3 Motor

The technical details of the motor [5] are as follows:

Speed(RPM)	Ratio 1-14
Voltage(V)	6-24 (DC)
Diameter	36mm
Model	36GP-555 permanent magnet planetary encoder gear motor
Size	36*114mm (excluding shaft and terminal block)
Axis length	20 mm one-way shaft
Shaft diameter	8mm D-shaped shaft double ball bearing positioning structure
Wiring specification	PH2.0-6PIN terminal connector
Encoder specifications	AB dual-phase encoder 11 line basic signal voltage 3.3V or 5.0V
Commutation	Brush
Type	Gear Motor
Protect Feature	Drip-proof
Output Power	30W
Construction	Permanent Magnet

Table 2: Motor specifications

4.1.4 Suspension

The suspension is important when the mule bot is under heavy loads. The suspension provides smooth movements and shock absorption. Stainless steel suspension springs with a mass of 300 g are to be employed in the mule bot. Similar, suspension springs can be found here [13].

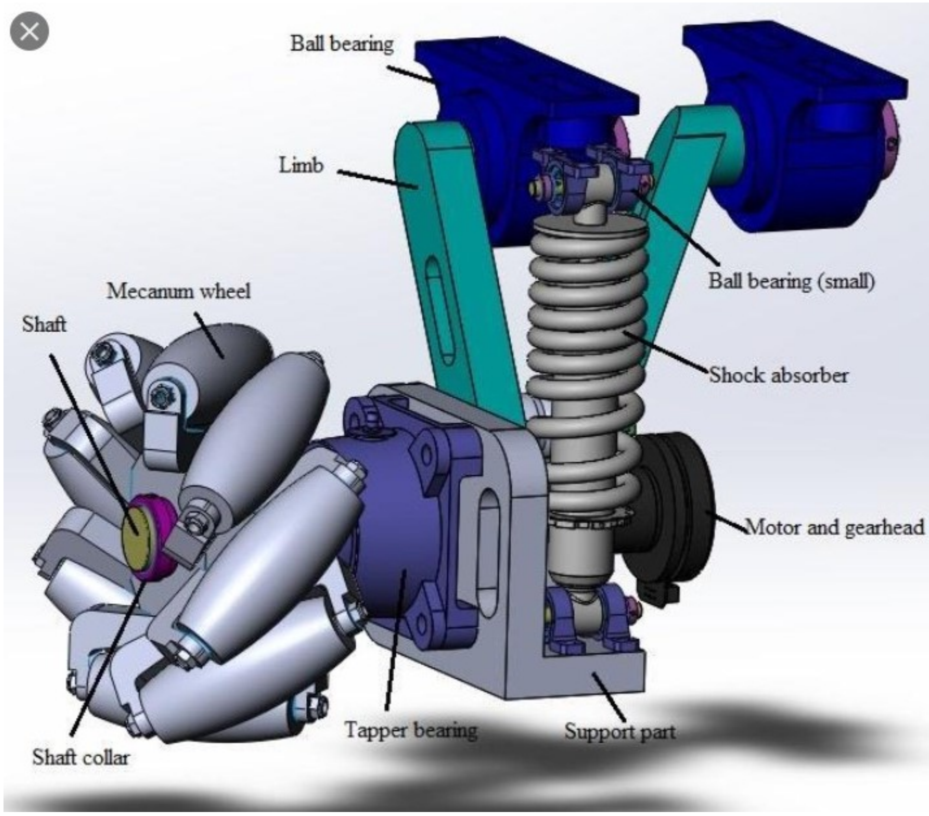


Figure 2: Wheel and Suspension

4.1.5 Aluminium alloy Chassis

We will use Aluminium alloy chassis due to its high strength and light weight.

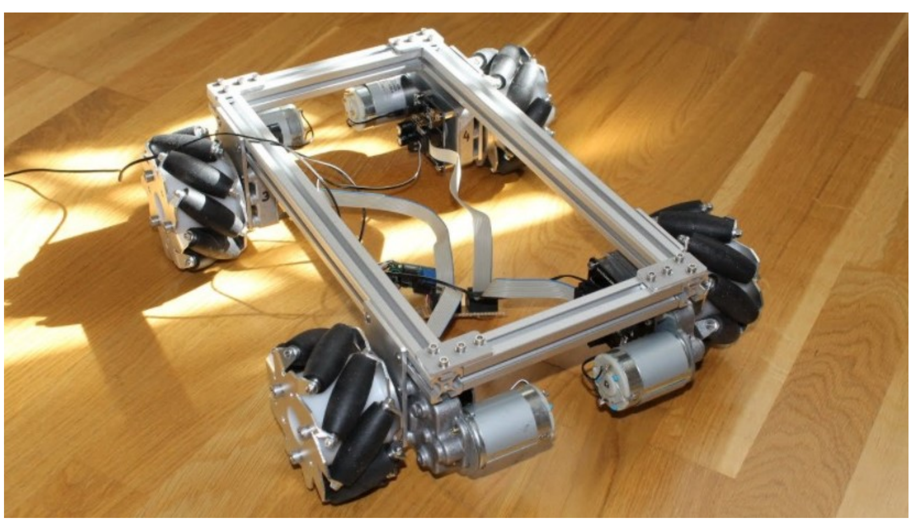


Figure 3: Chassis[26]

4.2 Control System

4.2.1 Raspberry Pi

This is the CPU of the system. All the computation will take place here so it need to have high performance speed and sufficient memory, so we chose Raspberry Pi 4 Model B+. It receives all sensor input processed using AI algorithm and control inputs are generated and send to the motor control driver board. This has high-performance quad-core 64-bit Broadcom 2711, cortex A72 processor, dual-display support at resolutions up to 4K via a pair of micro-HDMI ports which supports hardware video decode at up to 4Kp60, 4GB of RAM, dual-band 2.4/5.0 GHz WLAN. The technical details [6] are as follows:

Brand	Raspberry Pi
Series	Pi 4 Model B, 4 GB
Colour	Green
Item Height	10 cm
Item Width	15 cm
Product Dimensions(cm) LxWxH	20 x 15 x 10
RAM Size	4 GB
Maximum Memory Supported	4 GB
Connectivity Type	Wi-Fi
Operating System	Windows 10
Item Weight	80 g

Table 3: Raspberry Pi specifications

4.2.2 Motor Driver Board

This L293D [21] driver module is a medium power motor driver perfect for driving DC Motors and Stepper Motors. It uses the popular L293D motor driver IC. It can drive 4 DC motors in one direction, or drive 2 DC motors in both the directions. Features of L293D Motor Driver Board:-

- L293D motor driver IC.
- Male burg stick connectors for supply, ground and input connection
- Screw terminal connectors for easy motor connection
- On Board LM7805 Voltage Regulator

4.2.3 Speed Control

An Raspberry Pi appendable, IRF520 MOSFET Driver Module is to be employed for the speed control of the motors. The technical details [7] of the MOSFET based drive are as follows:

Voltage	3-5V
Ports	Digital
Output Load Voltage	0-24 V
Output Current Load	$<$ 5A (1A needed for the heat sink)
Platform	Raspberry Pi 4
MOSFET	IRF520 Power MOS

Table 4: Speed control drive specifications

4.2.4 Charging module

The IMAX B6 80W 6A Charger/Discharger 1-6 Cells is a very advanced charger, able to charge, balance and discharges LiIon, LiPoly, LiFe (A123), NiCd and NiMH batteries. It is microprocessor controlled just like all the best chargers and will balance the individual cells in you Li-XX batteries. The technical specifications [12] are as follows:

DC Input Voltage Range (V)	11-18
Output Power (W)	80 (max)
Charge Current Range (A)	0.1-6
Maximum Discharge Power (W)	5
Discharge Current Range (A)	0.1-1.0
Dimensions(mm) LxWxH	133x87x33
Weight(g)	277

Table 5: Charging module specifications

4.2.5 Gyroscope

The gyroscope chosen for the mule bot are the Murata SCC1300-D02. The technical specifications [11] of this gyroscope are as follows:

Output Type	SPI
Supply Voltage	3.3 and 5.0 V
Axis	3 / 1(X)
Mass	1.17g
Maximum Range	+/-2g,+/-100dps
Sensitivity	1800 LSB/g,50 LSB/dps
Offset Temp. Characteristics	+/-18mg,+/-0.6dps
Amplitude Response	30...55Hz,50Hz

Table 6: Gyroscope specifications

4.3 Sensors

4.3.1 Weight sensor

A generic FZ0728 HX711 weighing sensor [8], which converts mechanical force to electric signals which are then converted and displayed as digital bits.

Model	HX711
Weight(gm)	400

Table 7: Weight sensor specifications

4.3.2 Scanning sensors

RPLiDAR A2M7 360 Degree 16M Range Laser Scanner Kit has a core that runs clockwise to perform a 360 degree laser range scanning for its surrounding environment and then generates an outline map for the environment.

Range radius(m)	16
Thickness(cm)	4(ultra thin)
Sample rate	8000 times per second
Item Dimensions(cm) LxWxH	17.5 x 8.9 x 7.1
Item Weight(gm)	386

Table 8: Scanning sensor specifications

4.3.3 RGBD Sensors

In addition to having a regular RGB camera, RGDB sensors are equipped with an IR sensor to provide information on depth. This enables it to determine both the position and distance of the person accurately.

