ME3103 Mechanical Systems Design - GrassBot

CA4 Report

Acknowledgements

Our team would like to thank NUS and Catalyst Connector Pte Ltd for giving us the opportunity to work on this project. We would also like to extend our appreciation to our project tutor Dr Sergei Manzhos, course coordinator Mr Stanley Thian, project supervisors Andy Wee and Felix Lee for their constant guidance and advice throughout the course of this project.

We would also like to extend our gratitude to Ms Lim Jin Hong, Deputy Director (HortPark), for providing us access to and insights on their automatic lawn mower trial, Mr Mahadi from the NUS Office of Facilities Management for allowing us to conduct a field test for our final prototype and the E1A Lab Technicians for their assistance with the fabrication of our prototype.

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Introduction

In Singapore, the weather is sunny almost all year round coupled with regular rain resulting in a lush and green landscape. Grass cutting and trimming is a necessary activity in our parks and gardens. It has to be done regularly and the area to be covered is vast. It is a laborious activity as workers have to cut the grass manually using grass-cutting tools and walk great distances under the scorching sun, making the job unpleasant and undesirable. Currently, the two mechanisms used for grass cutting in Singapore are powered hand-held device with flexible monofilament nylon lines and ride-on mowers, with the former being more common. Hazards arising from the powered hand-held device are the unguarded cutting mechanism, possibility of “kicked up” flying particles and excessive noise. The ride-on mower has problems of its own such as being unable to handle steep slopes or do trimming at the kerb edges which ultimately requires the alternate method. Grass cutting has to be carried out as frequent as 6 to 10 days for events and sports lawns, 10 to 14 days for parks, and 14 to 21 days for streetscapes. Furthermore, with an efficiency of cutting approximately only 5 square meters of grass per minute at approximately 1100 rpm, there is undeniably immense room of improvement for the current method of using powered hand-held grass cutters.

Autonomous grass-cutters are currently being used in some parts of the world and it is a step forward from manual grass-cutting activity. It is mainly used by homeowners to trim their front yards or lawns. The concept of operation is rather simple. The automatic grass-cutter has cutting blades located underneath it at a desired cutting height. An electric boundary wire is first set up around the lawn to prevent the unit from going out of bounds, before releasing the robot unit within its boundaries. Each time its sensors detect the perimeter wire, it will re-orientate itself to travel back within its bounds. It roams within its area in a pseudorandom way, similar to how a roomba vacuums a room. Once the battery runs low, it will return to its docking station by following the boundary wire. Users can set a schedule to decide the desired operation frequency and duration. However, even though these products have automated grass cutting, there are areas where it is lacking. Thus, our project aims to tackle those issues and provide the modifications needed.

As grass cutting is a laborious activity where a lot of manpower and time is spent, we aim to design an automated grass cutting robot that is able to trim a football field in the shortest time possible with the push of a button, therefore reducing the labour requirement and enhancing operational efficiency.

This report aims to provide objective information about the modifications made to an existing automatic grass cutting robot to improve its operational capabilities and functions. First we study existing solutions and identify limitations and constraints faced by their users, followed by analysis and selection of which problems to tackle and the problem-solving process through numerous designs and calculations. Finally, the report looks at the final upgrades made in each modification aspect such as navigation, obstacles handling, movement speed, cutting capability and power management to meet our desired objectives, namely enhanced efficiency and full autonomy.

Ideation Process

Study of existing local system

The automated grass cutter is a product that has already been developed. In fact, there are many different types of such robots that have already been successfully commercialised, one of which is the Husqvarna Automower 430x, an autonomous grass cutter that is currently being used for trial operations in Hort Park. To deepen our understanding about the capabilities of an autonomous grasscutter, we decided to link up with the Hort Park officials and pay a visit to the park to observe the operations first-hand.

Fig. 1-1 The group discussing with Ms Lim Jin Hong, Deputy Director (HortPark) regarding the Husqvarna Automower 430x trial, including issues about its efficiency.

Fig. 1-2 The Husqvarna Automower at its docking station where it is charged.

Purpose

As stated above, one of the purposes of the study was to observe the robot during its operation and see how its use alleviates the manpower requirement in grass-cutting. Besides that, the purpose of this trip was also to pick out possible areas for improvement in the robot system. Hence, before the group started the field trip, we prepared questions that could accelerate our learning process on automatic grass cutting and finding out the issues pertaining to the use of the autonomous grass cutter. The questions were mainly regarding the installation process, efficiency, and technical issues that might arise.

Pros and Cons of the Husqvarna Automower

After the insightful visit, we managed to gather a long list of information surrounding the commercial grass cutter that is utilised by the NParks. Although it helps to carry out the arduous grass-cutting process, there are still several issues that are faced by the end users. Below is a table of pros and cons that can help us in the prototyping process in which we try to retain as much good qualities of the grass-cutting robot, while trying to improve on the qualities that it is lacking.

Pros	Cons
- Reduce manpower needs for grass-cutting - Can operate beyond office hours	- Requires installation of boundary wires, a tedious and expensive procedure - Requires long operating hours due to its inefficient cutting pattern (i.e. moves in random paths until it reaches a patch with tall grass, where it will move in a outwards circular motion)

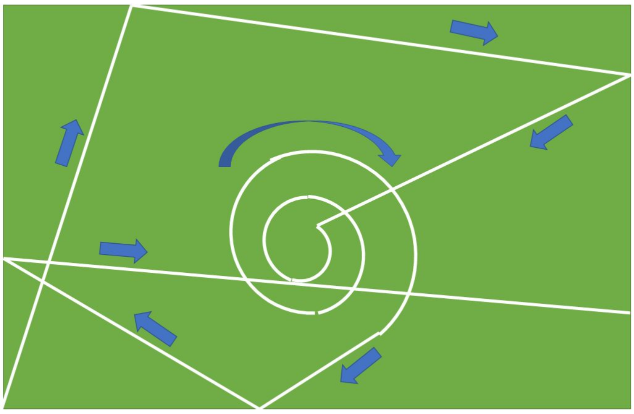

Fig. 2-1 The path taken by commercial automated grasscutters. It will start moving in a random path until it detects a patch of tall grass, where it will start moving in an outward circular path.

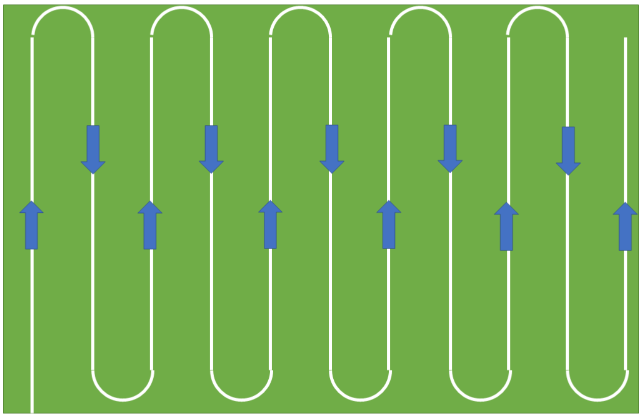

Fig. 2-2 The path that will increase the efficiency of the grass-cutting operation. An up and down, left-to-right sweeping movement that will cover almost the entire area once through.

