HOCHSCHULE RHEIN-WAAL
Rhine-Waal University of Applied Sciences

Group Project No. 4
Faculty of Technology and Bionics

Autonomous Robotic Cobble Cleaner

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Acknowledgement

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Cleve,
02.11.2021

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Executive Summary

In this report, we described the concept design of the robotic cobble cleaner we plan to construct and produce onto the market. The main function of our robotic cobble cleaner is to remove unwanted plant growth from the cracks between cobbles or tiles. This will be made possible by the Nylon brush roller component installed at the base of this machine. Our machine's secondary function is to collect the plant material residue/debris after the cleaning has been done. This will be facilitated by a vacuum that will be located at the base of the body of the robot. Regarding power supply, our robot will be powered by rechargeable batteries in its body and a charging station will be installed in the area of operation. Perimeter wires will also be laid down around the area where the robot will operate for navigation and self-charging purposes. The robot will have two ON/OFF switches, the main one to turn it on/off and activate every function exclusive of the vacuum system and the other to turn on the vacuum system. The decision to isolate the vacuum system from the rest of the robot was made due to sustainability and efficiency reasons. Our robot will be able to move on four wheels driven by two motors in the front, that is, front-wheel drive (FWD). Our robot will also engage the functionality offered by sensors for easy navigation and smooth operation in fulfilling its goal of autonomy. As a team, we opted to prioritize the small-scale commercial sector as our main market due to primarily financial and usability factors. After doing market research, we discovered that this market needed such a product the most and had sufficient area and capital to utilize it adequately. Regardless, our product will still be open to the other sectors in the economy, such as large-scale organisations and domestic consumers with regards to functionality and performance.

Keywords:
Cobble cleaner
Autonomous robot
Self-charging
Small-scale commercial market
Perimeter wire

Executive Summary for Product Design

This report contains a detailed description of the product design of the autonomous robotic cobblestone cleaner. The complete 3D CAD Model of the robot is designed in detail with all the make and buy parts included, according to ISO/DIN/EN standard. The functional principles of the parts assembled to bring this robot to life are researched and presented vividly. Secondly, the UML diagrams, that is, the activity diagrams, the class diagram and the state machine diagram are constructed to show the working principle of the electrical and mechanical components of the robot, their interdependencies, as well as the flow of operation. The circuit diagrams to show the connections between the various electrical components in the robot and charging station are also designed. In the process of selection of components to use for the project, make-or-buy decisions are made. The buy parts are decided upon and preparations to purchase them from the various suppliers are made. A requirement manual with specifications obtained from datasheets for these components is also included and documented. The materials and technology to realise this are selected and documented accordingly for the remaining components that must be constructed.

Finally, certain adjustments from the first milestone were made and documented accordingly. The changes include:

- Inclusion of an Infrared Transmitter and Receiver to make self-charging for the robot possible.

In this Report, Product Design, the following categories are covered:

- Complete 3D model (CAD), functional principles presented
- UML (activity diagram, class diagram or state machine diagram)
- Circuit diagram
- make-or-buy decision on a component basis
- Technology selection for “make” parts
- Requirements manual for “buy” parts

Keywords:
ISO/DIN/EN Standard
Circuit diagram
Make-or-buy
CAD Model
UML Diagram

Contents

Introduction

Our product is an autonomous cobblestone and brick cleaner. We are designing this product due to the presence of unwanted plant and weed growth from the cracks between cobbles which might cause damage to the cobblestones. Removing this unwanted plant growth will also make the area where they are located look neat.

Marketing Decisions

Market Size

Our main target is the small-scale commercial sector, which includes apartments, malls, company buildings, public offices, warehouses, small hospitals and clinics, gas stations, and other commercial buildings with small-to-medium parking lots and open spaces with a maximum area of approximately 500m^2 made of bricks or cobblestones.

Our product can also attract some domestic consumers with regards to functionality and efficiency.

We selected the small-scale commercial sector as our main consumer due to the following reasons:

- Our product would reduce the labour costs of maintaining such spaces because it could be monitored by just a single person while doing the job of many people.
- Our machine is more efficient as compared to humans regarding time, precision, quality of work and is also cost-effective long term.
- Targeting the small-scale commercial market would generate more profits and is huge concerning the domestic sector.
- As our principal target market is Germany, our product may not attract interest to private property owners since the citizens prefer to do such tasks by themselves.
- The sizes of parking lots owned by the domestic consumers are generally not big enough to invest in our product. Moreover, some private properties do not have space at all.
- Our machine would be quite expensive and would not make financial sense on the domestic market.
- Our product would not attract the large-scale commercial sector, such as walkways in towns, large airports, and other large areas of cobblestone because its navigation system is controlled by wired parameters with a maximum area range of 500m^2.
- The sizes of parking lots and spaces owned by the small-scale consumer market are generally small-to-medium scaled hence not too large to be covered by our product.

Market Price

The robotic cobble cleaner will be sold at an entry-level retail price of €1099.

The team chose this price based on various factors such as:
- The price of commercial-off-the-shelf (COTs) components.
- The cost of making parts.
- Production, manufacturing, and assembly costs.
- Labour costs.
- Cost of advertising and marketing.
- Location (rent) costs.
- Research and development costs.
- Profits.
- Overhead costs.

The cost price for the components is approximately 698.5 € see Table 1. Our profit margin will be approximately 100.5 €, the remaining 300 € will include the above-mentioned additional costs. In the initial phase, the profits are kept low to maintain the penetration strategy, keeping profits low and infiltrating the market.

To give consumers an incentive to purchase our product when it drops onto the market, we will give discounts to the first 50 purchasers after a review from their side within a month. These reviews will be published on our e-commerce platforms and hence attract more consumers.

With an increase in production and profits, we will be able to increase the functionality of the robot and maintain a constant price range. We will also make variations of the product, for example, without a vacuum section or a larger size, based on the success of the product.

Planned Sales Volume

In the first phase of our product launch, we will produce 100 units. Our aim to produce only a hundred units, in the beginning, is to achieve high sales velocity by lowering the sale cycle. We at first would restrict ourselves to the big cities in the state of North-Rhein Westphalia where the company is located, with definite plans to increase the production depending on how our product performs in the first financial quarter.

Once our target of selling the first 100 units in 3 months is accomplished, we will start the production of the next batch with improved functions based on customer reviews and the demand. Our further production will depend upon the law of supply and demand. By maintaining a regular check and balance on the sales matrix and the defined KPIs, we can ensure the success of our product.

For the first year, our goal is to sell at least 1000 units throughout Germany. This target shall be achieved based on improved functionality, durability, performance and efficiency of our product considering the consumer reaction.

Our vision is to infiltrate the European Union market and become the number one solution for cobblestone and brick maintenance.

Marketing Strategy

With the development in technology and the need for autonomous functionality in devices like this, we expect that large corporations might come up with similar ideas in future, but we are confident that our product would be the leading robot cobble cleaner in the market by then.

Figure *1* shows the overall growth of the robotic weeding machine market analysis between the years 2020 and 2024. With the increased demand for such a machine, our product will be sure to infiltrate the market in a short period.

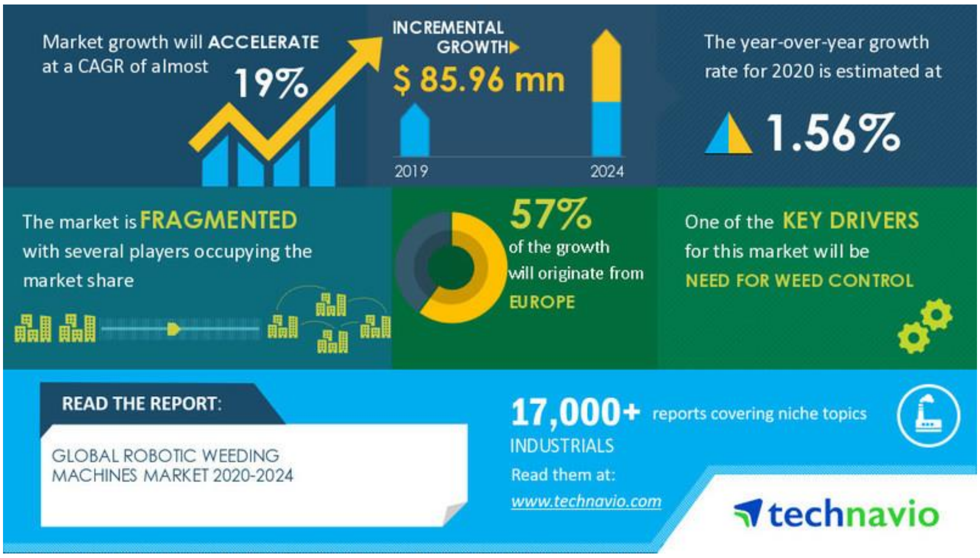

Figure 1 - Global robotic weeding machine market between 2020-2024

Robotic Weeding Machines Market | Nachricht | Finanzen.Net, n.d.

During the development and prototyping phase, we will launch our company website and will start advertising our product digitally on various e-advertising agencies such as Google, YouTube, Amazon, and other sites.

Our website will show the initial concept and design of our product and will be updated regularly for our potential customers to understand, in-depth, what this robot will be able to do in terms of operation and performance.
Our product will be sold on our website as well as on other e-commerce platforms such as Amazon, eBay and others.

The cleaner will have a guarantee and warranty of at least 24 months. This will imply that if the robot gets spoilt, the consumer can send the product back to our company for free repairs or replacement during this time frame.

After purchasing our product, we will send a technician from our team to install the boundary wire and charging station in the space where the customer desires to operate their robot cobble cleaner. This will be free of charge as a special give-back offer to our consumers. This will encourage people to purchase this product.

Overall Product Concept

Initial Sketches

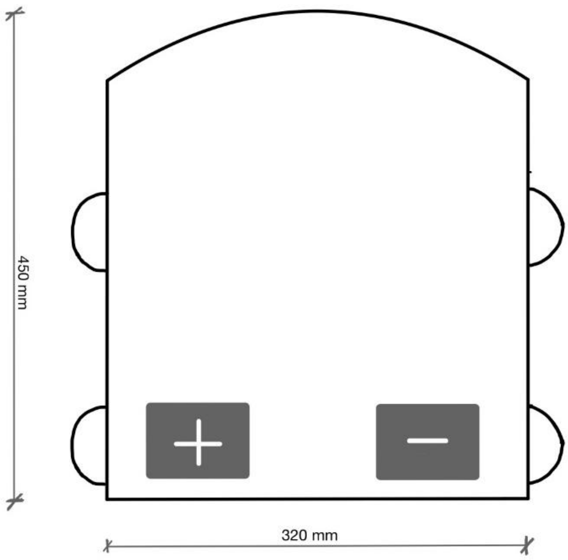

Figure 2 - Top view of the robot with dimensions

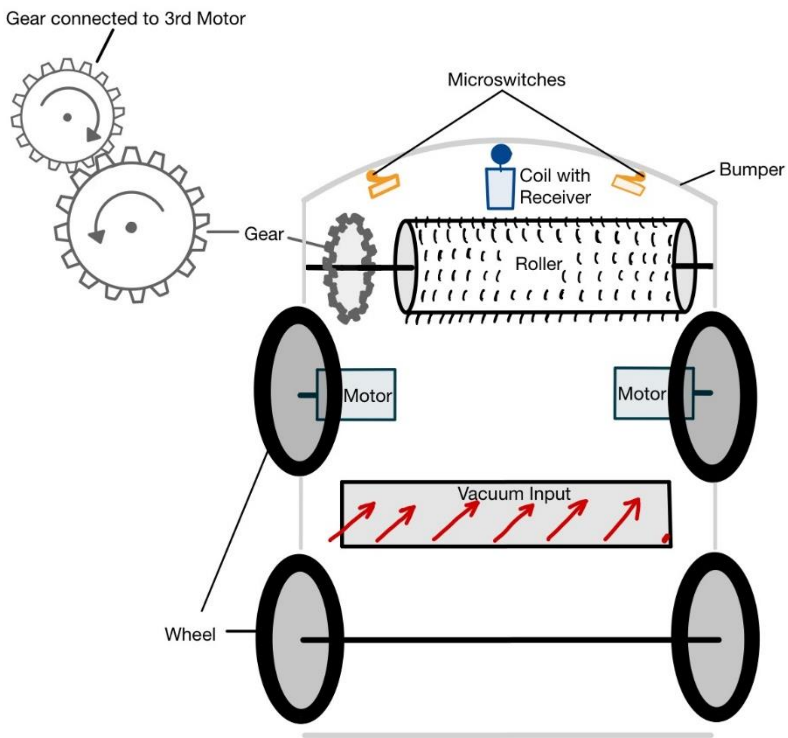

Figure 3 - Bottom view with inner mechanical components

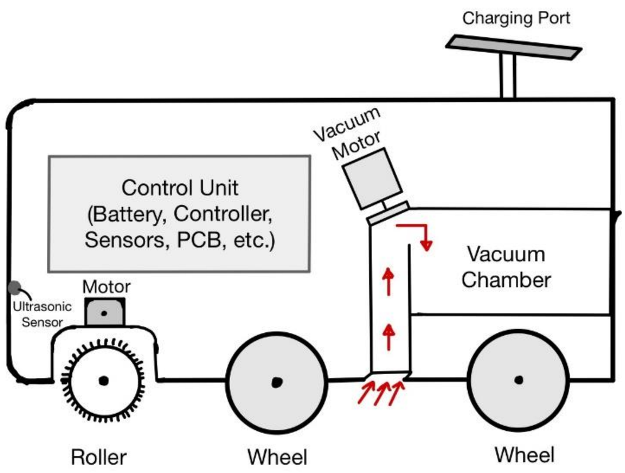

Figure 4 - Side view of the machine

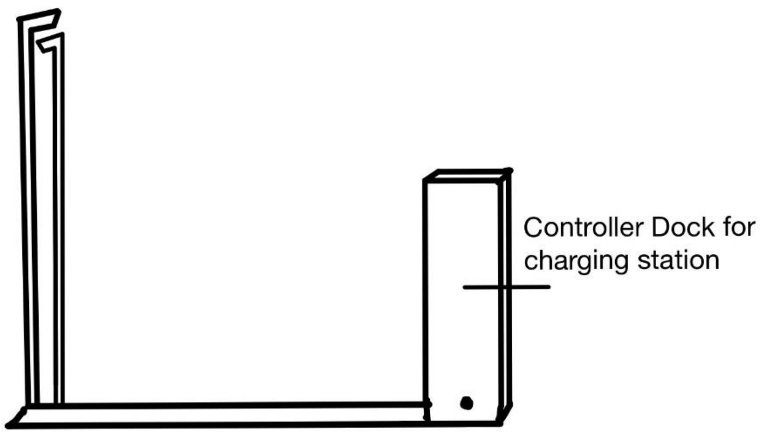

Figure 5 - Side view of the charging station

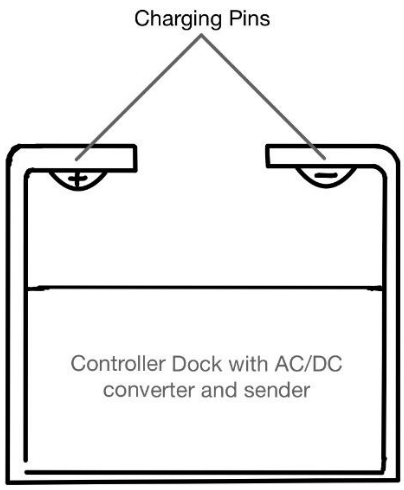

Figure 6 - Front view of the charging station

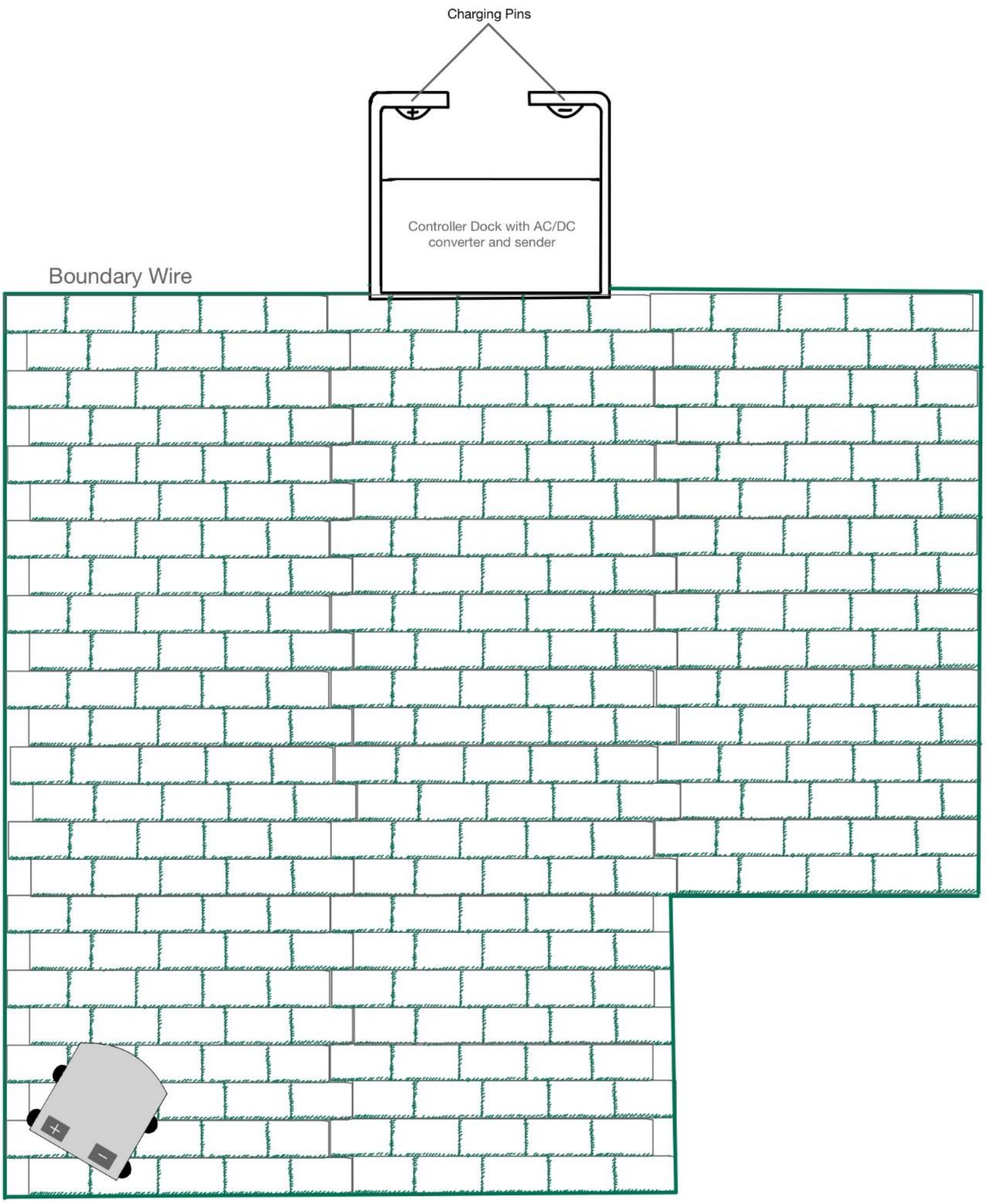

Figure 7 - Robot operating in certain space

Written Description

Our robot cobble cleaner will run on four wheels driven by two motors in the front, that is, front-wheel drive (FWD). Motor drivers will help increase the current supply from our controller to the motors. Our wheels would be big enough to roll over rough cobblestone surfaces and will also have good traction. Our main component is a roller with nylon brush bristles attached to complete the main purpose of our machine, which is removing unwanted plants and weeds in between the cobblestones. The roller will contain a shaft and a gear. The gear will be rotated by a motor.

Our machine will have two different ON/OFF switches. The main switch will activate the controller in the robot hence will turn on the rollers that are used to remove the unwanted weed growth between the cobblestones and the robot will start to move. The second switch will activate the vacuum cleaner whenever the user desires to use it. The decision to detach the vacuum from the main controller was made to save energy and to increase the efficiency in the primary function of cleaning. The robot will also have an emergency STOP button that will stop its whole operation, that is, the robot will stop moving and performing any of its other functions. This button was considered due to safety reasons.

The roller would move at a certain RPM (rotation per minute) large enough to be able to clean efficiently. The roller will be removable and replaceable in case of wear and tear. Regarding power supply, our robot will be powered by rechargeable batteries in its body and a charging station will be installed in the area of operation The charging dock will be installed in the area where the cleaning shall be held. Perimeter wires shall also be placed in a closed loop around the space. This will make sure that our robot does not go beyond the marked boundaries.

The perimeter wire, attached to the charging station, in a closed-loop will send a signal which will be detected by our machine.[1] The signal is detected using the perimeter wire sensor attached to the robot. The strength of the signal depends on how close the machine is to the perimeter wire. When the robot is close enough to the perimeter wire, it turns around at a random angle and changes the course of direction. The same reaction happens when it encounters an obstacle or a body in motion.

All our components will be assembled inside a cuboidal-shaped housing that will be made of high-quality plastic material. There will be an outlet for a vacuum on the base of the body in between the roller and the rear wheels. There will be a LED light on the body of the robot that will flash a green light when in proper operation, blue light when charging and a red light when the battery is low.
The machine will be programmed by a microcontroller board. The board will oversee the movement and cleaning functions. The mechanism of turning the robot at a random angle will be based on a differential gear mechanism and will be integrated with the microcontroller, where the microcontroller will generate a random angle and the motors in front wheels will react accordingly.

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[1] Robotshop – Perimeter wire sender and receiver: https://www.robotshop.com/community/blog/show/diy-perimeter-wire-generator-and-sensor accessed: 17.10.2021 (*DIY Perimeter Wire Generator and Sensor | RobotShop Community*, n.d.-a)

We will have an ultrasonic sensor, an IMU (Inertial Measurement Unit) sensor, current sensors, infrared sensors, wheel encoders and microswitches to enable automation, that is, self-navigation, movement, and charging. The ultrasonic sensor will detect the presence of obstacles and bodies in motion and send a signal to the controller to slow down the movement and eventually change the course of direction. This sensor uses a light transmitter and photoelectric receiver to perform this task.[2] The front bumper of the robot will have a microswitch on either side which will change its course of direction when it gets in contact with an obstacle.

The secondary function of our machine will be vacuuming. The vacuum will remove the debris from the surface of the cobblestone after the unwanted plant growth is cut. This will keep the surface of the area neat. There will be a section attached inside the machine where the debris will be collected and can be removed manually.

Our robot will return to the charging station as soon as its battery reaches a certain set level (enough for the robot to be able to return 'home') or if the timer, set by the operator runs out. When it reaches either state, that is, needs recharging, the roller motor will stop running and the primary goal of the robot will be to get back to the station hence only the motors attached to the wheels will operate and the robot will move towards the charging station. An infrared transmitter on the charging station and a receiver on the robot will make this possible.

[2] Last Minute Engineers – Ultrasonic Sensors: https://lastminuteengineers.com/arduino-sr04-ultrasonic-sensor-tutorial/ accessed: 09.10.2021 (How HC-SR04 Ultrasonic Sensor Works & How to Interface It with Arduino, n.d.)

List of Main Components

Item Name	Qty.	Price per unit	Price	Links
Body/ Housing	1	120.0 €	120.0 €	Make Part
Rechargeable Battery	1	57.91 €	57.91 €	Amazon
Charging station	1	60.0 €	60.0 €	Make Part
Nylon Brush Motor	1	55.20 €	55.20 €	Transmotec
Main Microcontroller	1	29.75 €	29.75 €	Arduino
Vacuum and IR Microcontroller	2	9.95 €	19.9 €	SparkFun
Gears	2	11.85 €	23.70 €	Misumi
Nylon brush roller	1	40.0 €	40.0 €	Make Part
Vacuum Motor	1	22.95 €	22.95 €	Amazon
Wheels	4	20.0 €	80.0 €	Make Part
Wheel Motor	2	26.09 €	51.18 €	Amazon
IMU sensor	1	13.80 €	13.80 €	Reichelt
Shafts	2	10.0 €	20.0 €	Make Part
Perimeter Wire Generator & Sensor Kit	1	10.0 €	10.0 €	Robotshop
Infrared Transmitter	1	1.40 €	1.40 €	Reichelt
Infrared Receivers	3	1.20 €	3.60 €	Reichelt
Step down Transformer	1	9.01 €	9.01 €	Reichelt
Current Sensors	4	4.63 €	18.52 €	AZ-Delivery
Motor drivers	3	5.70 €	17.10 €	Reichelt
Voltage Regulator	2	0.20 €	0.40 €	Reichelt
Ultrasonic Sensor	1	3.80 €	3.80 €	Reichelt
Microswitches	2	3.0 €	6.0 €	Amazon
Wheel Encoder	1	2.10 €	2.10 €	Reichelt
LED lights	1	0.39 €	0.39 €	Reichelt
ON/OFF Buttons	2	0.16 €	0.32 €	Reichelt
Emergency Stop Button	1	9.10 €	9.10 €	Reichelt
Perimeter Wire	1	14.99 €	14.99 €	Amazon
Total			**691.12 €**	

Table 1 - List of components with prices

Functional Structure

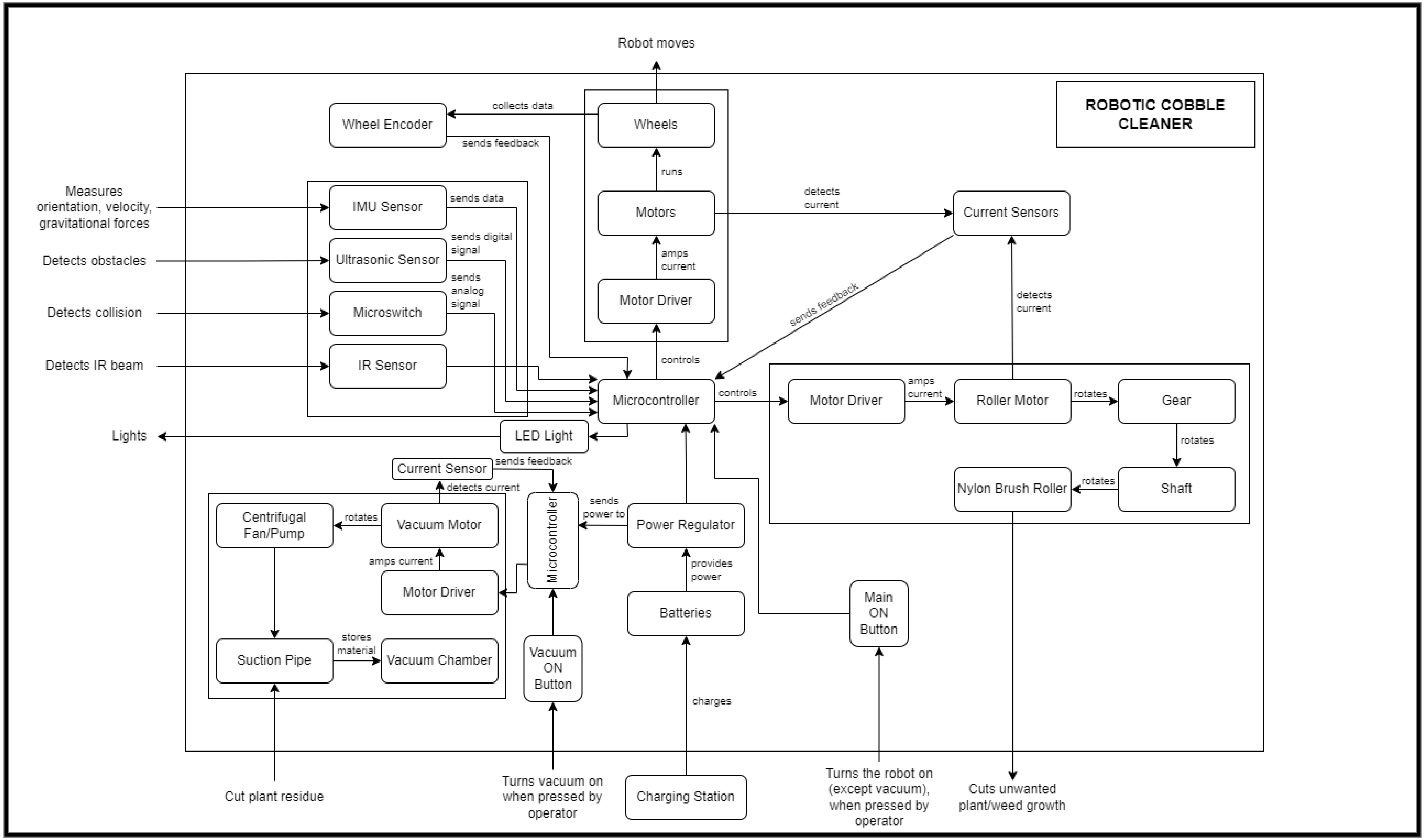


Figure 8 - Function Diagram and Interdependencies between Components

D-FMEA[3]

D-FMEA Design Failure Mode and Effects Analysis										
Robotic Cobblestone Cleaner										
						Control Methods				Recommended Action
Item	Functions	Failure Mode	Effects of Failure	Severity	Causes	Prevention Control	Occurrence	Detection	RPN (Risk Priority Number)	Action & Responsibility
Batteries	Power supply	Damaged cells, battery wear out, electrical leakage	Fires, explosions, low power supply	7	Overheating, charging fluctuations	Complete check and balance of battery health frequently	2	8	112	Avoid overcharging and draining, check for connections regularly, change the battery after the lifetime ends
Motors	Rotates the nylon brush, wheels, and vacuum fan	Unnecessary noise and vibrations, overheating, lubrication issues	Noise Pollution, rotary parts will be unable to rotate, the efficiency of the motor will reduce	8	Motor overload, voltage imbalance, lack of lubrication, excessive moisture	Proper covering of motors	3	3	72	Replacing, checking, and lubricating of motors
Shaft and Gears[4]	Rotates and transmits the power from the motor	Misalignment of gears, corrosion of shaft	The roller will not rotate	6	Thermal effects cause the shaft to expand or contract hence misalignment	Replacing the lubricant or keeping it clean	2	8	96	Keep track of the movement of the brush to detect shaft failure and proper lubrication
Nylon Brush Roller	Cuts off the unwanted plant growth	Wear and tear of the bristles	The main purpose of cutting the grass will not be fulfilled	3	Too much friction, irregular replacement of roller	Regular replacement of roller	5	9	135	Regular checking and replacement of roller
Ultrasonic Sensors	Detects obstacles & motion	The sensor might be faulty	The robot will bump into an obstacle or the moving body will lose navigation patterns	7	The sensitivity or angle may not be adjusted correctly, power outages, failure of either a transmitter or receiver component	Cleaning of the photocell, replacing the batteries, replacing the faulty sensor, attaching microswitches	2	7	98	Change the faulty sensors
IMU Sensor	Measures orientation, velocity, gravitational forces	The sensor might be faulty	A robot may lose navigation patterns, will not rotate when necessary	9	Errors in repeatability, stability, and drift	Insulate the sensor in a body during manufacture	2	4	72	Replace and repair faulty sensors
Current Sensor (Yu et al., 2018)	Detects the electric current in a wire and generates the signal respectively	The analogue voltage may go beyond the normal range	The vector control system will breakdown	6	When the attached current sensor goes outside of the normal range	Online monitoring of current sensors	4	7	168	Switch the system to tolerant vector control mode after it gets faulty
Perimeter Wire	Guides and sends signals to the robot	The wires might break/tear	The robot will move out of the boundary, and will not be able to return to the charging station	9	External factors such as animal interference, movement of vehicles over the wire	Laying down the boundary wire inside the soil	6	4	216	Avoid any movement of vehicles when the wire is above ground, keep animals away
Charging Station	Charges the batteries	Damage of components of the station	The robot will not be charged hence will not function	9	External factors such as harsh climate (rain, hailstorm, and snowfall), animal interference	Creating an insulation body for protection	3	6	162	Keeping the charging station away from the external environment when not in use and during harsh climate
Vacuum System	Collects and stores the debris	No information when the vacuum bag is full, clogging	The machine will not collect grass particles when the vacuum bag is full or clogged	3	The vacuum might stop functioning	Vacuum bag to be checked and emptied regularly	4	9	108	Remove the debris from the filters and regular checks
Wheels	Moves the robot	They may lose traction and experience wear/tear	The robot will be unable to move appropriately	6	Rough cobblestone surfaces, debris, sharp particles, long usage of robot	Regular checking and replacing of tires	2	7	84	Replace the tires

Table 2 - Design Failure Mode and Effects Analysis (D-FMEA)

[3] iQASystem – DFMEA: Complete Guide To The Design FMEA https://www.iqasystem.com/news/dfmea/ accessed: 22.10.2021 (*DFMEA - Complete Guide to the Design FMEA | IQASystem*, n.d.)
[4] Amarillo Gear Service – Important things you should know about gear failure https://www.amarillogearservice.com/8-important-things-know-gear-failure/ accessed: 23.10.2021 (*8 Important Things You Should Know About Gear Failure*, n.d.)