4.3.4 Indoor real time locating system via Ultra-Wideband [14]

Ultra-Wideband has in comparison to WiFi and bluetooth a very high accuracy, which goes down to 10cm. It also has a very high range and can therefore be used well for industrial applications where exact positioning is required. Ultra-Wideband is a type of short-range radio communication that can be used for indoor localization. In contrast to Bluetooth Low Energy and WLAN, the position determination is not based on the measurement of signal strengths, but on a transit time method (Time of Flight, ToF). The time of flight is measured between a tag and several anchors. For the exact localization of an object at least 3 receivers are necessary (trilateration).

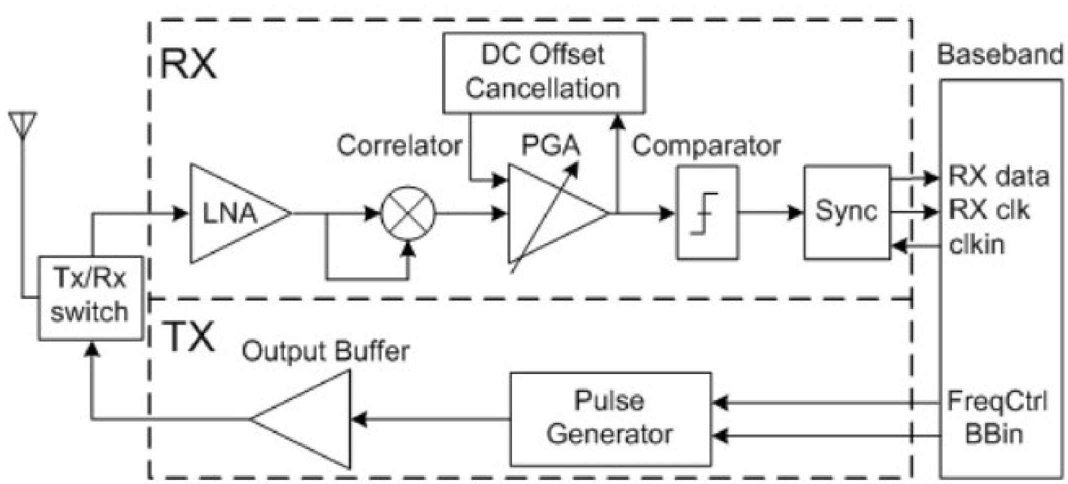


Figure 4: UWB Circuit Diagram

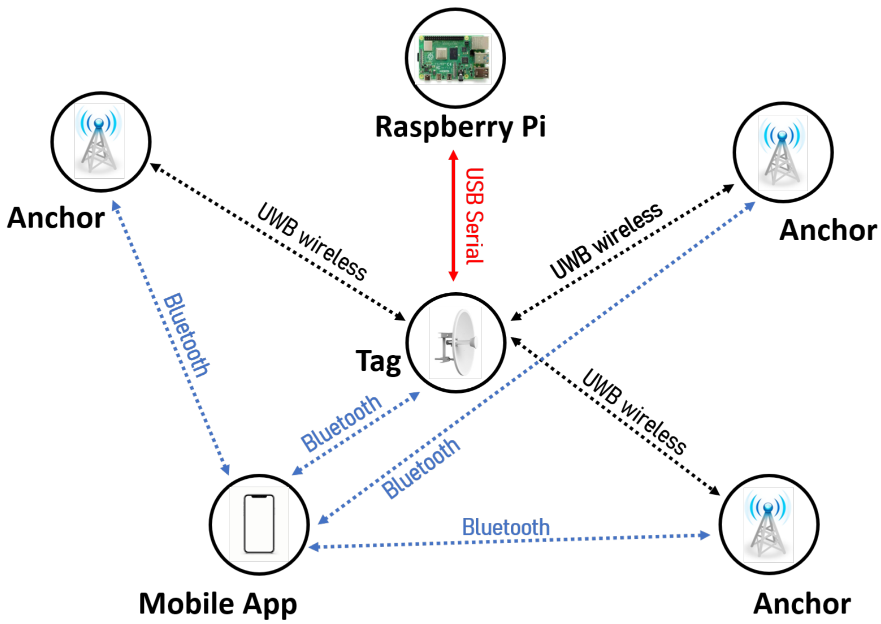


Figure 5: UWB Sensors and Raspberry

4.3.5 Infrared Sensors

An infrared sensor is an electronic device, that emits in order to sense some aspects of the surroundings. An IR sensor can measure the heat of an object as well as detects the motion. These types of sensors measure only infrared radiation, rather than emitting it that is called a passive IR sensor. Usually, in the infrared spectrum, all the objects radiate some form of thermal radiation. When a moving object that generates infrared radiation enters the sensing range of the detector, the difference in IR levels between the two pyroelectric elements is measured.

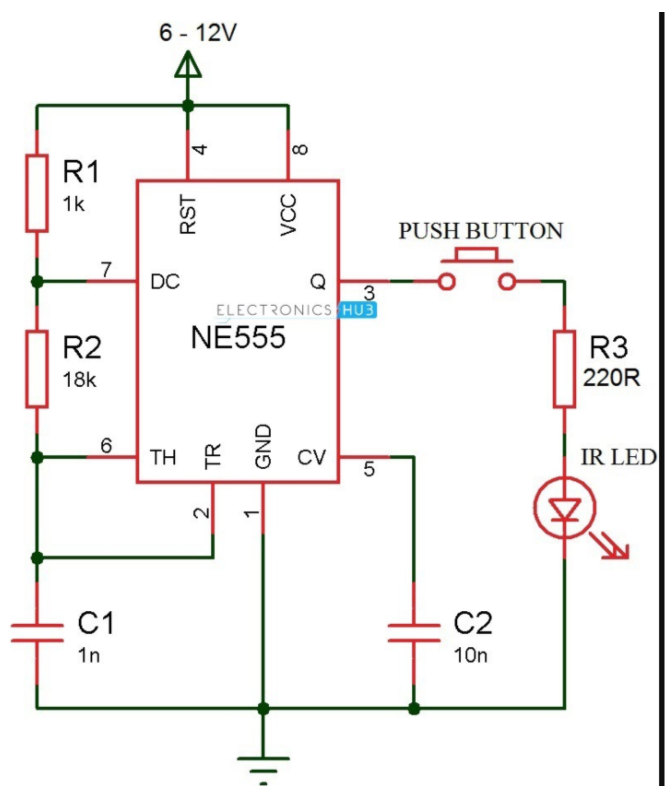


Figure 6: IR Sensor Circuit Diagram - 1

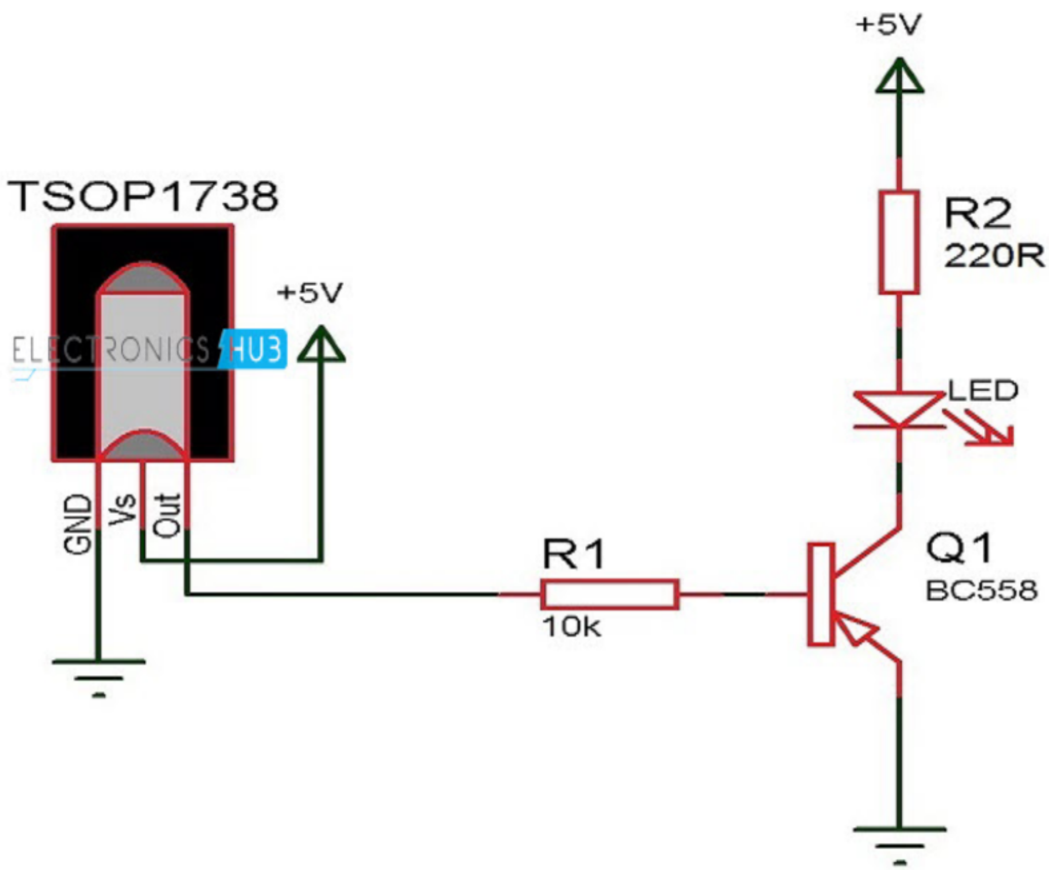


Figure 7: IR Sensor Circuit Diagram - 2

4.4 Power Supply System

It consists of the following components:

4.4.1 BMS

A 24V, 7S, 45A 18650 Li-ion Li-polymer Battery BMS PCB PCM Battery Protection Board is to be employed with the following specifications [9] :

Dimension	$24 \times 62 \times 9mm$
Charging Voltage range	$28.8V - 30V$
Maximal continuous discharging current(upper limit)	60A
Dimensions	2

Table 9: BMS specifications

4.4.2 Single cell

The single cells used are the 18650 3.7V 2600 MAH LI-ION CELL. These cells provide a 3.7V DC output and have a charge holding capacity of 2600 MAH.