Design Process

a. Issues & Solutions

Identified Issues	Current Solution	Proposed Solution(s)
Unable to trim the edges if there is a kerb as most designs have their blades situated in the middle of the unit	Trim manually with handheld grass cutters	Place blades closer to the front end of our prototype for greater reach, minimizing amount of trimming required
High initial cost in terms of installation	NIL	Eliminate the use of perimeter wires to lower initial cost
Takes very long to cut	Running the unit for longer hours and more frequently	Increase the motor speed Have the unit move in an organized manner to ensure higher efficiency Increasing the cutting width of the unit
Requires a flat terrain with no protruding tree roots	Limit operation to smooth, gentle terrain	Better obstacle avoidance systems. Current unit uses bumper switches

Fig. 3-1 Identified issues and proposed solutions

Our group decided to focus on improving the cutting effectiveness and obstacle detection and avoidance capabilities of current automated grass cutting units. Evaluating our proposed solutions, we have decided to implement the following modifications:

1) Eliminating the need for perimeter wires by incorporating GPS navigation

2) Increasing the robot's movement speed
3) Increasing the overall cutting width
4) Replacing bumper switches with ultrasonic sensors

Our group then decided on how we should build the prototype. We had two options:

1) reconfiguring a radio-controlled (RC) car, or
2) modifying an existing automated grass cutter.

Item	Size (cm)	Practical & Modifiable	Cost	Lead time
YomBand YB-M13-320 Lawnmower	59 × 58 × 23	+ No major modification required to achieve primary function of grass cutting, leaving, more time to focus on our improvement modifications - limited capacity and flexibility to include modifications of our own as compared to RC Car models	USD 450	3-4 Days
XinLeHong Toys 9125 1:10 4WD	34.5 × 30.5 × 16.5 Wheels ϕ11 × 6.5	+ Very accomodating to modifications + Good in rough terrain + Cheap. However, cost does not include the grass-cutting equipment that needs to be purchased separately - A lack of expertise may lead to a long time required to modify this into a working grass cutter - Need to manufacture or purchase basic grass cutting components such as blades - Small wheelbase may require extension to house required modifications	SGD 87.89	1-2 weeks

Fig. 3-2 Comparison table between existing automatic lawn mower and RC car. The specific units compared were chosen after weighing its cost and functionality.

Therefore after careful consideration, we have decided upon modifying the current YomBand automated grass cutter to suit our design requirements. One of the main factors for our choice was the time constraint of this project. It would take a shorter amount of time to hack an existing unit than building one with our minimal knowledge.

Quick Details

Model Number:	YB-M13-320	Power Type:	Electricity
Type:	Robotic Mowers	Feature:	Cordless, Height Adjustable Handles
Certification:	CE	Forward Speed:	18m/min
Cutting Width:	320mm	Product name:	YB-M13-320
Cutting power:	130W	Color:	Black
Working Voltage:	24V	Working Time:	3-3.5H
Charge Time:	3-4hours	Battery Available:	7 AH Lithium Battery
Max Cutting Width:	32CM	Max Cutting Height:	14CM
Noise:	<70db		

Fig. 3-3 YomBand YB-M13-320 Specifications

After analysing the YomBand YB-M13-320 unit, we calculated the new required specifications for our prototype in order to meet the design requirements. We proposed 4 major design modifications.

b. Higher Capacity Battery With Replaceable Capability

Area covered/min = cutting width × forward speed = 0.32 × 18 = 5.76 m^2/min

Area of grass that can be cut per full charge = 5.76 × 60 × 3 = 1036.8 m^2

Area of football field = 7140 sqm ~7x cutting capacity of YB-M13-320

Hence, a battery with larger capacity is required if we want one full charge of battery to cut at least ½ of a football field. Furthermore, a separate battery is required to power the Pixhawk autopilot module as the maximum input voltage for the module is 5V. However, due to budget constraints, we would only provide a proof of concept and theoretical extrapolation of data from experimental testings of our Grassbot's operational life.

Furthermore, our company supervisors stated that one of the design requirements of the final Grassbot is to allow the battery to be replaceable. Currently, most of the automated grass cutters have in-built rechargeable batteries. The problem lies with the grass cutters taking long, valuable hours to charge that could otherwise be spent more productively. Therefore, with replaceable and rechargeable batteries, the user can simply replace the batteries on the Grassbot and resume operation when the battery runs out. To this end, we fit an EC2 connector onto the 24V YomBand battery leads for ease of replacement.

Fig. 3-4 A sample airtight jar

To make it replaceable, we used the concept of a simple airtight jar. The user would simply need to open the battery cover, located on the top cover, by unlocking the swivel mechanism.The two batteries, 2S Li-Po and 24V Yomband battery, will be fitted into a compartment with an acrylic insulator separating them. Like a closed, airtight jar, the cover is sealed with a layer of silicone around it to keep it weatherproof and prevent water ingress.

Safety Considerations:

- Leakage of water through the cover

  Water may enter through our designed cover and possibly short-circuiting and eventually damaging our entire internal systems. Therefore, the silicone layer surrounding the cover will ensure that water will not seep through.

- Cross-wiring of the two batteries

There is a risk of a user accidentally connecting the batteries to the wrong circuits, which would damage the Pixhawk module due to its lower maximum input voltage. Therefore, the two batteries are fitted with different type of connectors which are also of separate colours. This would eliminate the chance of damaging the Grassbot due to negligence. Furthermore, we designed two separate compartments of different size so that users are able to visually associate the correct battery with its designated compartment.

c. Increase in Overall Cutting Width

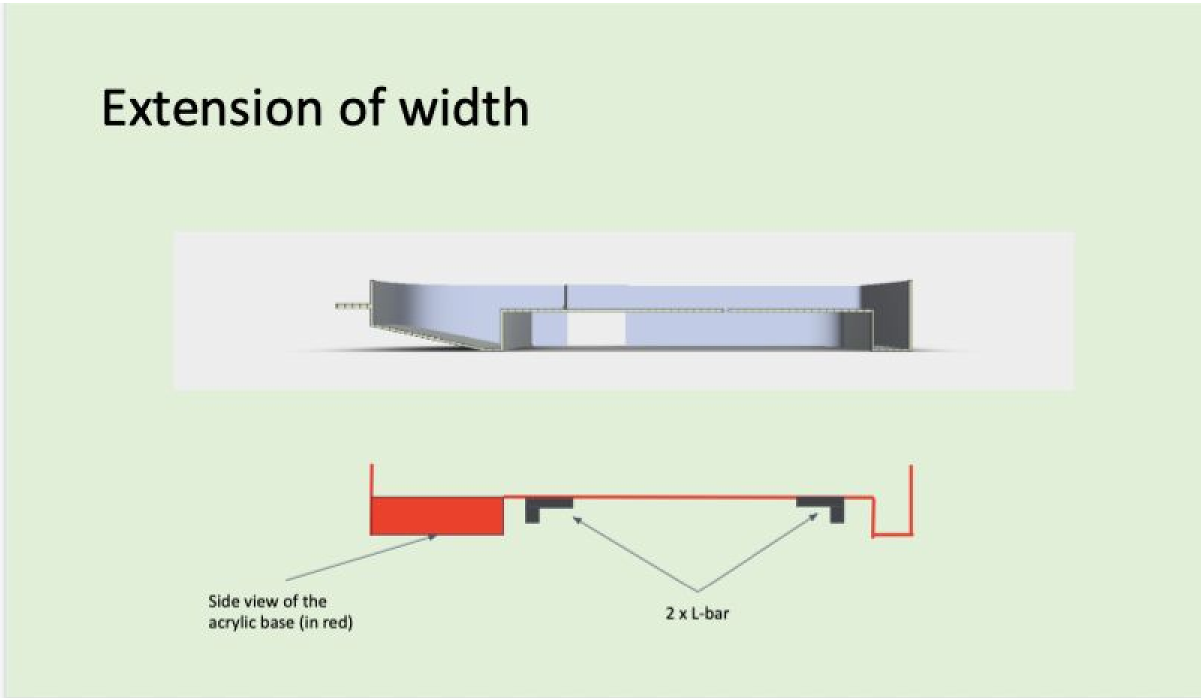

Fig. 3-5 Chassis extension

The cutting width of the Yomband unit that we purchased was 32 cm. Theoretically, by increasing the overall cutting width, we would be able to cover more area of grass within the same amount of time, thus increasing the operational effectiveness of our Grassbot. We decided to cut the original Yomband lower chassis into two and fabricate a base extension in the middle.