D-FMEA

D-FMEA Design Failure Mode and Effects Analysis										
Robotic Cobblestone Cleaner										
						Control Methods				Recommended Action
Item	Functions	Failure Mode	Effects of Failure	Severity	Causes	Prevention Control	Occurrence	Detection	RPN (Risk Priority Number)	Action & Responsibility
Wheel encoders[5]	Controls the motor rotation and rotation angle	Loose connections, phase fluctuations, module fault	There will be no feedback from the wheels back to the controller	5	A bent shaft which is no longer sitting on bearings properly	Checking the connections and alignment of the encoder and the shaft	4	7	140	Replace the encoders when the machine operates erratically
Voltage regulator[6]	Maintains a constant voltage	The regulator can blow if the motor is disconnected	The robot will not operate	8	Due to poor contact with the battery terminal	Using a shunt diode, the voltage should be kept within the prescribed range	1	7	56	Replace the voltage regulator
Microcontroller[7]	Controls input and output devices	Constant disruption of power source might damage the microcontroller	The robot will not perform its functions	7	Constant disruption of power source	Using a stable voltage regulator and providing constant power input	2	8	112	Providing a constant power input
LED	Lights	Improper or loose pin connections damaged LED	The LED will not respond to the controller	2	Improper or loose pin connections damaged LED	Proper connection of pins	1	9	18	Frequent checking of the robot by the user to ensure the LED is lighting the appropriate colours
Body	Protects and houses the electrical and mechanical components of the robot	Structural damage	The performance of the robot will decrease electric shock	8	Improper handling and bad design, external factors such as harsh weather, animal interference	Investing in the proper design of the body in terms of materials and time	2	9	144	Proper handling of the robot and keeping animals away

Table 3 - Design Failure Mode and Effects Analysis (D-FMEA) - continued

[5] PLCS.net – Forum - http://www.plctalk.net/qanda/showthread.php?t=98592 accessed: 30.10.2021 (*Unusual Encoder Failure Modes ? - PLCS.Net - Interactive Q & A*, n.d.)
[6] MVOrganizing.org – What causes voltage regulators to go bad - https://www.mvorganizing.org/what-causes-a-voltage-regulator-to-go-bad/ accessed: 30.10.2021 (*What Causes a Voltage Regulator to Go Bad? – MVOrganizing*, n.d.)
[7] Altium – How microcontroller failure mode effects a system - https://resources.altium.com/p/microcontroller-failure-modes-why-they-happen-and-how-to-prevent-them accessed: 30.10.2021 (*Microcontroller Failure Modes: Why They Happen and How to Prevent Them* | *CircuitMaker*, n.d.)

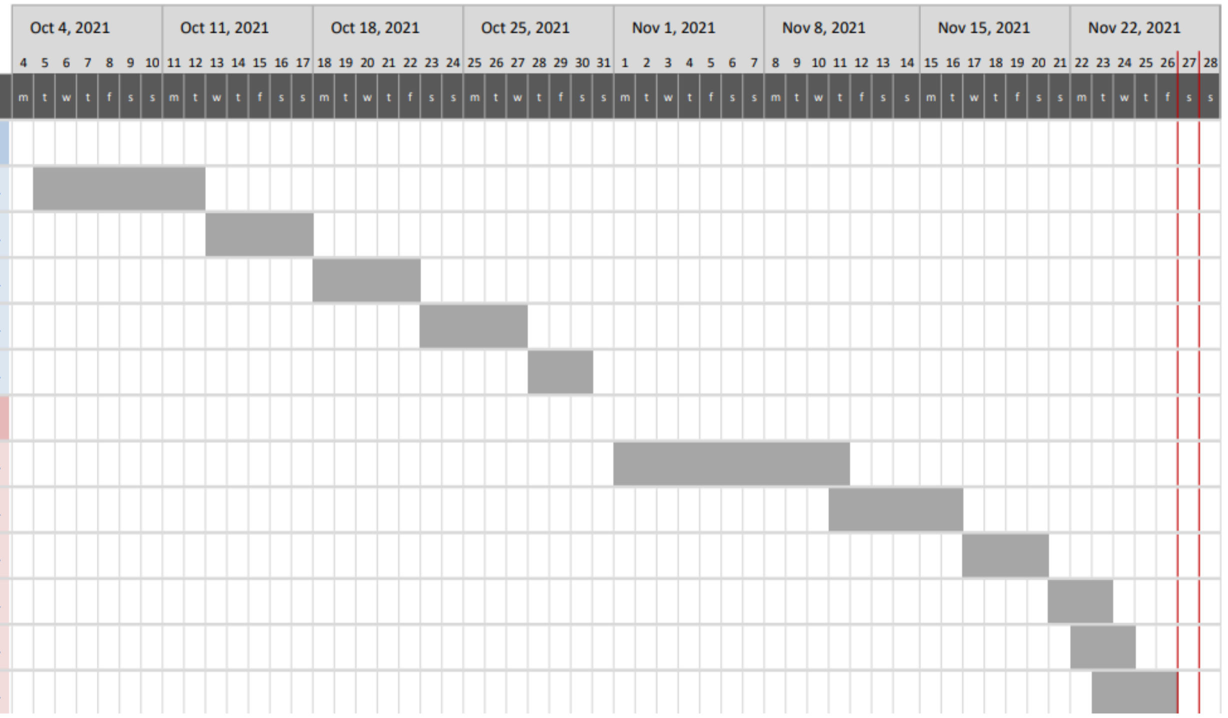
Project Plan

GANTT-Chart[8]

Project Start: Tue, 05.10.2021

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Concept Design				
Project Plan	Abdul, Anirudh, Banza, Jibran	100%	05.10.21	12.10.21
Product Concept	Abdul, Anirudh, Banza, Jibran	100%	13.10.21	17.10.21
Functional Structure	Anirudh, Banza	100%	18.10.21	22.10.21
Marketing Decisions	Abdul, Anirudh, Banza, Jibran	100%	23.10.21	27.10.21
D-FMEA Analysis	Abdul, Anirudh, Banza, Jibran	100%	28.10.21	30.10.21
Product Design				
3D Model (CAD)	Abdul, Anirudh, Jibran	100%	01.11.21	11.11.21
UML	Anirudh, Banza	100%	11.11.21	16.11.21
Circuit Diagram	Anirudh, Banza	100%	17.11.21	20.11.21
Make-or-Buy Decisions	Abdul, Jibran	100%	21.11.21	23.11.21
Technology selection for "make" parts	Abdul, Anirudh, Banza, Jibran	100%	22.11.21	24.11.21
Requirments manual for "buy" (CotS) parts	Abdul, Anirudh, Banza, Jibran	100%	23.11.21	26.11.21



Project Start: Tue, 05.10.2021

Display Week: 9

TASK	ASSIGNED TO	PROGRESS	START	END
Project Documentation				
Technical Drawings for main assembly	Abdul, Anirudh	100%	29.11.21	03.12.21
Pseudo-Code	Anirudh, Banza	100%	04.12.21	07.12.21
Bill of Material (Mechanical or Electrical)	Abdul, Anirudh, Banza, Jibran	100%	08.12.21	11.12.21
Production planning (especially: capacity calculation)	Abdul, Anirudh	100%	12.12.21	15.12.21
Cost Calculation	Abdul, Anirudh	100%	16.12.21	19.12.21
Documentation	Abdul, Anirudh, Banza, Jibran	100%	20.12.21	24.12.21
Product Presentation				
Ideas (brain storming)	Abdul, Anirudh, Banza, Jibran	20%	31.12.21	01.01.22
Video Concept	Abdul, Anirudh, Banza, Jibran	0%	02.01.22	04.01.22
Video Making	Abdul, Anirudh, Banza	0%	05.01.22	08.01.22
Video Editing	Abdul, Anirudh, Banza	0%	09.01.22	12.01.22
Presentation	Abdul, Anirudh, Banza, Jibran	0%	13.01.22	17.01.22

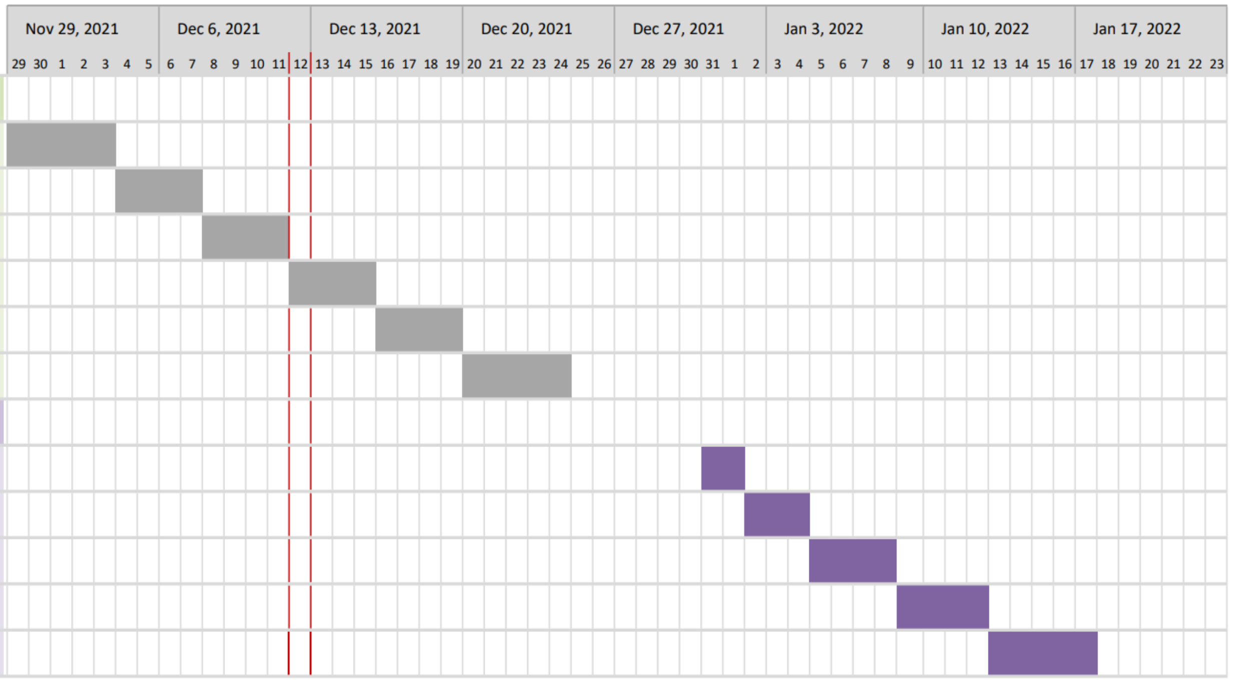


Figure 9 - GANTT Charts

[8] Office.com – Simple Gantt Chart - https://templates.office.com/en-us/simple-gantt-chart-tm16400962 accessed: 01.11.2021 (*Simple Gantt Chart*, n.d.)

Work Packages

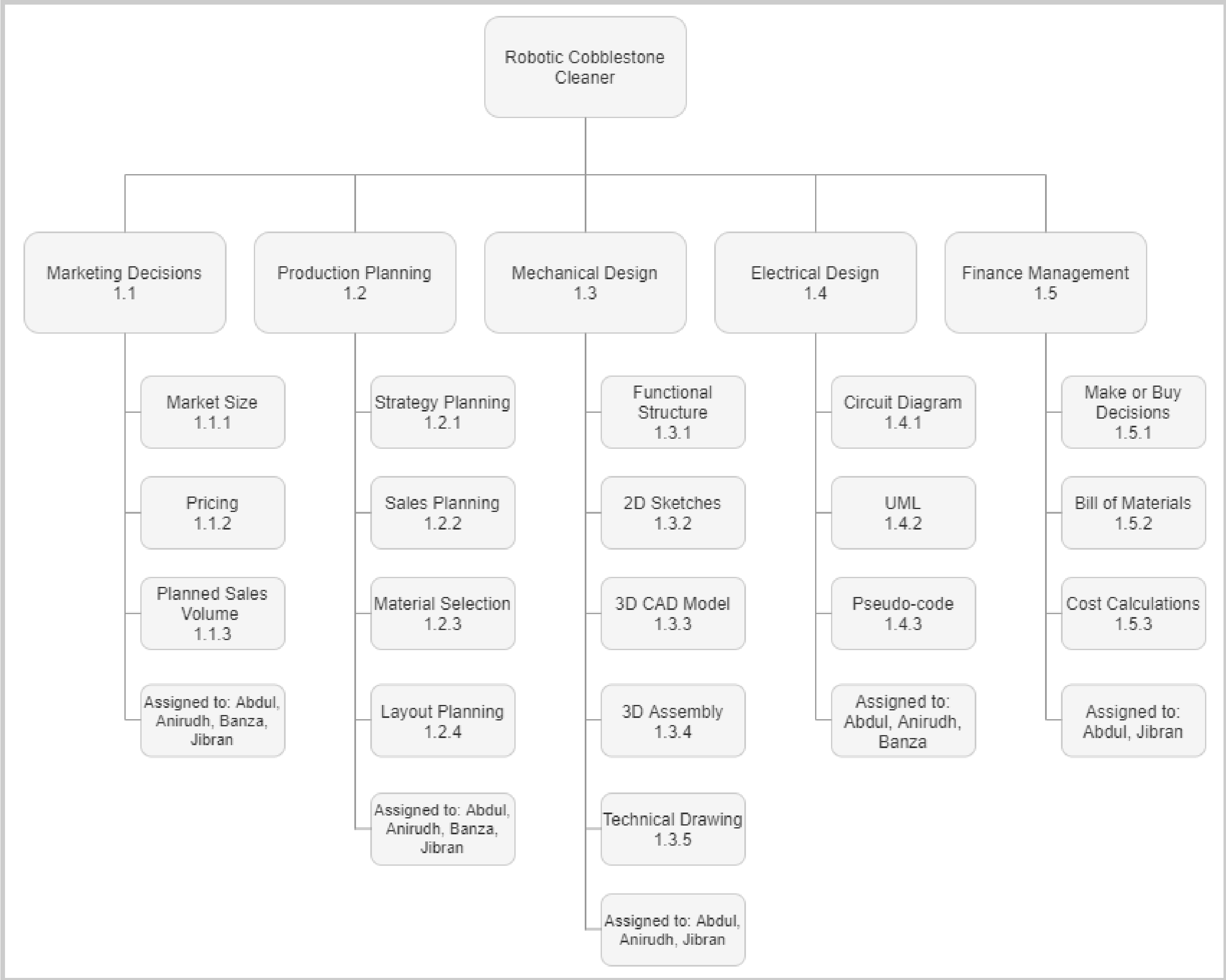


Figure 10 - Work packages and responsibilities

Make/Buy Decisions

Make Parts

Item #	Part Name	Description	QTY.	Material	Technology Selection
1	Base Plate	It is where all the electrical and mechanical components of the robot are placed.	1	ABS	3-D printing
2	Bearing Cap	It is a removable disk that prevents unwanted particles from entering the place where the bearings are mated.	2	ABS	Injection Moulding
3	Bearing Inner Cover	It is the standard cover to protect personnel from injury and keep contaminants out.	4	ABS	Injection Moulding
4	Bumper	It is used to prevent the front part of the robot from being damaged when in contact with obstacles.	1	PUR	Injection Moulding
5	Charging Dock Base	It is where the electrical components in the charging station are placed.	1	ABS	Injection Moulding
6	Charging Dock Control Unit	It is used to activate and control the charging station.	1	ABS	Injection Moulding
7	Charging Dock Control Unit Lid	It is used to cover the charging station control unit box.	1	ABS	Injection Moulding
8	Charging Dock Port	It connects the robot to the charging station.	2	Brass	Sand and Die Casting
9	Charging Port	It is used to charge the robot.	2	Brass	Sand and Die Casting
10	Control Unit Box - Vacuum	It controls the pump operation to maintain the pre-set vacuum level in a remote vacuum chamber.	1	ABS	Injection Moulding
11	Control Unit Box Lid - Vacuum	It is used to cover the Vacuum Control Unit Box.	1	ABS	Injection Moulding
12	Control Unit Box Lid - Main	It is used to cover the Main Control Unit Box.	1	ABS	Injection Moulding

13	Control Unit Box Main	It contains all the electrical components to control and monitor the mechanical processes.	1	ABS	Injection Moulding
14	Housing	It protects and houses all the electrical and mechanical components of the robot.	1	ABS	3-D printing
15	Hub For Wheels	It is the central part of the wheel, which is connected to the wheel shell, via the hex screws through which the axle is fitted that enables the wheel to freely spin on the set of bearings.	2	PPE	Injection Moulding
16	Hub For Wheels	It is used to fix wheels to the shaft using screws.	4	PPE	Injection Moulding
17	Nylon Brush Roller	It is used for cutting the overgrown grass between the cobblestones.	1	Nylon	Injection Moulding & Gluing
18	Rear Axle Cover	It is used to cover up the rear wheel axle.	1	ABS	Injection Moulding
19	Roller Bushing	It is used with the rotating shaft inside the nylon brush to have better efficiency and reduce noise and vibrations.	2	ABS	Injection Moulding
20	Roller Cover	It is used to cover the nylon brush roller so that the dust particles do not affect the functionality of other components.	1	ABS	Injection Moulding
21	Roller Motor - Clamp	It is used to support the motor in charge of the Nylon Brush Roller.	1	ABS	Injection Moulding
22	Roller Motor Shaft Extension	It is used to connect the shaft and gear which are mated through the key.	1	Carbon Steel	CNC Turning
23	Roller Motor Support	It is used to support the motor in charge of the Nylon Brush Roller.	1	ABS	Injection Moulding
24	Shaft - Rear Wheel	It connects the two rear wheels.	1	Carbon Steel	CNC Turning
25	Shaft Front Wheel	It is used to transmit power to the wheels from gears and motors.	2	Carbon Steel	CNC Turning

26	Vacuum Chamber	It is a section in the vacuum system where the debris inserted by the vacuum is stored before being removed by the user.	1	ABS	Injection Moulding
27	Vacuum Chamber Lock	It locks the vacuum chamber to the base plate.	1	ABS	Injection Moulding
28	Vacuum Fan	It is used to cover the Main Control Unit Box.	1	ABS	Injection Moulding
29	Vacuum Motor Support	It is used to support the motor in charge of the vacuum.	1	ABS	Injection Moulding
30	Vacuum Suction Pipe	It is used to supply an evenly distributed flow of air to the pump suction with sufficient pressure to pump the debris.	1	ABS	Injection Moulding
31	Wheel	They are connected to an axle that is following the front wheels. They do not receive any power on their own.	2	ABS	Injection Moulding
32	Wheel	They pull the robot as the power from the motors connected through high-torque gears is delivered to them.	4	PPE	Injection Moulding
33	Wheel	They pull the robot as the power from the motors connected through high-torque gears is delivered to them.	1	PPE	Injection Moulding
34	Wheel Motor Shaft Extension	It is used to connect the shaft and gear which are mated through the key.	1	Carbon Steel	CNC Turning
35	Wheel Motor Support	It is used to connect the mating gears that enable high torque transmission to turn the wheels.	1	Carbon Steel	CNC Turning
36	Wheel Motor Support - Right	It is used to connect the mating gears that enable high torque transmission to turn the wheels.	1	Carbon Steel	CNC Turning
37	Wheel of Wheel Encoder	It is used to record linear movements and convert them into speed or position values.	1	ABS	Injection Moulding

Table 4 - Make Parts List with Descriptions

Buy Parts

#	Item Name	Description	QTY	Price per Unit	Total Price	Link
1	ACS712	It is installed to measure the current flowing through the circuit and send feedback to the microcontroller	3	€ 5.79	€ 17.37	AZ-Delivery
2	Arduino Mega 2560	It is used to control and program the electronic components	1	€ 29.75	€ 29.75	Arduino
3	Arduino Pro Mini	It is used to control the functionality of the vacuum system	1	€ 9.95	€ 9.95	Sparkfun
4	Arduino Pro Mini	It is used to program and activate the Infrared Transmitter	1	€ 9.95	€ 9.95	Sparkfun
5	Battery	It is used to supply power to the whole system	1	€ 57.91	€ 57.91	Amazon
6	Circlip DIN 471 - 10 X 1 (Plain Carbon Steel)	It is used to fasten shafts/axle and to lock the movement of shaft/axle in axial directions	10	€ 0.75	€ 7.50	Amazon
7	DIN 7984 - M4 X 16 16C (Plain Carbon Steel)	It is used as a fastening element	50	€ 0.31	€ 15.72	Amazon
8	DIN 7991 - M3 X 16 16C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.08	€ 7.89	Amazon
9	DIN 7991 - M3 X 20 20C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.06	€ 5.87	Distrelec
10	DIN 7991 - M3 X 30 30C (Plain Carbon Steel)	It is used as a fastening element	50	€ 0.16	€ 7.93	Amazon
11	DIN 912 M2 X 10 10C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.04	€ 3.97	Distrelec
12	DIN 912 M2.5 X 6 6C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.04	€ 3.77	Distrelec
13	DIN 912 M2.5 X 8 --- 8C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.04	€ 3.77	Distrelec

14	DIN 912 M2.5 X 8 8C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.04	€ 3.77	Distrelec
15	DIN 912 M2.5 X 8 8N (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.04	€ 3.77	Distrelec
16	DIN 912 M3 X 10 --- 10C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.05	€ 4.52	Distrelec
17	DIN 912 M3 X 16 16C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.06	€ 5.65	Distrelec
18	DIN 912 M3 X 8 8C (Plain Carbon Steel)	It is used as a fastening element	10	€ 0.55	€ 5.53	Amazon
19	DIN 912 M4 X 16 16C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.08	€ 8.08	Distrelec
20	DIN 988-3X6X1 (Plain Carbon Steel)	It is used as a fastening element	25	€ 0.25	€ 6.25	Amazon
21	DIN EN ISO 7046-1 - M3 X 10 - Z - 10C (Plain Carbon Steel)	It is used as a fastening element	200	€ 0.01	€ 2.88	Distrelec
22	DIN Spur Gear 1M 20T (POM)	It is used to reduce/increase the power supplied from the motor to the shafts	3	€ 1.88	€ 5.64	Norelem
23	DIN Spur Gear 1M 25T (POM)	It is used to reduce/increase the power supplied from the motor to the shafts	2	€ 1.99	€ 3.98	Norelem
24	DIN Spur Gear 1M 40T (POM)	It is used to reduce/increase the power supplied from the motor to the shafts	1	€ 2.57	€ 2.57	Norelem
25	IMU Sensor MPU9250	It measures orientation, force, magnetic field, angular velocity, rate, and acceleration and sends the results to the microcontroller for feedback	1	€ 13.80	€ 13.80	Reichelt
26	Infrared Receiver	It is used to receive IR signals sent by the charging station to travel back when recharging is required	3	€ 1.40	€ 4.20	Reichelt
27	IR Transmitter	It is used in the charging station to emit the rays towards Infrared receivers on	1	€ 1.40	€ 1.40	Reichelt

		the robotic cobble cleaner				
28	L298N Motor Driver	It is connected to allow both the control and power supply of the vacuum, wheel, and roller DC motor	3	€ 5.70	€ 17.10	Reichelt
29	LM393 Motor Speed Measuring Sensor Module	It measures the speed of wheels and sends feedback to the microcontroller	1	€ 1.40	€ 1.40	Amazon
30	Microswitch	It is used in this robot to detect when a robot makes physical contact with an obstacle and sends feedback to the controller to change the course of direction	2	€ 3.00	€ 6.00	Amazon
31	Perimeter Wire Generator Board	It sends signals to the perimeter wire sensor on the robot to prevent it from crossing the perimeter wire	1	€ 8.00	€ 8.00	RobotShop
32	Tapping Screw Din 7049-St2.9X6.5-F-H-N (Plain Carbon Steel)	It is used as a fastening element	200	€ 0.03	€ 5.09	Distrelec
33	Tapping Screw DIN 7049-ST4.8X19-F-H-C (Plain Carbon Steel)	It is used as a fastening element	100	€ 0.06	€ 6.21	Distrelec
34	Transformer	It converts the high primary voltage to a low secondary voltage	1	€ 9.01	€ 9.01	Reichelt
35	Ultrasonic Sensor	It is used to detect obstacles and send feedback to the microcontroller to avoid collision	1	€ 3.80	€ 3.80	Reichelt
36	Vacuum Motor	It is rotated at high speed and is used to suck plant waste through the suction pipe into the chamber	1	€ 35.00	€ 35.00	Transmotec
37	Voltage Regulator	It is used to create and maintain a fixed output voltage, irrespective of changes to the input voltage	2	€ 0.20	€ 0.40	Reichelt
38	Wheel Motor	They control the rotary motion and the speed of the front wheels	2	€ 26.09	€ 52.18	Amazon

Table 5 - Buy Parts List with Descriptions and Prices

Functional Principles

FINAL ASSEMBLY.SLDASM

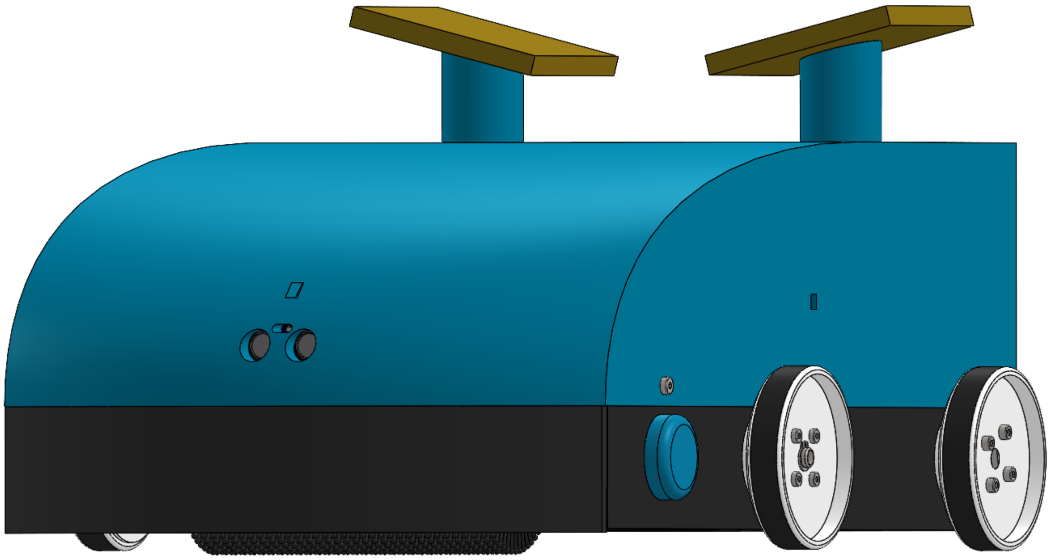


Figure 11 - Autonomous Robotic Cobblestone Cleaner

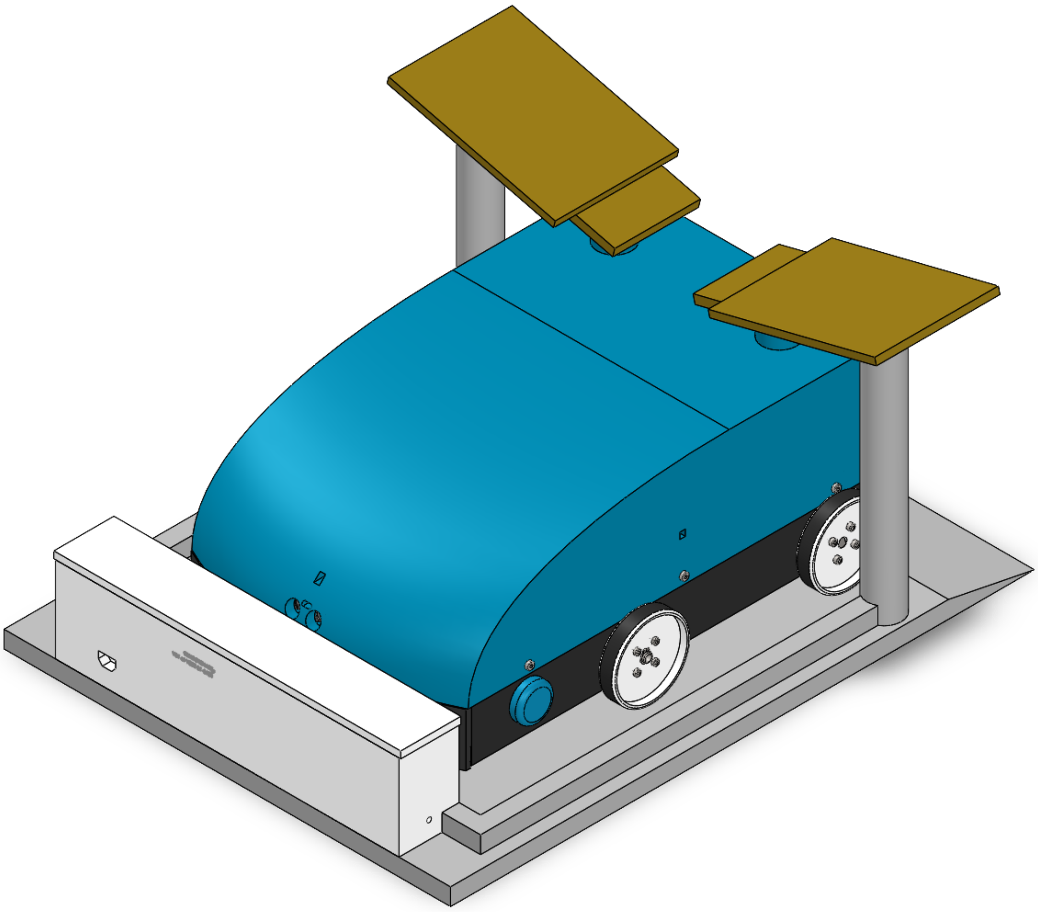


Figure 12 - Robot inside the Charging Station

Main Control Unit Box

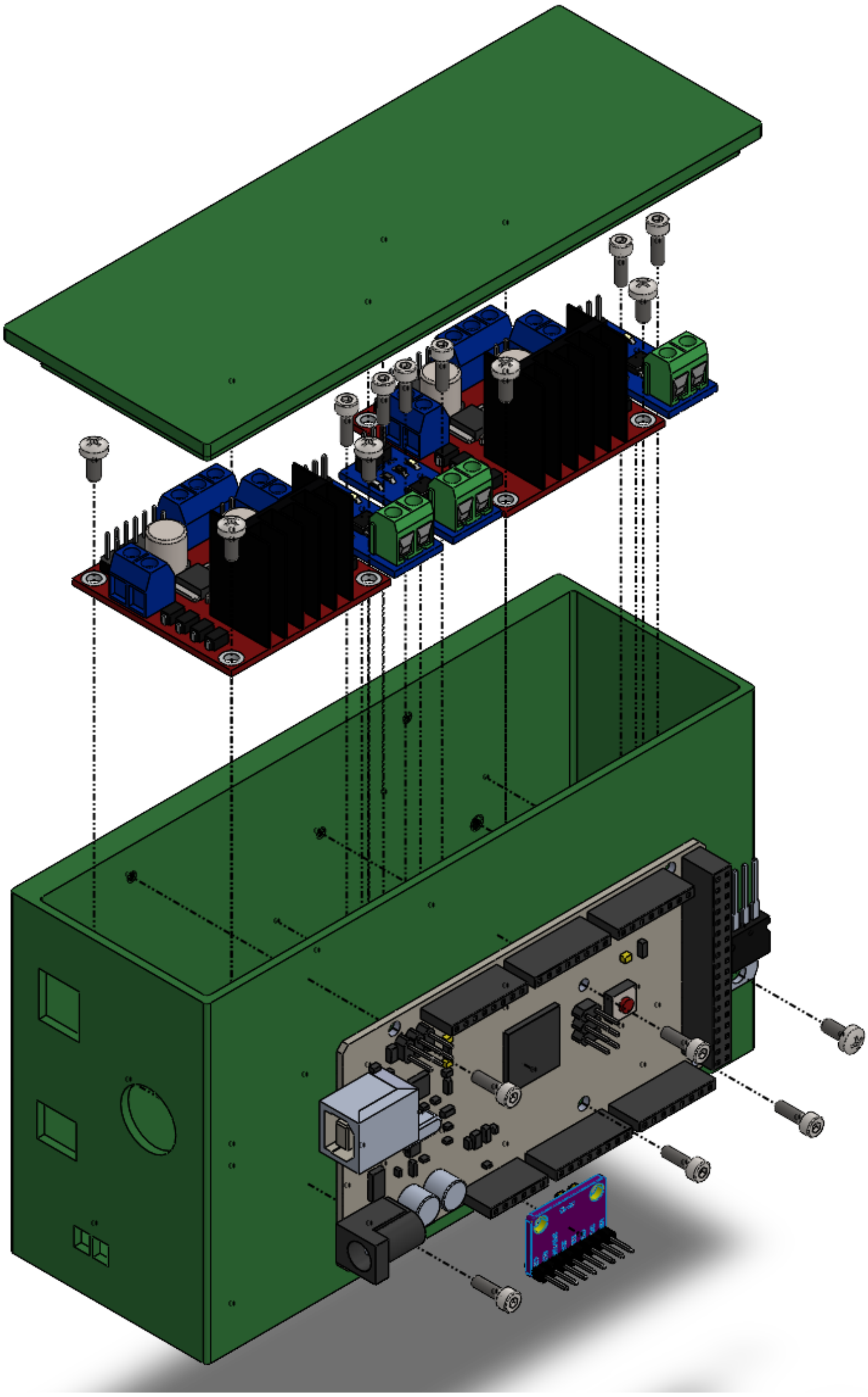


Figure 13 - Main Control Unit Box

The Main Control Unit contains an Arduino Mega 2560, an LM317 Voltage Regulator, two L298N Motor Drivers and two current sensors. All the electrical components will be screwed inside the Control Unit Box that is covered with a Lid. The Control Unit Box will then be screwed to the Base Plate.