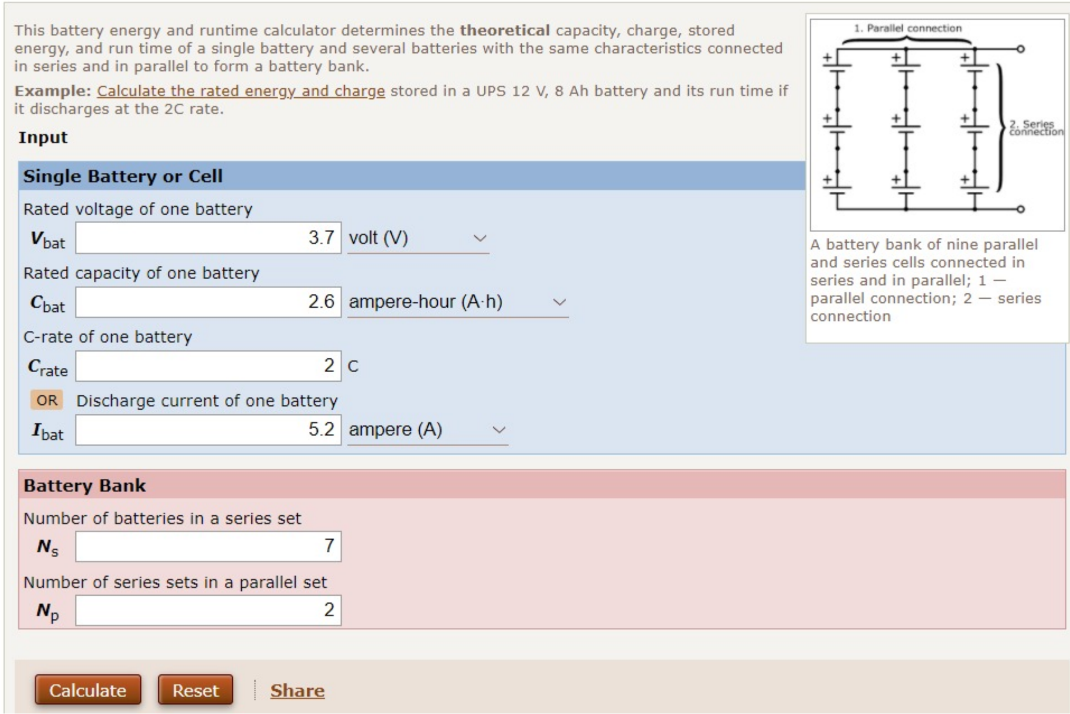


Figure 8: Battery Specifications

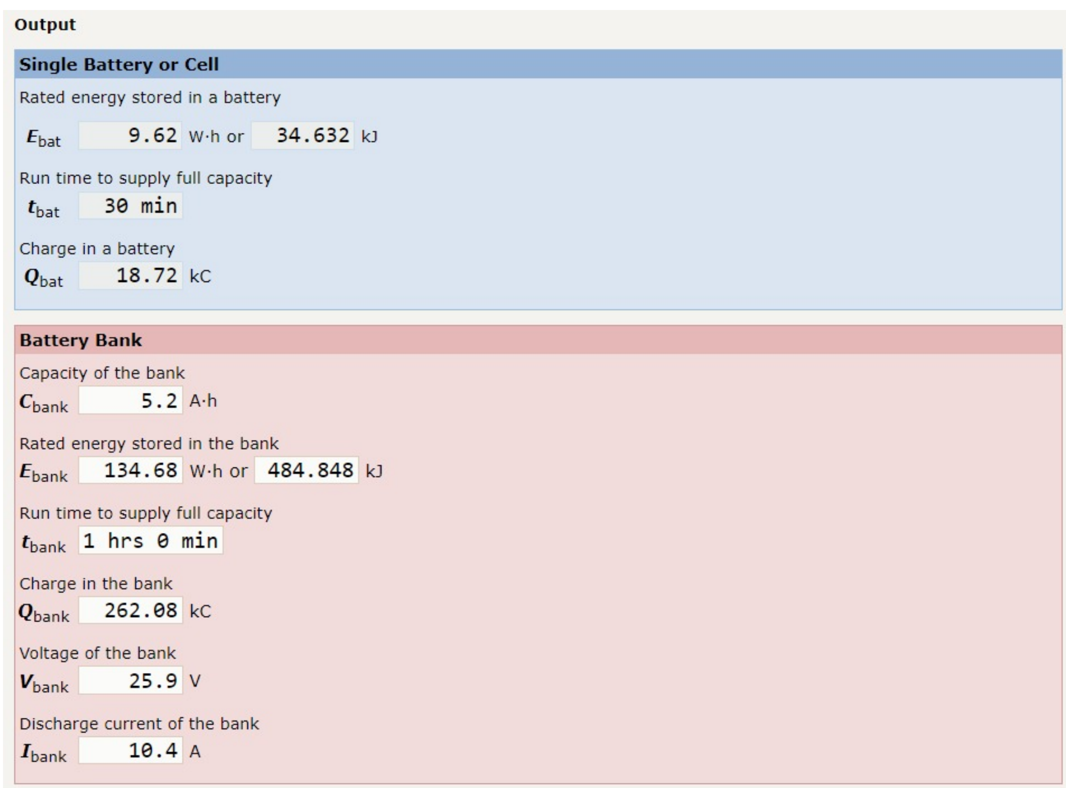


Figure 9: Battery Specifications

4.4.3 Voltage Regulator

Voltage Regulator LM317T [27] of max input voltage $40V$ and max output voltage as $1.2 - 37V$. The technical details are as follows:

Brand	STMicroelectronics
Max Operating Temperature	125 ° C
Product Dimensions(mm) LxWxH	$10.4 \times 4.6 \times 9.15$
Max Output Current	1.5A

Table 10: Voltage Regulator specifications

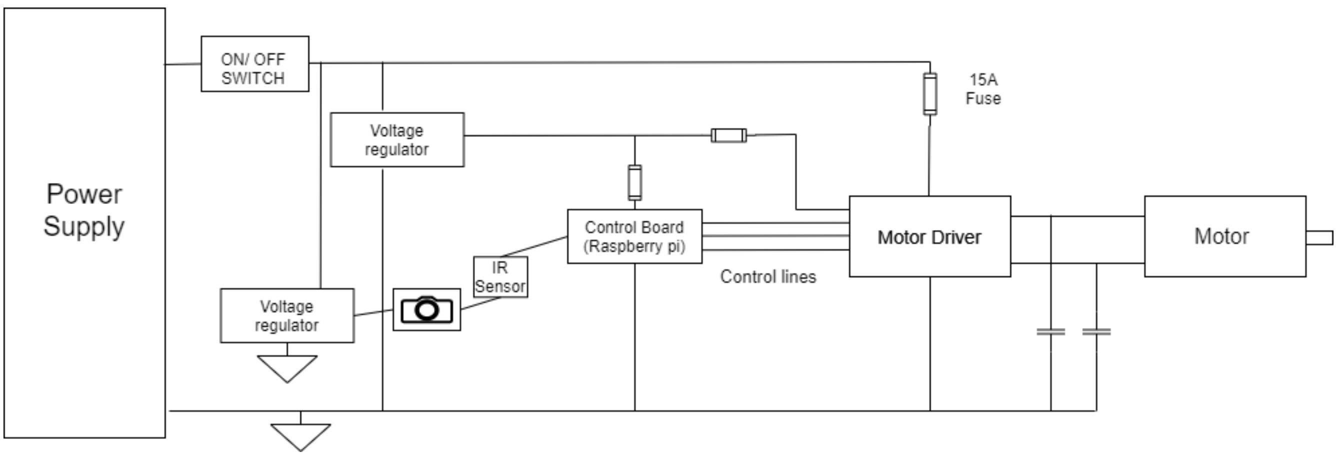


Figure 10: Voltage regulator circuit

4.5 Components for Safety Measures

4.5.1 Weight Sensor

It is to measure the weight carried by the bot and then indicate with an alarm in case of overweight. If an overweight occurs(here, the desired load limit is 40 Kg), then the alarm turns on with a frequency of 1 Hz.

4.5.2 Temperature Sensor

It also continuously monitors the temperature of the bot and gives alert in case of overheating.