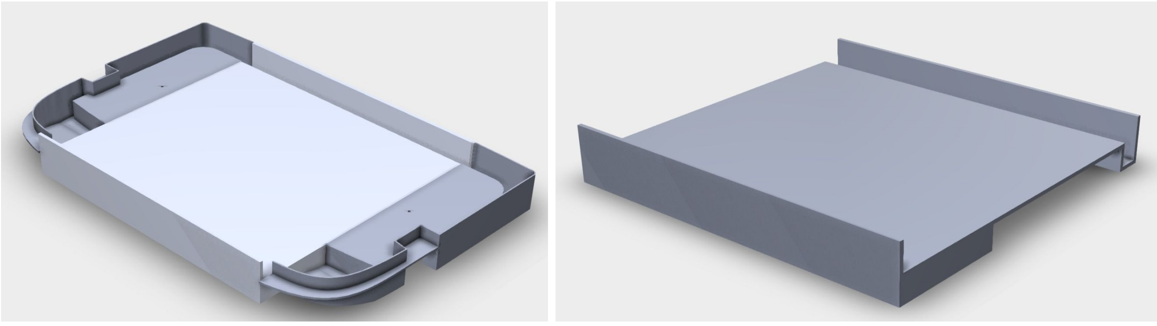

Fig. 3-6 Extension panel design

We modelled the extension component based on the side view of the cut section in Figure 5. Furthermore, in order to maintain structural integrity and prevent excessive chassis flex under load, we added 2 steel angle bars to connect the three pieces together and stiffen the chassis base.

d. Cutting Blade System Redesign

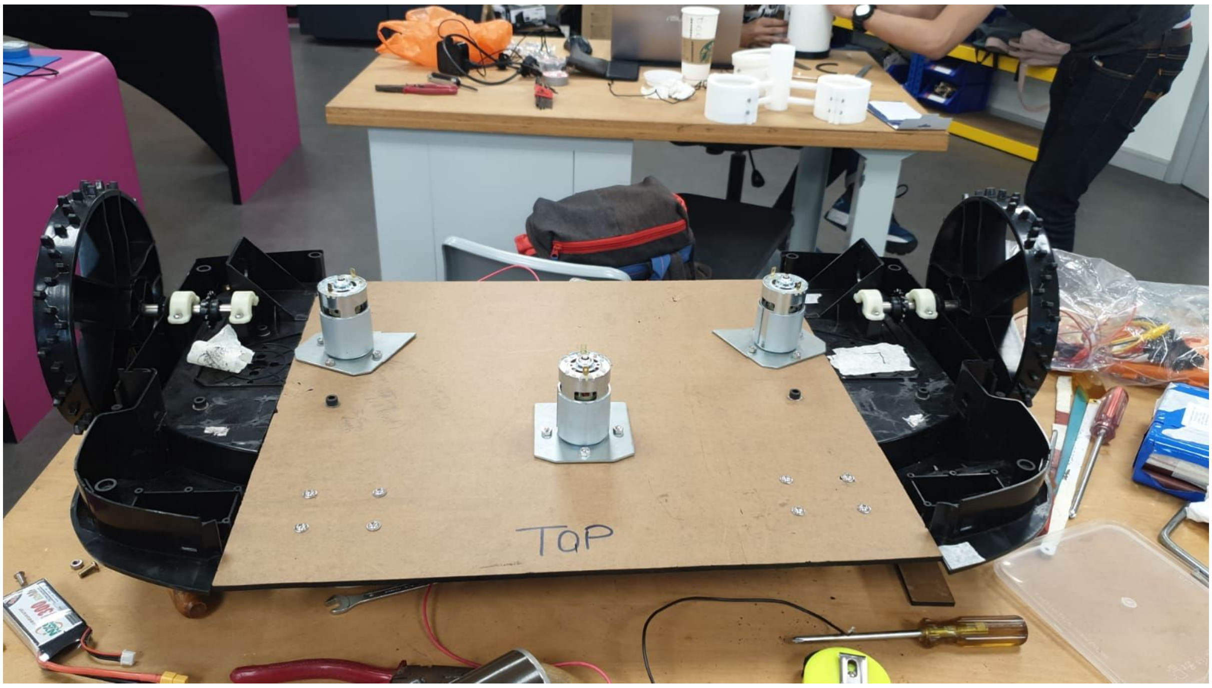

Fig. 3-7 Extended Chassis base showing position of blade motors

With an increase in overall width, we also needed to redesign the cutting blades' layout and specifications to take advantage of the increased allowable cutting area of 64cm. For the interest of cost-saving for the prototype, we re-used some components from the original blade system such as the motors, mounting plates and blade adapters.

e. Increased Wheel Speed

Sprocket teeth	17
Shaft diameter (Wheel)	12 mm
Shaft Diameter (Motor)	8 mm
Chain number	25
Gear ratio	1:1
Pitch	6.35 mm
Face width	2.8 mm

Fig. 3-8 Original Sprocket and Chain Dimensions and Analysis

Fig. 3-9 YB-M13-320 wheel motor

Our group agreed that increasing the wheel speed of the prototype would result in an increase in effective cutting area given the same amount of time. We achieved this by increasing the gear ratio of the driven gear to the driver gear, based on the formula below.

$$Gear\ ratio = \frac{No.\ of\ Driven\ teeth}{No.\ of\ Driver\ teeth} = \frac{RPM\ (Motor)}{RPM\ (Wheel)}$$

As such, we could either increase the number of driver sprocket teeth or decrease the number of driven sprocket teeth. Therefore, we based our decision on the following key considerations:

1) Shaft diameters

    The potential sprocket is restricted to both the wheel and motor shaft diameters.

    The current wheel shaft is 12 mm in diameter and attached to a 15-teeth sprocket. However, based on our supplier's catalogue[1], a 14-teeth sprocket has a maximum shaft hole diameter of 10 mm. Thus, we cannot decrease the sprocket teeth of wheel.

    The current motor shaft is 8 mm in diameter and attached to a 15-teeth sprocket. A 19-teeth sprocket has minimum shaft hole diameter of 10mm. We decided to machine a bush to enable the large sprocket to fit into the smaller motor shaft.

2) Chassis allowance for sprockets

    The chassis only has 60 mm allowance between motor shaft and the base. Thus, we can only increase the wheel sprocket teeth to 26 whereby its outer diameter is 56mm.