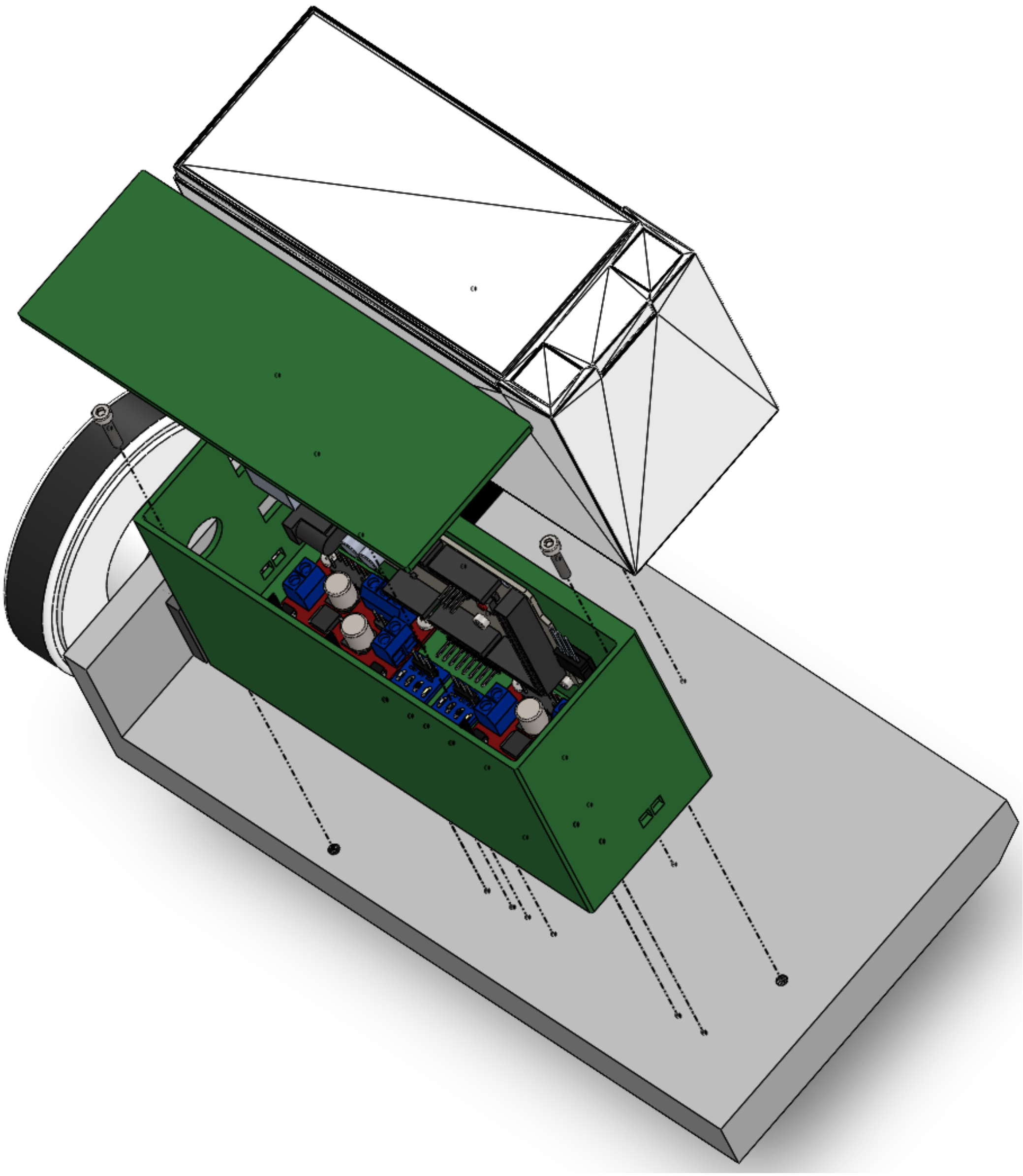


Figure 14 - Main Control Unit Box and Battery Assembled with Base Plate

Functional principles of components of main control unit box:

Arduino Mega 2560 (Main microcontroller board) – The Arduino Mega 2560 is a microcontroller board based on the ATmega2560. The function of this board is to control and program the electronic components, that is, input and output devices. It receives and reads data signals from input devices and controls and activates the output devices. The input devices are an ultrasonic sensor, IMU sensor, microswitches, wheel encoder, receiver and current sensor and the output devices are the wheel motors, Nylon brush roller motor and the RGB LED. This Arduino board was selected due to the many I/O lines, amount of sketch memory and RAM it provides. Our robot requires PWM output pins to run certain output devices like the motors and this board satisfies this demand. It is also highly recommended for robotics projects with many components.

LM317 Voltage Regulator[9] – The LM317 device is an adjustable three-terminal positive-voltage regulator capable of supplying more than 1.5A over an output-voltage range of 1.2V to 37 V. It is used in this robot to create and maintain a fixed output voltage, irrespective of changes to the input voltage. It is used in the power supply circuit to take the 12V voltage from the battery and supply 8V to the microcontroller. It is also used in the charging station circuit in charging the battery. The LM317L voltage regulator has an input voltage range of 4.25V to 40V and an output voltage range of -0.3V to 40V. It is capable of supplying an output current of more than 100mA, uses two external resistors to set the output voltage, has a load regulation accuracy of 1% and has an operating temperature of 0°C to 25°C. It includes current limiting, thermal overload protection, and safe operating area protection. Overload protection remains functional even if the adjusted terminal is disconnected.

L289N Motor Driver[10] – This is a Dual H-Bridge Motor driver which allows speed and direction control of two DC motors at the same time. The module can drive the DC motors of voltages between 5V-35V with a peak current up to 2A.

ACS712 Current Sensor[11] – A current sensor is installed to measure the current flowing through the circuit and send feedback to the microcontroller. An increase in the amount of current above its requirement leads to overload and can damage the device hence current measurement is necessary for the proper operation of devices. In the robot, current sensors are used to measure the flow of current in the motors. This sensor can take note of current flow without affecting the system performance. This sensor can measure current over a wide range of -30A to +30A.

MPU2950 IMU Sensor Module[12|13] – An Inertial Measurement Unit (IMU) is a sensor that is a combination of a Gyroscope, Magnetometer, and Accelerometer. It measures orientation, force, magnetic field, angular velocity, rate, and acceleration. This robot uses an IMU to measure these variables and sends the results to the microcontroller for feedback. The MPU2950 IMU is a 9-axis motion tracking device that combines a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer. This module features three 16-bit ADC for digitizing the gyroscope outputs, three 16-bit ADC for digitizing the magnetometer output and three 16-bit ADC for digitizing the gyroscope outputs. It was selected for this project due to its low power consumption, low cost, wide detecting range, and high performance.

After the Main Control Unit Box is screwed to the Base Plate then the Battery will be placed next to it onto the base plate.

12V Lead-acid Battery – The Lead-acid battery is a rechargeable battery that is used to supply power to the whole system. This battery delivers large amounts of electricity and high currents due to its large power-to-weight ratio. This battery has a good life cycle and cycle stability due to special lead plates and a special electrolyte which makes it perfect for its purpose in this machine. It has high cycle stability, a low self-discharge rate and a low internal resistance making it highly powerful. This battery in our robot is charged using a charging station installed in operation.

[9] (*LM317 Voltage Regulator - Texas Instruments* | *DigiKey*, n.d.)
[10] (*L298N Motor Driver - Arduino Interface, How It Works, Codes, Schematics*, n.d.)
[11] (*ACS712 Current Sensor - Working Principle and Applications*, n.d.)
[12] (“Miniature Inertial Measurement Unit,” 2018)
[13] (IMU Sensor: Working Principle, Usage, and Its Applications, n.d.)

Vacuum Control Unit Box

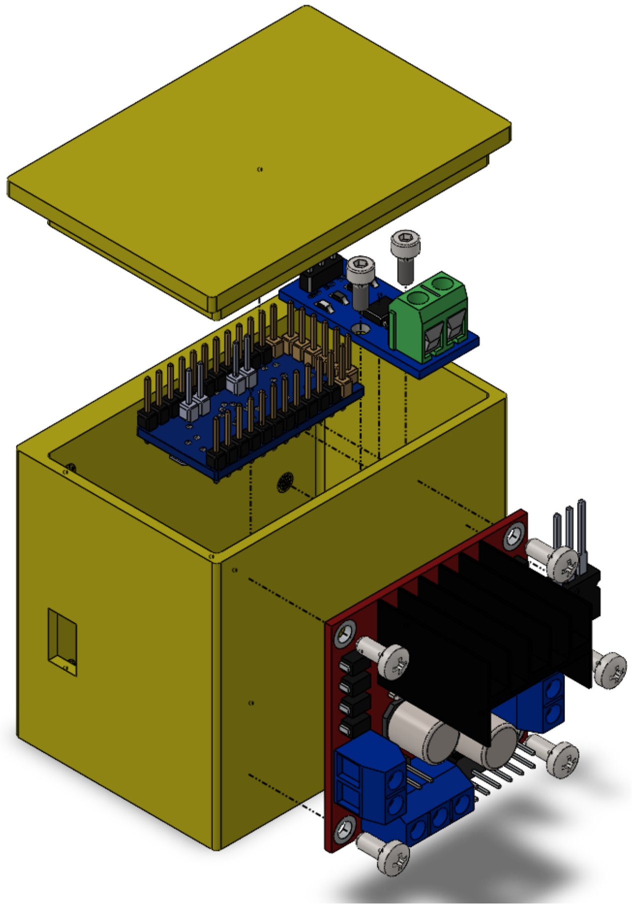


Figure 15 - Vacuum Control Unit Box Assembly

The Vacuum Control Unit Box contains an Arduino Pro Mini, one L298N Motor Drivers and one current sensor to control the vacuum motor. All the electrical components will be screwed inside the Control Unit Box that is covered with a lid. Here, an extra microcontroller is used because the vacuum is a secondary function of our robot and as per our design, it should be turned on/off manually which should not interfere with the main control unit. The control unit box will then be screwed to the base plate.

Functional principles of components of main control unit box:

Arduino Pro Mini – The Arduino Pro Mini is a microcontroller board based on the ATmega328. The function of the first board is to control the functionality of the vacuum system with the vacuum motor as its main output device as well as a current sensor that is connected to detect the current flow from the motor and send feedback to the board. The second board is used to program and activate the Infrared Transmitter; hence its main output device is the Infrared Transmitter. This board was selected due to its low cost and small size which is adequate for the vacuum system and IR transmitter. It has PWM pins that are required to run the vacuum motor.

L289N Motor Driver [10] | ACS712 Current Sensor [11]

Front Wheel Motor Assembly

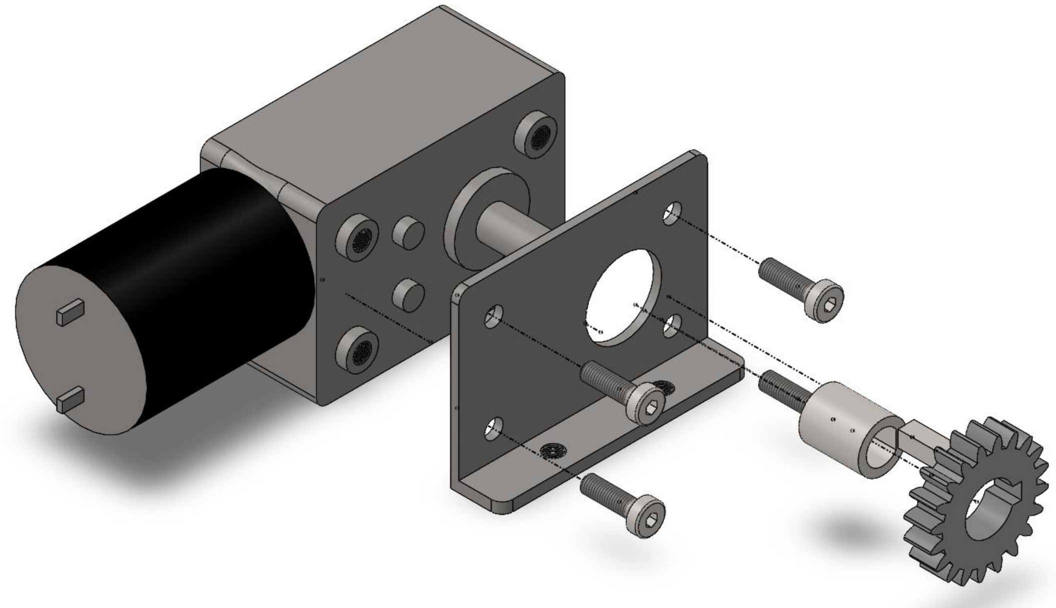


Figure 16 - Front Wheel Motor Assembly

The DC 12V Reversible 6RPM High Torque Turbo Screw Gear DC Motor is connected to the front wheels using parallel Spur gears of Ratio 1:0.8 for High torque and Low RPM (4.8 RPM) for the smooth forward movement of the robot. The DC Motor shaft is connected to the gears through a shaft extension via a key in between the shaft extension and the gear with shaft support screwed to the motor for easy assembly.

Functional principles of the components of the front motor assembly:

Wheel DC Gear Motor – These wheel motors control the rotary motion and the speed of the front wheels. In-wheel motor systems replace the transmission, driveshafts, axles and differentials normally used hence reducing energy losses and the bulk. This also improves wheel control. An electromagnetic field is generated when power is applied to the stationary coils on the inside of the wheel causing the outer part of the motor to follow it, hence turning the attached wheel. Two DC gear motors attached to the two front wheels are used for this robot. Each motor has a voltage of 12V provided by the motor driver and a speed of 6RPM and is further reduced to 4.8 RPM using gears. This motor has high precision metal transmission, low speed, low noise, a large torque, and long service life to run the wheels. It has low heat and loss and is efficient.

Shaft Extension – It is fitted into the butt of the DC Motor Shaft and underneath the grip to extend shaft length which is connected to the gears via the key seated in the keyways of the shaft extension and the spur gear.

Spur Gears (1:0.8) – Spur Gears transmit motion and high torque from the motor to the shaft to turn the wheels. The motor here supplies high torque to overcome the internal friction from a standstill.

Wheel Motor Support – To fix the motor in a certain position with the base plate.

Front Wheel Assembly with Motor and Base Plate

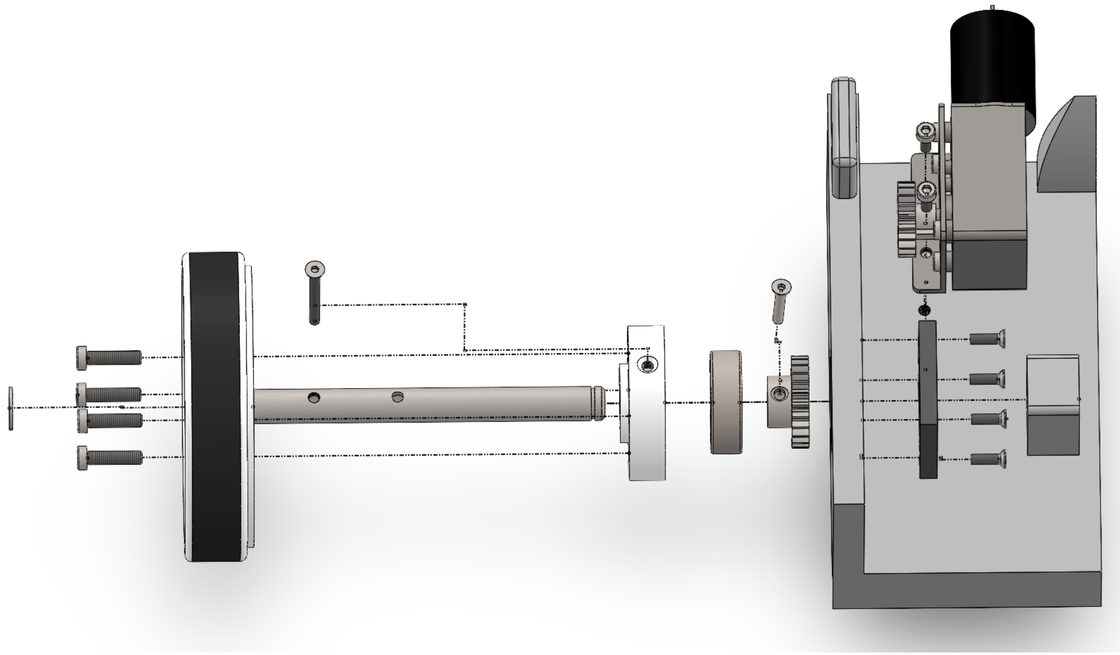


Figure 17 - Front Wheel with Motor with the Base Plate

The Wheel is connected to the hub via the shaft that has a bearing to assist the wheel rotation. The shaft is inserted inside the base plate with a bushing screwed on the base plate to reduce friction between the rotating shaft and the base plate. Furthermore, the spur gears are mated in parallel with the shaft and the motor for power transmission. Retaining rings are placed on the shaft at different positions to hold the wheel and gear on the shaft.

Functional principles of the components of the front wheel assembly with the motor:

Wheel - Wheels are used to move the robotic body over the rough cobblestones.

Shaft – A rotating machine element used to transmit power from the DC Motor. Shafts carry gears to transmit rotary motion and power via mating spur gears.

Bearing – A mechanical element used to reduce friction between the rotating shaft and the baseplate.

Hub – It keeps the wheel attached to the base plate and enables the wheels to turn freely. Furthermore, it integrates the bearings and the surrounded components.

Deep Groove Ball Bearing – It is used to accommodate radial and axial loads in both directions. They have a low coefficient of friction and a high-speed limit.

Roller with Shaft Assembly

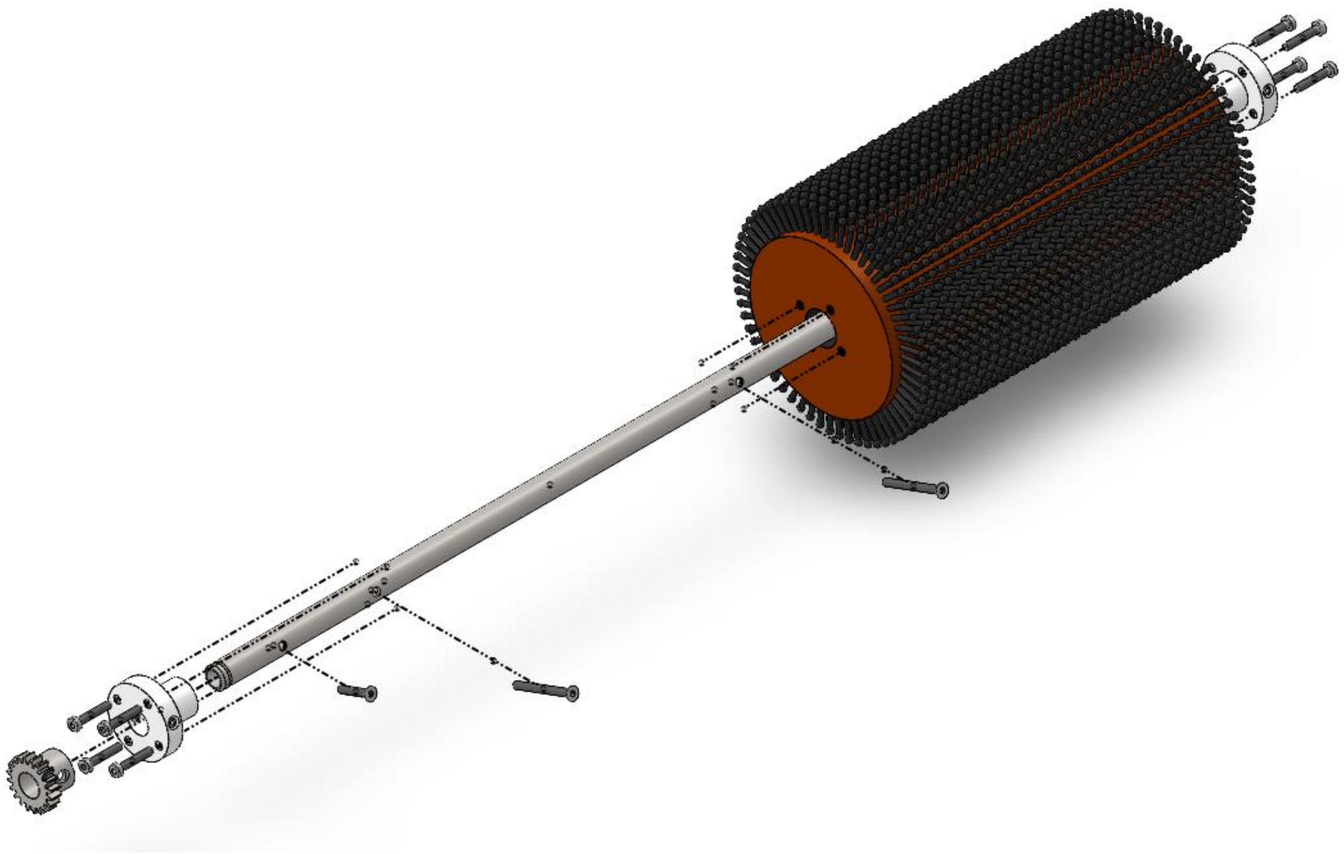


Figure 18 - Roller Assembly with Shaft

The hollow shaft is inserted inside the nylon brush roller. The nylon brush roller is supported and fixed to the shaft by the use of hubs screwed with the shaft in the radial direction and with the roller in the axial direction. The hollow shaft is also carrying the spur gear which helps the roller rotate and cut down the overgrown grass between cobblestones. This assembly is then fixed with a base plate and motors.

Functional principles of the components of roller-shaft assembly:

Hub – It keeps the roller attached to the base plate and enables the roller to rotate freely, to cut down grass and clean cobblestones.

Gears – Module-1, 20-teeth. They are rotated by the gear from the roller motor and are overloaded to help rotate the roller at twice the speed provided by the motor to help facilitate the function of the robot efficiently.

Shaft – Here shaft helps integrate all the parts with the base plate and bearings along with screw tightening.

Roller-Shaft Assembly with Base Plate

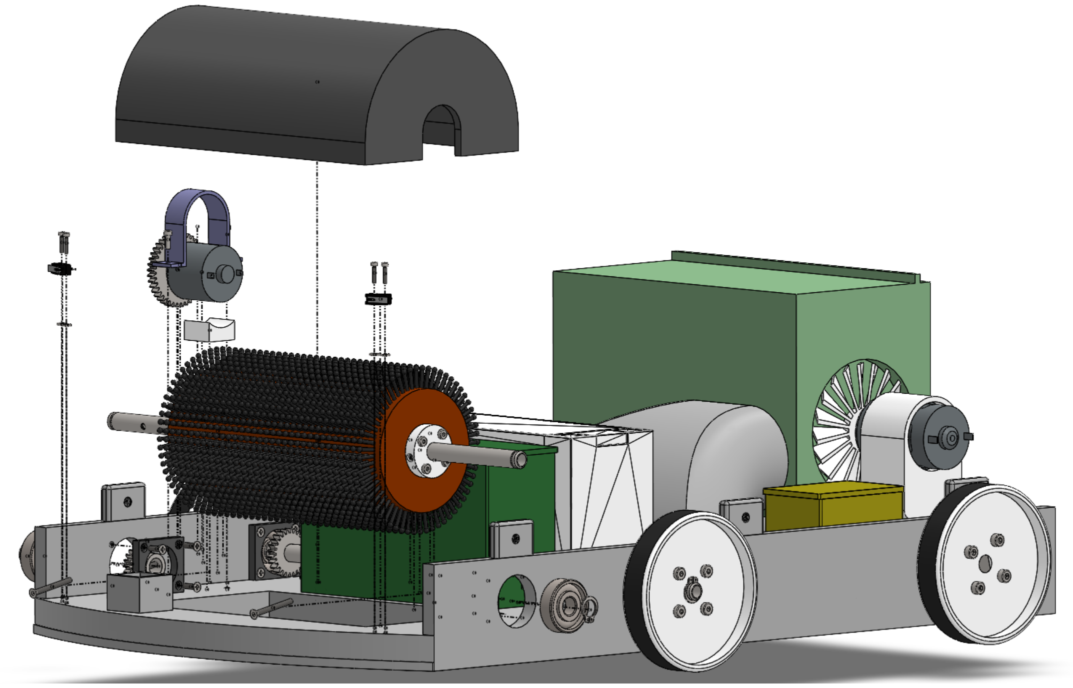


Figure 19 - Roller and Roller Motor Assembly with Base Plate

The Nylon Brush Roller is mounted onto a hollow shaft that is fixed by a hub from either side of the roller through screws. The roller is covered with a cover from the top which is glued to the base. The roller shaft carries the spur gears mated in parallel that is connected to the 12V DC Motor for high power transmission for the Nylon brush Roller to rotate at High RPM. The bushing is screwed on the baseplate and a bearing is placed on the shaft to reduce friction. Microswitches are screwed at the front part of the base plate.

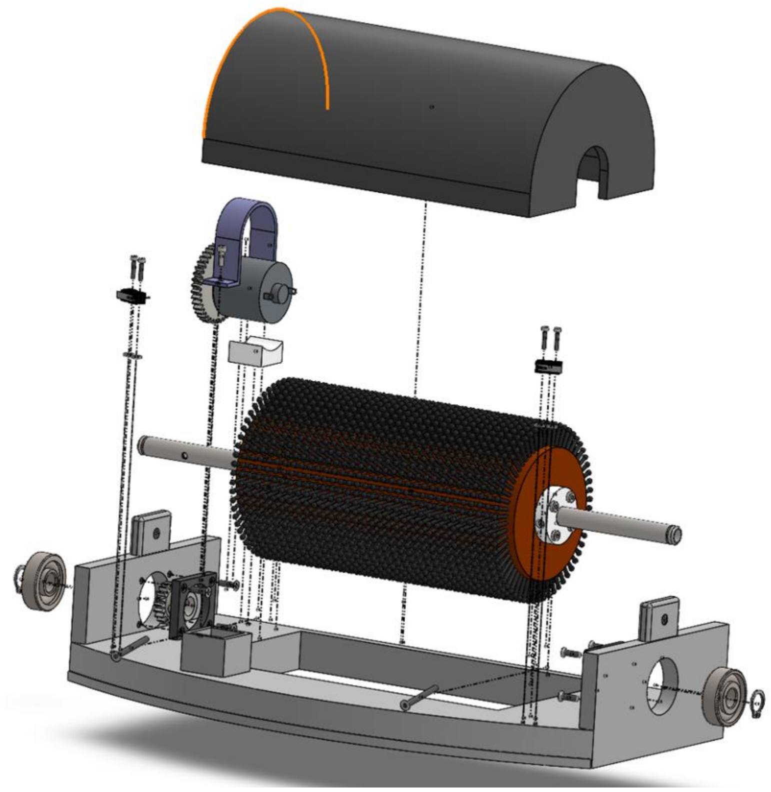


Figure 20 - Roller and Motor Assembly with the Base Plate

Functional principles of the components of the roller-base plate assembly:

Nylon Brush Roller DC Motor – The main function of a DC motor is to convert electricity into mechanical energy. This motor controls the rotary motion and the speed of the Nylon brush roller. It offers a highly controllable speed of 3600 RPM and is further increased to 7200 RPM with the use of gears, which is sufficient to perform the primary purpose of the robot of clearing the unwanted plant growth.

Nylon Brush Roller – It is used to rotate and cut the overgrown weed between the cobblestones.

Clamp & Support – It is used to hold the motor onto the base plate.

Microswitches – A microswitch sensor is a type of momentary contact switch with a very small contact gap. It is used in this robot to detect when a robot makes physical contact with an obstacle and sends feedback to the controller to change the course of direction.

Bearings[14] – These are used to assist the smooth, frictionless rotation of the shaft between the baseplate, and are used to maintain the correct position of the shaft using circlips and inner cover.

Rear Wheel Assembly

Figure 21 - Rear Wheel Axle Assembly

The rear wheels are assembled onto the baseplate with an axle in between. A wheel encoder (LM393 Speed Sensor) is glued onto the wheel of the wheel encoder. The hubs are screwed onto the wheels to hold them. Bearings are placed on either side of the shaft to assist rotation.

[14] (*What Are Bearings? Let’s Learn about the Basic Functions of Bearings! / Bearing Trivia / Koyo Bearings(JTEKT)*, n.d.)

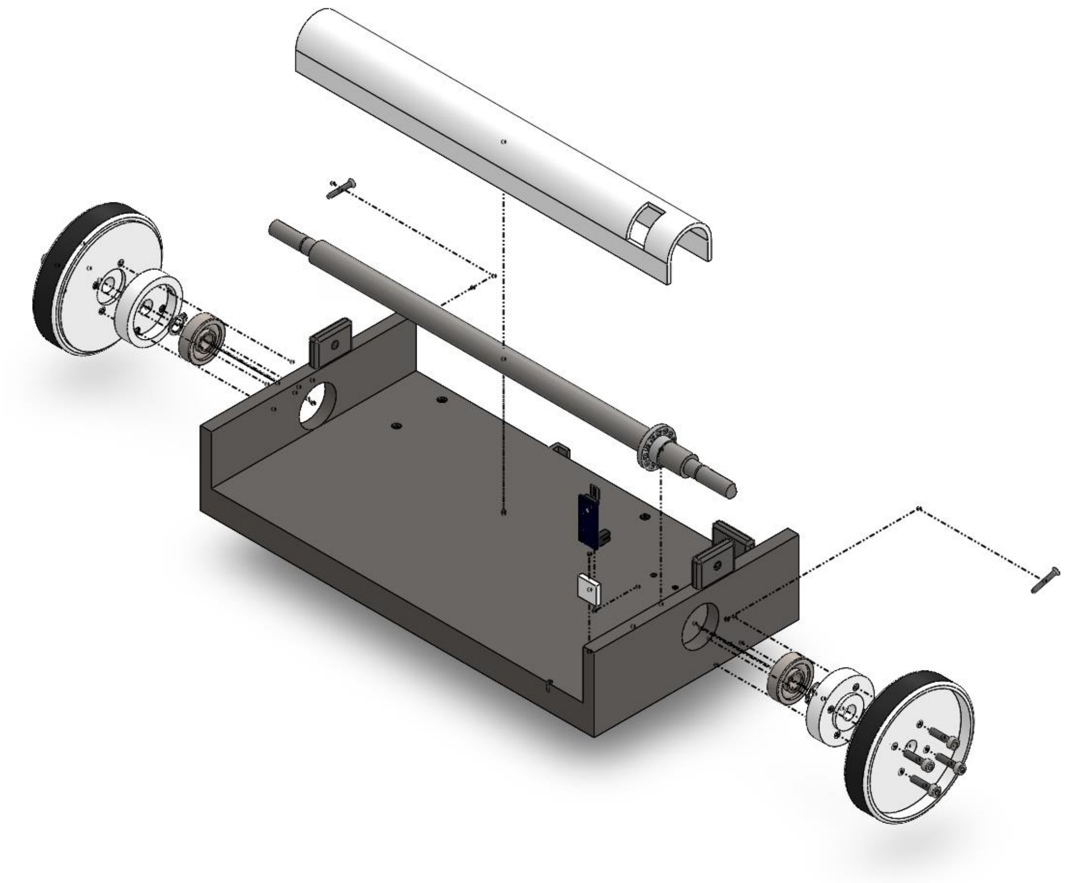


Figure 22 - Rear Wheel Assembly with Base Plate

Functional principles of the components of the rear-wheel assembly:

LM393 Speed Sensor (Wheel Encoder) – The function of a speed sensor is to measure the magnetic rotation speed to provide a corresponding voltage. It is used in this robot to study the movement pattern and speed of the wheels and send feedback to the microcontroller, for example, if the robot is losing traction, a signal will be sent to the controller to determine the course of action.

Axle[15] – The purpose of the axle here is to hold wheels relative to front wheels along with a hub in a specified location with the help of bearings on either side, here it is also used to rotate the wheel of the wheel encoder which is glued to it in a speed same as the main wheels for wheel encoders to sense the speed. The cover here is used so that there is no interference of axle with other parts of the body.

Bearings[14] | Wheels | Hub

[15] (What Is an Axle? n.d.)