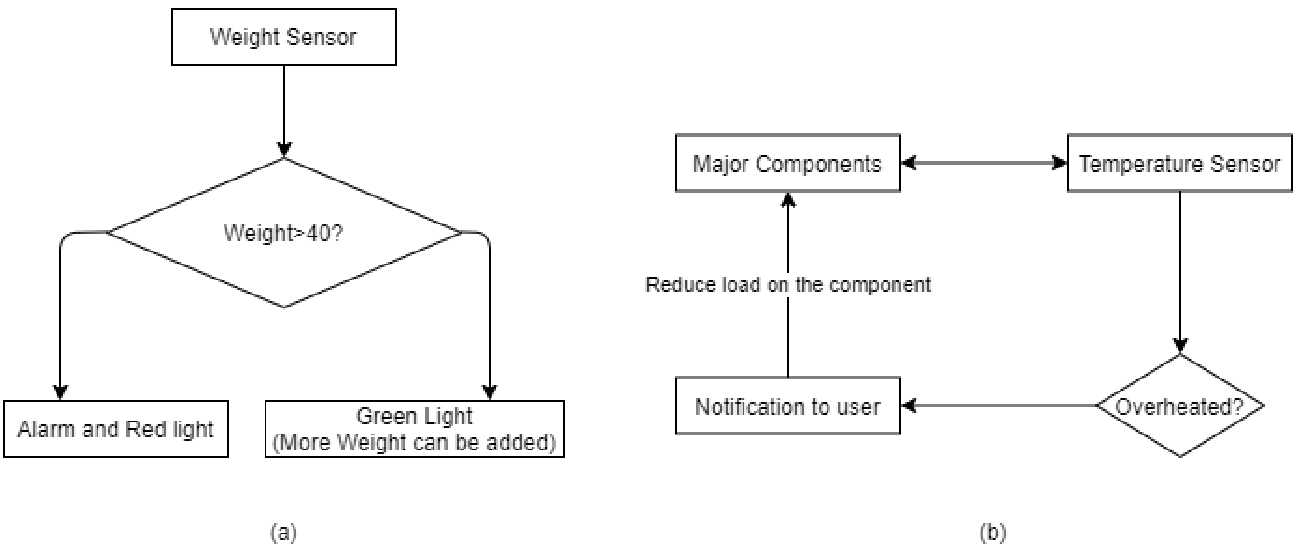


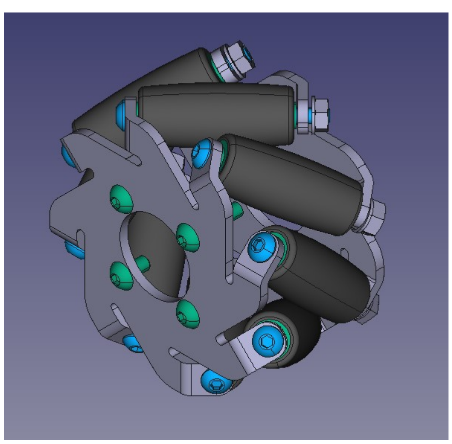
Figure 11: Basic flow chart of weight(a) and temperature(b) sensor

4.5.3 Battery Sensor

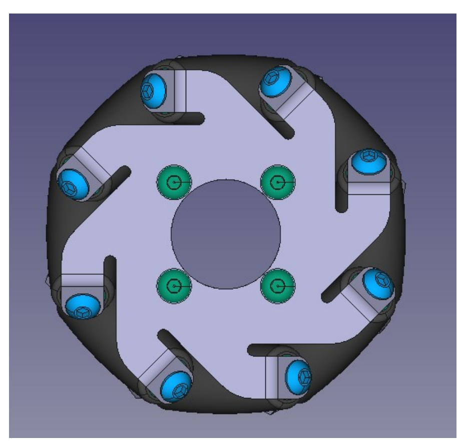
It monitors the battery status of the mule bot and gives full battery or low battery notification. We will have different notification options like vibration, alarm, Red/green light.

5 Structural design of the Mule bot

The requirements, functionalities, mock-up and the specifications of the individual components required for the design of the Mule bot were discussed in the section above. This section includes the description of the enclosure or the structure of the Mule bot. The 3D CAD model of the Mule bot was designed using FreeCAD, taking the specifications and the mock-up as a reference.
One of the principal component of the Mule bot is the Mecanum wheel, this wheel is made up of Aluminium and have a diameter of 6 inches. The wheel comprises of 8 rubber rollers and have a weight capacity of 50 Kilograms. The 3D model of the Mecanum wheel is illustrated using the isometric and the side views, which are attached below:



(a) Isometric view of the 3D model of the Mecnaum wheel



(b) Side view of the 3D model of the Mecnaum wheel

Figure 12: 3D model of the Mecnaum wheel

The 3D models of the Mecanum wheels and various other parts are assembled together to build a 3D model for the Mule bot. The various parts are listed in the table below :

Part No.	Part Name	No. of Units
01	Basket	01
02	Handle	01
03	Mecnaum wheels	04
04	Trolley Base	01

Table 11: Parts of the Mule bot

The Mule bot is assembles using the parts listed in the above table. The labelled isometric view of the 3D model of the Mule bot and the orthographic projections of the 3D model are shown in the figures below:

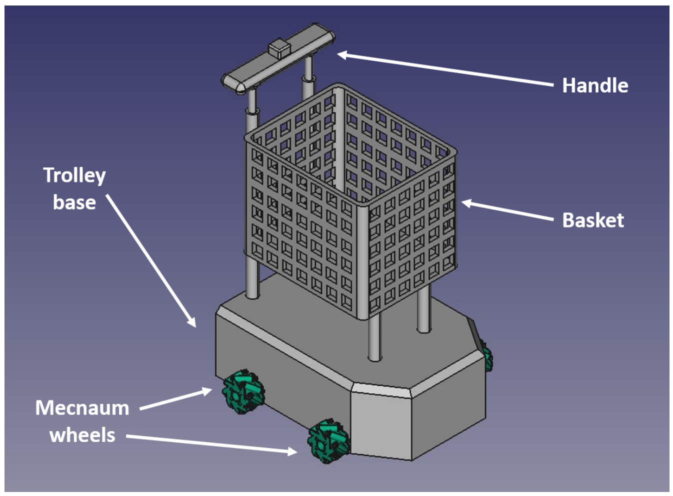


Figure 13: Isometric view of the 3D model of the Mule bot

The orthographic projections of the 3D model include the top, side and the from view along with all the dimensions. The major dimensions of the enclosure of the Mule bot are approximately $1045mm \times 500mm \times 400mm$. The dimensions are extensively labelled in the following figure :

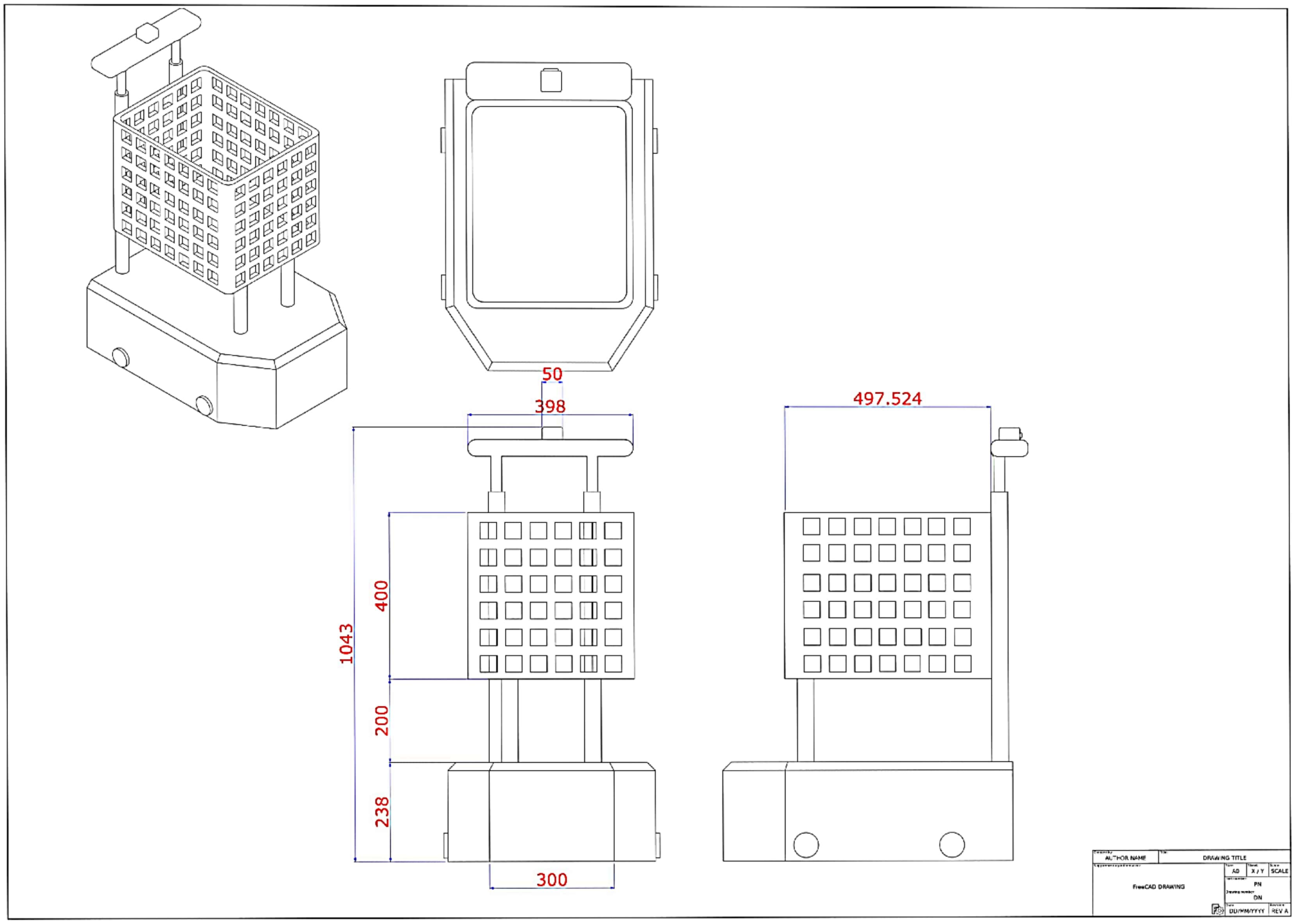


Figure 14: Orthographic projections of the 3D model of the Mule bot

The following figure can be clicked upon to see our proposed Mule bot in action. The picture will take the viewer to our Youtube video:

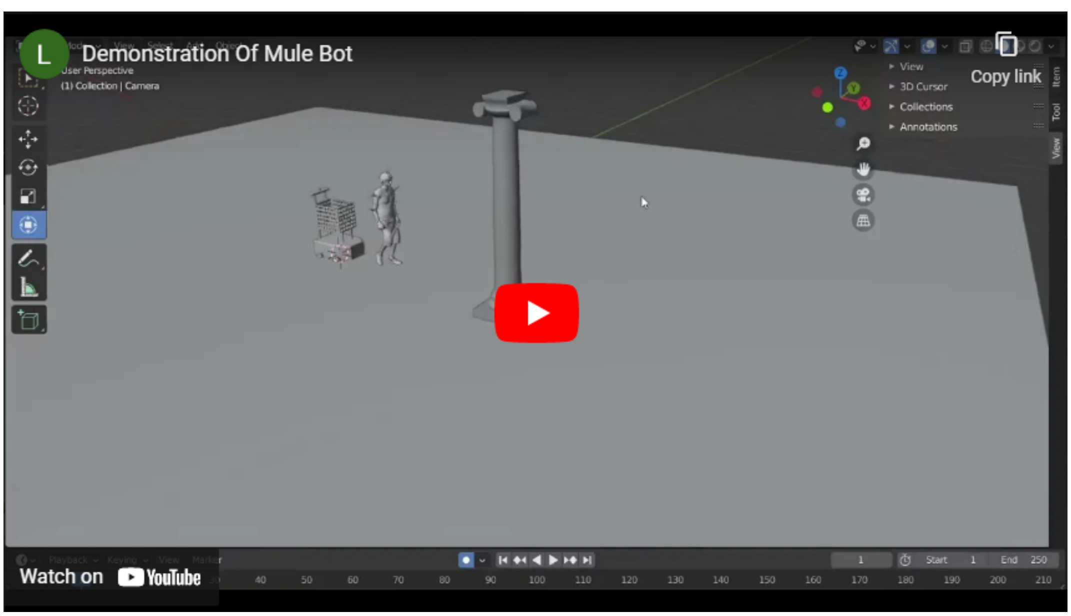
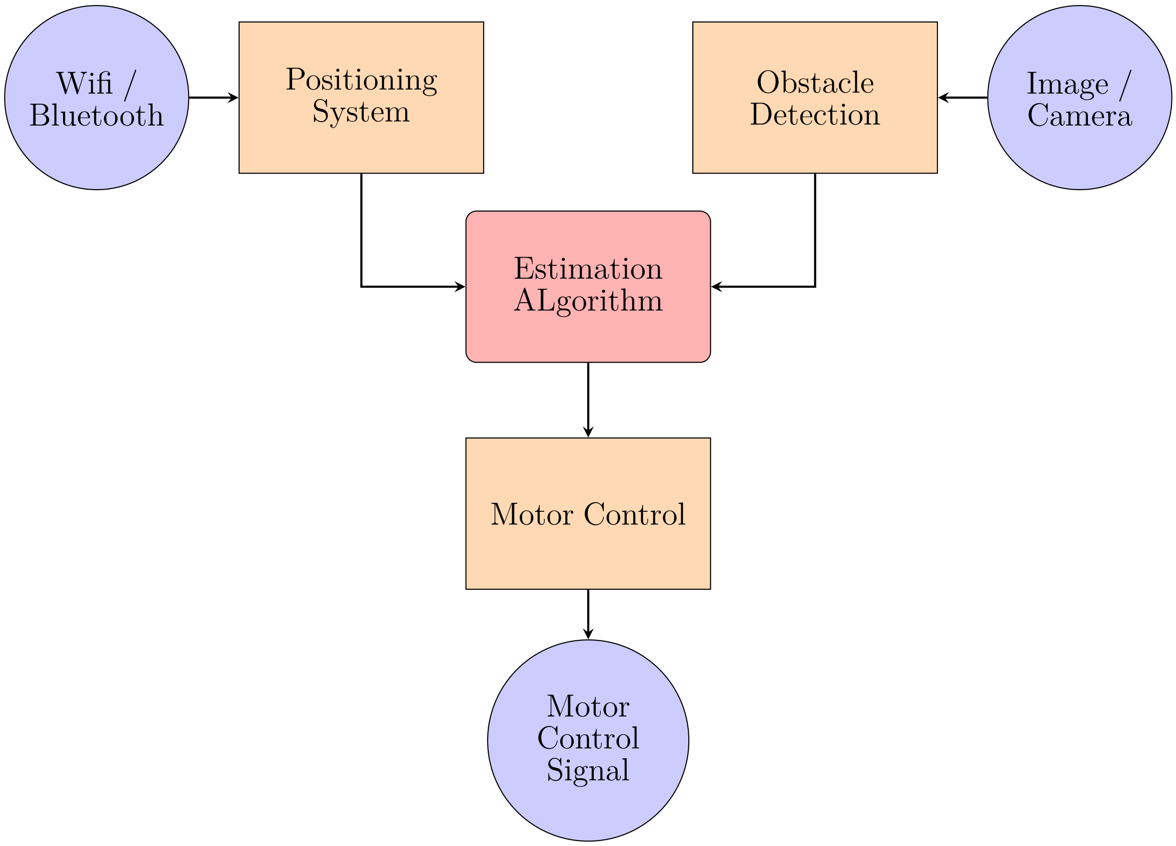


Figure 15: Youtube video of the assembly of our proposed Mule bot

6 Software level Description of the Mule bot

The basic working principle of the Mule bot is illustrated in the following flow-chart :



6.1 Position Estimation

Various techniques were considered to estimate the relative position of the User with respect to the Mule Bot. It was decided to use UWB radio wave technology[14] to estimate the position of the user as other methods such as Bluetooth [23] and WiFi did not promise the required accuracy.
Pre-Requisites

- Anchor points(Ultra-Wide Band Radars) setup inside the mall which estimate user and bot locations with high accuracy, which goes down to centimeter level.(10cm)
- One transmitter with the user. (Preferably a bracelet or watch)
- One transmitter on the mule bot itself.

Algorithm

1. Calculate distances from at least three nearest anchor points for both the user and the bot.Distance calculated on basis of time of flight.
2. Get an estimate of user's and bot's positions and therefore the user's position relative to the bot.
3. Communicate the user's co-ordinates back to the bot.

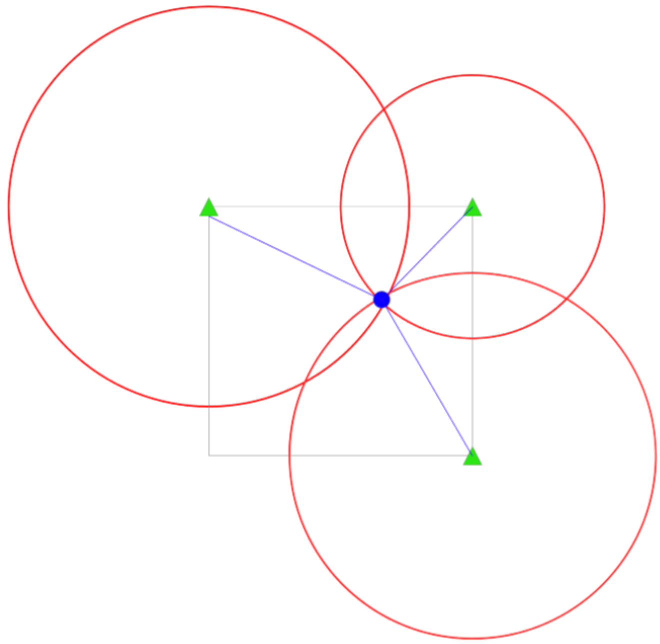


Figure 16: Graphical Representation of anchors(triangles) estimating the location of bot/user(blue dot)

6.2 Obstacle Detection

We will use IR emitter/sensor [24] to detect obstacles and use CNNs [25] to find the distance between the obstacle and the bot using the depth information provided by the RGB-D cameras. An infrared sensor transmits an infrared signal which is bounced from the surface of an object and the signal is received at the infrared receiver. Real-time detection of parameters of obstacle is done for every instant. Data is stored in the form of distance and angle of the obstacle.