Therefore,

$$Wheel\ RPM\ (theoretical) = \frac{26}{15} \times 28 \approx 48.5\ (improvement\ of\ 73\%)$$

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[1] Katayama Chain. "Standard Sprocket 25B Shape." *Monotaro.sg*. 2019.
https://www.monotaro.sg/g/00272303/#

f. Electronics Assembly

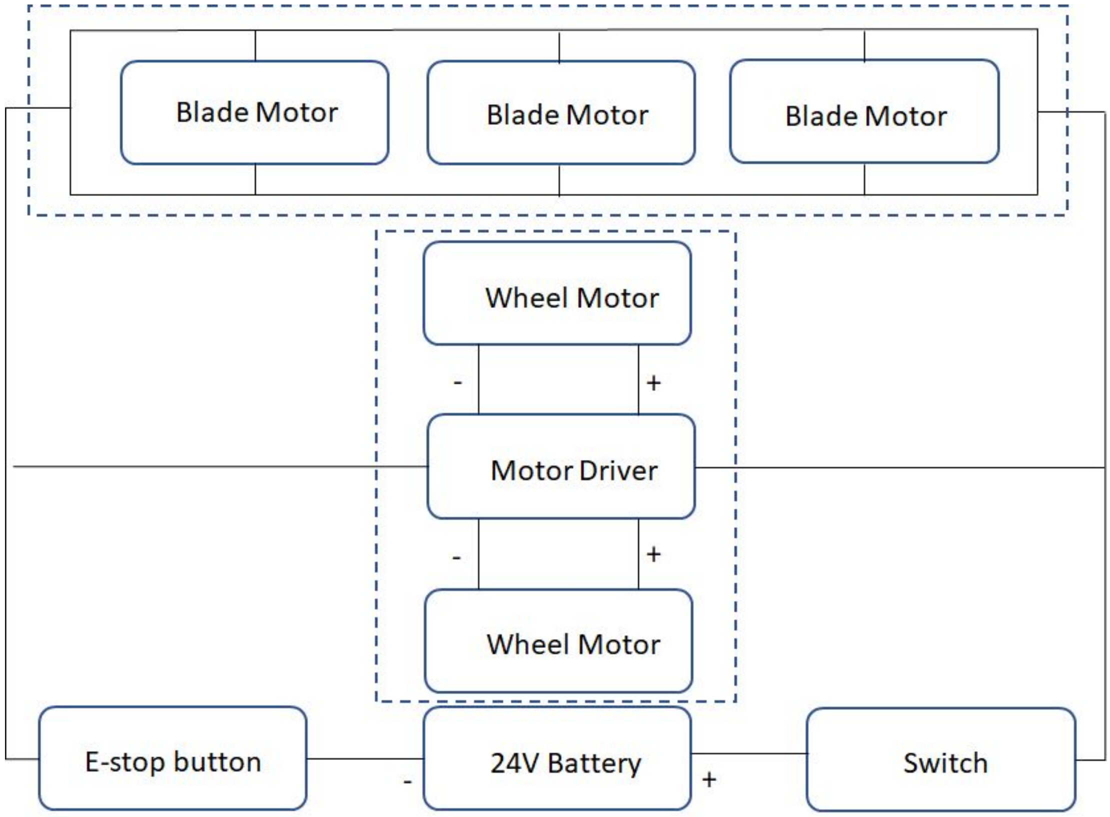


Fig. 3-10 Diagram of Electronic System (excluding the autopilot system)

After examining the original YomBand electronic system, we have decided to come up with our own electronic system due to the complication of understanding their original motherboard. We reduced their interface with a simple on/off switch while retaining the emergency stop button. At the same time, by removing the motherboard, we disabled the ability for the battery to be recharged within the prototype. Lastly, another modification was to introduce a motor driver that is compatible with our autopilot system to control the wheel movement.

g. GPS navigation with ultrasonic sensors

One of the major design requirements of our prototype was to eliminate the use of guide wires. Many of the current systems use them to ensure that their unit does not escape the intended boundary. However, this would incur high installation costs.

Many ideas were generated to allow our prototype to independently follow a desired path and avoid obstacles. We decided upon the ArduPilot system as it would allow the prototype to follow a set of waypoints via GPS which would dismiss the need for guide wires. Another option that was considered was dead reckoning. However, a lack of local features to orient itself by, coupled with high error accumulation in operation on uneven terrain meant that it was ill-suited to our purpose. Our autopilot system also uses ultrasonic sensors to detect obstacles in its path avoid them.

Design Specifications

Parts

This section features the parts that were fabricated by our group. The drawings can be found in Appendix A.