Vacuum Assembly with Base Plate

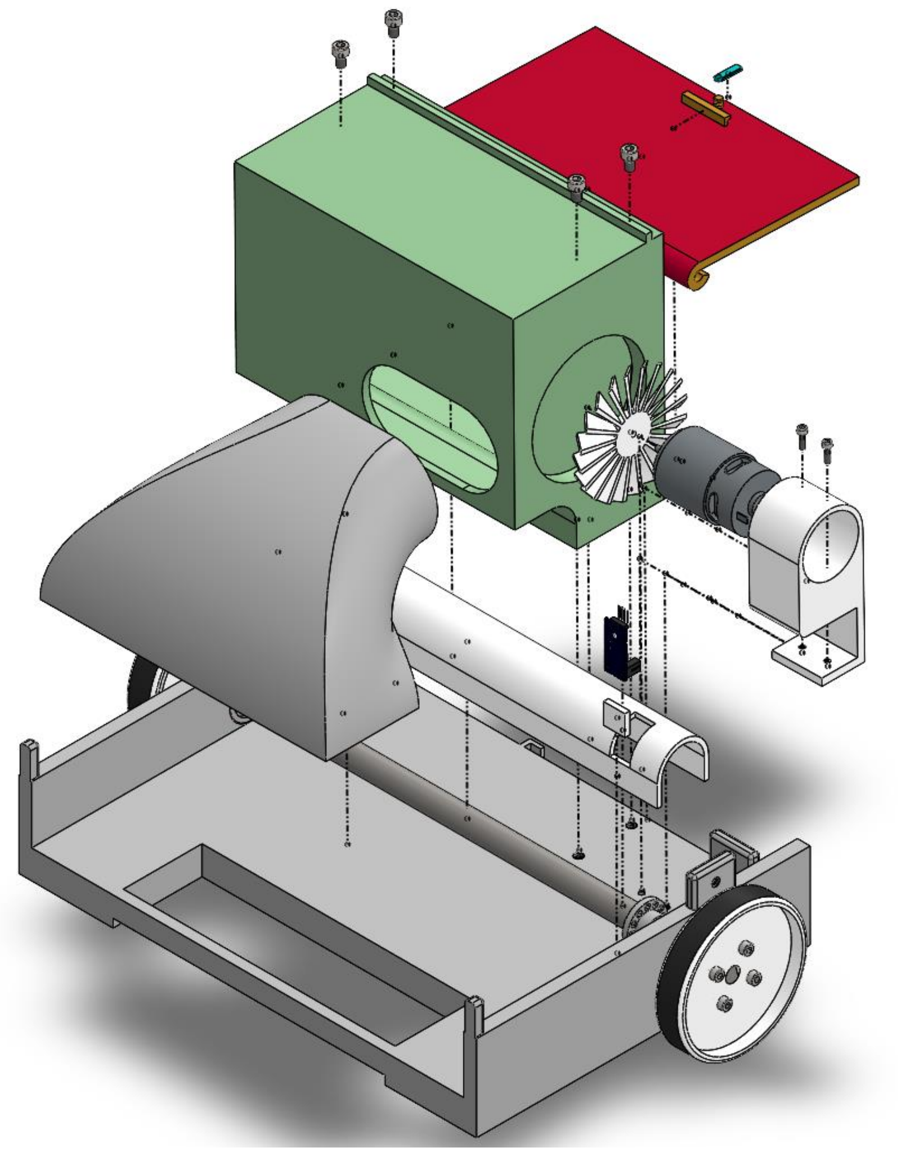


Figure 23 - Vacuum Chamber Assembly

The Vacuum Chamber will first be screwed onto the base plate and then the cover will be hinged at the back of the chamber. The Vacuum Motor with a centrifugal fan is attached to the chamber from the left side. The motor is positioned with motor support that is screwed onto the base plate. The Suction pipe is super-glued onto the vacuum chamber cut out from the front and on the base plate from below, to hold it in place.

Functional principles of the components of the vacuum assembly:

Vacuum Motor – The main function of a vacuum motor is to cause a pressure difference in a contained space to create a vacuum. The negative pressure difference leads to a suction of the debris from the cutting operation into a vacuum chamber in the machine. This motor operates at 12V, supplied by the motor driver, from the microcontroller, and rotates at high speed along with the centrifugal fan attached, hence operating efficiently.

Vacuum Chamber – The Vacuum Chamber stores the debris that is being sucked by the suction pipe connected in front of it.

Vacuum Chamber back covers – It is the back cover of the vacuum chamber hinged on the sides of the chamber and has a sliding lock at the bottom to be able to open and empty it when the chamber is full.

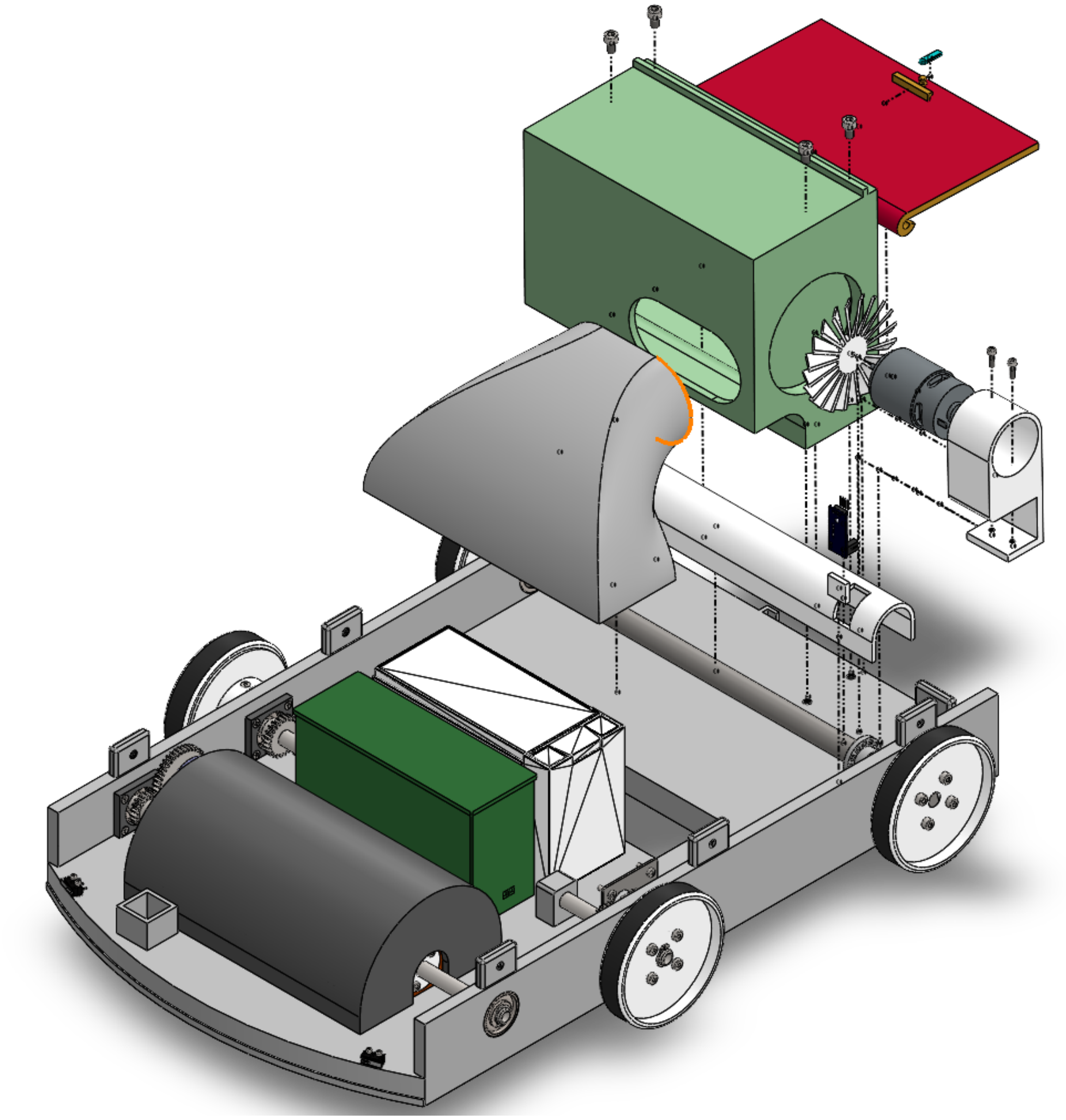


Figure 24 - Final Base Plate Assembly

Housing Assembly

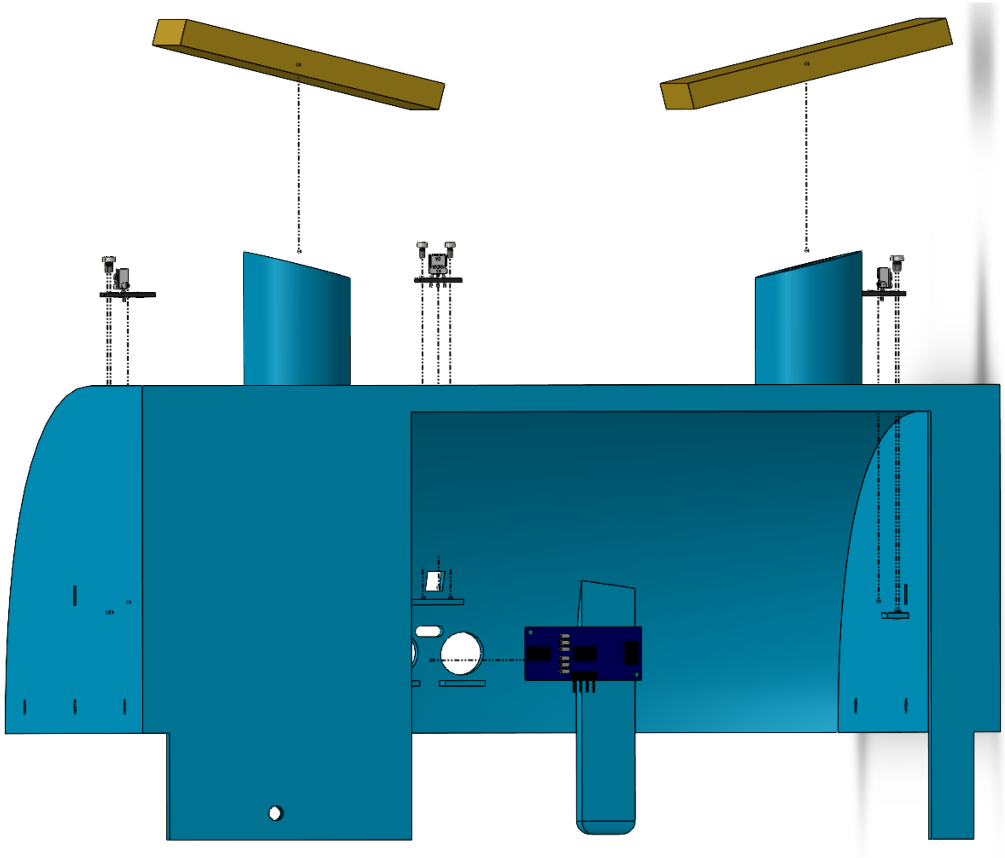


Figure 25 - Assembly of housing with IR Sensors and an Ultrasonic Sensor

The housing is the upper part/cover of the robotic cobblestone cleaner seated from the top onto the base plate and screwed from the sides, back and front. The housing has an Ultrasonic sensor in front and three IR sensors one in front and two on the sides. RGB Light shows the status of the robot and buttons are used to turn the robot on/off. (Light and buttons are not shown in exploded view above)

Functional principles of the components of the housing assembly:

RGB LED light[16] – The RGB LED light is a type of LED that is used in different electrical systems to produce almost any colour using the three internal LEDs (Red, Green and Blue). The intensity of each LED is adjusted accordingly using PWM to produce the desired colour. In this robot, the LED is used to flash green, blue and red. A green light is flashed when the robot is in operation, a blue light when it is charging, and red light is flashed when the battery is low (hence needs recharging).

IR Receiver[17] – An Infrared Receiver is a device designed to receive infrared signals from a transmitter. This robotic cobble cleaner has three IR receivers on the front and both sides respectively, which can interact with the IR transmitter at the charging station. When the timer runs out, the rays which are emitted from the charging station are used by the robot to sense where the charging station is and navigate home.

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[16] (*How RGB LEDs Work and How to Control Color - Tutorials* | *CircuitBread*, n.d.)
[17] (*IR Sensor Working Principle and Applications* | *Robu.In*, n.d.)

TASTER 9305 Push Button – A pushbutton is a switch that is added to the circuit to switch the circuit either on or off. When it is switched on, the circuit is connected and current flows through it hence turning on the robot system to start its operations. Switching it off stops the flow of current hence turns off the robot. It is also used in the vacuum system circuit to do the same purpose. The vacuum system can be turned on or off, regardless of the state of operation of the robot system. This feature was added for sustainability reasons, that is, to save energy. Push buttons are added to circuits to give the user control of the operation.

HC-SR04 Ultrasonic Sensor Module[18] – An ultrasonic sensor is an electronic device that measures the distance of a target object by using ultrasonic sound waves and converting the reflected sound into an electric signal. The distance between the sensor and the target object is determined by measuring the time between the transmission and reception of the waves using the formula, $D = ½ T \times C$ where D is the distance, T is the time and C is the speed of sound. In this robot, an ultrasonic sensor is used to detect obstacles and send feedback to the microcontroller to avoid the collision. The HC-SR04 has a range of 3cm to 400cm, implying that if an obstacle is detected in that range, a signal is sent to the controller.

ZB5 Emergency Stop Button[19] **–** The purpose of an emergency push button is to stop the machine quickly when there is a risk of injury, or the workflow requires stopping. It breaks the circuit and removes the power supply to the whole system instantly when pressed. This button was included in case of emergencies. It has a bright colour red which can be seen easily by a user of the robot to avert the danger easily and immediately.

[18] (*What Is an Ultrasonic Sensor? | FierceElectronics*, n.d.)
[19] (*How Does an Emergency Stop Button Work? - Quisure*, n.d.)

Charging Station Assembly

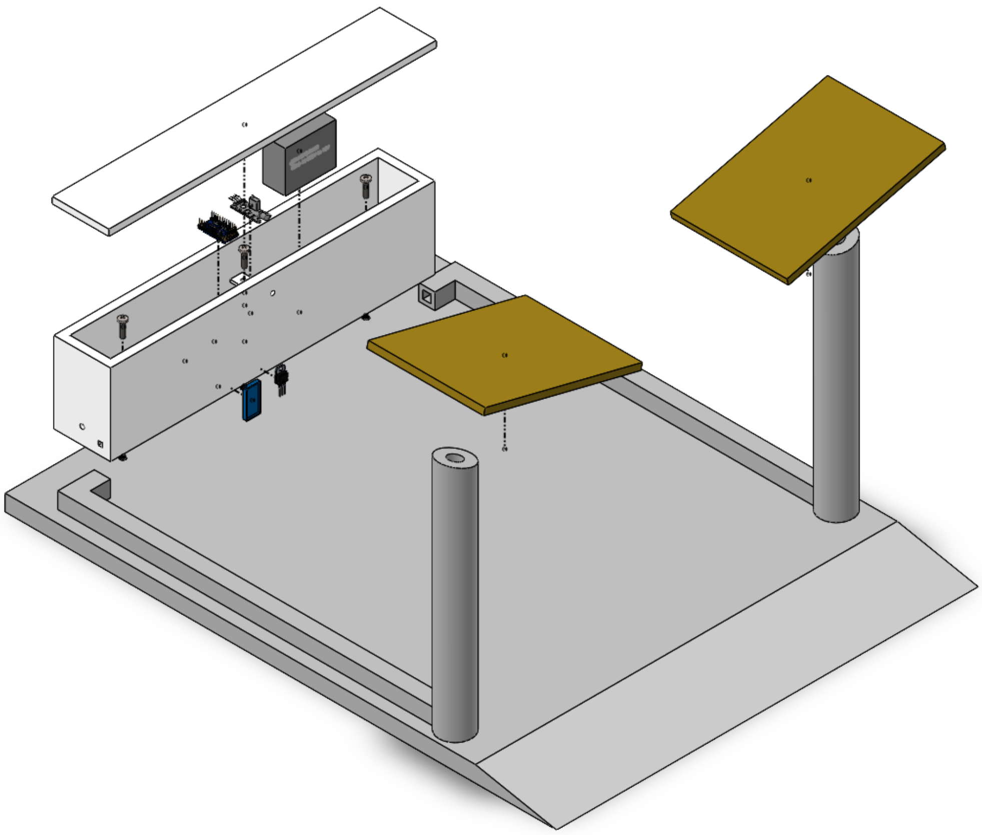


Figure 26 - Charging Station Assembly

The charging station is a dock installed in the area of operation of the robotic cobble cleaner and its purpose is to charge the robot and set the area of operation by installing perimeter wires in a closed loop. The perimeter wire generator and IR transmitter are also housed in this station. When the robot needs recharging, it activates its IR sensor and autonomously moves towards the charging station where its battery is recharged.
It is made up of a step-down transformer, a bridge rectifier module, a voltage regulator, diodes, resistors, and a capacitor to supply AC power to a DC battery.
It will be installed in such a way that on the base plate, the Control Unit will be screwed. The step-down transformer, a voltage regulator, a bridge rectifier module, diodes, resistors, and capacitors are assembled in this control unit. Furthermore, the wires are installed in a closed loop on the sides of the base plate connecting the Control Unit Box and the charging plates made of brass.

Function Principle of the components of the Charging Station Assembly:

Perimeter Wire – The perimeter wire is a boundary wire which sets the zone where the robot is meant to operate. It interacts with the robot using a generator and sensor to perform its role hence the robot is unable to leave this area of operation.

Perimeter Wire and Generator Kit – This is a signal generator and sensor soldering kit that is assembled for an electric perimeter wire. The generator board is based on the NE555 Timer, and the sensor board is based on two LC (tank) amplified circuits. The generator and sensor are installed in the charging station and robot respectively to be able to guide and keep the robotic cobble cleaner in a certain area. The kit enables the robot to interact with the perimeter wire and hence keep it in the zone.

IR Transmitter Board – An Infrared Transmitter LED is a special type of LED that emits Infrared rays of the Electromagnetic Spectrum. The wavelength of Infrared Rays is greater than that of Visible light hence invisible to the human eye. It is used in the charging station to emit the rays towards Infrared receivers on the robotic cobble cleaner. These Infrared rays are emitted when the timer for operation runs out so that the robot can navigate back to the charging station for recharging. It has a light range of 19m hence sufficient for this project where the distance between the robot and the station may be large.

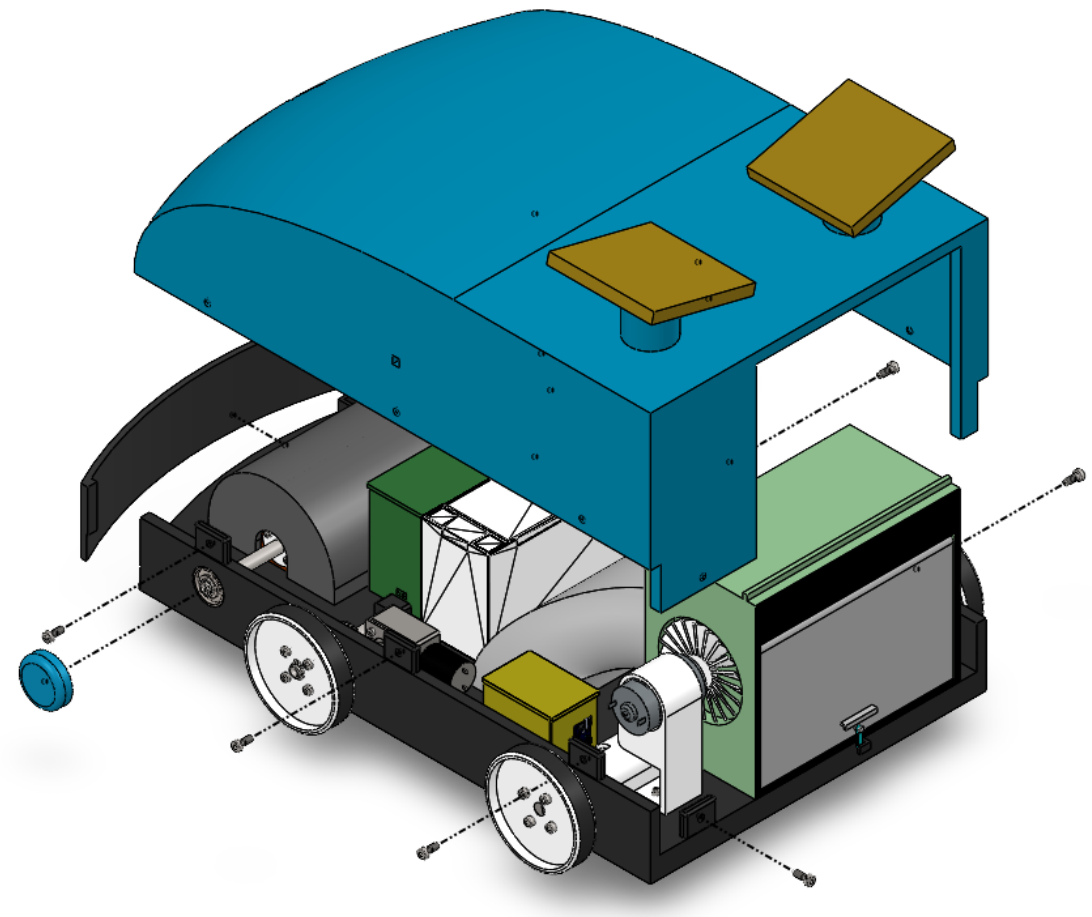


Figure 27 - Final Assembly of Base Plate and Housing

UML

Activity Diagram[20]

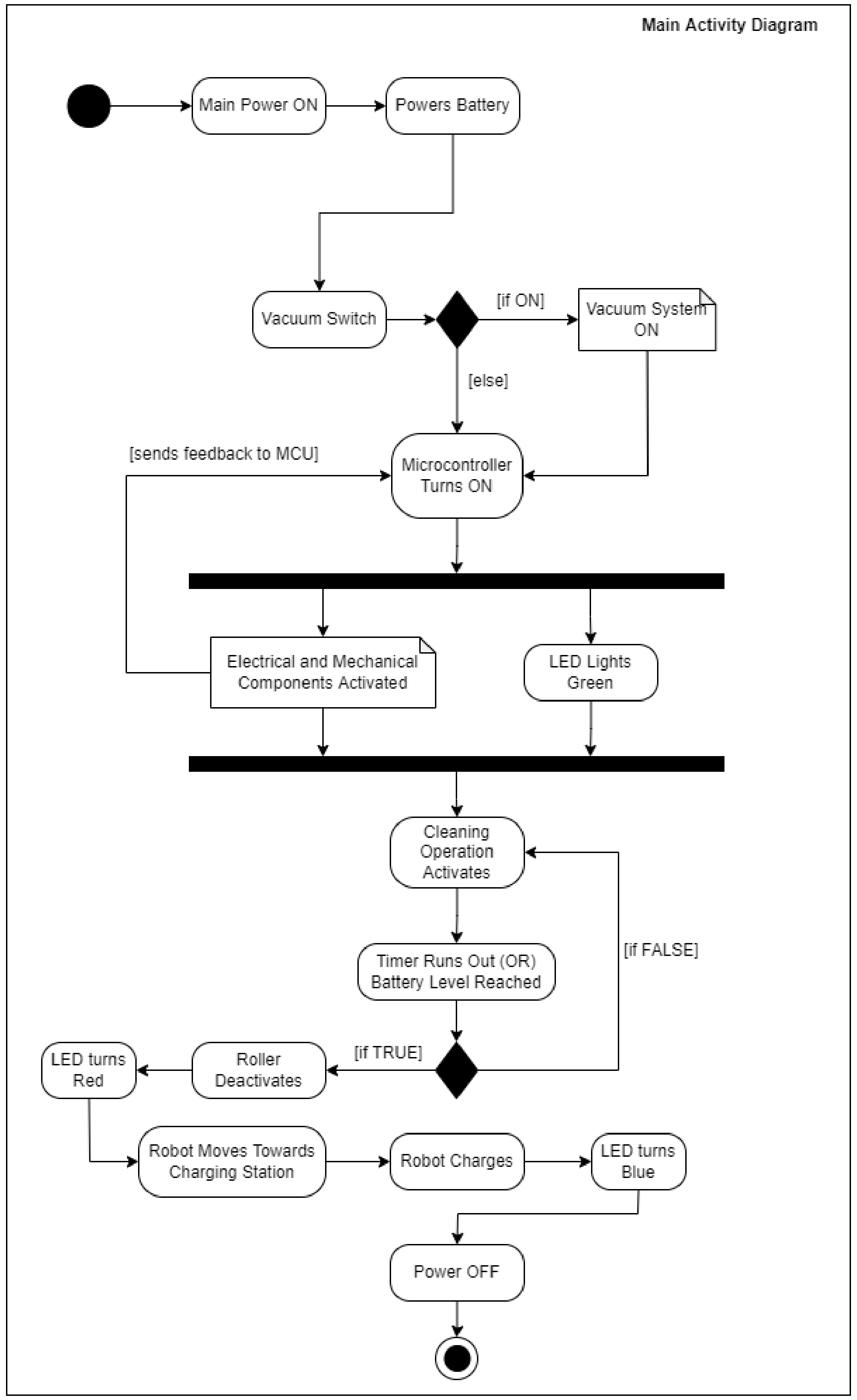


Figure 29 - Main Activity Diagram

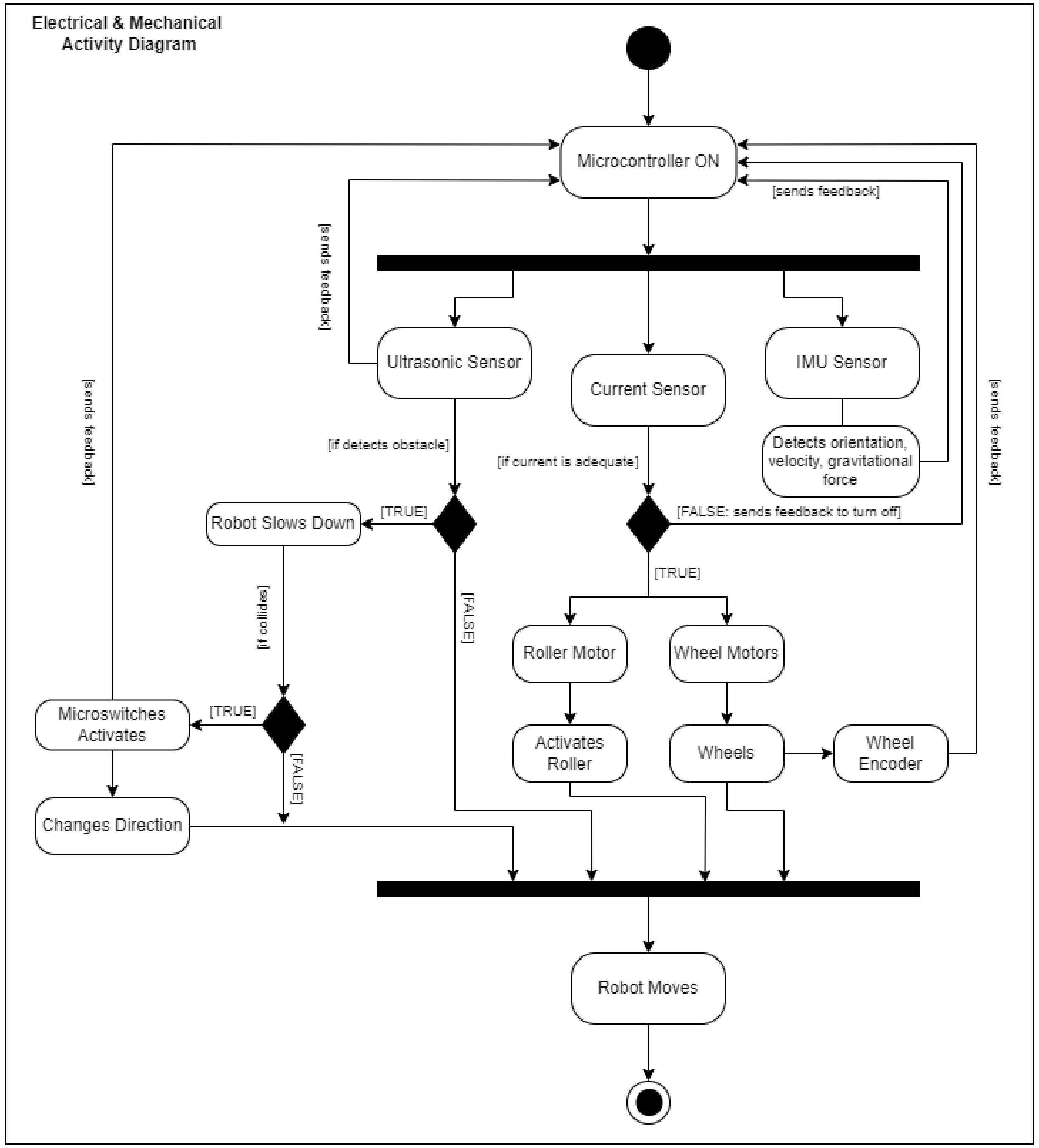


Figure 28 - Electrical and Mechanical Components Activity Diagram

[20] (*What Is Activity Diagram?*, n.d.)

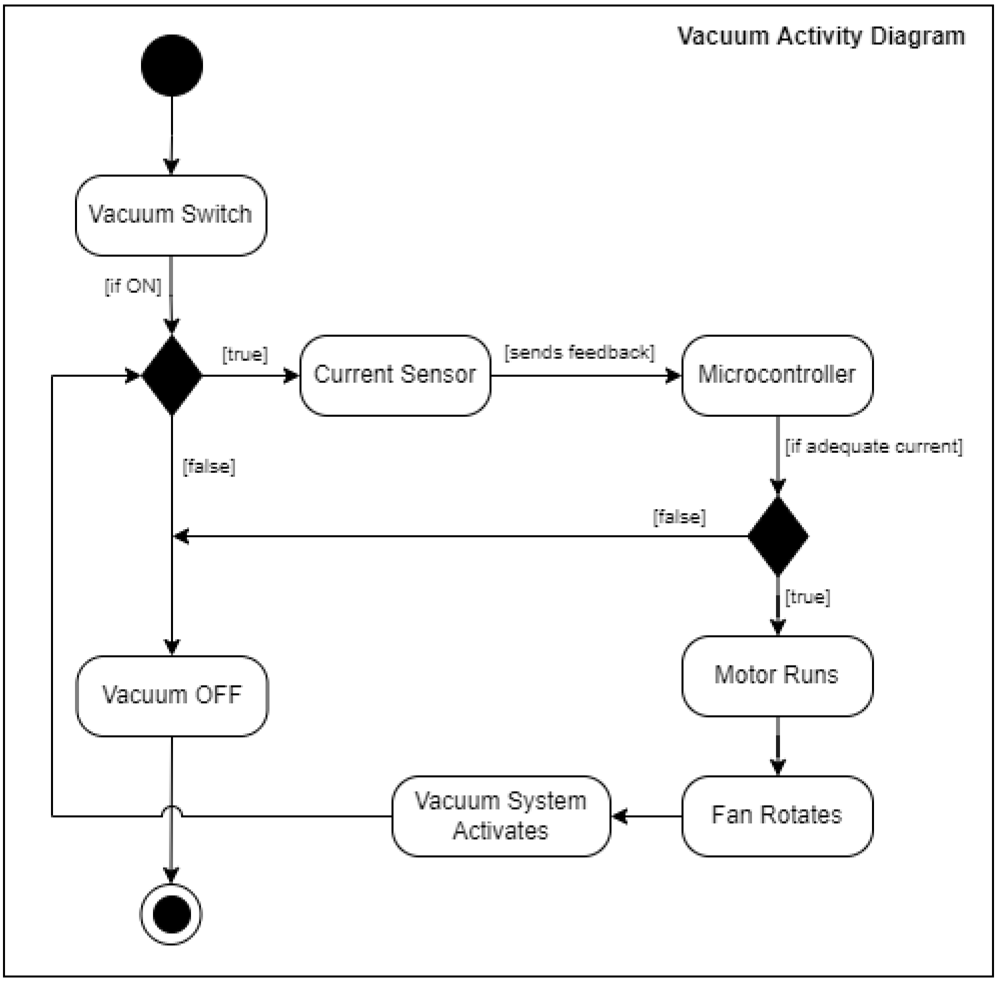


Figure 30 - Vacuum System Activity Diagram

State Machine Diagram[21]

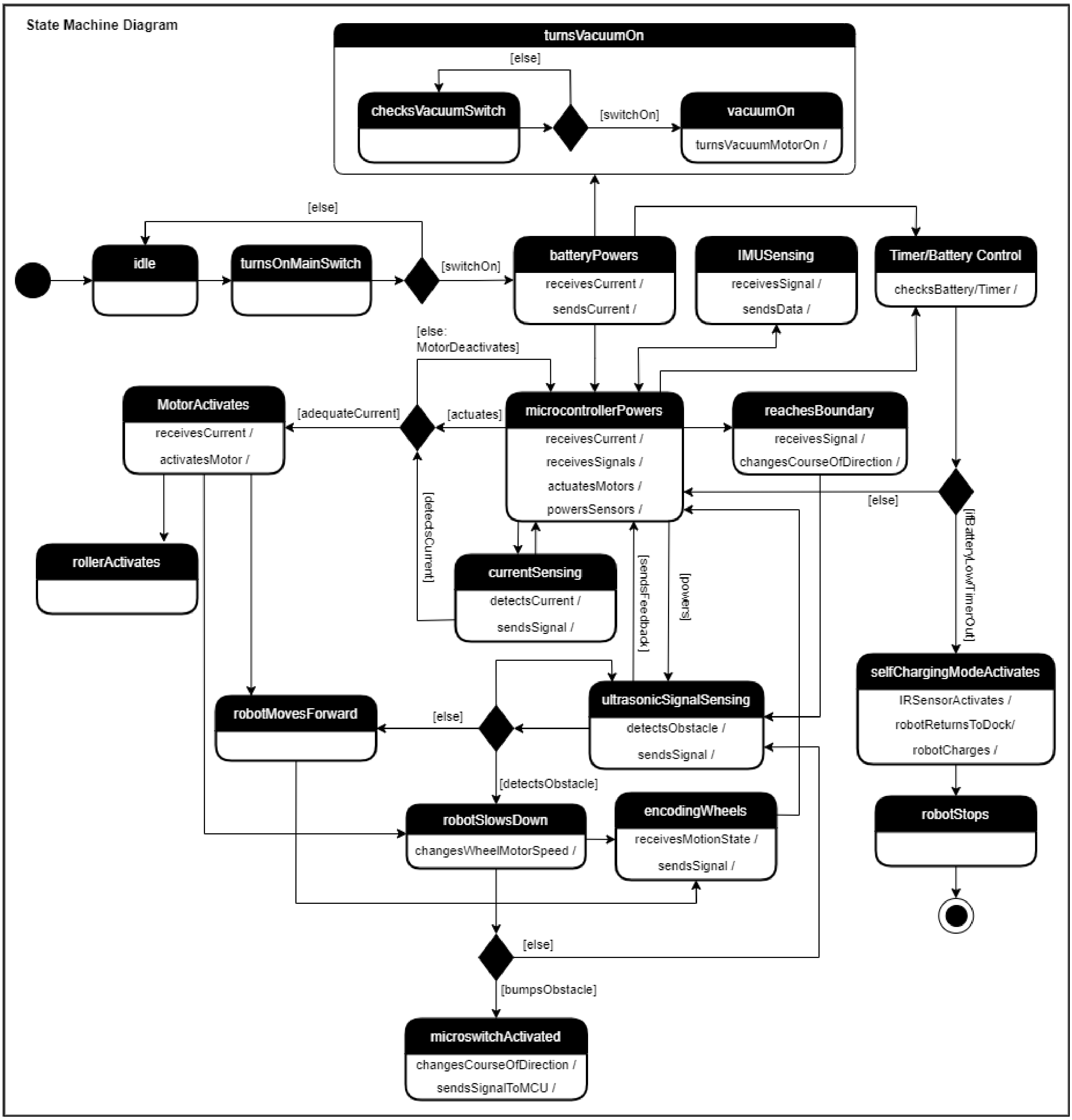


Figure 31 - State Machine Diagram of the System

[21] (*State Machine Diagram Tutorial* | *Lucidchart*, n.d.)