6.3 Path Planning and Motor Control

[22] We plan to use the Rapidly Exploring Random Tree(RRT/RRT*) which is a (optimal) sampling-based path planning algorithm to find a clear path from the bot's current location to the user. Taking into account the information of obstacle boundaries, the path is continuously updated. The central idea around the Rapidly Exploring Random Tree(RRT) algorithm is as follows:

1. Build up a tree in the search space through generating "next states"
2. Select a random point and expand the nearest vertex in the tree towards the sampled point

Algorithm 1: Pseudo code for the RRT Algorithm

GENERATE_RRT (x_{init}, K, Δt)
τ.init(x_{init});
for k=1 to K do
  $x_{rand} \leftarrow$ RANDOM_STATE();
  $x_{near} \leftarrow$ NEAREST_NEIGHBOR(x_{rand}, τ);
  $u \leftarrow$ SELECT_INPUT(x_{rand}, x_{near});
  $x_{new} \leftarrow$ NEW_STATE($x_{near}, u, \Delta t$);
  τ.add_vertex(x_{new});
  τ.add_edge(x_{near}, x_{new}, u);
Return τ

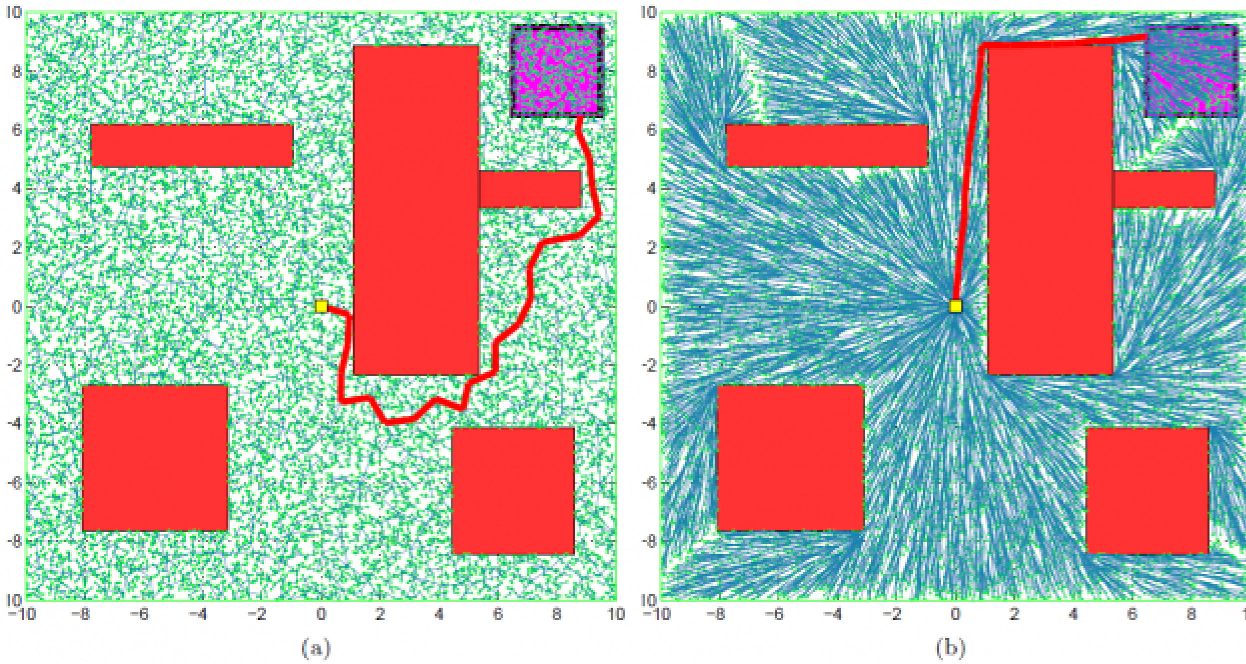


Figure 17: A comparison of RRT (a) and RRT* (b) algorithms on a simulation example with obstacles

After the optimal path is decided, control signals are passed on to the four motors of the bot to:

- increase/decrease speed depending on the distance to the user/nearest obstacle in the chosen path
- re-orient the mule bot according to the chosen path or on encountering an obstacle

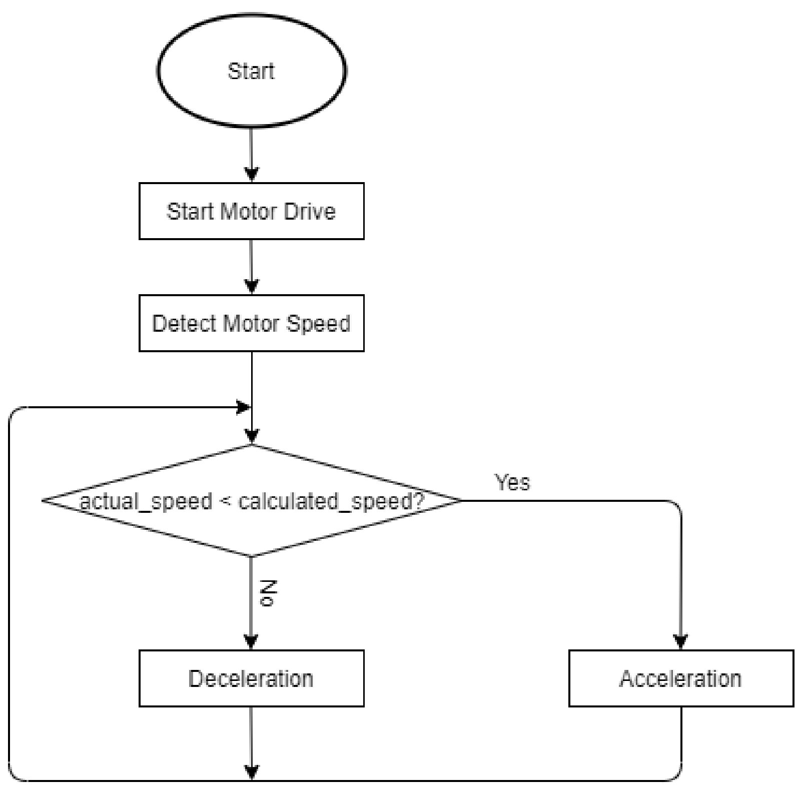


Figure 18: Basic flow chart of motor speed control

6.4 Safety Measures

6.4.1 Weight Sensor

It is to measure the weight carried by the bot and then indicate with an alarm in case of overweight. If an overweight occurs(here, the desired load limit is 40 Kg), then the alarm turns on with a frequency of 1 Hz.

6.4.2 Temperature Sensor

It also continuously monitors the temperature of the bot and gives alert in case of overheating.

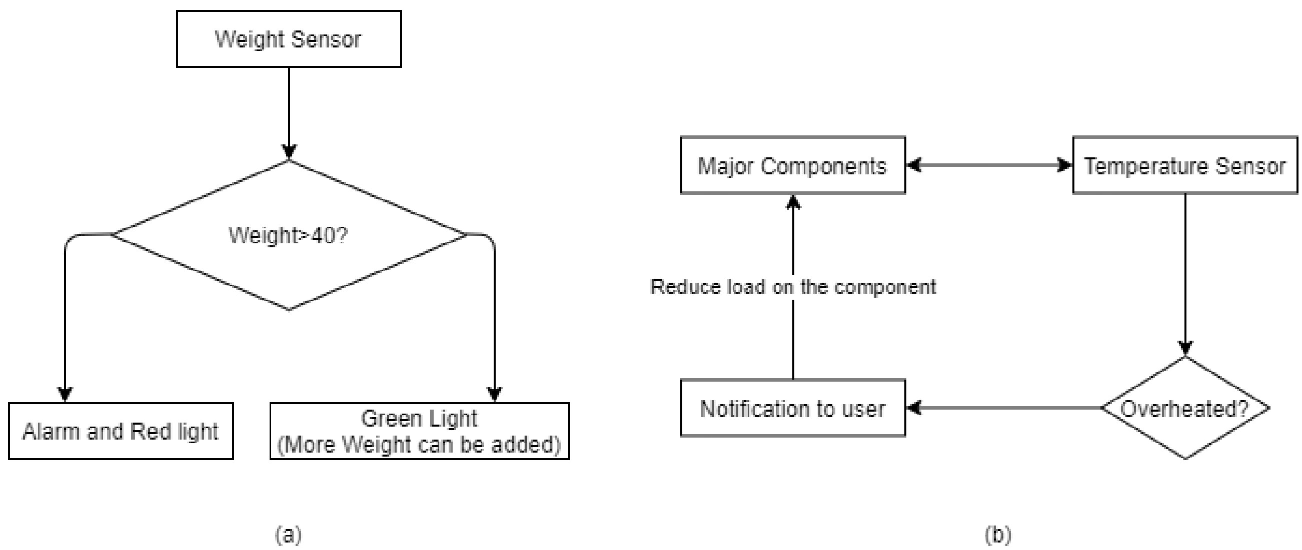


Figure 19: Basic flow chart of weight(a) and temperature(b) sensor

6.4.3 Battery Sensor

It monitors the battery status of the mule bot and gives full battery or low battery notification. We will have different notification options like vibration, alarm, Red/green light.

6.5 Fault Detection and Analysis

Real-time continuous scanning to ensure all parts are working correctly. Look for flags like increased power consumption, abnormal high temperatures and broken connections in the circuit. Send an alarm to the user's device in case of any malfunctions.

6.6 Find my basket

The app also helps us to find our basket in shopping centres if the user lost it and lock it until he/she get it back. We will be able to see the location of the bot in the app. It can play a sound/ blink light if prompted by the user.