1. Chassis

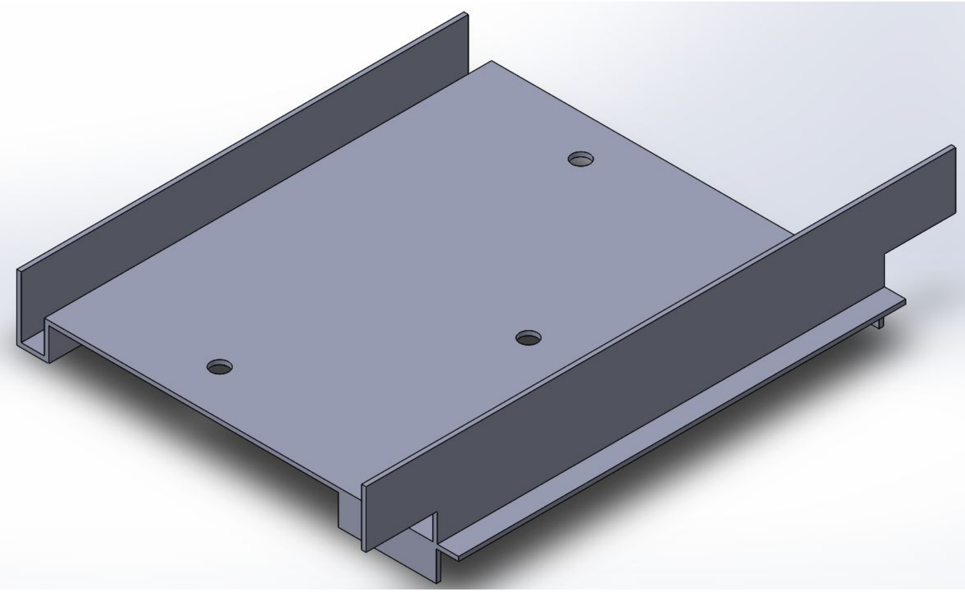


Fig. 4-1 Acrylic part of the bottom assembly

2. Top Cover

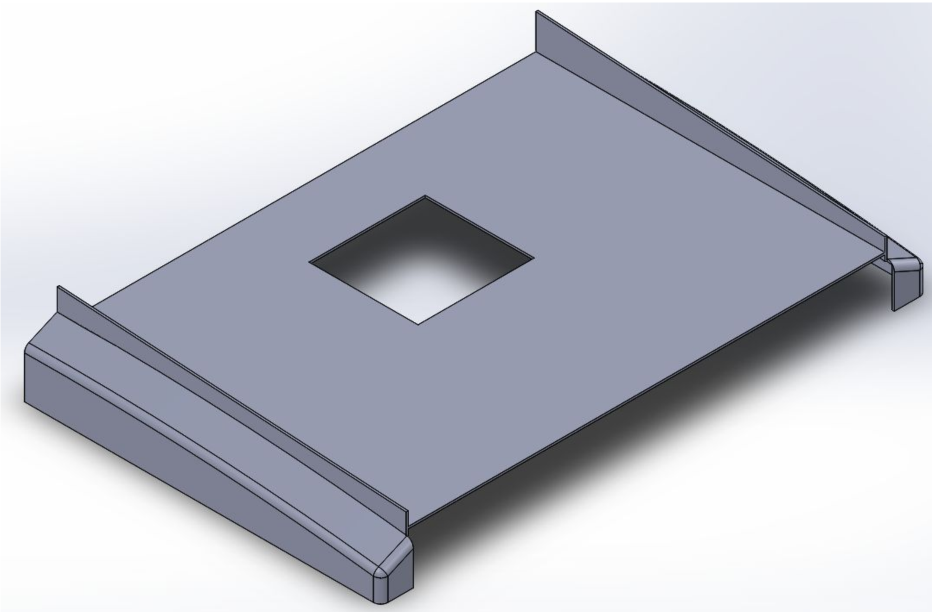


Fig. 4-2 Acrylic part of the top cover

3. Blade Bushing

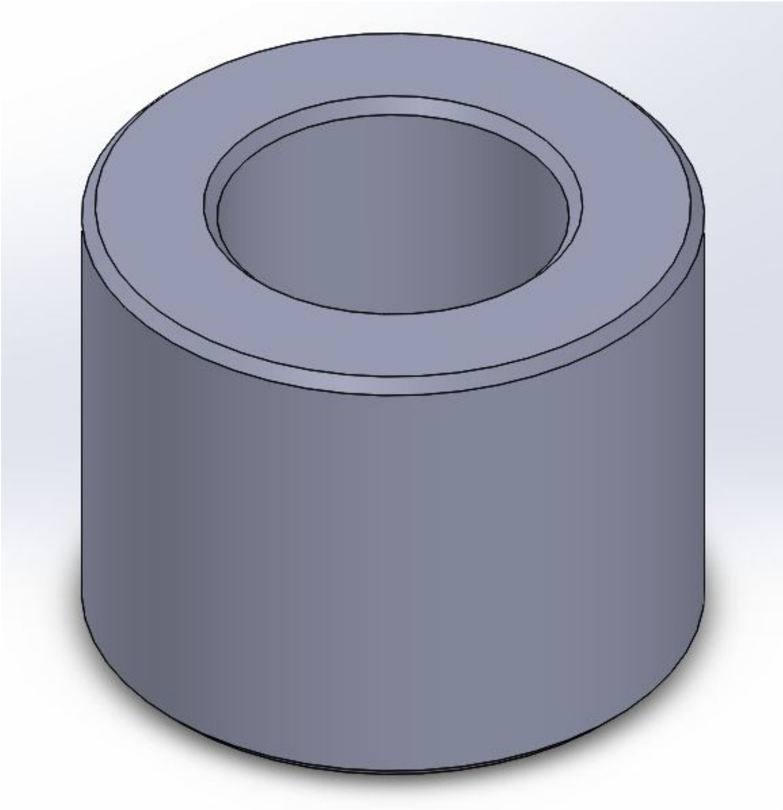


Fig. 4-3 Blade bushing

4. Blade Adapter

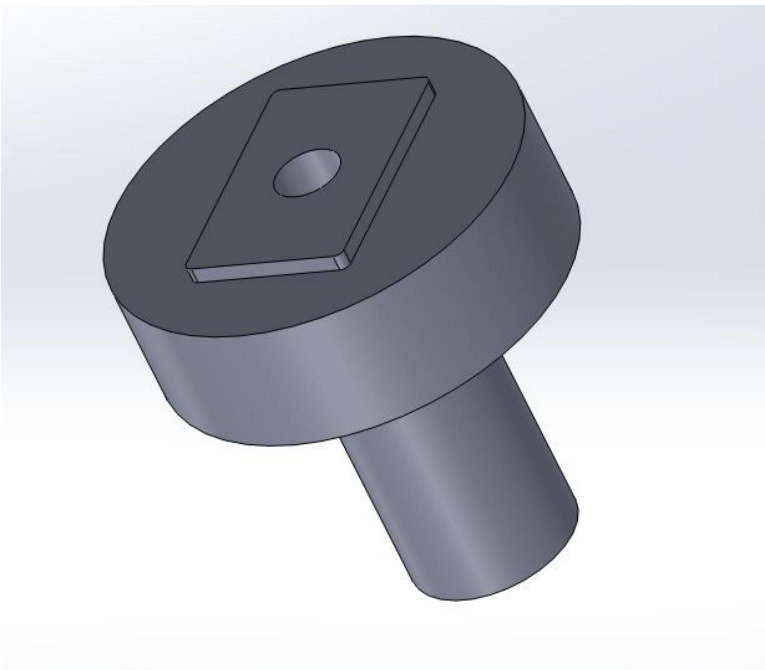


Fig. 4-4 Blade adapter

5. Blade

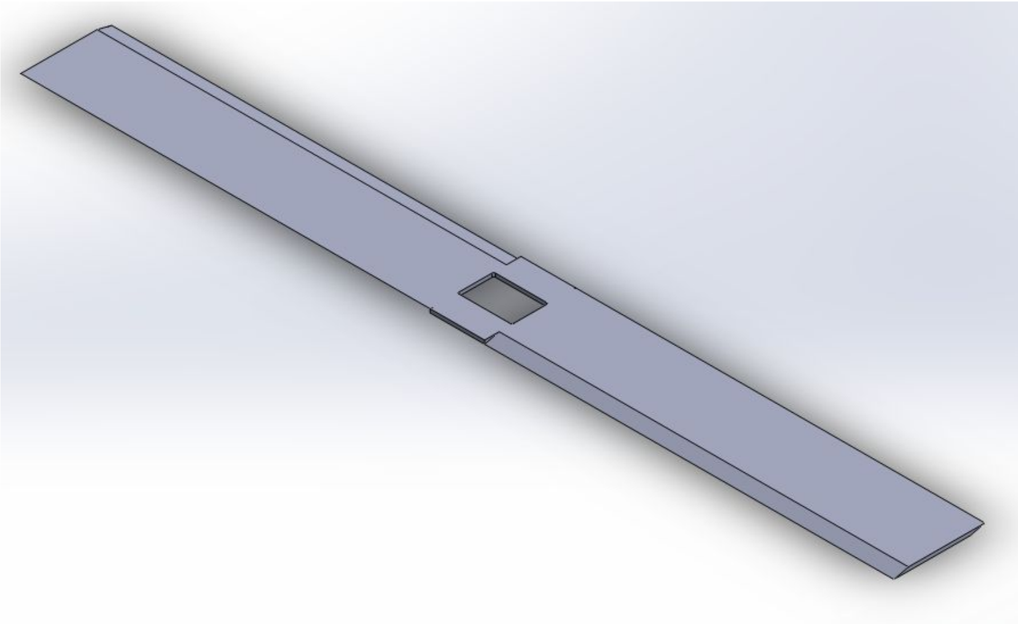


Fig. 4-5 Blade

Assemblies

This section features the assemblies of a few of our modules in the entire project which includes the blade assembly, the chassis assembly and the whole assembly of the system.