Class Diagram[22]

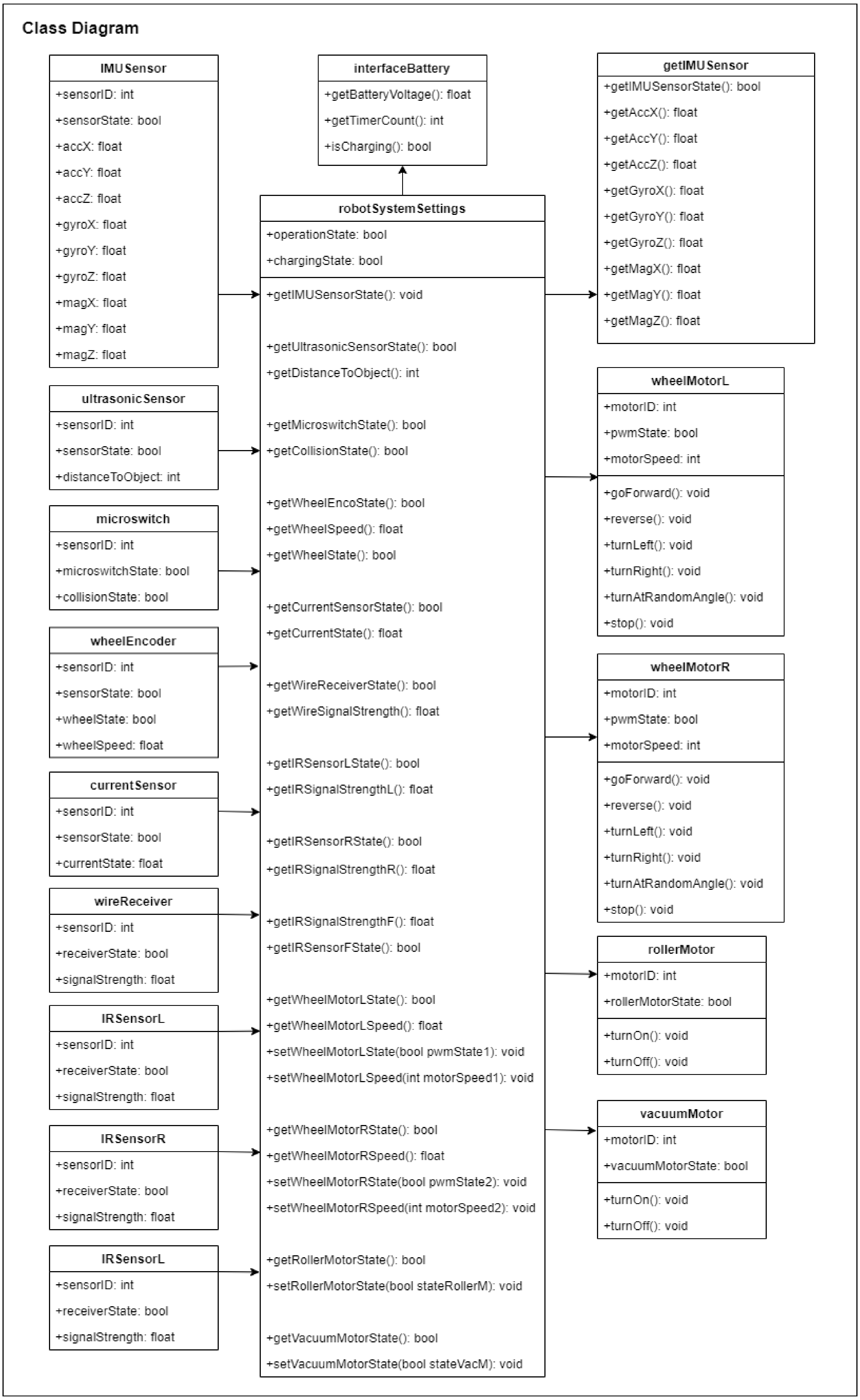


Figure 32 - Class Diagram of Actuators, Sensors and Microcontroller

[22] (What Is Class Diagram? n.d.)

Circuit Diagrams

Main Circuit Diagram

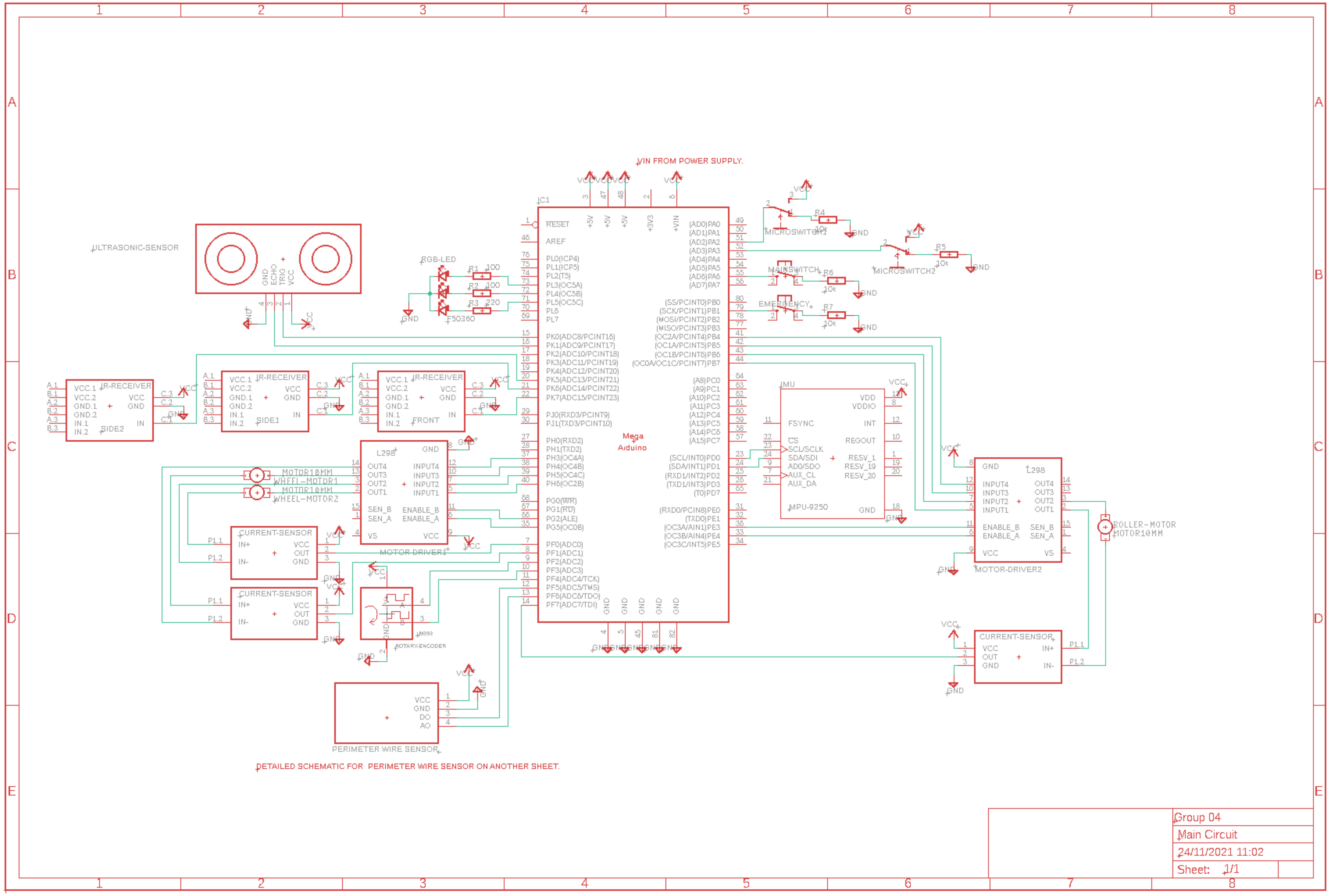


Figure 33 - Main Circuit Diagram (Actuators, Sensors, and Microcontroller)

Power Supply Circuit Diagram

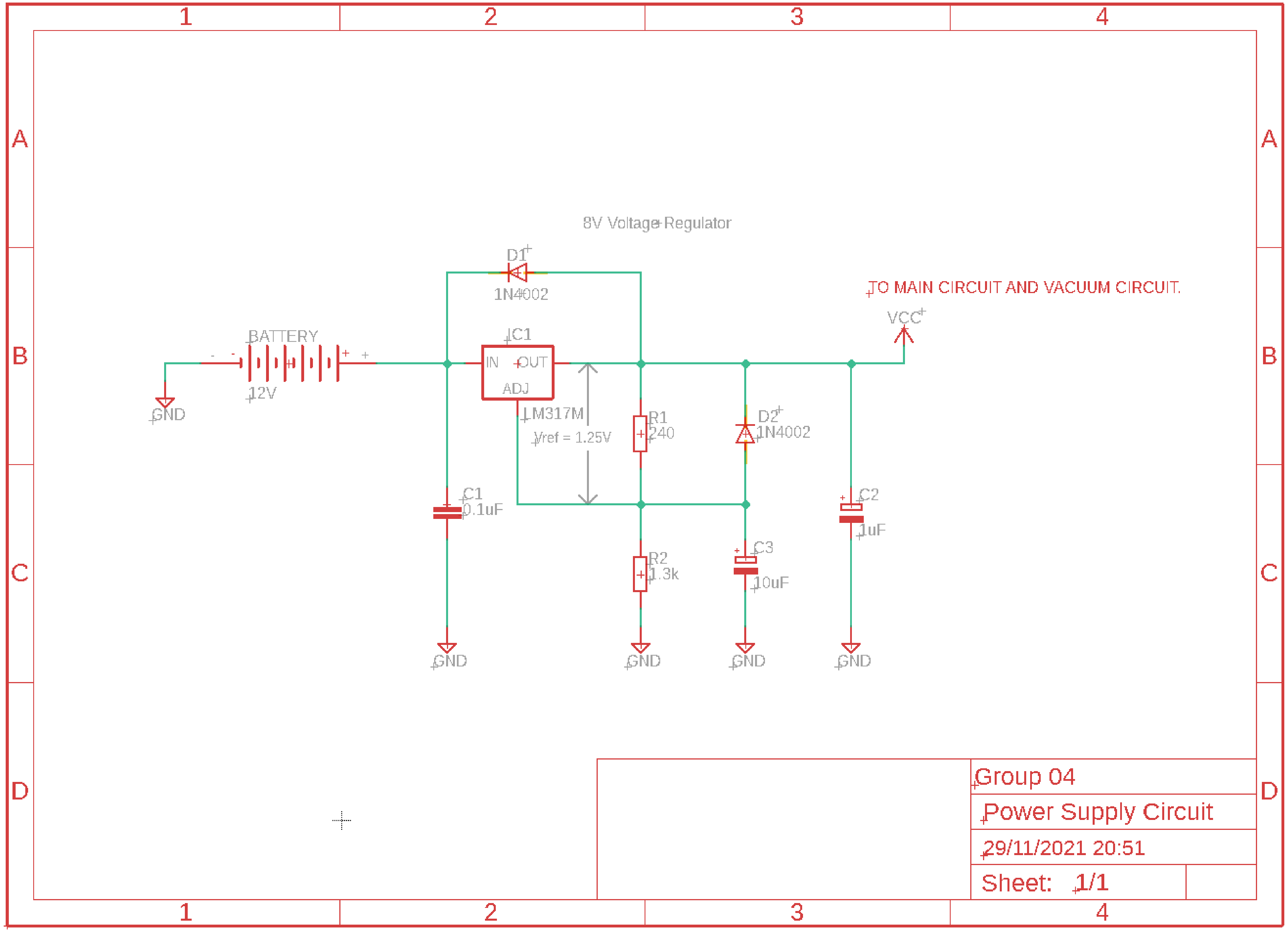


Figure 34 - Power Supply Circuit Diagram (Battery and Voltage Regulation)

Vacuum System Circuit Diagram

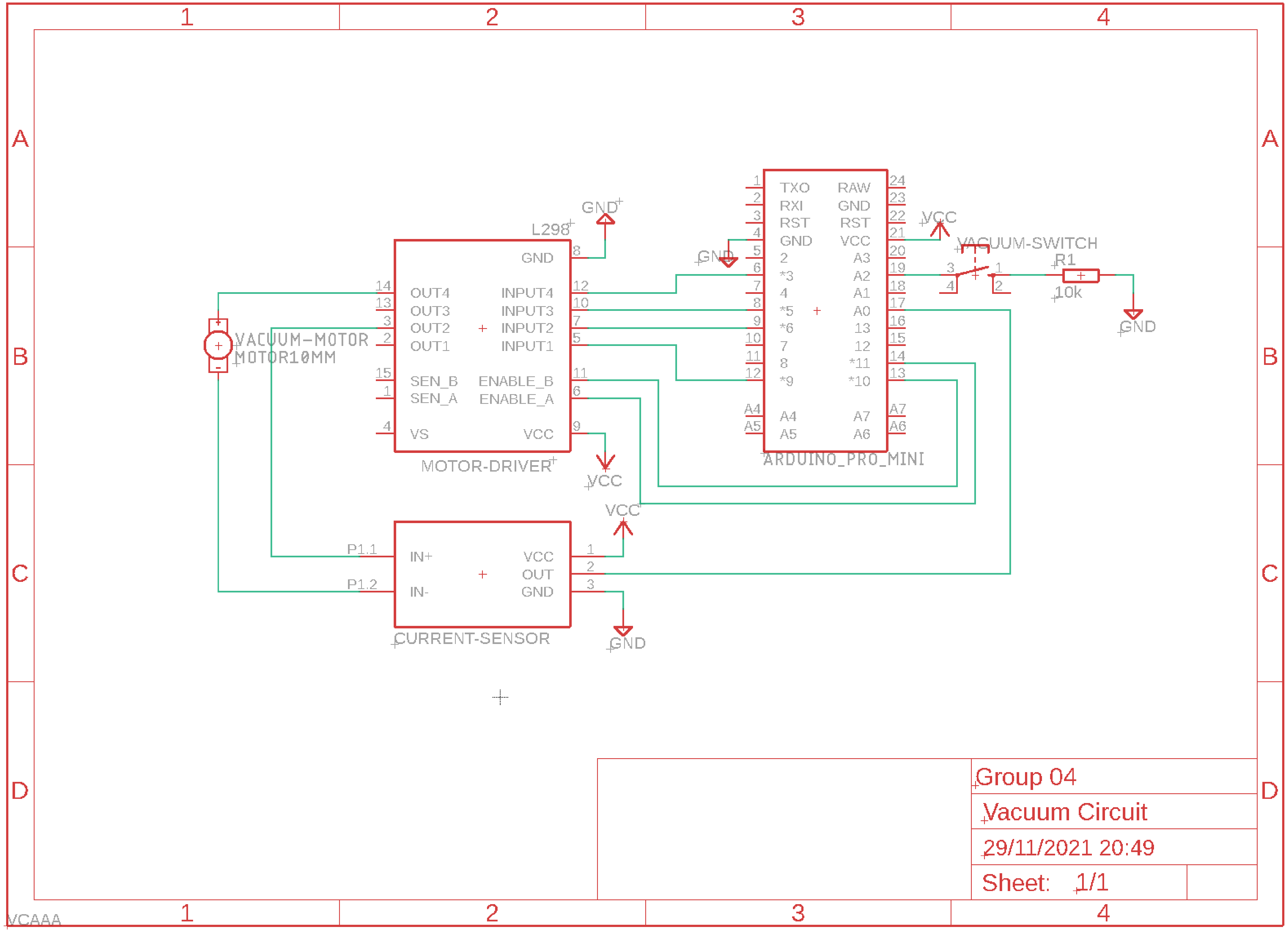


Figure 35 - Vacuum System Circuit Diagram (Sensor, Actuator, and Microcontroller)

Perimeter Wire Sensor Circuit Diagram[23]

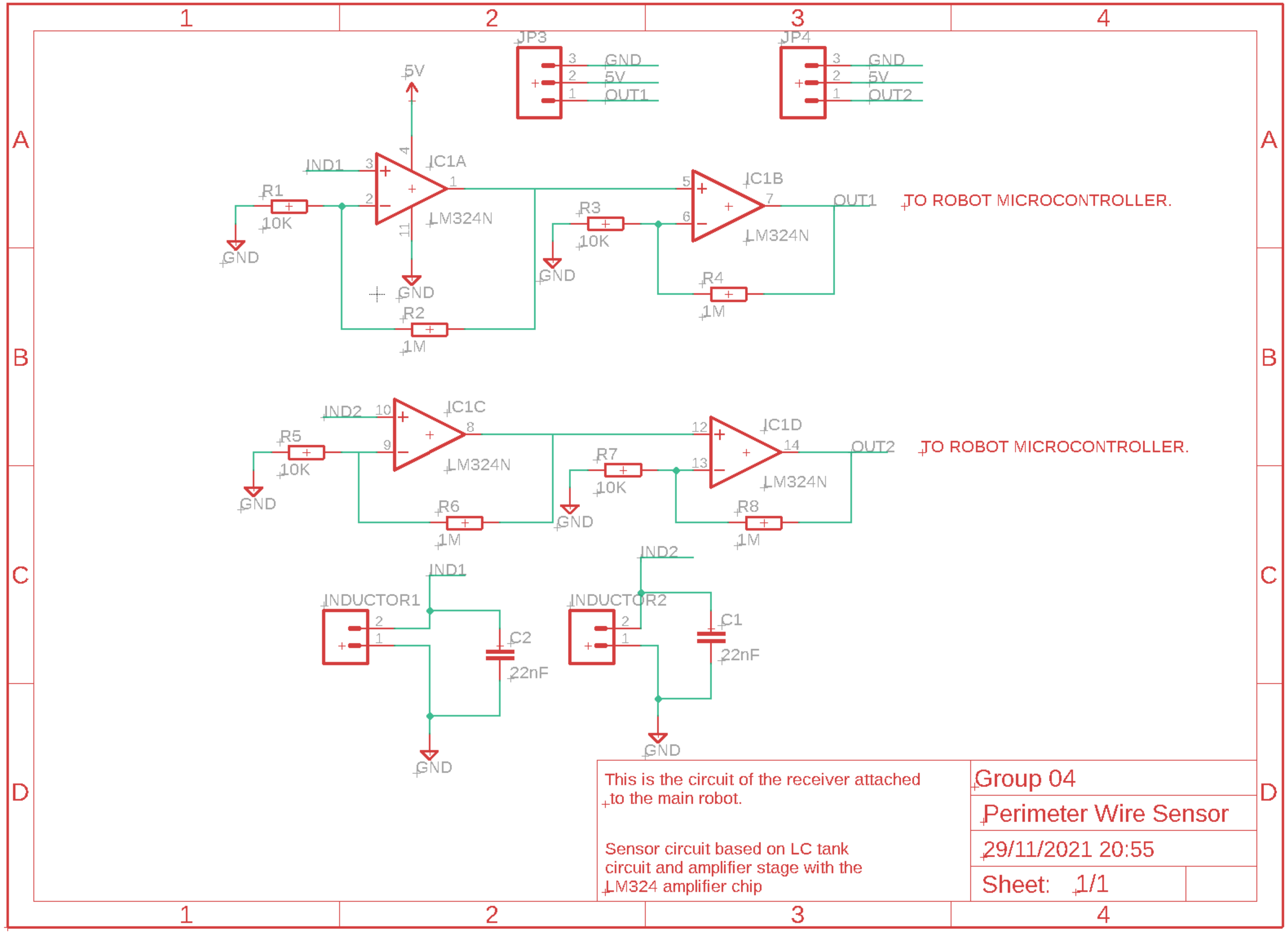


Figure 36 - Perimeter Wire Sensor Circuit Diagram

[23] (*DIY Perimeter Wire Generator and Sensor | RobotShop Community*, n.d.-b)

Charging Station Circuit Diagram[24]

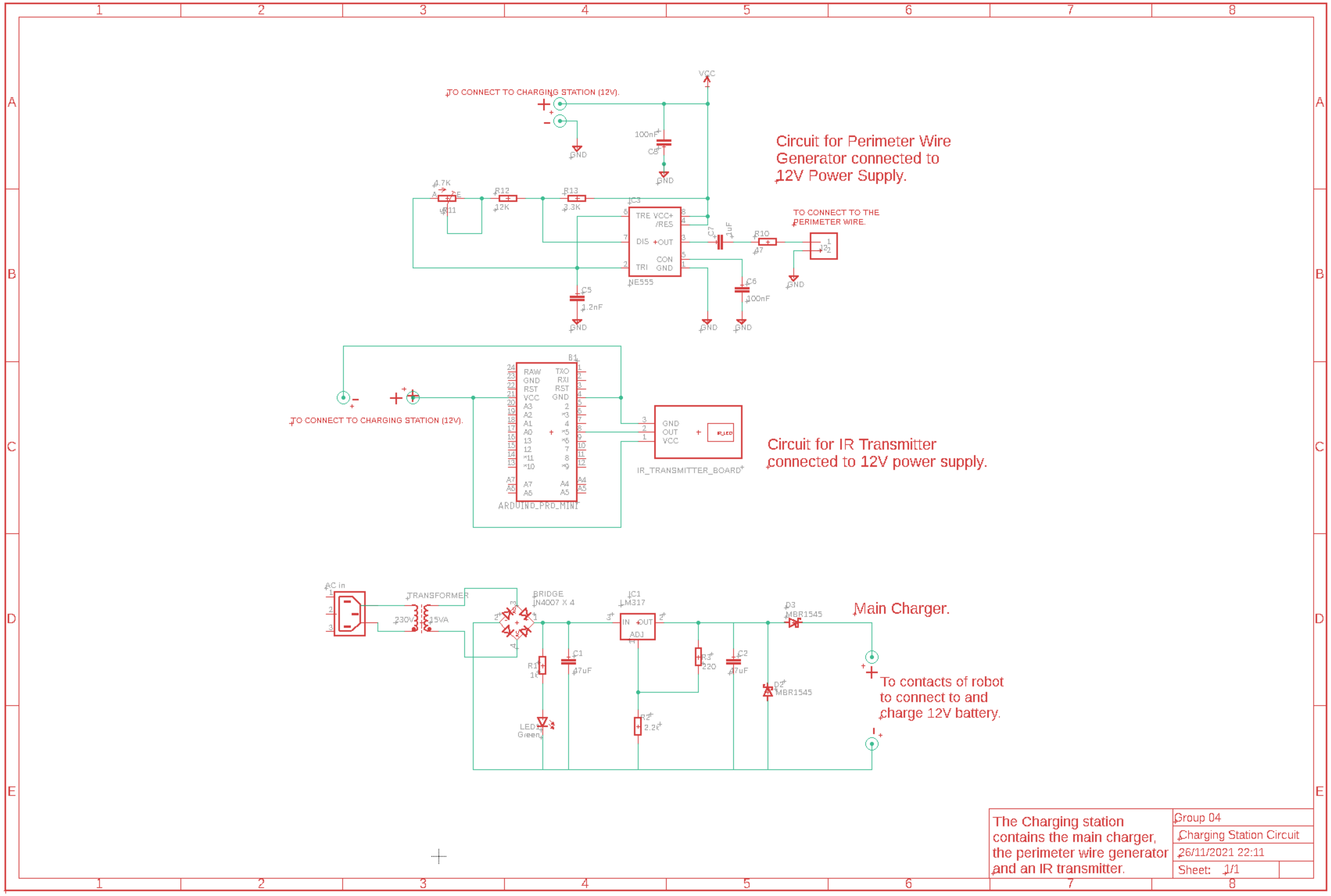


Figure 37 - Charging Station Circuit Diagram

[24] (*DIY Perimeter Wire Generator and Sensor | RobotShop Community*, n.d.-b)

Technology Selection

1. **Material**: ABS Plastic
   Method: Injection Moulding.
   Machine Used: Injection Press and FDM Printer

Why ABS Plastic[25]?
- Impact Resistance
- Structural Strength and Stiffness
- Chemical Resistance
- Excellent High and Low-Temperature Performance
- Great Electrical Insulation Properties
- Easy to Paint and Glue

Manufacturing Process[26]:
Choosing the right manufacturing process for plastics is determined by several factors including volume/cost, lead time, material etc.

Thermoplastics are preferable because of their numerous melt and solidification cycles. The material is supplied in small pallets which then can be melted into the desired shape under different manufacturing processes.
The process is reversible and hence there is no change in properties even if they are treated many times.

There are several processes we can use for manufacturing e.g., 3-D printing, CNC machining, vacuum forming, injection moulding, extrusion, blow moulding etc. All these processes have different degrees of freedom and hence vary in cost and time.

[25] (Spencer, n.d.)
[26] (Formlabs, n.d.)

Injection Moulding:

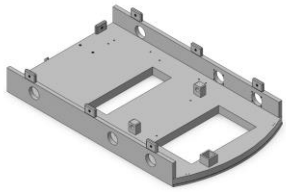
Injection moulding is most widely used for the mass production of plastic parts. The product is manufactured against tight tolerances which ensure the production of high-quality parts. The initial cost of installing an injection moulding is high but it offers a high degree of freedom and cycle time takes up only a few seconds. The moulds for injection moulding are made up of metals like hardened steel. Following the Design Manufacturing (DFM) guidelines, the cost for tooling can be manageable.

Process:

1. *Mould setup*: If the part has inserts, these are added either by hand or robotically. The mould is closed by a hydraulic press.
2. *Plastic extrusion*: small plastic pellets are melted and extruded through a heated chamber by a screw.
3. *Moulding*: The molten plastic is injected into the mould.
4. *Cooling and release*: The part cools in the mould until it is solid enough to be ejected, either mechanically or by compressed air.
5. *Post-processing*: Sprues, runners, and any flash (if applicable) is removed from the part, often automatically as part of the mould opening. [27]

[27] (Plastic Injection Moulding Process | EAS Change Systems | EAS Change Systems, n.d.)

Base Plate –
Material: ABS
Manufacturing Process: Injection Moulding



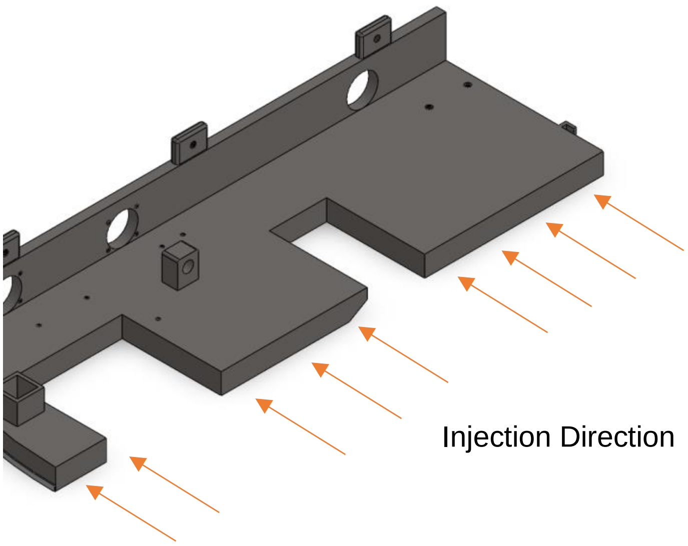


Figure 38 - Isometric View showing Injection Direction

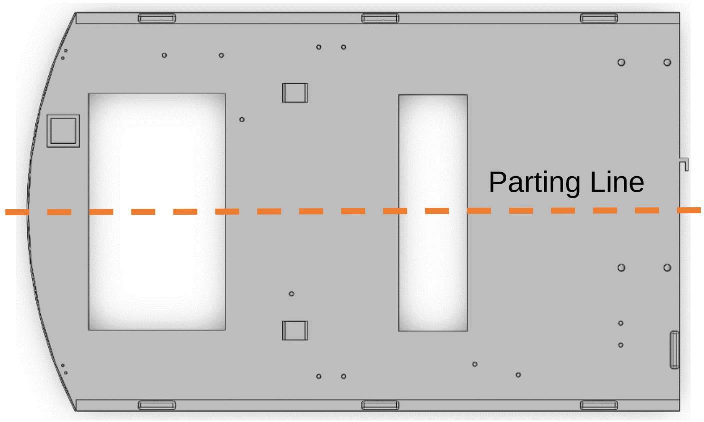
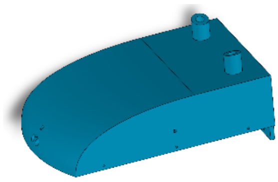


Figure 39 - Top View showing Parting Line

Housing –
Material: ABS
Manufacturing Process: Injection Moulding



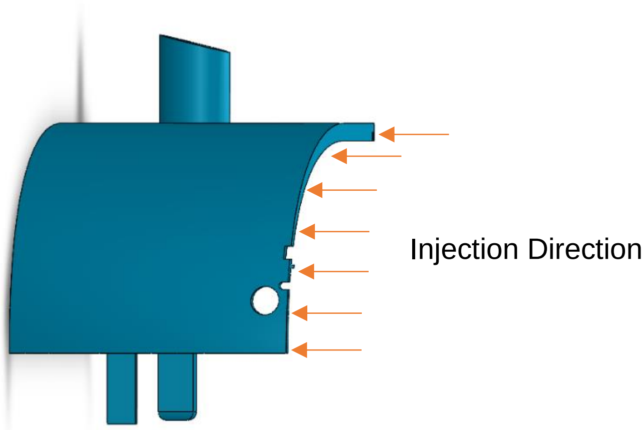


Figure 41 - Isometric View showing Injection Direction

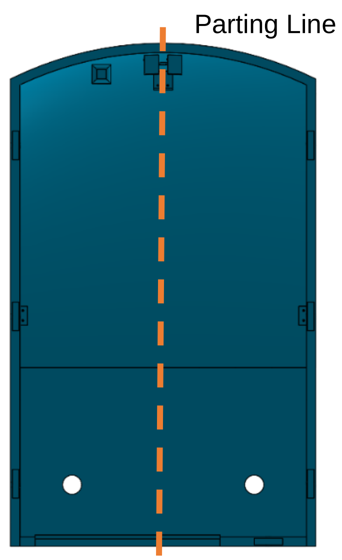


Figure 40 – Bottom View showing Parting Line

Roller Cover –
Material: ABS
Manufacturing Process: Injection Moulding

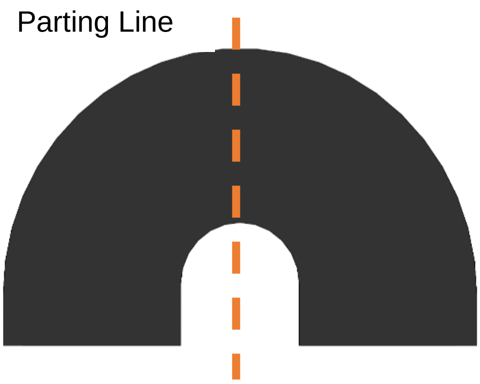


Figure 42 - Front View showing Parting Line

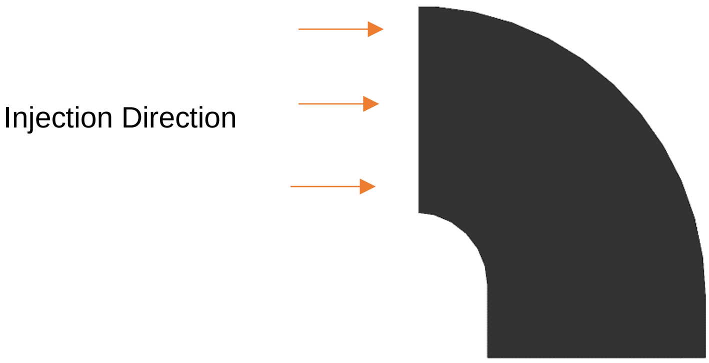
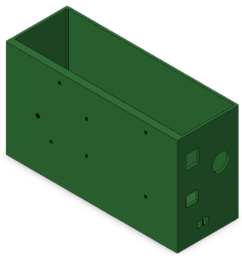