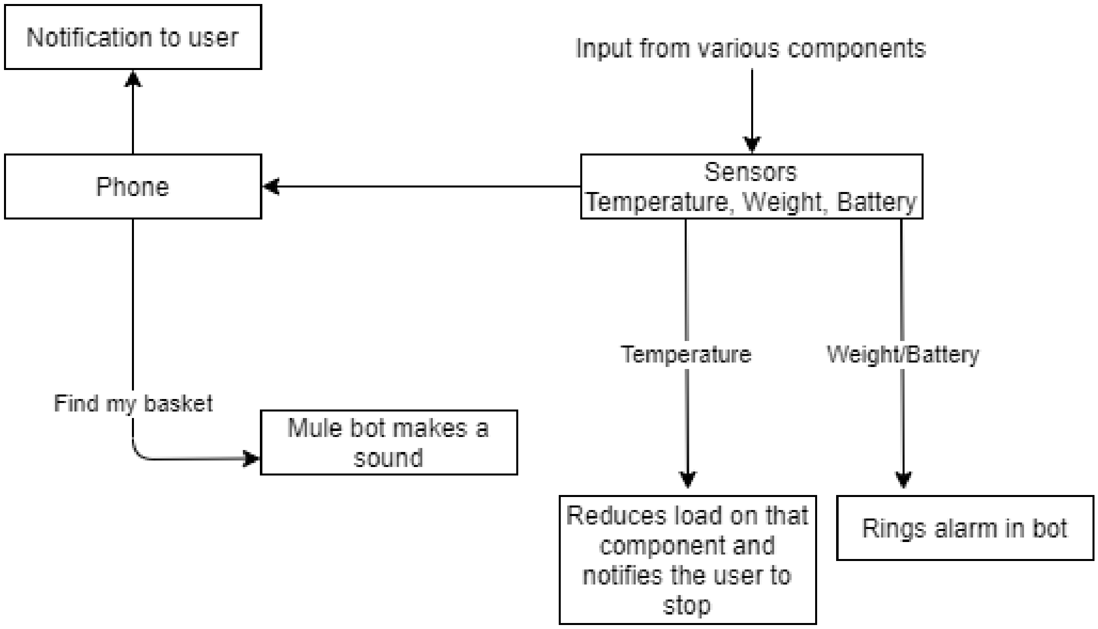


Figure 20: Basic flow chart of Safety Measures

7 Communication between Bots

7.1 Communication Protocols:

There are various wireless communication protocols like Radio Frequency Indenification (RFID), Wi-Fi, Bluetooth and Infrared. The ideal communication protocol for our network of Mule Bots must have the following characteristics:

1. Low power dissipation with high data transfer speeds.
2. Support for easy implementation of Intelligent communications.
3. Support for multiple connected components.
4. High efficiency even without a direct line of sight.

The communication and encryption protocol employed in our Mule Bot is inspired by the ZigBee protocol. The ZigBee protocol is a simple communication protocol which offers many of the critical functionalities, mentioned above. The ZigBee protocol is designed for static networks but our network of Mule Bots is dynamic and changes with time. Thus, rather than using the ZigBee protocol directly, we employ a protocol which have the characteristics and elements of ZigBee along with support for dynamic communication networks.
Thus, we will use a slightly modified version of the ZigBee protocol and to understand it's components and security plan, understanding the ZigBee protocol becomes critical. The ZigBee protocol and it's security is discussed in detail in the following sections.

7.1.1 Zigbee

Zigbee is a wireless technology standard that defines a set of communication protocols for short range communcations. Zigbee supported device can talk to any other zigbee device just like bluetooth.

7.1.2 Why use Zigbee and not bluetooth or wifi?

- Zigbee[30] has more range(upto 100m indoors and 300m outdoors) as compared to wifi(50m) and bluetooth(10m).
- It consumes less power, hence has better battery life.

- Low data rate which is ideal for our application in which video communication is not needed.
- Network size (upto 65000 devices) compared to 32 in wifi and 7 in Bluetooth.
- Very Low latency and network join time.
- Zigbee itself adds three important features:
  1. **Mesh Routing:** uses routing tables that define how one radio can pass messages through a series of other radios along the way to their final destination.
  2. **Ad hoc network creation:** an automated process that creates an entire network of radios on the fly, without any human intervention.
  3. **Self-healing mesh:** a process that automatically figures out if one or more radios is missing from the network and reconfigures the network to repair any broken routes.

7.1.3 How does Zigbee work?

Types of nodes:
The radio modules, or nodes, in each Zigbee network are assigned different roles. These [31] are some of them:

1. **Coordinator:** This radio is responsible for forming the network, handing out addresses, and managing the other functions that define the network, secure it, and keep it healthy. Each network must be formed by a coordinator and theres never more than one coordinator in our network.

2. **Router:** It is a full-featured Zigbee node which can join existing networks, send information, receive information, and route information. Routing means acting as a messenger for communications between other devices that are too far apart to convey information on their own. They are typically plugged into an electrical outlet because they must be turned on all the time. A Zigbee network generally has multiple router radios.

3. **End device:** End devices are essentially stripped-down versions of a router. They can join networks and send and receive information, but thats about it. They dont act as messengers between any other devices, so they can use less expensive hardware and can power themselves down intermittently, saving energy by going temporarily into a non-responsive sleep mode. End devices always need a router or the coordinator to be their parent device to help them join the network, and to store messages when they are asleep. Zigbee networks may have any number of end devices.

Zigbee Network Architecture:

1. **STAR TOPOLOGY**
   This is the simplest and less expensive implementation. There are no routers in this architecture. End device cannot communicate directly with another device.

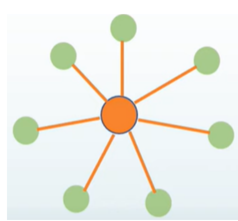


Figure 21: Star Topology

2. **MESH TOPOLOGY**
   Every node is connected with the neighbouring node(except for the end devices).In this, a message hops from one device to another in order to reach its destination. And, if a node fails, data can be re-routed using another path. It also has self-healing process.

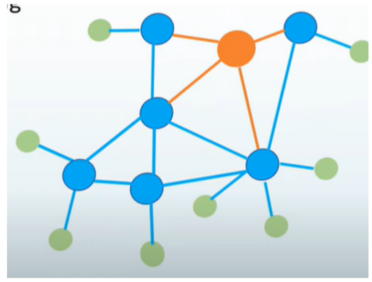


Figure 22: Mesh Topology

3. **TREE TOPOLOGY**
   It is very similar to mesh configuration. In this topology, routers are not inter-connected.

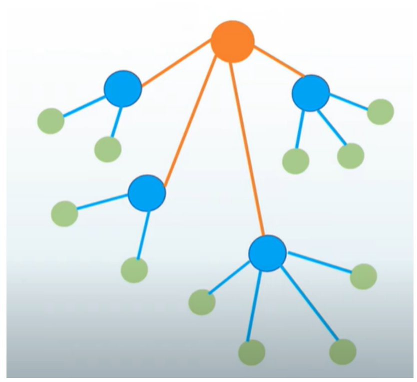


Figure 23: Tree Topology

7.1.4 Channel Access

Upon network establishment, the coordinator assigns a single network for all communication purposes between the devices. Out of the two methods for channel access, we use the contention free method, given its merits.

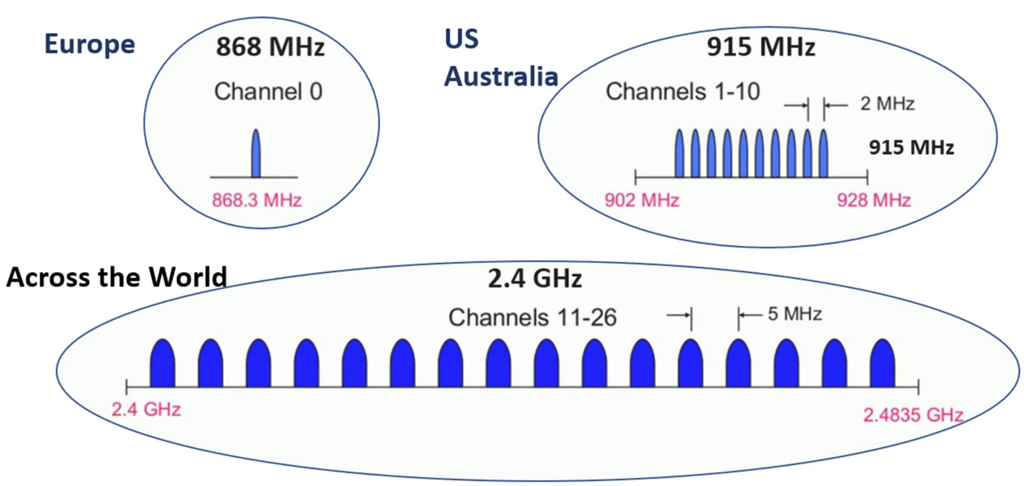


Figure 24: Operating Frequency Bands assigned to Zigbee across the globe

In the contention-free method, the coordinator dedicates a specific time slot to a particular device such that there are no overlaps between time slots of any two devices. This is called as a guaranteed time slot(GTS).

To correctly assign the GTS, the coordinator needs to make sure that all the devices in the network are synchronized with a common clock. To achieve this, the coordinator sends out a beacon to synchronize all devices in the network. The beacon also contains information about when each can transmit data.

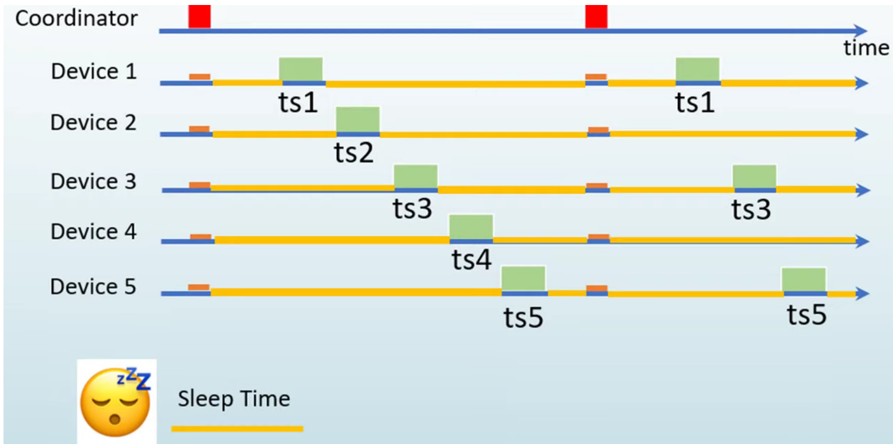


Figure 25: Synchronization achieved using the Beacon

Now that all the devices know the time when they can transmit data, they can be put in sleep mode at all times except when receiving the beacon signal or when transmitting data, thus promoting low power consumption.