1. Blade Assembly

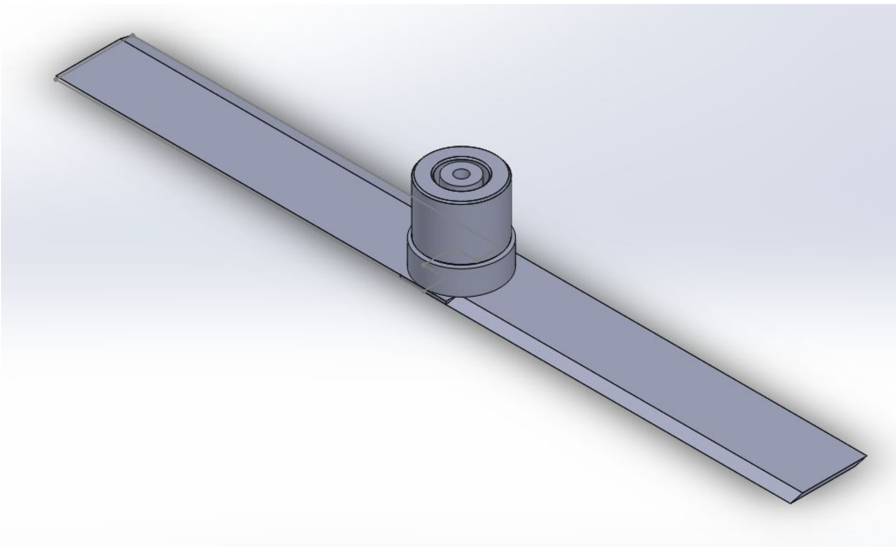


Fig. 4-7 Isometric view of the blade assembly which includes the blade, blade adapter and blade bushing