Figure 43 - Section View from front plane showing Injection Direction

Main Control Unit Box –
Material: ABS
Manufacturing Process: Injection Moulding



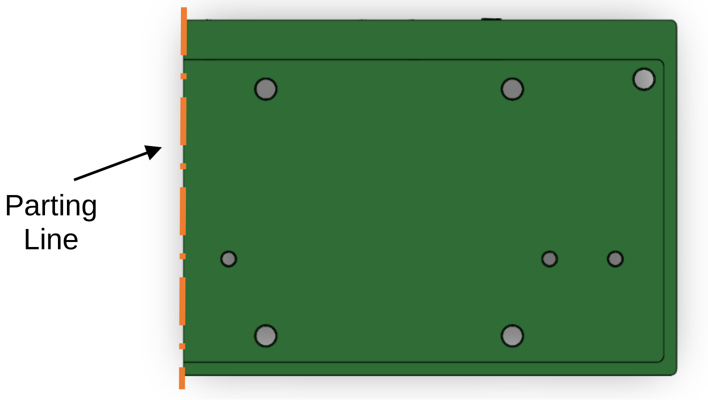


Figure 45 - Section View showing Parting Line

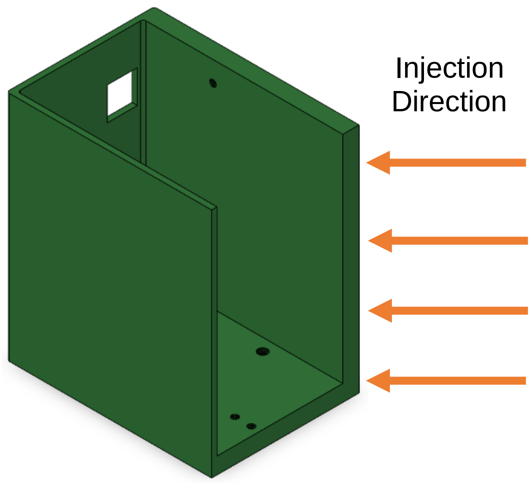
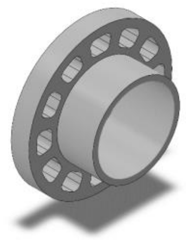


Figure 44 - Isometric Section View showing Injection Direction



Wheel Encoder –
Material: ABS
Manufacturing Process: Injection Moulding

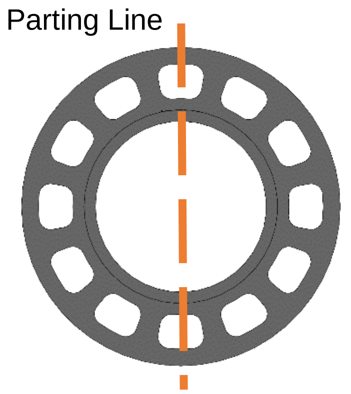


Figure 47 - Top View showing Parting Line

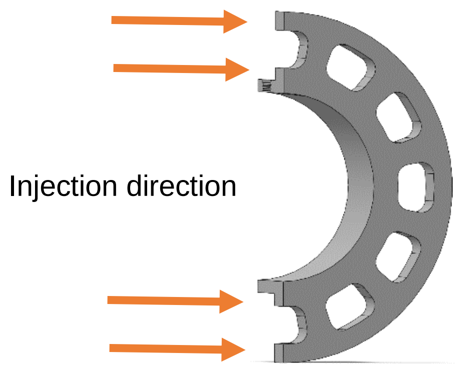
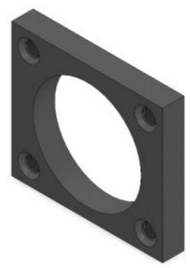


Figure 46 - Section View showing Injection Direction



Bearing Inner Cover –
Material: ABS
Manufacturing Process: Injection Moulding

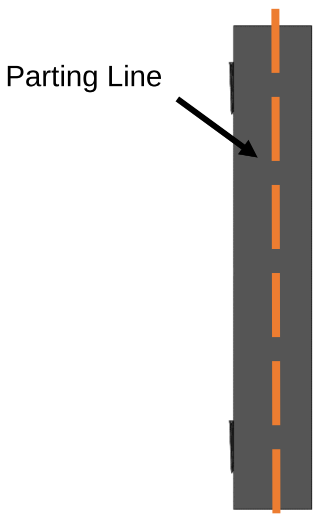


Figure 48 - Side View showing Parting Line

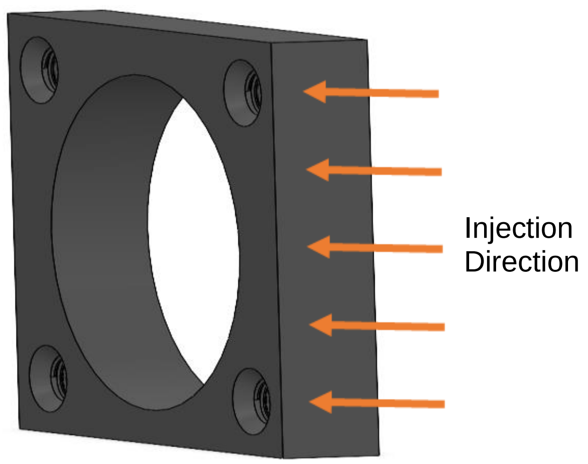
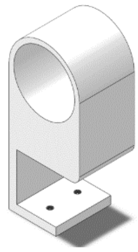


Figure 49 - Draft View showing Injection Direction

Vacuum Motor Support –
Material: ABS
Manufacturing Process: Injection Moulding



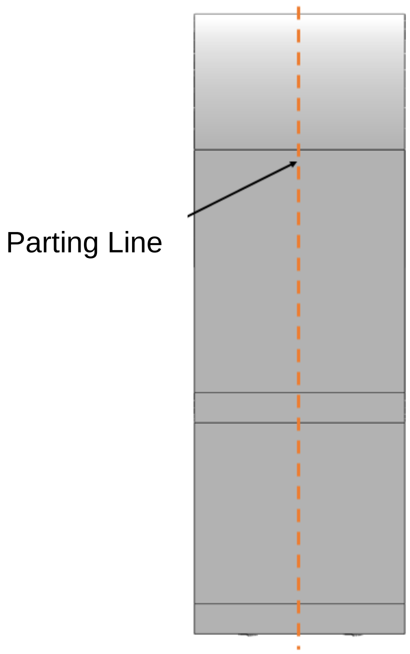


Figure 51 - Side View showing Parting Line

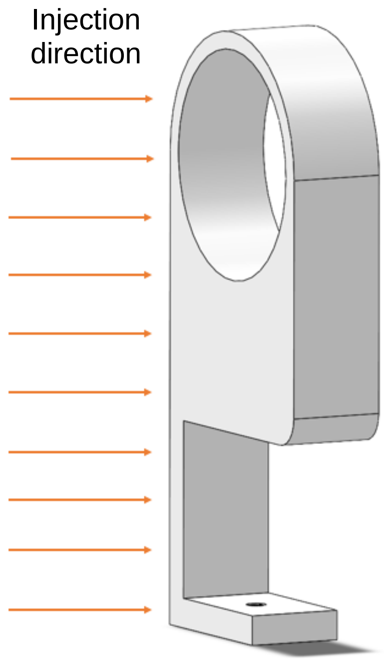
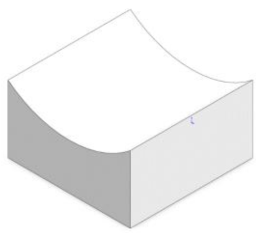


Figure 50 - Draft View showing Injection Direction

Roller Motor Support –
Material: ABS
Manufacturing Process: Injection Moulding



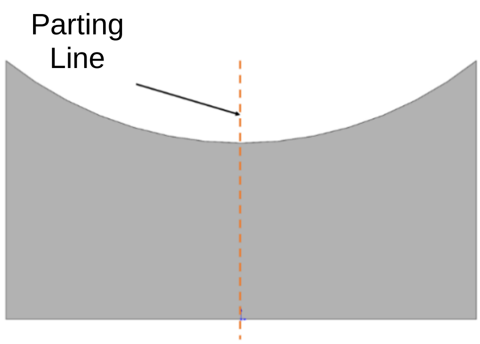


Figure 53 - Side View showing Parting Line

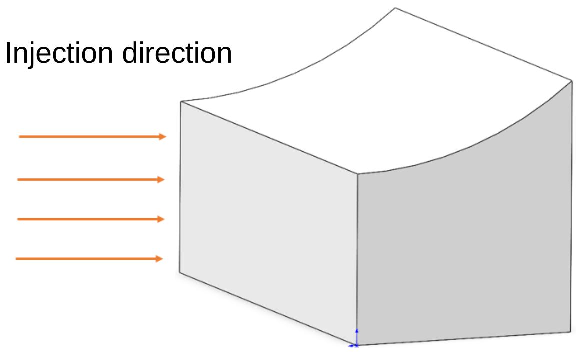
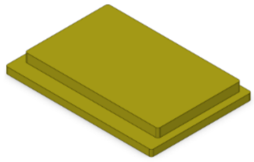


Figure 52 – Sectional Draft View showing Injection Direction

Vacuum Control Unit Box Lid –
Material: ABS
Manufacturing Process: Injection Moulding



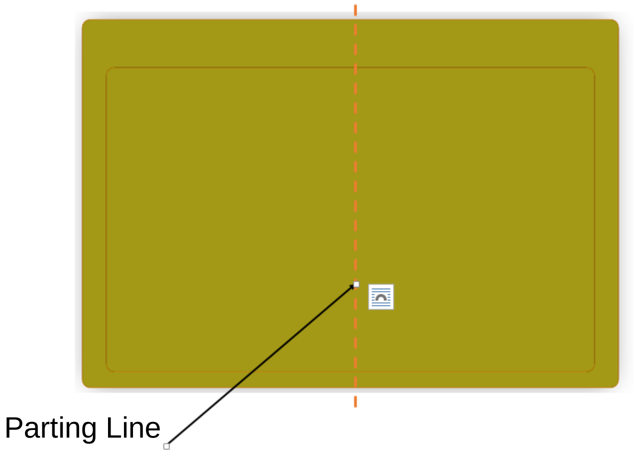


Figure 54 – Bottom View showing Parting Line

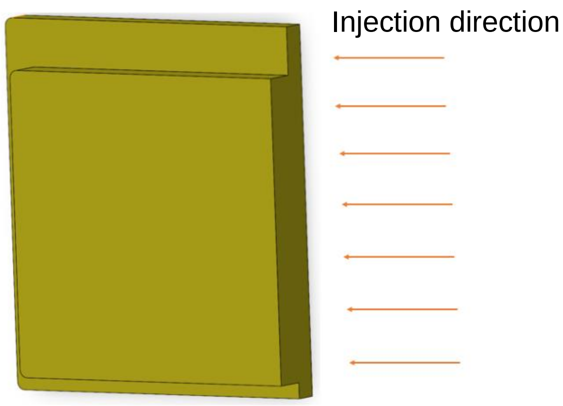
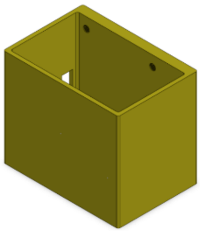


Figure 55 – Sectional Draft View showing Injection Direction

Vacuum Control Unit Box –
Material: ABS
Manufacturing Process: Injection Moulding



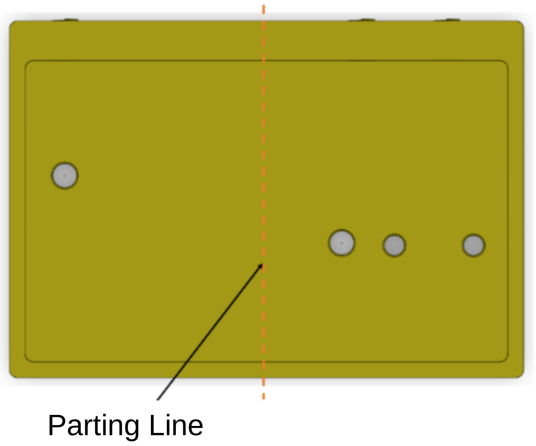


Figure 56 - Top View showing Parting Line

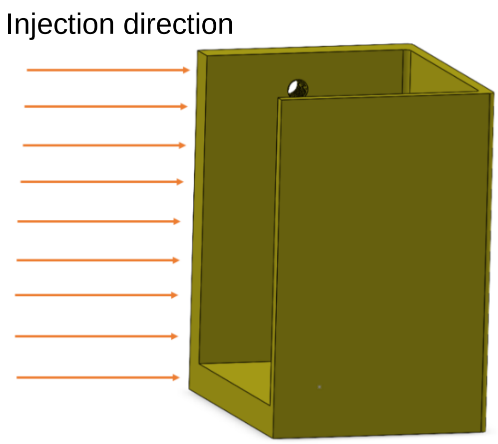
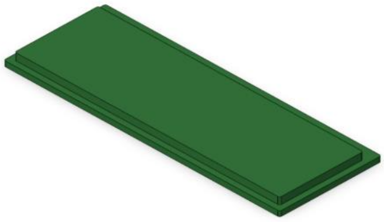


Figure 57 – Sectional Draft View showing Injection Direction

Main Control Unit Box Lid –
Material: ABS
Manufacturing Process: Injection Moulding



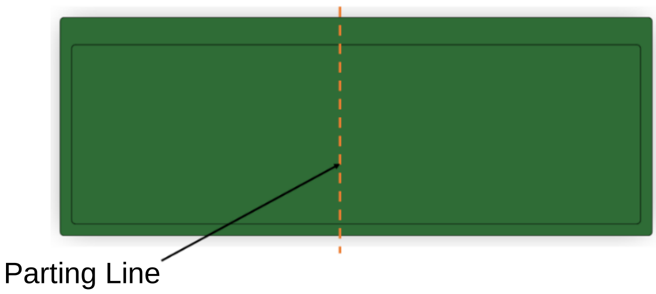


Figure 59 - Bottom View showing Parting Line

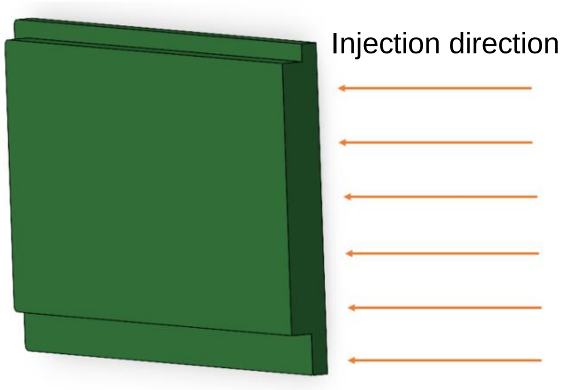
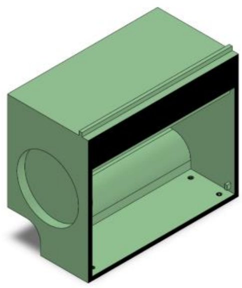


Figure 58 - Sectional Draft View showing Injection Direction

Vacuum Chamber –
Material: ABS
Manufacturing Process: Injection Moulding



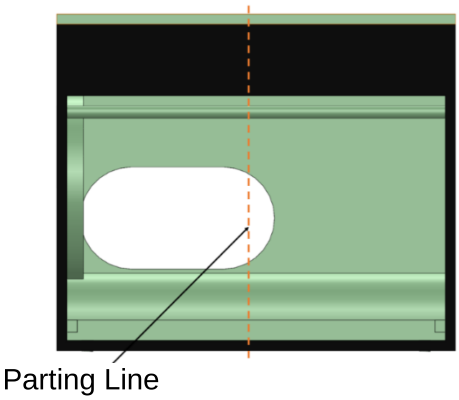


Figure 61 - Back View showing Parting Line

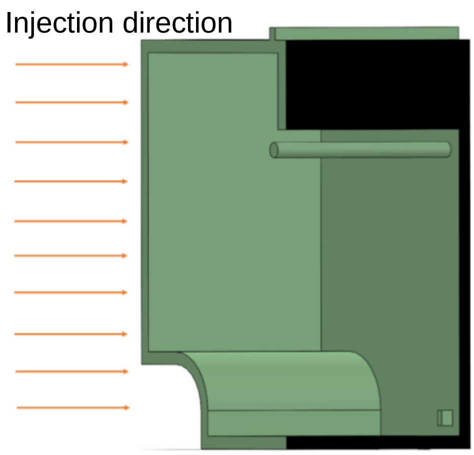


Figure 60 – Sectional Draft View showing Injection Direction

Roller Bushing –
Material: ABS
Manufacturing Process: Injection Moulding

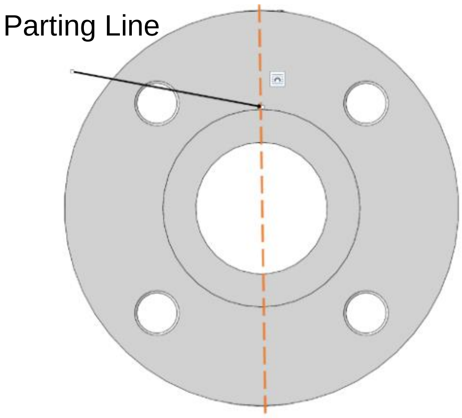


Figure 63 - Top View showing Parting Line

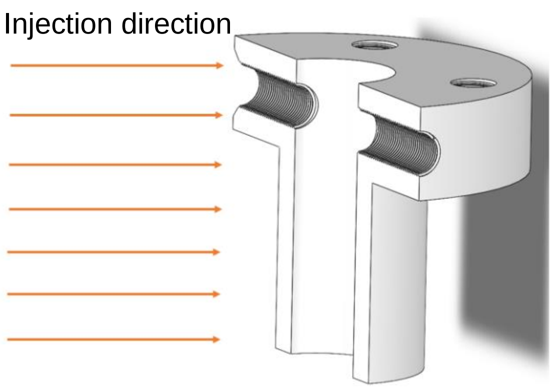
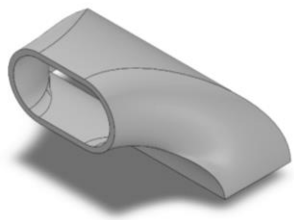


Figure 62 - Sectional Draft View showing Injection Direction

Vacuum Suction Pipe –
Material: ABS
Manufacturing Process: Injection Moulding



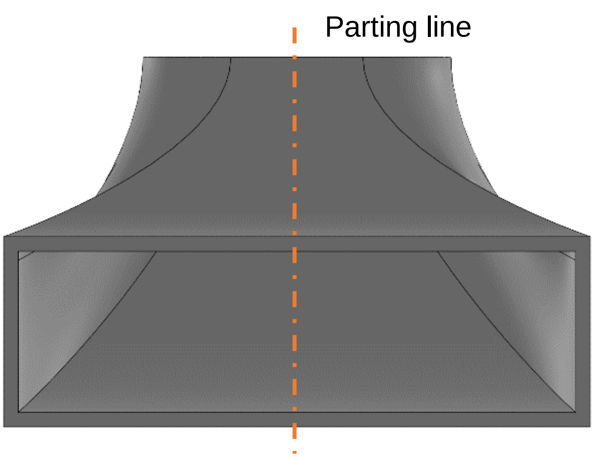


Figure 65 - Bottom View showing Parting Line

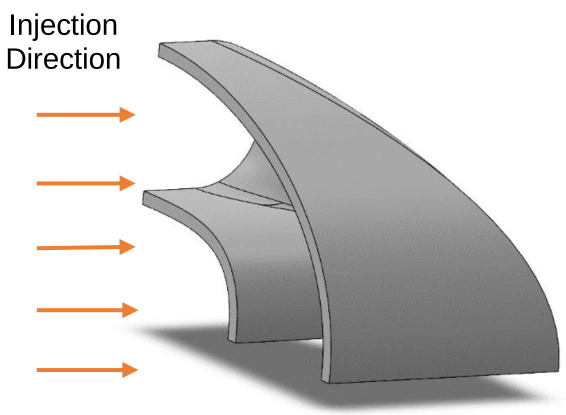


Figure 64 - Sectional Draft View showing Injection Direction

Vacuum Chamber Back Cover –
Material: ABS
Manufacturing Process: Injection Moulding

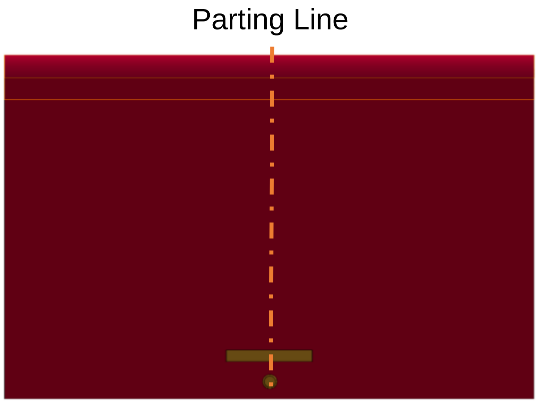


Figure 67 - Front View showing Parting Line

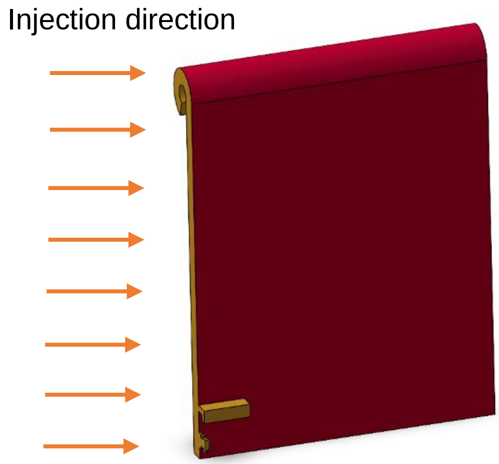
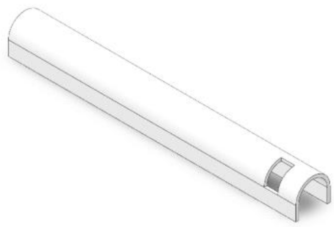


Figure 66 - Sectional Draft View showing Injection Direction

Rear Wheel Axle Cover –
Material: ABS
Manufacturing Process: Injection Moulding



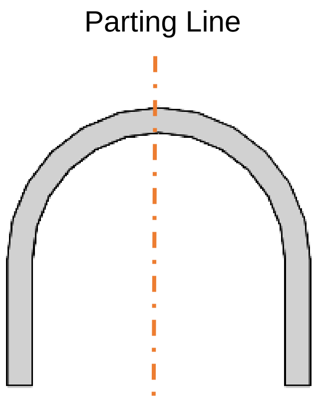


Figure 68 - Side View showing Parting Line

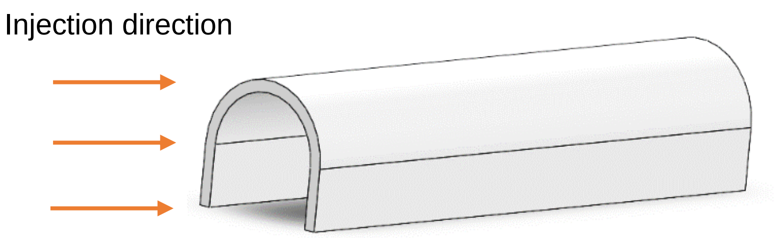
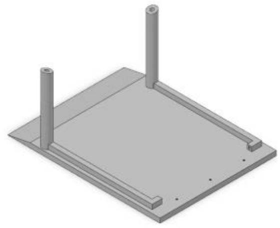


Figure 69 - Sectional Draft View showing Injection Direction

Charging Station Base –
Material: ABS
Manufacturing Process: Injection Moulding



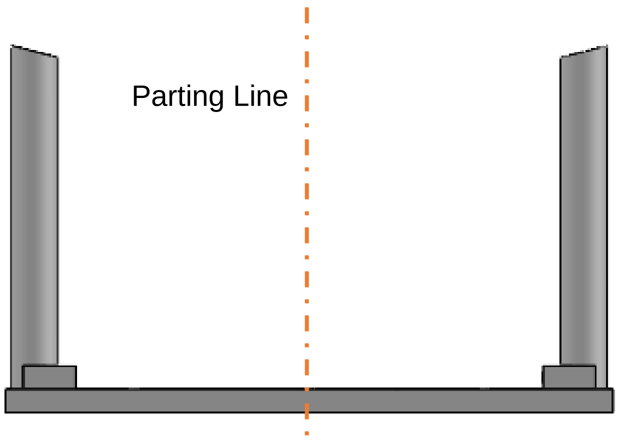


Figure 71 - Back View showing Parting Line

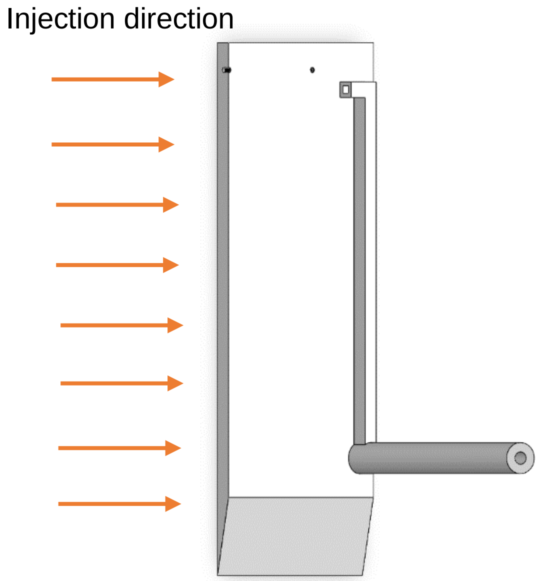
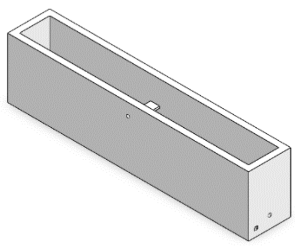


Figure 70 - Sectional Draft View showing Parting Line

Charging Station Control Unit Box –
Material: ABS
Manufacturing Process: Injection Moulding



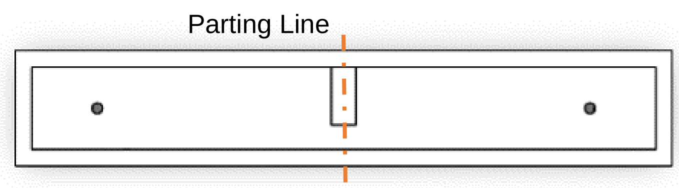


Figure 73 - Bottom View showing Parting Line

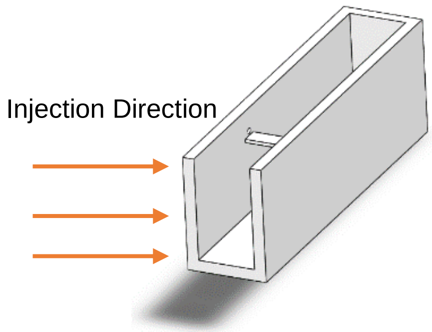


Figure 72 - Sectional Draft View showing Injection Direction

Charging Station Control Unit Box Lid –
Material: ABS
Manufacturing Process: Injection Moulding

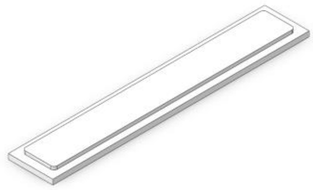


Figure 75 - Bottom View showing Parting Line

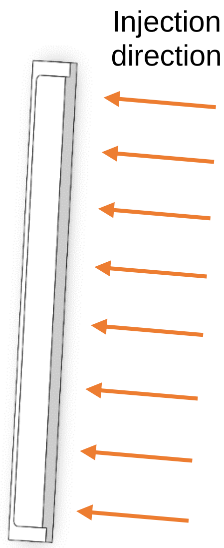
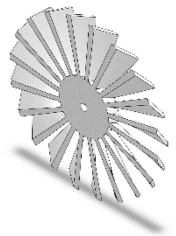


Figure 74 - Sectional Draft View showing Injection Direction

Vacuum Fan –
Material: ABS
Manufacturing Process: Injection Moulding



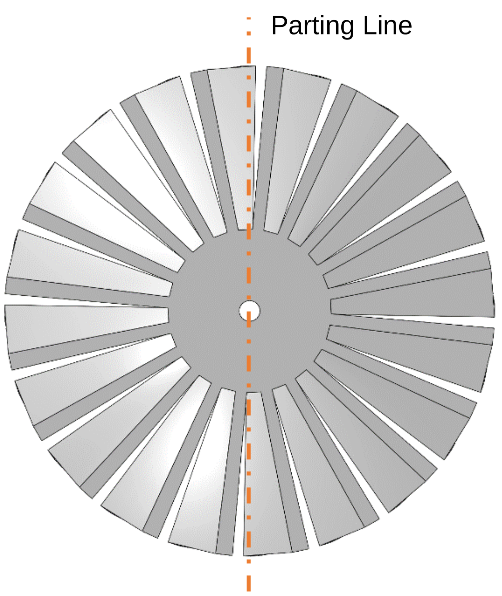


Figure 76 - Front View showing Parting Line

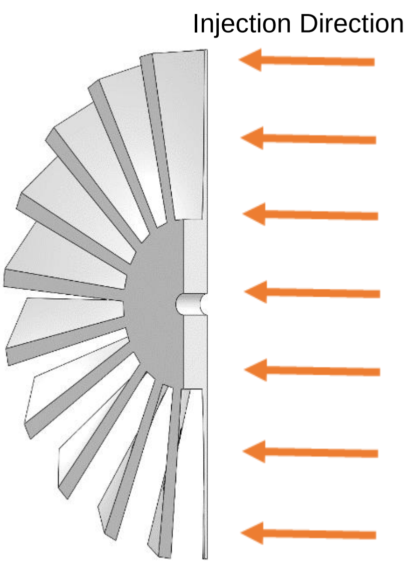


Figure 77 - Sectional Draft View showing Injection Direction

2. **Material**: PPE (Polypropylene)
   Method: Injection Moulding
   Machine Used: Injection Press

   Why PPE?
   Polypropylene wheel is made of high-quality impact-resistant synthetic materials. The wheels made of PPE are fracture-resistant, have high load capacity, and lower the cost of the overall wheel. [28]

Rear Wheel Hub –
Material: PPE
Manufacturing Process: Injection Moulding

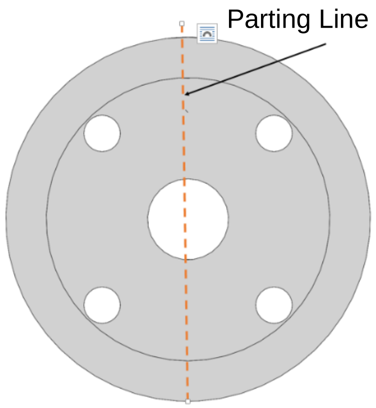


Figure 79 - Front View showing Parting Line

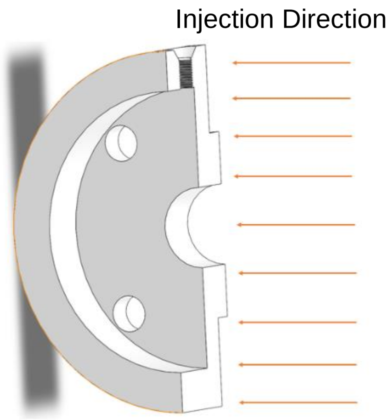


Figure 78 - Sectional Draft View showing Injection Direction

Wheels –
Material: PPE
Manufacturing Process: Injection Moulding

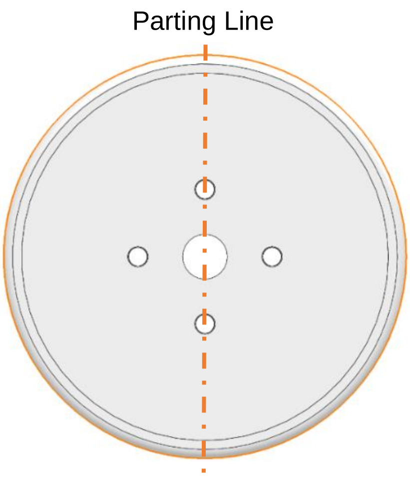


Figure 80 - Front View showing Parting Line

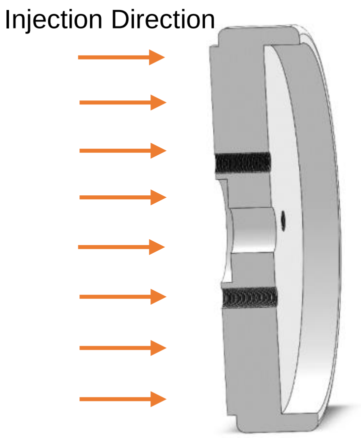


Figure 81 - Sectional Draft View showing Injection Direction

[28] (*Plastic and Resin Wheels*, n.d.)

3. **Material**: PUR (Polyurethane) Thermoplastic
   Method: Injection Moulding
   Machine Used: Injection Press

Why PUR?

PUR is most frequently used in the automotive industry; it is much lighter and more aerodynamic than other metals. Since it is a thermoplastic polymer, it can easily be formed into any shape.
PUR has excellent chemical and heat resistance and is generally resistant to impact.

Manufacturing process:

Firstly, the plastic extrusion is done under which the material PUR thermoplastic is heated and pushed through a warm chamber by a screw. The molten plastic is injected into the mould. Then the plastic is forced through a die that creates the final shape of the part. After that, the extruded plastic is cooled and solidified to be cut up to the desired length. It is carefully removed, and further processing is done.