7.1.5 Adaptation

In the Zigbee networks system, it is assumed that the nodes/devices are stationary. However, that is not the case with our mule-bots. We can tackle this problem in the following ways:

1. We can make it so that the coordinator and the routers are fixed. This is probably the better solution but does require some prior infrastructure. We can have the coordinators and routers already setup at the mall / shopping center. The robots coming in can be added to the network in a few milliseconds (30ms to be exact). This would mean that we can use the mesh architecture and enjoy the benefits of features like self healing.

2. Another solution is changing the whole network (including the coordinator) on the fly. This is the more complex solution but probably the cheaper one. Assuming that the number of robots in the mall is not in the thousands, we can use the star architecture and take out the need for routers altogether. Suppose we have a network in the mall where one robot is acting as the coordinator for others. Now, lets say that this robot leaves the mall. The network cannot function without a coordinator and thus it needs to be rebuilt. Once the old coordinator has left a new coordinator can be appointed based on a priority order. This priority can depend on factors like robot model, its position in the mall (i.e how many robots are currently in its range). Here, we can also use the functionality of the beacon(previously defined) to figure out when the coordinator has left. This has been depicted as a flow chart as follows:

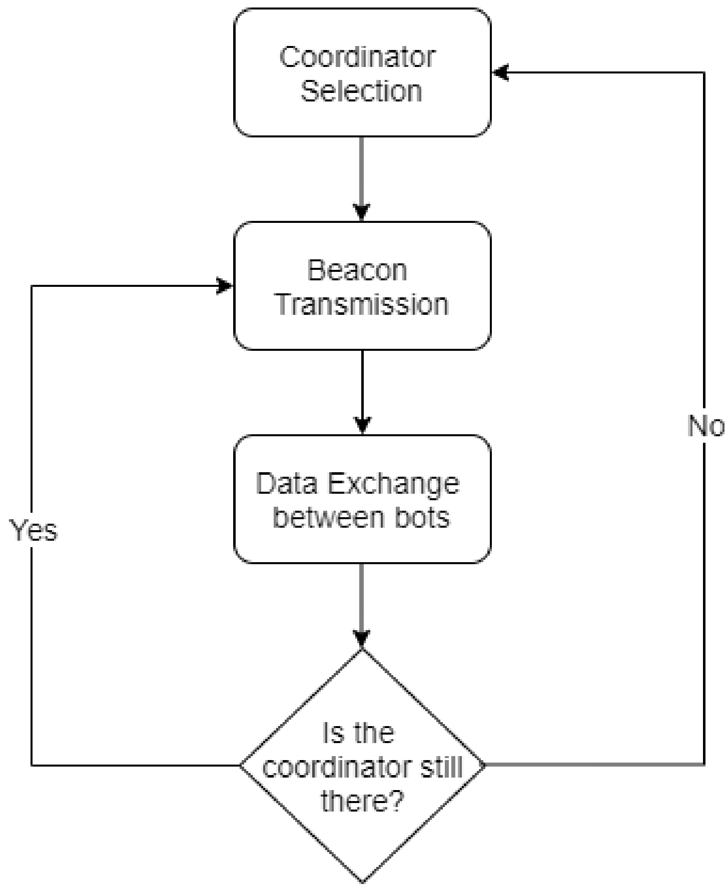


Figure 26

7.1.6 ZigBee Encryption and security plan

ZIGBEE security and data encryption [32] [33] is based on security standard defined in IEEE 802.15.4 protocol. The security is based on symmetric - key cryptography, in which two parties must share the same key to communicate. The encryption algorithm used in ZIGBEE is 128 bit AES (Advanced Encryption Standard) with a 128 bit key length (16 bytes). The AES algorithm is not only used to encrypt the information but also to validate the data which is sent. It has two network architectures and corresponding security models: distributed and centralized. They differ in how they admit new devices into the network and how they protect messages on the network however the common feature is that to participate in the network, all the devices must be pre-configured with a link key:

- **Distributed security model:** it provides a less-secured and simpler system. It has two device types: routers and end devices. Each router can issue network keys. As more routers and devices join the network, the previous routers on the network send the key. All the devices in the network encrypt messages with the same network key.
- **Centralized security model:** it provides higher security. It is also more complicated as it includes a third device type, the Trust Center (TC), which is usually also the network coordinator. The Trust Center forms a centralized network, configures and authenticates routers and devices to join a network. The TC establishes a unique TC Link Key for each device on the network as they join and link keys for each pair of devices as requested. The TC also determines the network key.

It is to be noted that although the AES algorithm for data encryption and data authentication provides ZIGBEE encryption with sufficient robustness, but the security also depends on the secrecy of the encryption keys, which may be breached during the keys initialization or distribution.
Pictorial depiction of above discussed security models of the ZIGBEE protocol are as follows:

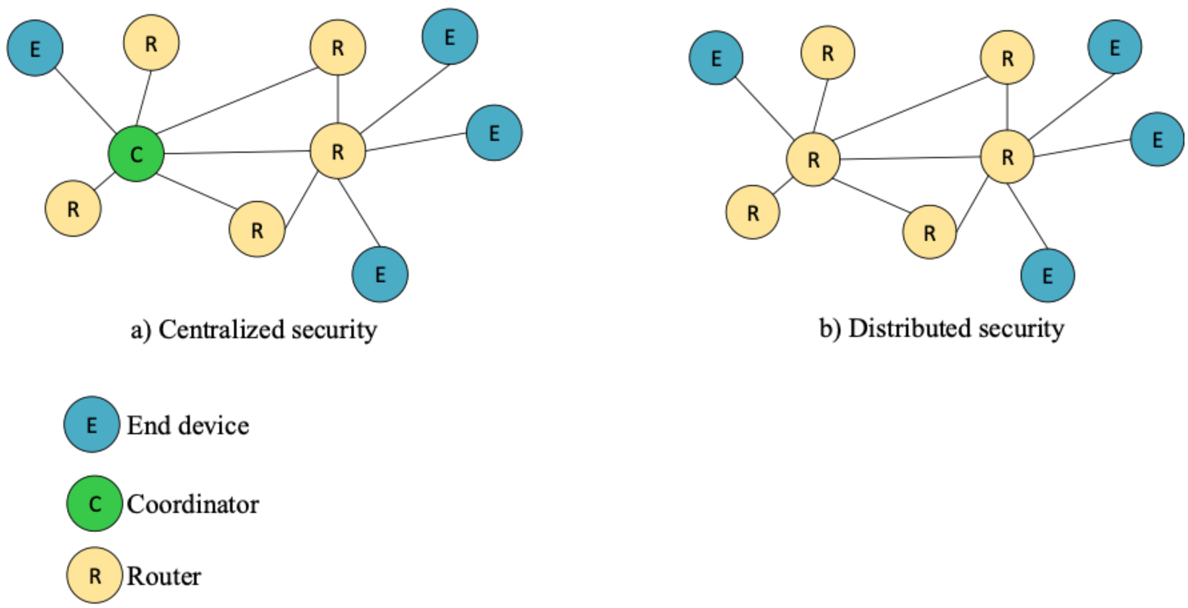


Figure 27: ZIGBEE Security Models

7.2 Hardware

7.2.1 Communication Module

We have used EM250, it is wireless communication module which supports ZigBee protocol. It is a single chip solution that integrates a a 2.4GHz, IEEE 802.15.4-compliant transceiver with a 16-bit XAP2b microprocessor. [28] It contains integrated Flash and RAM memory and peripherals of use to designers of ZigBee-based applications. It has the following specifications [29]:

Dimension ($L \times W \times H$)	$7mm \times 7mm \times 0.9mm$
Product Category	RF System on a Chip - SoC
Weight	$256.760mg$

Table 12: EM250 Specifications

7.3 Applications

- Bots can be **charged efficiently** if a bot with less charging can communicate with a significantly charged bot to balance the currents in such a way that the less charged bot receives more power.
- Setting up a communication medium between the bots can help in **easier motion planning**. Earlier, a bot used to identify obstacles between two points using the camera which took images of its surroundings. Now it would be able to receive the location and surrounding images of all other bots for a more efficient motion planning and prediction.
- If the battery of a bot becomes low while still in use, some other bot can identify and replace it. In another case, if the mule bot that is in use achieves full capacity, an extra mule bot can assist the user.
- The density of the bots throughout the mall can be communicated. This can help the user in identifying the shops which do not have a rush.

8 Budget

Week 1			
Tasks	**Members**	**Cost (elpu/ person/ week)**	**Total Cost (elpu)**
Design (PCB +Electrical)	14	1	14
Requirements	6	1	6
Documentation	7	2	14
Total			34

Week 2			
Tasks	**Members**	**Cost (elpu/ person/ week)**	**Total Cost (elpu)**
Design Enclosure	13	3	39
Specs	6	1	6
Simulation Schematics	11	3	33
Documentation	7	2	14
Total			92

Week 3 and Week 4			
Tasks	**Members**	**Cost (elpu/ person/ week)**	**Total Cost (elpu)**
Design Software Hardware Specifications	 7 7 6	 7 7 4	 49 49 24
Enclosure	9	6	54
Documentation	9	5	45
Total			221

Week 5			
Tasks	**Members**	**Cost (elpu/ person/ week)**	**Total Cost (elpu)**
Communication protocol	11	4	44
Hardware	10	3	30
Encryption	6	3	18
Documentation	6	3	18
Total			110

Total Budget	**457**

Table 13: Budget

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