Bumper –

Material: PPE
Manufacturing Process: Injection Moulding

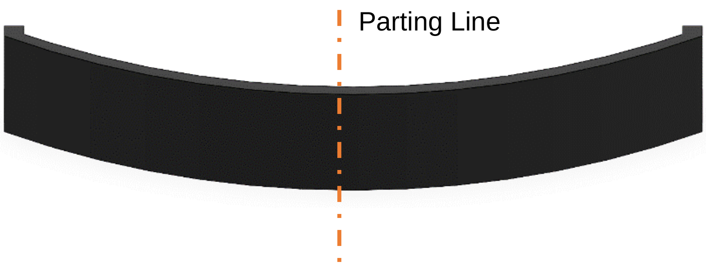


Figure 83 - Front View showing Parting Line

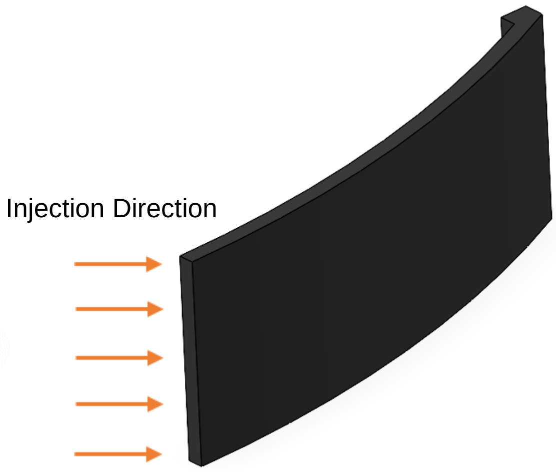


Figure 82 - Sectional Draft View showing Injection Direction

4. **Material:** Mild Steel
   Method: CNC Turning
   Machine Used: CNC Turning machine

Why Mild Steel?

Mild steel is used because of its affordability. It has low carbon content which makes it highly machinable. It offers high tensile strength, impact strength and ductility which makes it suitable to be used in shafts.

Manufacturing process:

The process used to manufacture shafts is CNC turning. Firstly, the shaft is placed in a milling machine. The cutting tools inside the machine rotate and move across the surface of the workpiece. This is how slowly the excess material is removed to have our desired shape and size. After the desired shape is achieved, chamfering is done at the ends of the shafts for easy assembly and to get rid of sharp edges.

Roller Shafts –

Material: Mild Steel
Manufacturing Process: CNC Turning

Figure 84 - Top View of Roller Shaft

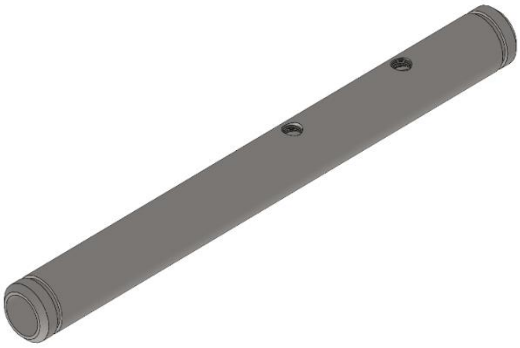


Figure 86 - Isometric View of Front Wheel Shaft

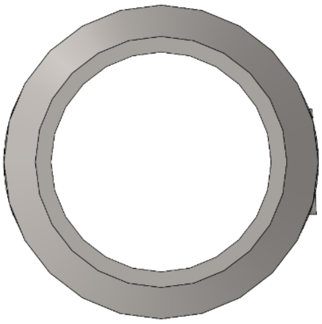


Figure 85 - Front View of the Shaft

Roller Motor & Wheel Motor Shaft Extension –

Material: Mild Steel
Manufacturing Process: CNC Turning

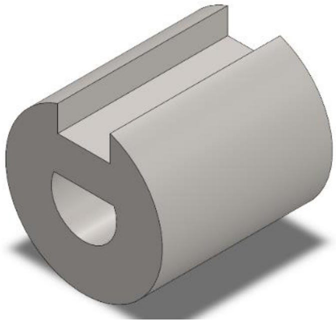


Figure 87 - Isometric View of Roller Motor Shaft Extension

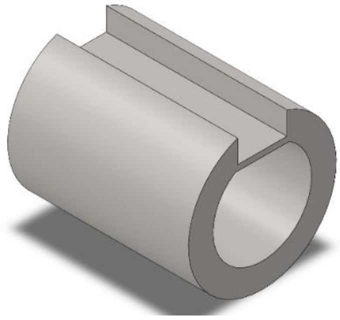


Figure 88 - Isometric View of Front Motor Shaft Extension

Wheel Motor Support –
Material: Mild Steel
Manufacturing Process: CNC Turning

These supports are added to fix the front wheels motor to the base plate.

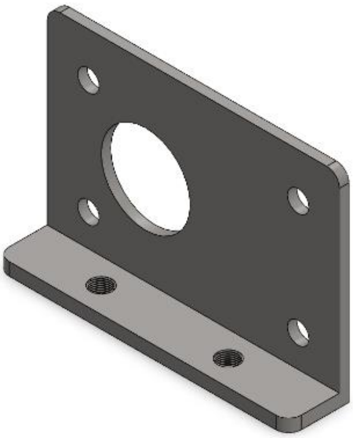


Figure 89 - Isometric View of Wheel Motor Support

Rear Wheel Axle –
Material: Mild Steel
Manufacturing Process: CNC Turning

Figure 90 - Side View of the Rear Wheel Axle

Figure 91 - Isometric View of Rear Wheel Axle

5. **Material:** Brass
   Method: Sand Casting and Die Casting
   Machine(s) Used: Lathe→Milling→Drill Press→Polishing→Brushing

Manufacturing process:

Casting is the process used for all metalworking. The following are the 3 main principal machining processes:

- *Turning:* The metal piece is rotated against the cutting tool. Lathes are the principal machine tools used in turning**.**
- *Milling:* The workpiece is being milled using the milling machine in which the cutting tool rotates to bring the cutting edges to bear against the workpiece.
- *Drilling:* Holes are being produced or refined by bringing the rotating cutter towards the lower extreme position into contact with the workpiece.
- *Finishing:* Finally, the surface of the part is being polished, brushed and lacquered to prevent it from corrosion.[29]

Charging Port –
Material: PPE
Manufacturing Process: Sand and Die Casting

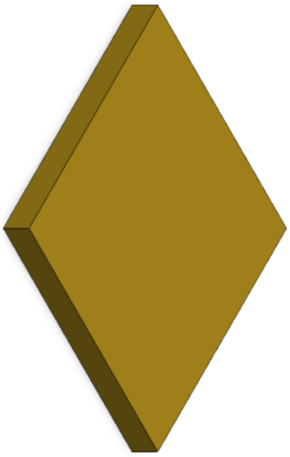


Figure 92 - Isometric View

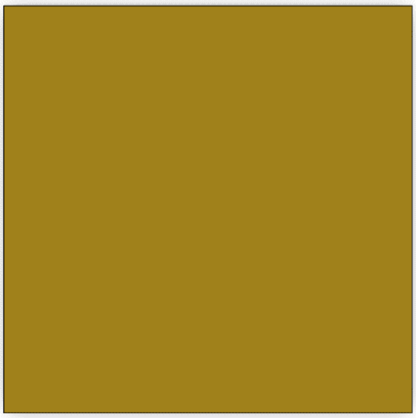


Figure 93 - Top View

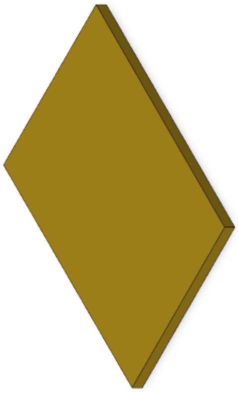


Figure 94 - Isometric View

Figure 95 - Top View

[29] (*Manufacturing Process of Brass Hardware*, n.d.)

6. **Material:** Nylon 101 & ABS
   Method: Injection Moulding

Why Nylon 101?

Nylon 101 is chosen because of its toughness, wear resistance, and high tensile strength. It is lightweight, cost-effective, waterproof, and easy to manufacture.

Manufacturing Process:

The body of the roller inside (cylindrical shaped roller) is manufactured using an Injection press on the principle of Injection moulding.
The bristles are made up of a special kind of Nylon that can be machined into a very thin fibre. Then these long lengths of thin fibres are cut into equal lengths. They are folded in half and then pocked into the holes on nylon. By simple technique of plastic mechanics. Bristles are squeezed into the hole like spaces arranged on the brush head. It is done by machines. Change in plasticity due to temperature is used instead of glue.

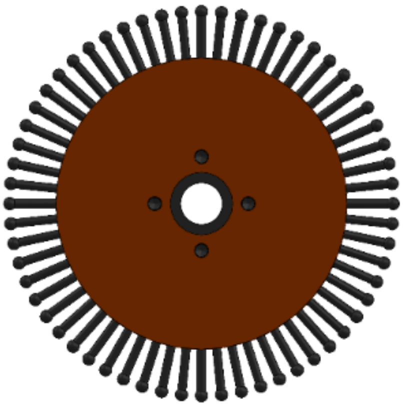


Figure 96 - Front View

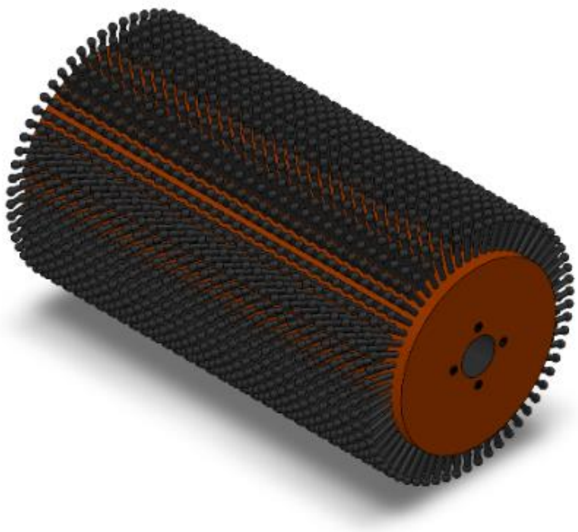


Figure 97 - Isometric View showing Nylon Bristles

Requirements Manual (CotS Parts)

1. Arduino Mega 2560 (Main Microcontroller Board)

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7V-12V
Input Voltage (limit)	6V-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
Flash Memory	256 KB of which 8 KB used by the bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
LED built-in	13
Operating Temperature	-40℃ - +85℃
Length	101.52 mm
Width	53.3 mm
Weight	37g

Table 6 - Specifications of Arduino Mega 2560

2. Arduino Pro Mini (Vacuum and IR Transmitter Microcontroller Board)

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	6V-12V
Input Voltage (raw)	5V-16V
Digital I/O pins	14 (of which 6 provide PWM output)
Analog input pins	6
DC Current per I/O pin	40 mA
Flash Memory	32 KB of which 2 KB used by the bootloader
SRAM	2 KB
EEPROM	1 KB
Clock Speed	16 MHz
LED built-in	13
Operating Temperature	-40℃ - +105℃
Length	33.0 mm
Width	17.8 mm
Weight	2g

Table 7 - Specifications of Arduino Pro Mini

3. Nylon Brush Roller DC Motor (770-7040-CC)

Nominal Voltage	12V
Nominal Speed	3400RPM
Nominal Torque	4.1mNm
Nominal Current	0.2A
No Load Speed	4300RPM
No Load Current	0.07A
Stall Torque	23.8mNm
Starting Current	1A
Output Power	1.5W
Efficiency	57%
Operating Temperature	-10℃ - +60℃
Diameter	29mm
Length	37.8mm
Weight	110g

Table 8 - Specifications of DC Motor for Nylon Brush Roller

4. Wheel Motor DC

Rated Voltage	12V
Speed	6RPM
Standby Current	0.82A
No-Load Current	0.12A
Stable Torque	36.4kg.cm
Reduction Ratio	1:972
Length	82mm
Width	32mm
Height	39.2mm
Weight	181.44g

Table 9 - Specifications of DC Motor for Wheels

5. Vacuum Motor DC

Nominal Voltage	12V
Nominal Speed	15800RPM
Nominal Torque	57.3mNm
Nominal Current	9.8A
No Load Speed	17600RPM
No Load Current	1.2A
Stall Torque	527.5mNm
Starting Current	82.5A
Output Power	95W
Efficiency	81%
Operating Temperature	-10℃ - +60℃
Diameter	39mm
Length	57mm
Weight	303g

Table 10 - Specifications of DC Motor for Vacuum System

6. L298N Motor Driver Modules

Drive Voltage	5V – 35V
Logical Voltage	5V
Drive Current	2A
Power Max.	25W
Length	43mm
Width	43 mm
Height	27mm
Weight	27 g

Table 11 - Specifications of Motor Driver Modules

7. 12V Lead-acid Battery

Voltage	12V	
Charging Voltage Max.	14.8V	
Nominal Capacity	25Ah – 280Ah	
Battery Technology	AGM (VRLA)	
Cycles	50% discharge depth	600 - 750
	75% discharge depth	400-500
Power	25W	
Length	183 mm	
Width	79mm	
Height	170mm	
Weight	7kg	

Table 12 - Specifications of Battery

8. LM317 Voltage Regulator

Input-Output Voltage Differential	40V
Power Dissipation	Internally Limited
Output Voltage	-0.3V – 40V
Output Current	0.1A
Operating Temperature	0°C - +125°C
Length	4.48mm
Width	3.86mm
Height	19.05mm
Weight	0.2g

Table 13 - Specifications of Voltage Regulator

Additional Components for Power Supply Circuit:

- Capacitor Values:
  - C_a: 0.1uF
  - C_b: 1uF
  - C_c: 10uF
- Resistor Values:
  - R_a: 240Ω
  - R_b: 1.3kΩ
- Diodes: 1N4002

9. TASTER 9305 (Push Button for the Main circuit and Vacuum circuit)

<table>
<tr><td>Type</td><td colspan="2">Short-Stroke Key</td></tr>
<tr><td>Design</td><td colspan="2">Round Control Button</td></tr>
<tr><td>Assembly</td><td colspan="2">Vertical Actuation</td></tr>
<tr><td>Material</td><td colspan="2">Silver-Plated Brass Contacts</td></tr>
<tr><td>Connection</td><td colspan="2">PCB Mounting</td></tr>
<tr><td>Load Limit</td><td colspan="2">12V DC/ 0.05A</td></tr>
<tr><td>Bounce Time</td><td colspan="2">10ms</td></tr>
<tr><td>Travel Operation</td><td colspan="2">0.25mm</td></tr>
<tr><td>Force Operation</td><td colspan="2">1.6N</td></tr>
<tr><td>Energy Efficiency Durability</td><td colspan="2">100,000h</td></tr>
<tr><td>Contact Resistance Max.</td><td colspan="2">100mΩ</td></tr>
<tr><td>Insulation Resistance</td><td colspan="2">100 MΩ Min. / 100 VDC</td></tr>
<tr><td>Dielectric Strength</td><td colspan="2">250VAC (50 or 60Hz.) for 1 min</td></tr>
<tr><td>Connected Resistor Value</td><td colspan="2">10kΩ</td></tr>
<tr><td>Housing</td><td colspan="2">Nylon 66G30</td></tr>
<tr><td>Connections</td><td colspan="2">Silver-Plated Brass</td></tr>
<tr><td>Contacts</td><td colspan="2">Phosphor Bronze</td></tr>
<tr><td rowspan="2">Material</td><td rowspan="2">Actuator</td><td>PBT (JTP-1236)</td></tr>
<tr><td>PPS (JTP-1130)</td></tr>
<tr><td>Operating Temperature Range</td><td colspan="2">-20°C - 70 °C</td></tr>
<tr><td>Tolerance</td><td colspan="2">±0.3mm</td></tr>
<tr><td>Length</td><td colspan="2">6mm</td></tr>
<tr><td>Width</td><td colspan="2">6mm</td></tr>
<tr><td>Height</td><td colspan="2">8mm</td></tr>
<tr><td>Weight</td><td colspan="2">0.3g</td></tr>
</table>

Table 14 - Specifications of Push Button

10. ZB5 Emergency Stop Button

Type	Front element
Assembly	for XB5
Model	Harmony XB5 Series
Technology	ZB5 Single Module
Design	Unlocking Design
Mechanical Life	300,000 cycles
Connected Resistor Value	10kΩ
Protection Class	IP69K
Operating Temperature	-40 - 70 ° C
Material	Plastic
Mounting Diameter	22mm
Diameter	30mm
Height	30mm
Weight	42g

Table 15 - Specifications of Emergency Stop Button

11. HC-SR04 Ultrasonic Sensor Module

Specification	HC-SR04
Range	300 – 400cm
Operating Voltage	5V DC
Operating Current	15mA
Frequency	40kHz
Trigger Pulse Width	10us
Maximum Deviation	0.3mm
Length	43mm
Width	20mm
Height	15mm
Weight	9g

Table 16 - Specifications of Ultrasonic Sensor

12. MPU2950 IMU Sensor Module

<table>
<tr><td>Specification</td><td colspan="2">MPU-9250</td></tr>
<tr><td>Working Voltage</td><td colspan="2">5V</td></tr>
<tr><td>VDD Operating Range</td><td colspan="2">2.4V – 3.6V</td></tr>
<tr><td>VDDIO</td><td colspan="2">1.8V</td></tr>
<tr><td>Operating Current</td><td colspan="2">3.7mA</td></tr>
<tr><td>Control Mode</td><td colspan="2">IIC</td></tr>
<tr><td>Interface</td><td colspan="2">I2C/SPI Interface</td></tr>
<tr><td>I2C Frequency</td><td colspan="2">400kHz</td></tr>
<tr><td>SPI Frequency</td><td colspan="2">1MHz</td></tr>
<tr><td rowspan="3">Digital Output 3-Axis</td><td>Gyroscope user-programmable full-scale range</td><td>±250, ±500, ±1000, and ±2000°/sec (DPS)</td></tr>
<tr><td>Accelerometer programmable full-scale range</td><td>±2g, ±4g, ±8g and ±16g</td></tr>
<tr><td>Magnetometer full-scale measurement range</td><td>±4800μT</td></tr>
<tr><td>Operating Temperature</td><td colspan="2">-40 - +85 °C</td></tr>
<tr><td>Length</td><td colspan="2">40mm</td></tr>
<tr><td>Width</td><td colspan="2">20mm</td></tr>
<tr><td>Weight</td><td colspan="2">7g</td></tr>
</table>

Table 17 - Specifications of IMU Sensor

13. ACS712 Current Sensor

Supply Voltage	5V DC
Supply Current	8mA
Measuring Range	± 30 A
Chip	ACS712ELC-30A
Output	66mV/A
Voltage at 0A	VCC/2 (nominally 2.5V DC)
Operating Temperature	-40 – 85 °C
Length	31.73mm
Width	13.25mm
Height	14mm
Weight	2.72g

Table 18 - Specifications of Current Sensor

14. Microswitches

Working Voltage	250V
Working Current	5A
Working Node	Self-reset
Pole	SPDT
Contact Type	1NO + 1NC
Action Type	Momentary
Actuator Type	Roller Lever Arm
Terminal Type	3 Pin
Mounting Hole Diameter	2mm
Distance Of Mounting Holes	9.5mm
Connected Resistor Value	10kΩ
Material	Plastic, Metal
Length	19.8mm
Width	6.4mm
Height	13.5mm
Weight	90g

Table 19 - Specifications of Microswitches

15. LM393 Speed Sensor (Wheel Encoder)

Working Voltage	3.3V – 5V
Current	15mA
Slot Width	5mm
Output Format	Digital Switching Output (0 and 1)
Length	32mm
Width	14mm
Weight	4g

Table 20 - Specifications of Wheel Encoder

16. RGB LED light

Type	4-Pin	
Colour	Red/Green/Blue	
Wave Lengths	626/525/470 nm	
Mounting Form	5 MM T1 ¾	
Design	RGB	
Light Intensity	7000/8000/4000 mcd	
Light Colour	N/A K	
Operating Voltage Max.:	2.5/4.0/4.0V	
Normal Current	20mA	
PEAK FORWARD CURRENT (0.1ms PULSE WIDTH)	100mA	
Continuous Forward Current	35mA	
Derating Linear From 50°C	0.4mA/°C	
Power Dissipation Max	100mW	
Forward Current	35mA	
Reverse Voltage	5V	
Angle Of Radiation	25°	
Operating Temperature	-40 - +80 °C	
Material	Red	ALGaInP
	Green	GaN/SiC
	Blue	GaN/SiC
Tolerance	±0.25mm	
Length	8.36nm	

Inner Diameter	5.0mm
Outer Diameter	5.8mm
Weight	1g

Table 21 - Specifications of RGB LED Light

Additional Components for RGB LED:

- Resistor Values:
  - R_a, R_b: 100Ω
  - R_c: 220Ω

17. Perimeter Wire Generator and Sensor Kit

Specifications of the Generator:

Output Frequency Range	33.5kHz – 39kHz	
Output Amplitude	11.8V	
Operating Voltage	12V	
Operating Current	3A	
IC: NE555 Precision Timer	Supply Voltage	4.5 – 16V
	Output Current	±200mA
	Operating Temperature	0 - 70°C
	Storage Temperature Range	-65 - 150°C

Table 22 - Specifications of Perimeter Wire Generator

Additional Components:

- Capacitor Values:
  - C_a: 100nF
  - C_b: 1.2nF
  - C_c: 1uF
- Resistor Values:
  - R_a: 3.3kΩ
  - R_b: 12kΩ
  - R_c: 47Ω
  - Pot: 4.7kΩ

Specifications of the Sensor:

Resonance Frequency	33.932Hz	
Operating Voltage	5V	
IC: LM324N Amplifier	Supply Voltage	3 – 32V
	Supply Current	0.7mA
	Operating Temperature	0 - 70°C
	Signal Amplitude	80mV
	Amplifier Gain	100

Table 23 - Specifications of Perimeter Wire Sensor

Additional Components:

- Inductor Value: 1mH
- Capacitor Value: 22nF
- Resistor Values:
  - R1: 10kΩ
  - R2: 1MΩ

18. IR Transmitter

Peak Wavelength	940nm
Light Range	19m (18m - 20m)
Power Dissipation	100mW
Pulse Current	60mA
Forward Current	30mA
Max. Reverse Current	10uA, Reverse Voltage 5V
Forward Voltage	1.2V – 1.6V, Forward Current 20mA
Reverse Voltage	6V
Operating Temperature	-55℃ TO +100℃
Lead Soldering Temperature	260℃ for 5 seconds
Luminous Distance	19m, Forward Current 20mA
Luminous Angle	45°
Tolerance	0.25mm
Diameter	5.8mm
Inner Diameter	5.0mm
Length	37.2mm
Weight	2.2g

Table 24 - Specifications of Infrared Transmitter

19. IR Receiver

Input Frequency	38kHz
Operating Voltage	5V
Output	Digital
Receiving Distance	15m
Acceptance Angle	± 35°
Operating Temperature	-25 - 85°C
Length	23.5mm
Width	21.5mm
Weight	2g

Table 25 - Specifications of Infrared Receiver

20. Step Down Transformer (Battery Charger):

Output Voltage	15V DC	
Adjustable Voltage Range	13.5V – 16.5V DC	
Output Current	1A	
Output Power	15W	
Efficiency	81%	
Ripple	120mV	
Input Voltage Range	88–132/176–264 V AC (47–63 Hz), 248–373 V DC	
Max. Inrush Current	65A	
Max. Leakage Current	2mA	
Output Voltage Adjustment	+10/-5%	
Overload Protection	>105%	
Insulation Voltage	I/P-O/P	3000V AC
	I/P-FG	1500 V AC
	O/P-FG	500 V AC
Operating Temperature Range	-25 - +70 °C	
Length	62.5mm	
Width	51mm	
Height	28mm	
Weight	130g	

Table 26 - Specifications of Step-Down Transformer

Additional Components:

- Bridge Rectifier Module: 1N4007 * 4
- Capacitor Value: 47uF
- Resistor Values:
    - R_a: 1kΩ
    - R_b: 2.2kΩ
    - R_c: 220Ω
- Diodes:
    - Green LED
    - MBR1545 SCHOTTKY
- Regulator IC: LM317

21. Spur Gears M1 20T x 3:

Supplier	Norelam
Material	POM
Module	1
Number of Teeth	20
Pitch Diameter (mm)	20
Bore Diameter (mm)	10 with keyway
Max Torque (Nm)	28.2
Price	1.88

Table 27 - Specifications of Spur Gears 20T

22. Spur Gears M1 40T x 1:

Supplier	Norelam
Material	POM
Module	1
Number of Teeth	40
Pitch Diameter (mm)	40
Bore Diameter (mm)	10 with keyway
Max Torque (Nm)	58.5
Price	2.57

Table 28 - Specifications of Spur Gears 40T

23. Spur Gears M1 25T x 2:

Supplier	Norelam
Material	POM
Module	1
Number of Teeth	25
Pitch Diameter (mm)	25
Bore Diameter (mm)	10 with keyway
Max Torque (Nm)	35.3
Price	1.99

Table 29 - Specifications of Spur Gears 25T

24. Bearings:

Supplier	SKF
Material	Steel
Dynamic Load Rating (kN))	5.4
Static Load Rating (kN)	2.36
RPM	56000
Weight (g)	32

Table 30 - Specifications of Bearings

25. Screws:

Type	Length (mm)	Supplier
Tapping Screw DIN 7049	8	Distrelec
DIN EN ISO 7046 M3 X 10	10	Distrelec
DIN 912 M2.5 X 8	8	Distrelec
DIN 912 M3 X 10	10	Distrelec
DIN 7991 - M3 X 20	20	Distrelec
Tapping Screw Din 7049	8	Distrelec
DIN 912 M2.5 X 8	8	Distrelec
DIN 912 M2.5 X 8	8	Distrelec
DIN 912 M3 X 8	8	Amazon
DIN 988 X 6	6	Amazon
DIN 912 M2.5 X 6	6	Distrelec
DIN 912 M3 X 16	16	Distrelec
DIN 912 M4 X 16	16	Distrelec
DIN 7991 - M3 X 16	16	Amazon
DIN 7991 - M3 X 30	30	Amazon
DIN 7984 - M4 X 16	16	Amazon
DIN 912 M2 X 10	10	Distrelec
Circlip DIN 471 - 10	10 mm diameter	Amazon

Table 31 - Specifications of Screws

Pseudo-Code (Program Flow Charts)

Main Program Flow Chart

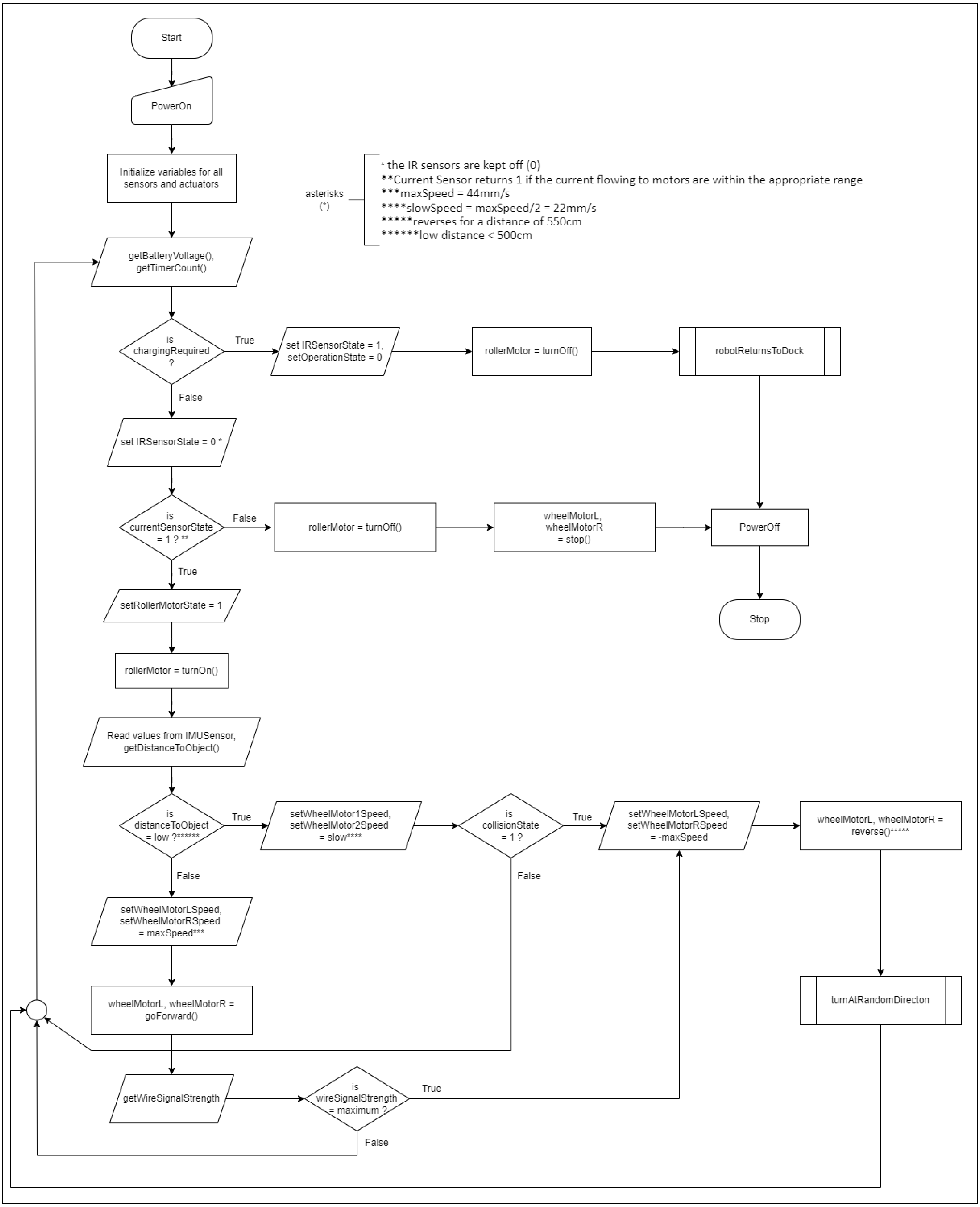


Figure 98 - Main Program Flow Chart

robotReturnsToDock Program Flow Chart

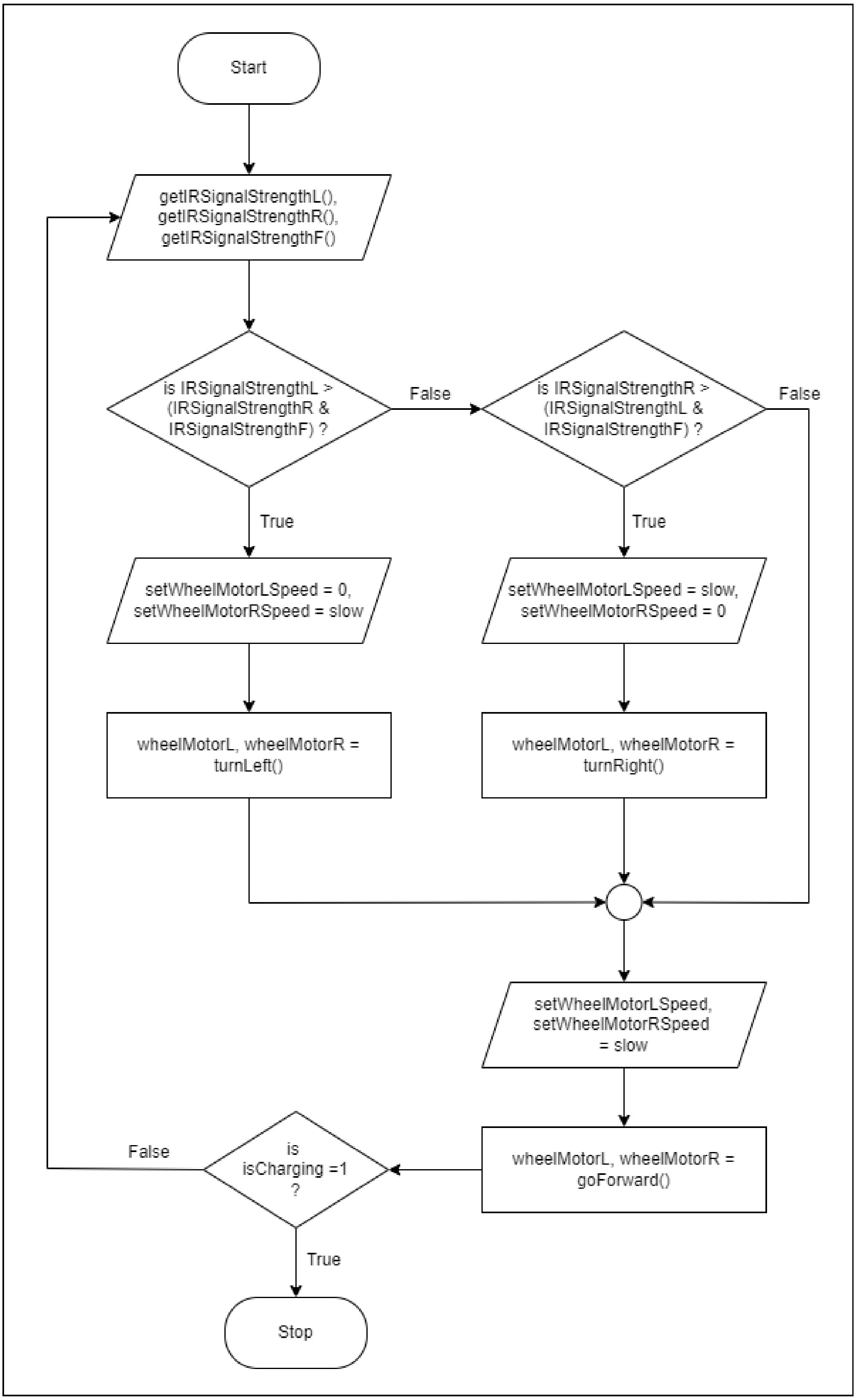


Figure 99 - Program Flow Chart showing Robot Returning to Dock

turnAtRandomDirection Program Flow Chart

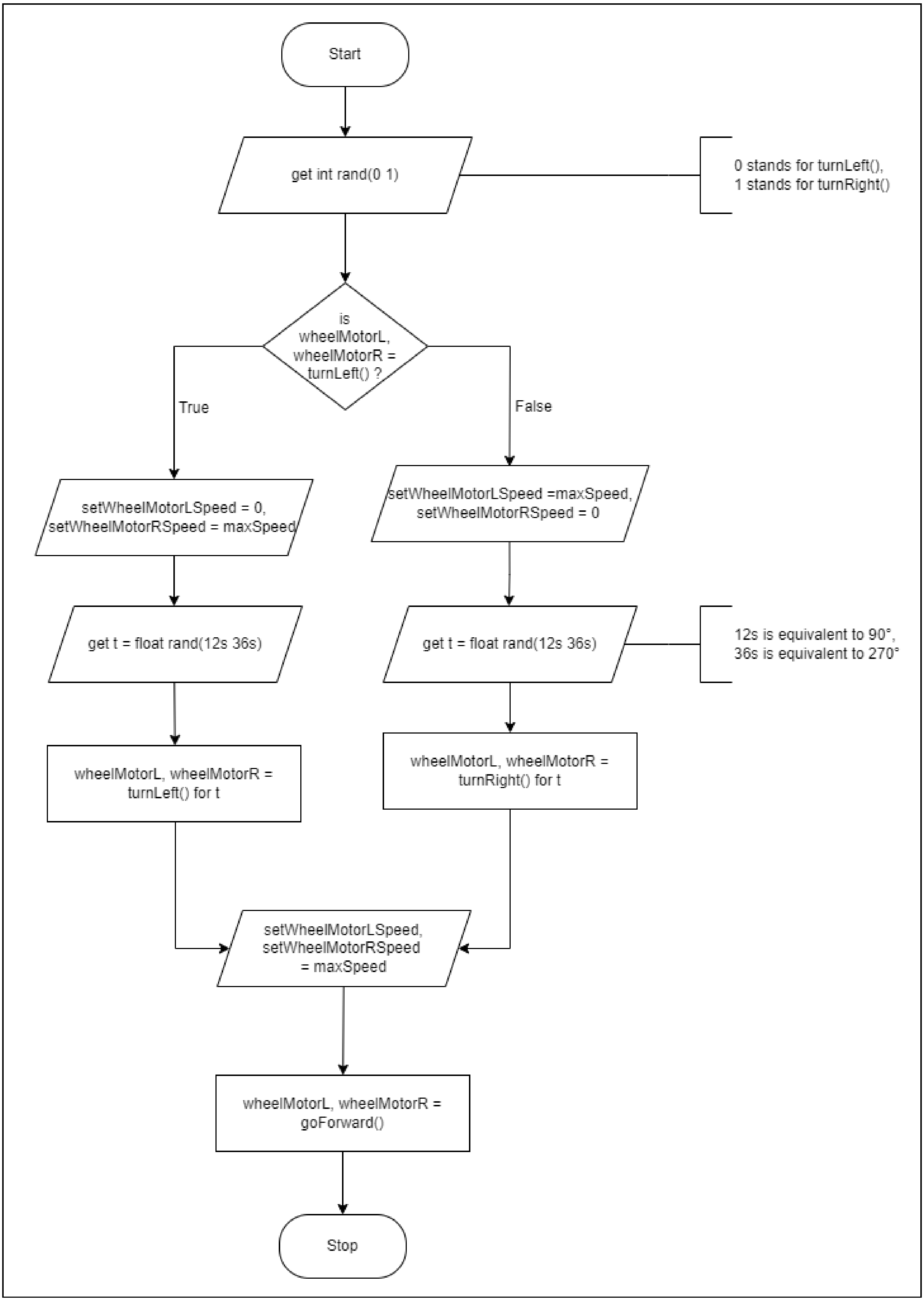


Figure 100 - Program Flow Chart showing Robot Turning at Random Direction

Vacuum Program Flow Chart

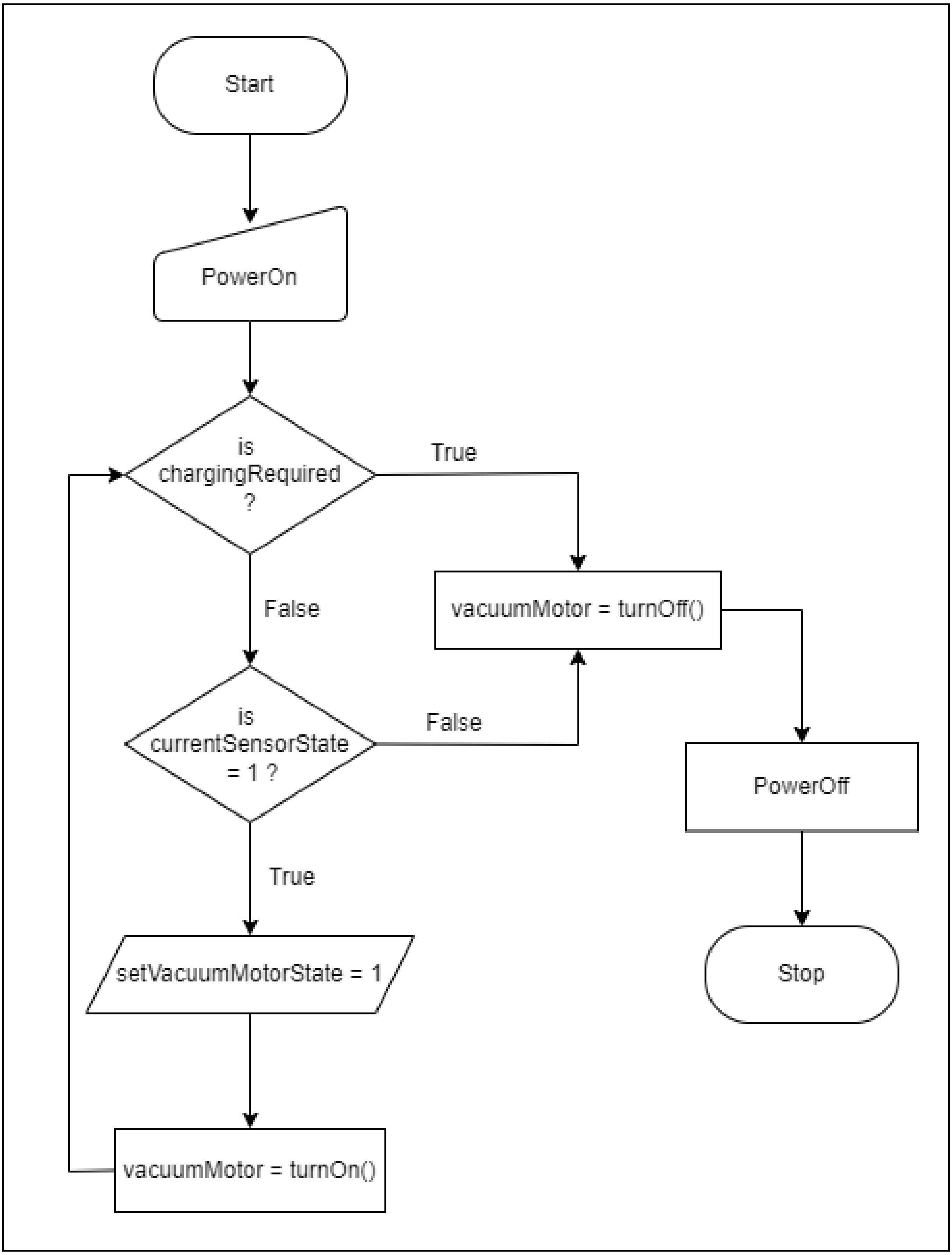


Figure 101 - Program Flow Chart showing the working of Vacuum System

Production Planning

Capacity Calculation

Shift Model and Available Production Time

Capacity Analysis
No. of days per year = 365 days
Weekends and public holidays = approx. 115 days
No. of working days annually = 250 days
Annual sales target = 700 units
Sales price per robot = 1,399 €
No. of shifts per day = 1

The main goal of the company is to achieve the annual revenue sales of 979,300 € set by the CEO and other board members of the company. To translate this target to a production plan, the calculation for the number of finished goods is done which will be produced in the factory each year.

$$No. of\ units\ produced\ annually = \frac{Target\ annual\ revenue}{product\ price} = \frac{979{,}300\ €}{1{,}399\ €} = 700\ units$$

To translate the annual production goals to daily production goals, the working days of the company is assumed to be 365 days.

Consumer Takt Time
The Takt time is the required production duration to meet the customer demand.
The aim here is to produce 750 units in the first year. This is based on the market research done in Milestone 1, which were 300 units in the initial launch phase.

$$No. of\ units\ produced\ per\ day = \frac{No.\ of\ units\ produced\ annually}{annual\ working\ days} = \frac{700\ units}{250\ days} \approx 3\ units/day$$

We assume that some units will be discarded during the quality assurance cycle and the production and sales targets will not be achieved; therefore, some safety buffers will be kept which will increase our annual production to 750 units.

Factory Working Hours

The factory will be active for 8 hours per day in a single shift. Out of those 8 hours, 30 minutes will be break time and daily 10 minutes will be taken for short staff meetings and briefings. Hence, the overall productive working hours will be 7 hours 20 minutes (7.33 hours) each day.

There are many advantages of 8-hour shift schedules, for both the employee and the employer. There’s a likelihood of a reduction in staff accidents and/or errors due to the amount of rest time in between shifts. The factory can get around-the-clock coverage. It also simplifies scheduling. Scheduling fewer employees may help with reducing extra costs with insurance and healthcare costs. The disadvantage of this shift model is it requires up-front planning, but it pays in the long run.

Item #	Part Name	Machine	Production time per Piece [min]	Qty	No. of units produced daily	No. of units produced per shot	Daily time of production [min]	Lot Size	Factory working time per day [min]	Set-Up & Manual Operation Time	Time per Order [hh:mm]
1	Base Plate	Injection Moulder	5	1	3	1	15	10	440	280	05:30
2	Housing	Injection Moulder	5	1	3	1	15	10	440	280	05:30
3	Bearing Cap	Injection Moulder	1	2	6	6	1	10	440	280	04:50
4	Bearing Inner Cover	Injection Moulder	2	4	12	12	2	10	440	280	05:00
5	Bumper	Injection Moulder	2.5	1	3	1	7.5	10	440	280	05:00
6	Charging Dock Base	Injection Moulder	5	1	3	1	15	10	440	280	05:30
7	Charging Dock Control Unit Box	Injection Moulder	3.5	1	3	1	10.5	10	440	280	05:15
8	Charging Dock Control Unit Lid	Injection Moulder	1.5	1	3	3	1.5	10	440	280	04:55
9	Control Unit Box - Vacuum	Injection Moulder	2	1	3	1	6	10	440	280	05:00
10	Control Unit Box Lid - Vacuum	Injection Moulder	1.5	1	3	3	1.5	10	440	280	04:55
11	Control Unit Box Lid - Main	Injection Moulder	1.5	1	3	3	1.5	10	440	280	04:55
12	Control Unit Box Main	Injection Moulder	2.5	1	3	1	7.5	10	440	280	05:00
13	Hub For Wheels	Injection Moulder	2.5	4	12	6	5	10	440	280	05:00
14	Rear Axle Cover	Injection Moulder	2.5	1	3	1	7.5	10	440	280	05:05
15	Roller Bushing	Injection Moulder	2.5	2	6	6	2.5	10	440	280	05:05
16	Roller Cover	Injection Moulder	1.5	1	3	1	4.5	10	440	280	04:55
17	Roller Motor - Clamp	Injection Moulder	1	1	3	3	1	10	440	280	04:50
18	Roller Motor Support	Injection Moulder	1	1	3	3	1	10	440	280	4:50
19	Vacuum Chamber	Injection Moulder	3.5	1	3	1	10.5	10	440	280	5:15
20	Vacuum Chamber Lock	Injection Moulder	0.25	1	3	3	0.25	10	440	280	4:42.5
21	Vacuum Fan	Injection Moulder	5	1	3	3	5	10	440	280	5:30

22	Vacuum Motor Support	Injection Moulder	2.5	1	3	3	2.5	10	440	280	05:05
23	Vacuum Suction Pipe	Injection Moulder	4	1	3	1	12	10	440	280	05:20
24	Wheel	Injection Moulder	4	4	12	4	12	10	440	280	05:20
25	Wheel of Wheel Encoder	Injection Moulder	0.5	1	3	3	0.5	10	440	280	04:45
26	Nylon Brush Roller	Injection Moulder and Gluing	30	1	3	1	90	10	440	280	09:40
27	Axle - Rear Wheel	Lathe, Milling, Drilling, Grinding	15	1	3	1	45	10	440	185	05:35
28	Roller Motor Shaft Extension	Lathe, Milling, Drilling, Grinding	10	1	3	1	30	10	440	185	04:45
29	Shaft- Front Wheel	Lathe, Milling, Drilling, Grinding	10	1	6	1	60	10	440	185	04:45
30	Wheel Motor Shaft Extension	Lathe, Milling, Drilling, Grinding	10	1	3	1	30	10	440	185	04:45
31	Wheel Motor Support	Lathe, Milling, Drilling, Grinding	15	1	3	1	45	10	440	185	05:35
32	Wheel Motor Support - Right	Lathe, Milling, Drilling, Grinding	15	1	3	1	45	10	440	185	05:35
33	Charging Dock Port	Sieve, Striker, Cutter and Trowel	25	2	6	1	150	10	440	170	07:00
34	Charging Port	Sieve, Striker, Cutter and Trowel	20	2	6	1	120	10	440	170	06:10

Table 32 - Capacity Calculation of Make-Parts

$$\boldsymbol{Time\ per\ order}\ [\boldsymbol{min}] = \boldsymbol{Setup\ time}\ [\boldsymbol{min}] + (\boldsymbol{Lot\ size}\ \times \boldsymbol{Time\ per\ piece}\ [\boldsymbol{min}])^{\boldsymbol{*}}$$

*This calculation is done in Table 32 (above) with required conversions of time

Number of Machines Needed

Workload needed for each part is calculated based on the number of units produced, production time for one unit (''Floor-to-floor''). Assumptions are made for the production and set-up time

$$Production\ time\ per\ day = Production\ time\ per\ unit \times no.\ of\ units\ produced\ daily$$

[min]

$$No.of\ machines = \frac{Production\ time\ per\ day\ [min]}{Factory\ Working\ Time\ per\ day\ [min]}$$

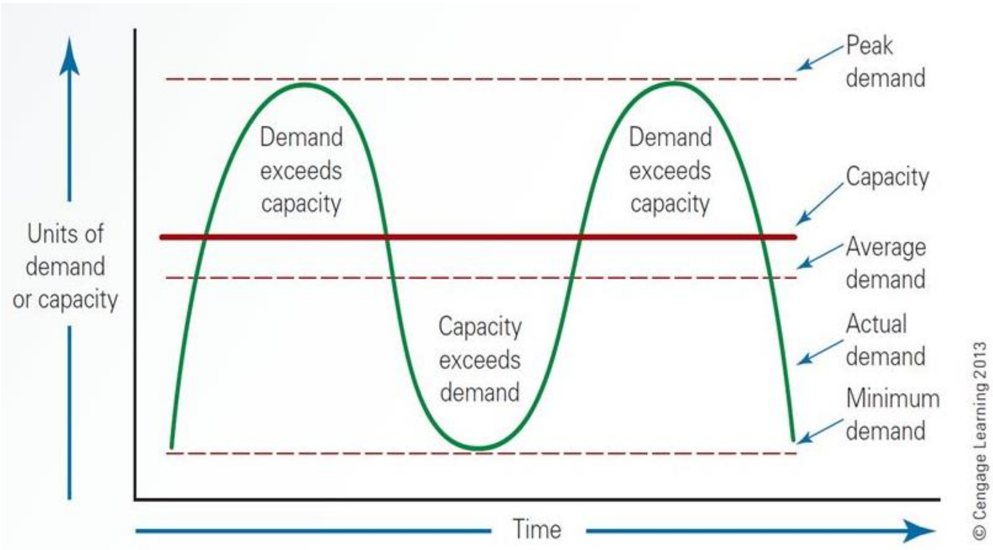


Figure 102 - Demand vs Capacity Problem Structure

Machine	Number of machines required	Working time of the machine per day [min]	Manual operation time	Employees per Machine
Injection Moulding	1	310	130	2
Lathe Machine	1	90	10	1
Grinding Machine	1	80	15	1
Milling Machine	1	110	20	1
Drilling Machine	1	95	20	1
Sieving Machine	1	75	50	1
Striking tool	1	65	40	1
Cutting/Sawing Machine	1	70	45	1
Trowelling Machine	1	60	35	1
Total	**9**			**10**

Table 33 - Machine Requirement & Operation Time

Lot Size

Lot size describes the number of units manufactured in a single production run. Keeping in mind the size of the autonomous robotic cobblestone cleaner, and the dimensions of the euro pallet, it is decided to produce 750 units in 75 lots. Where, each lot will contain 10 units, that will be placed on pallets and will further be supplied in the market.

Euro Pallet Dimension (L x W): $1200\,mm \times 800\,mm$
Product Packaging Size (L x W x H): $690\,mm \times 530\,mm \times 340\,mm$
Final Pallet Packaging Size (L x W x H): $1100\,mm \times 700\,mm \times 1700\,mm$

Each pallet will contain 10 units stacked in 5 layers reaching 1700 mm, where each layer will consist of two units.

Assembly Time per Unit

Total units produced = 3 units

Total man-hours = 7.33 hours

Units per man-hour = $\frac{3\ units}{7.33\ \ hours}$ = 0.409 units/man-hour

Time taken per unit = $\frac{60\ mins}{0.409\ units/man{-}hours}$ = 146.7 mins/units

Overall Equipment Effectiveness (OEE)

OEE is the gold standard for measuring manufacturing productivity.[30] OEE considers all losses. An OEE score of 100% means you are manufacturing only Good Parts, as fast as possible, with no Stop Time.

$$OEE = Availability \times Performance \times Quality$$

- Availability: A = Available time, B = Scheduled time
- Performance: C = Ideal production rate, D = Actual production rate
- Quality: E = Total units, F = Good units

$$OEE = \frac{B}{A} \times \frac{D}{C} \times \frac{F}{E}$$

Scheduled production time = 8 hours
Down time (planned/unplanned) = 0.67 hours
Up time (available time) = (8 – 0.67) hours = 7.33 hours

$$\text{Availability} = \frac{B}{A} = \frac{7.33\ hours}{8\ hours} \times 100 \approx 92\%$$

Available time = 8 hours
Actual production rate = 3 total units/7.33 (working) hours = 0.409 units/hour
Ideal production rate = 0.5 units/hour

$$\text{Performance} = \frac{D}{C} = \frac{0.409\ units/hour}{0.5\ units/hour} \times 100 \approx 82\%$$

30 (*What Is OEE (Overall Equipment Effectiveness)?* | *OEE*, n.d.)

Total number of units = 3 units
Number of good units = 2.8 units

$$\text{Quality} = \frac{F}{E} = \frac{2.8\,units}{3\,units} \times 100 \approx 93\%$$

$$\boldsymbol{OEE = Availability \times Performance \times Quality = 92\% \times 82\% \times 93\% \approx 70\%}$$

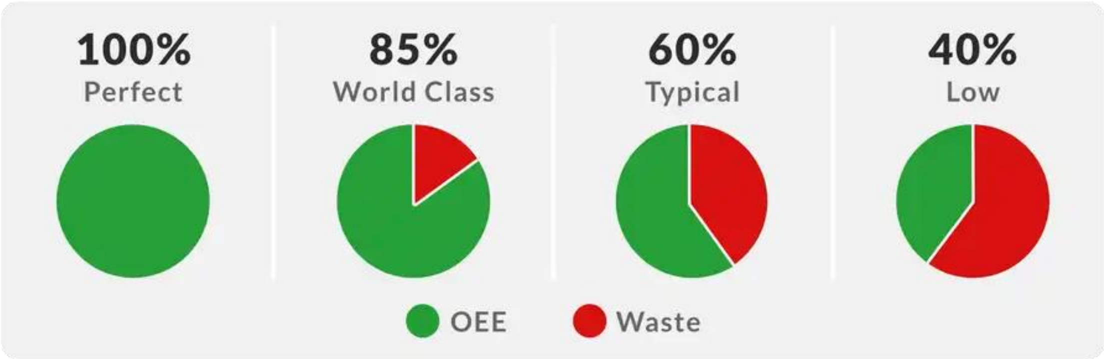


Figure 103 - Benchmark for OEE score against industry standards for discrete manufacturing

The typical industry standard for discrete manufacturing is rated 60% OEE, the OEE score of the robot manufacturing is 70%, which indicates there are about 30% total losses per lot size.

Staff Planning

An inside-out system is followed to hire employees based on their qualifications and the number of machines to achieve the daily production goal. Keeping these factors in mind, at least 1 employee per machine is required to fulfil the production demand.

Machine	Number of machines required	Employees per Machine
Injection Moulder	1	2
Lathe, Grinding, Milling, Drilling Machine	1 each	1
Sieving, Sawing Machine	1 each	1
Striking, Trowelling Tool	1 each	1
Total	**9**	**5**

Table 34 - Staff and Machine Requirement

$$Daily\ production\ staff = Total\ no.of\ employees \times Total\ no.of\ shifts$$
$$= 5\ employees \times 1\ shift = 5\ daily\ production\ staff$$

List of Employees

Position	Qualification	Job Description	Number of Employees	Salary [EUR/Year]	Total Amount [EUR/Year]
Cleaning Staff	Company Training	Maintains cleanliness in the warehouse	1	7,387.50 €	7,387.50 €
Assembly Supervisor	Mechatronics Engineer	Supervises employees at the assembly line	1	32,000.00 €	32,000.00 €
Electrical Component Assembly Employees	Technicians in Field	Assembles the electrical components of the robot	2	26,000.00 €	52,000.00 €
Financial Manager	Accountant	Manages the finance and accounts of the company	1	30,000.00 €	30,000.00 €
Software Engineer	Computer Science	Software development and maintenance	1	35,000.00 €	35,000.00 €
Logistics Manager	Industrial Engineer	Manages the logistics of the warehouse	1	32,000.00 €	32,000.00 €
Mechanical Component Assembly Employees	Technicians in Field	Assembles the mechanical components of the robot	2	26,000.00 €	52,000.00 €
Plant Manager	Industrial Engineer	Manages the machine operations	1	32,000.00 €	32,000.00 €
Production & Logistic Employees	Company Training	Operates machines at the factory	5	20,566.80 €	102,834.00 €
Production Manager	Mechanical Engineer	Manages the production line of the robot at the factory	1	32,000.00 €	32,000.00 €
Production Supervisor	Mechanical Engineer	Supervises employees at the production line	1	28,000.00 €	28,000.00 €
Quality Assurance Manager	Industrial Engineer	Inspects and approves the quality of the product at the factory	1	30,000.00 €	30,000.00 €
Safety & Environmental Manager	Safety Engineer	Ensures safety and good working conditions at the warehouse	1	32,000.00 €	32,000.00 €
Security Staff	Company Training	Ensures security at the factory	2	24,000.00 €	48,000.00 €
Total			**21**		**545,221.50 €**

Table 35 – List of Employees with Job description and Expected Salaries

Factory Layout

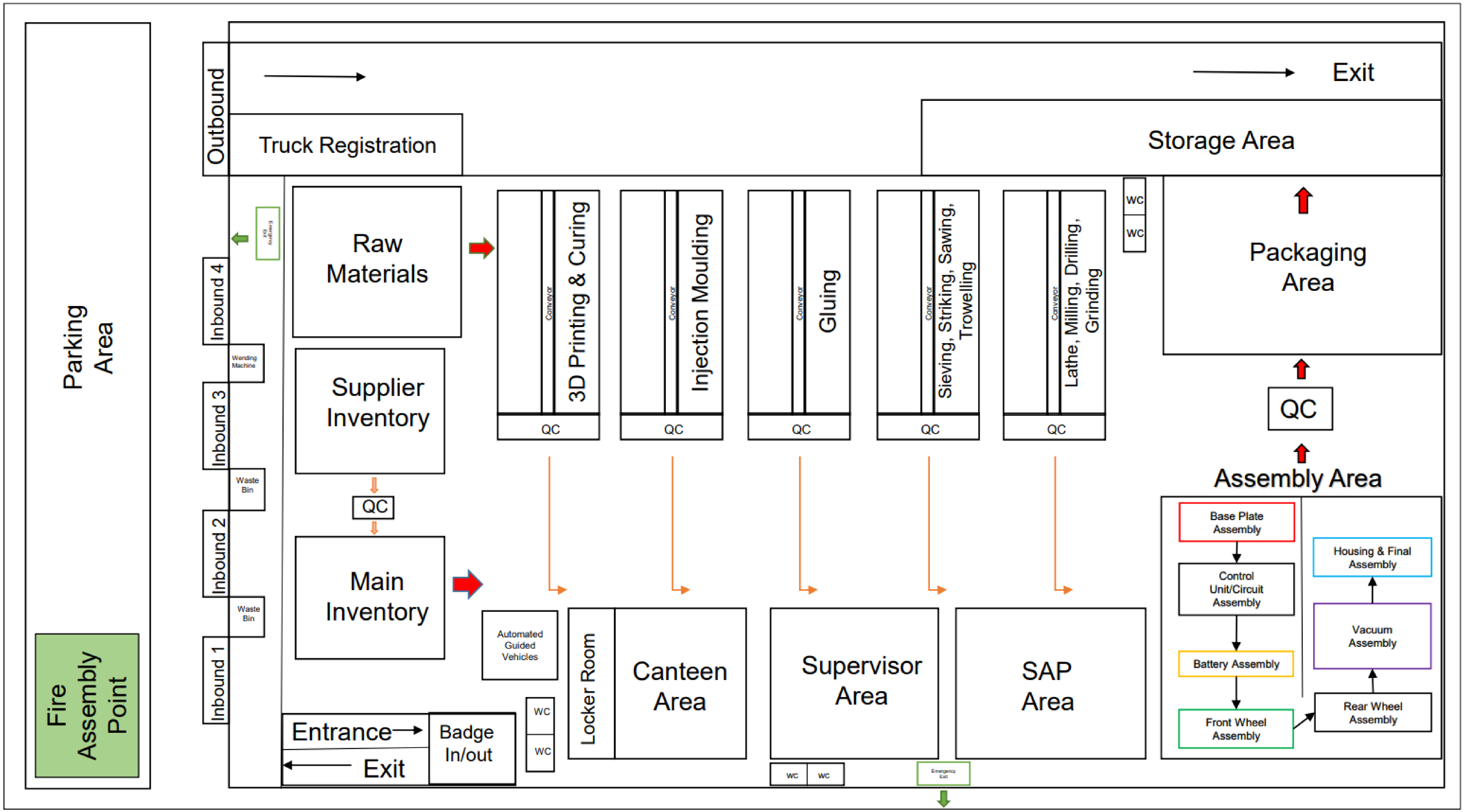


Figure 104 - Factory Layout Design

Cost Calculation

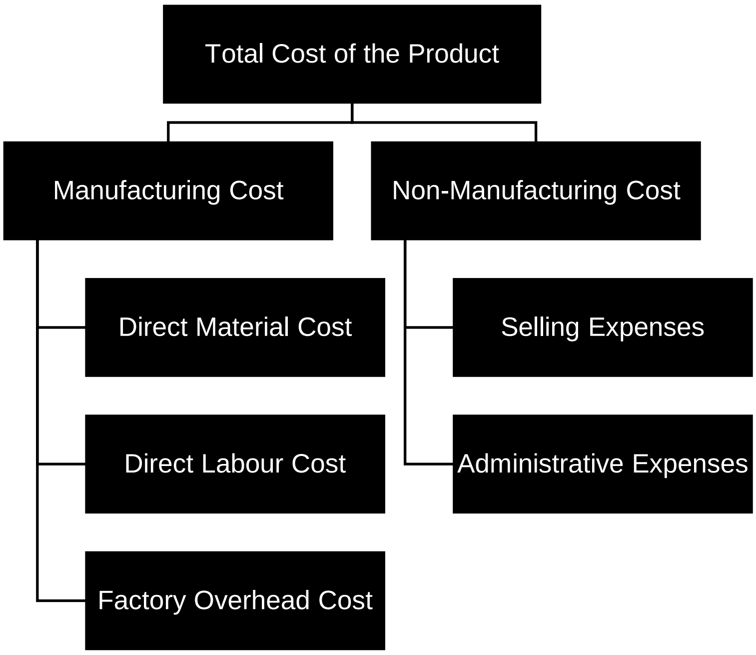


Figure 105 - Total Cost of the Product

Here, the manufacturing cost is the sum of costs of all resources, which is consumed during the process generation of a product.

$$\boldsymbol{Manufacturing\ Cost = Direct\ material\ cost + Direct\ labour\ cost + Factory\ overhead}$$

where:
$Direct\ Material\ Cost = Raw\ material\ costs + Tooling\ costs + Consumable\ costs$
$Direct\ Labour\ Cost = Processing\ time\ \times Labour\ rate$
$Factory\ Overhead\ Cost = Sum\ of\ costs\ of\ all\ manufacturing\ support\ elements$

Manufacturing Cost

Direct Material Cost

Raw Material Type	Total Material Requirement	Material Cost per Kilogram	Total Material Cost	Total Tooling Cost	Other Consumables	Direct Material Cost per Piece	Total Direct Material Cost per Year
Carbon Steel	667.05	2.75 €	1.83 €	55.74 €	20.00 €	77.57 €	58,180.79 €
ABS Plastic	17945.92	2.24 €	40.20 €	107.72 €	15.00 €	162.92 €	122,189.14 €
Brass	5616.80	2.15 €	12.08 €	26.21 €	10.00 €	48.29 €	36,214.59 €
PUR	132.66	1.78 €	0.24 €	3.23 €	- €	3.47 €	2,599.60 €
Nylon	25.00	1.76 €	0.04 €	1.42 €	- €	1.46 €	1,098.00 €
Total						**293.71 €**	**220,282.12 €**

Table 36 - Direct Material Cost for Manufacturing per Year

Direct Labour Cost

Total Working Time per Day	8
Number of Labours per Day	5
Hourly Wage [EUR/hour]	9.85 €
Direct Labour Costs per Day	394.00 €
No. of days in a year	365
No. of days at Weekends	104
Public Holidays (Paid)	11
Total Working Days Incl. Public Holidays	261
Labour Costs per Year	**102,834.00 €**

Table 37 - Direct Labour Cost for Manufacturing per Year

Direct Labour Costs (incl. other employees) per year = 545,221.50 €

Factory Overhead Cost

Electricity Consumption Cost:

Electricity Price = 0.3€/kWh

Machine	Electricity Price [EUR/kWh]	Operation Time per day [hours]	Material Weight per Piece [Kg]	Material Weight per Day [Kg]	Electricity Consumption [kWh/Kg]	Price per day [EUR]
Injection Moulder	0.3	2.55	18.08	54.24	1.47	61.00 €
CNC Turning Machines	0.3	4.25	0.67	2.01	1.68	4.31 €
Sand and Die Casting Tools	0.3	1	5.6	16.8	2.36	11.89 €

Table 38 - Electricity Consumption for Machines

Total Electricity Consumption Cost for Machines per Day = 77.20 €
Additional Electricity Costs per Day = 5€
Total Electricity Consumption Cost per Year = 250 working days x 82.20 € = 20,550 €/year.

Warehouse Cost:

According to the factory layout design, the overall space covered by the machines and other utilities is approximately 50 square meters. Therefore, according to market price, the overall rent of the warehouse is estimated to be 1000€ per month.
Warehouse Cost per Year = 12,000 €/year.

Maintenance and Repair Cost:

Taking 5% of the overall costs of machines which is 9,346€. Hence, the maintenance and repair costs per month are 467.3€.
Maintenance & Repair Costs per Year = 5,607.6 €/year.

Injection Moulding Machine = 7,900€
Lathe Machine = 450€
Drilling Machine = 99€
Milling Machine = 220€
Grinding Machine = 177.5€
Overall Sand & Die Casting Tools = 500€
Total Machine Buying Cost = 9,346€ approximately

Depreciation:

$$Depreciation = \frac{Cost\ of\ Machine - Residual\ Value}{Estimated\ Life\ of\ Machine}$$

Residual Value of Injection Moulder = 2,100€
Estimated Life of Injection Moulder = 10 years
Depreciation of Injection Moulder = 580€

Residual Value of Lathe Machine = 110€
Estimated Life of Lathe Machine = 20 years
Depreciation of Injection Moulder = 17€

Residual Value of Drilling Machine = 20€
Estimated Life of Drilling Machine = 8 years
Depreciation of Injection Moulder = 10€

Residual Value of Milling Machine = 60€
Estimated Life of Milling Machine = 8 years
Depreciation of Injection Moulder = 20€

Residual Value of Grinding Machine = 45€
Estimated Life of Grinding Machine = 10 years
Depreciation of Injection Moulder = 13.25€

Residual Value of Sand Die Casting Tools = 220€
Estimated Life of Grinding Machine = 5 years
Depreciation of Injection Moulder = 56€

Total Depreciation Amount per Year = 696.25€

Tools & Supplies:

The expected cost of additional tools and supplies such as screwdrivers, pliers, cutters, etc. would round up to 300€/year.

Interest:

The expected interest rate comes up to 7%.
Total Interest Rate on Machines = 654.22 €/year.

Total Factory Overhead Cost per Year = 39,808.07 €/year.

$$\boldsymbol{Manufacturing\ Cost = Direct\ material\ cost + Direct\ labour\ cost + Factory\ overhead}$$

Manufacturing Cost = 220,282.12 € + 545,221.5 € + 39,808.07 € = 805,311.69

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