2. Chassis Assembly

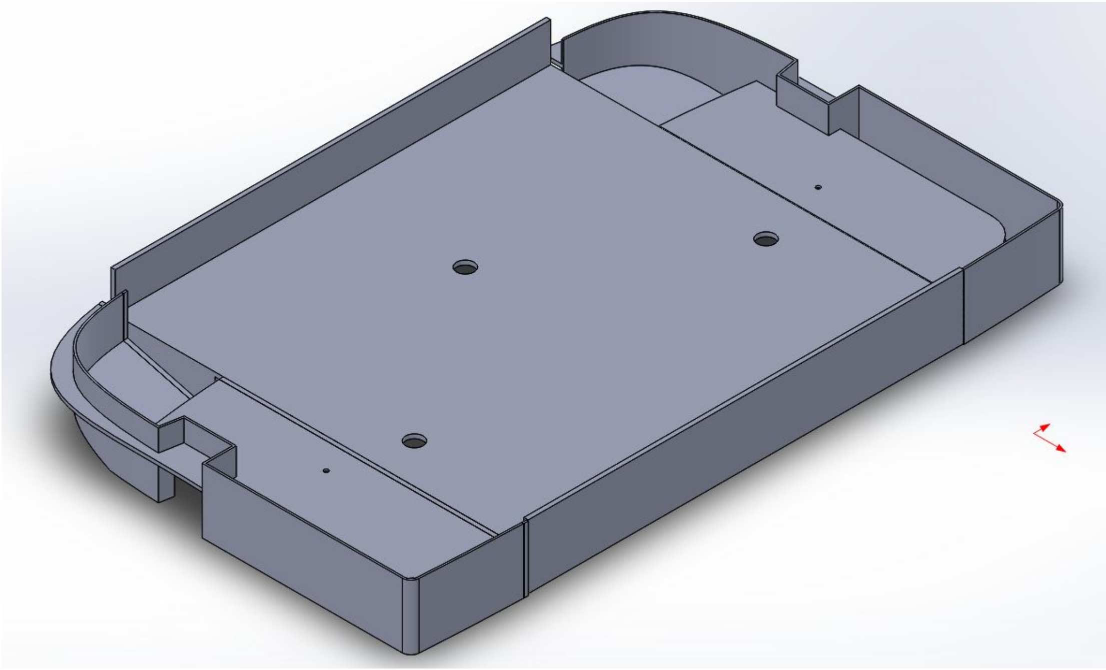


Fig. 4-8 Isometric view of the chassis assembly

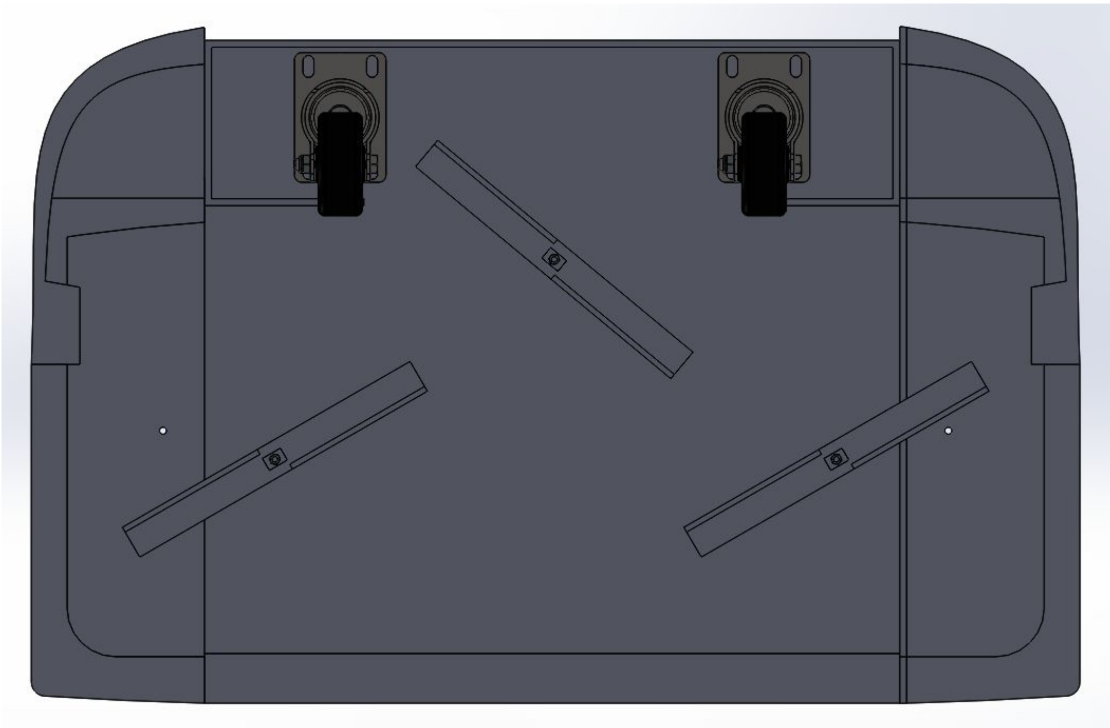


Fig. 4-9 Bottom view of the chassis assembly

3. Whole Assembly

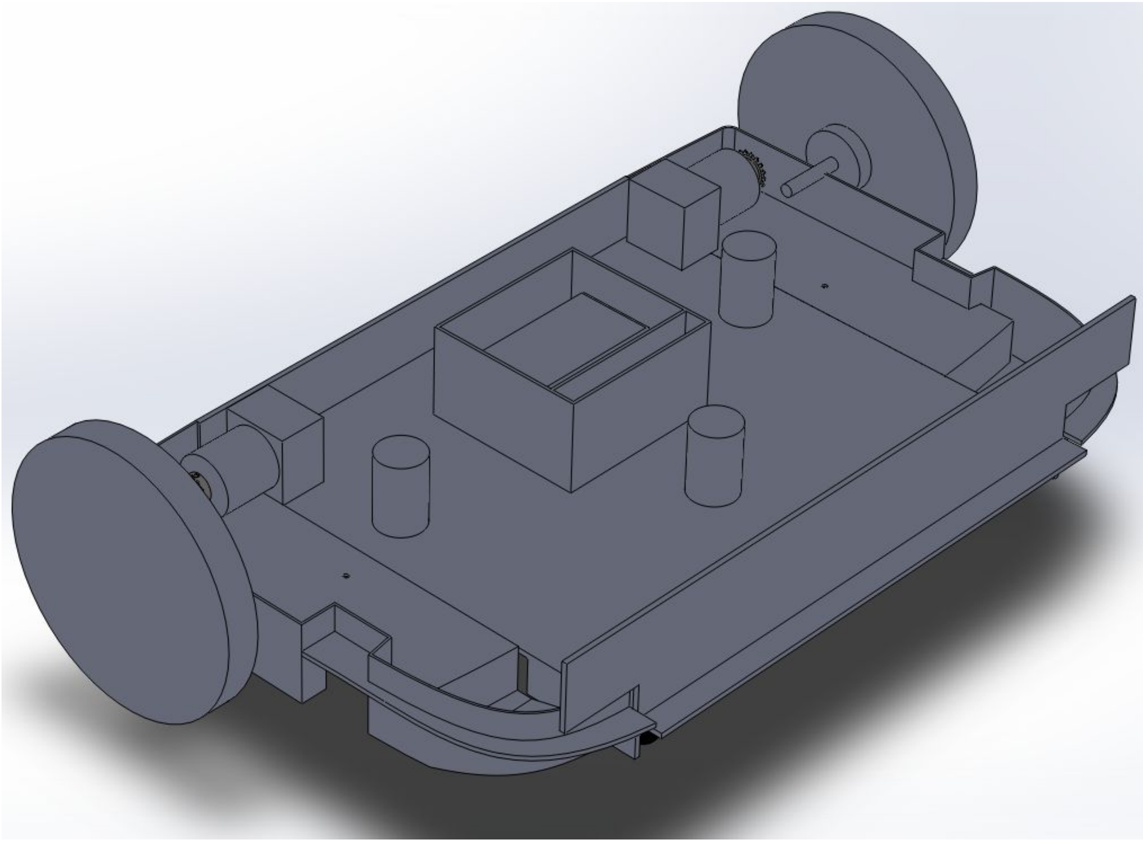


Fig. 4-10 Isometric view of Grassbot without the top cover

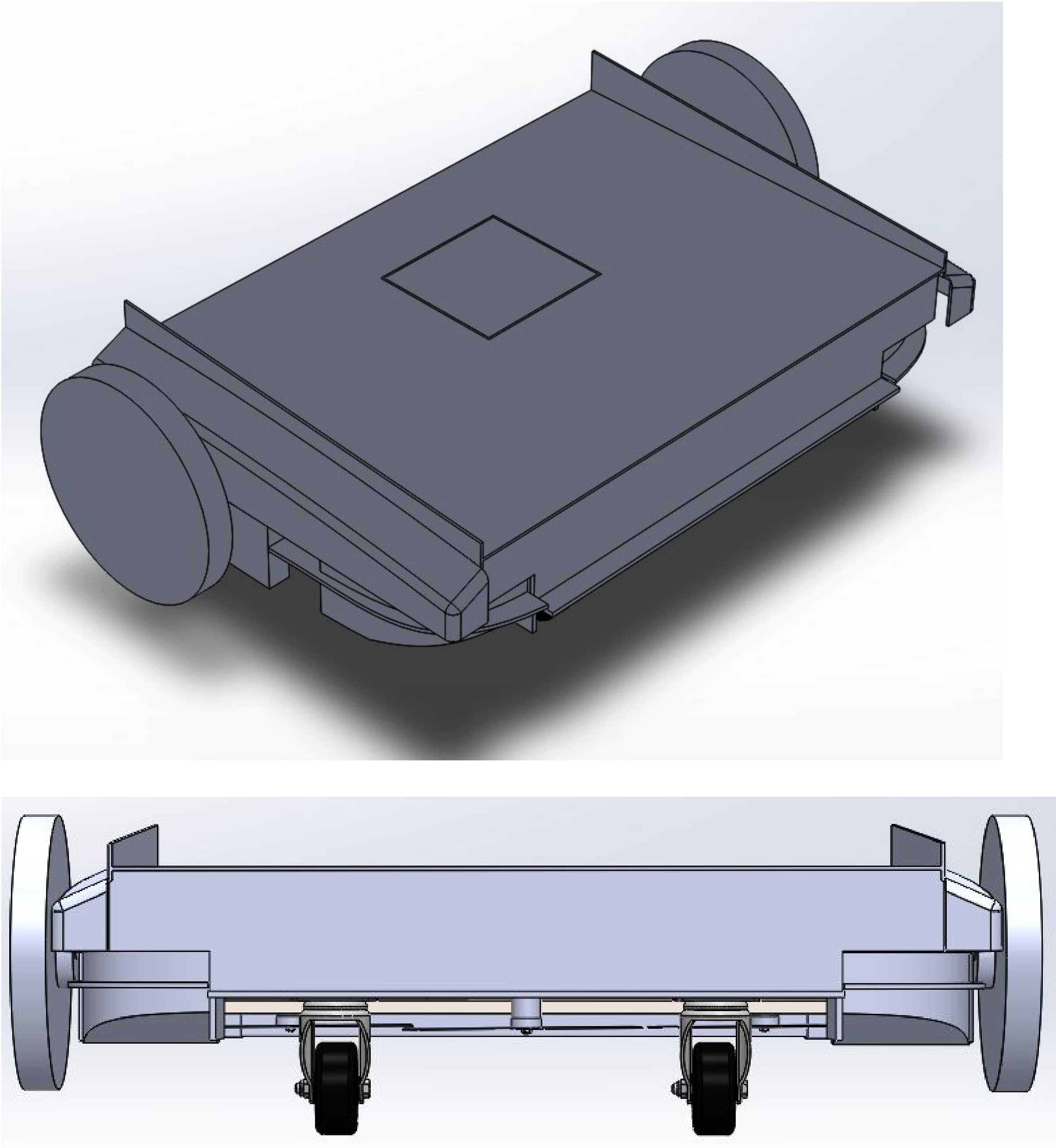


Fig. 4-11 Isometric and front view of Grassbot

Fig. 4-12 Depiction of the Grassbot in operation at a field

Electronic Diagrams

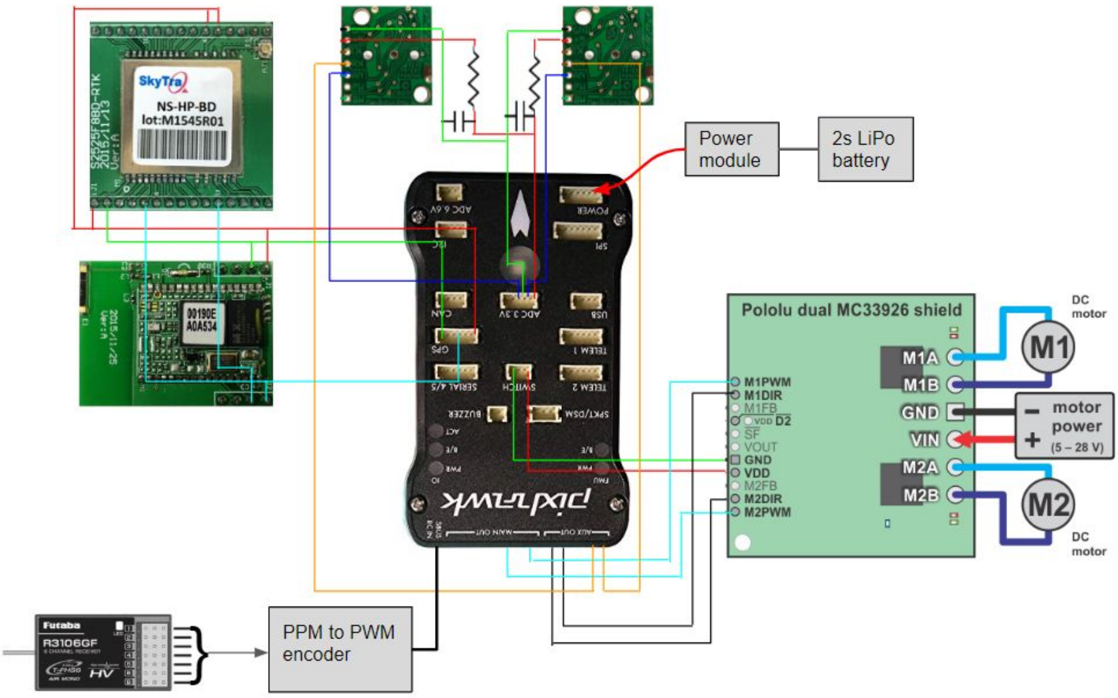


Fig. 4-13 Pixhawk circuit diagram

Connections as follows:

1. 2s LiPo battery → power module → Pixhawk power port
2. RC receiver → PWM encoder → Pixhawk RCIN port
3. GPS module and bluetooth serial link → GPS port as shown in diagram. GPS port pin mapping as follows:
    a. Pin 1 - VCC
    b. Pin 3 - GPS Rx
    c. Pin 6 - GND
4. Ultrasonic rangefinders → Pixhawk ADC 3.3V port as shown in diagram. To each ultrasonic sensor, connect a 10Ω resistor and a 100uF capacitor as shown. Pin mapping as follows:
    a. ADC port pin 1 - VCC
    b. ADC port pin 2 - Digital input pin 14
    c. ADC port pin 3 - GND
    d. ADC port pin 4 - Digital input pin 13
    e. Left sensor RX → AUX 2
    f. Right sensor RX → AUX 1
5. Motor driver → Pixhawk output pins as follows:
    a. M1PWM → CH 1
    b. M1DIR → AUX 5
    c. M2PWM → CH 3
    d. M2DIR → AUX 6
    e. GND → Pixhawk switch port pin 3
    f. VDD → Pixhawk switch port pin 1

The selected parts and their specifications are found in Appendix A.

Design Synthesis

During design synthesis, we will verify the critical dimensions and intended specifications of the modified chassis that have been previously calculated. Assumptions are also stated where necessary.

Five important factors of the design will be discussed thoroughly. The factors are:

1. Cutting Width Dimensions
2. Tolerance Analysis of Blades
3. Bending of Acrylic Board
4. Gear Torque Calculation
5. Autopilot System Specification

Cutting Width Dimensions

The reason for extending the width of the chassis is to accommodate for a bigger cutting width. Hence, the cutting width is derived from the largest possible chassis width that we thought of. For that, we investigated certain ideas that can help us determine the maximum size of blades possible that caters to the convenience of working with this prototype.

We chose 900mm to be the max width of the prototype (wheel to wheel). This specific length was chosen because it is the regulation width of the smallest possible width for a wheelchair walkway for width of kerbs, minimum width of accessible routes, etc., as specified by BCA in its Accessibility Code 2013. We decided to adhere to the BCA codes for wheelchair access because it could be easily moved from place to place via these access routes. From there, we used the width as a guide to model our final product on Solidworks, experimenting on the dimensions until we obtained the right configuration. As a result, the modified cutting width is 64.5cm.

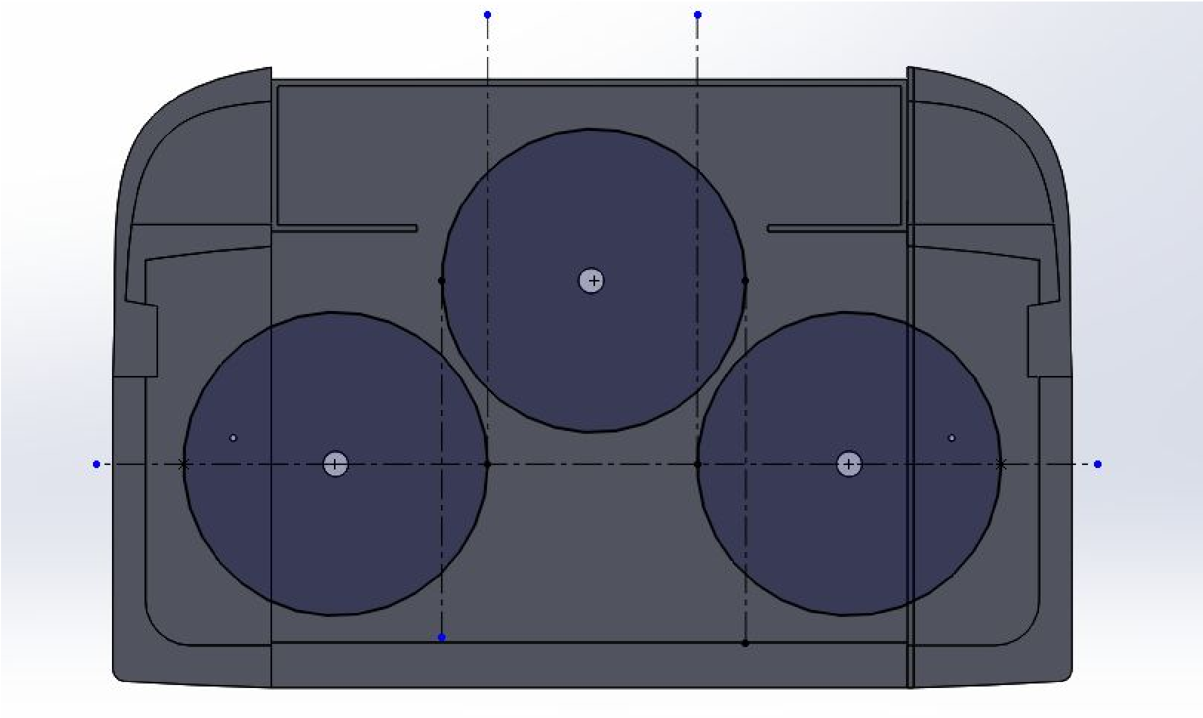


Fig. 5-1 Bottom view of the chassis showing locations of the blades. The blades are depicted as circles to show their full area of coverage.

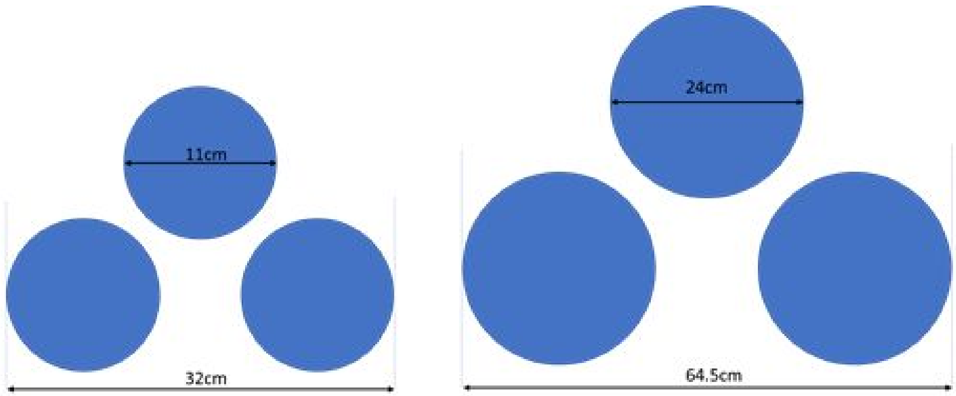


Fig. 5-2 Blade dimensions of the previous model (left) and the new model (right)

Tolerance analysis of Blades

A critical issue that might arise from the fabrication and assembly of the blades is the risk of the blades not having an overlapping area, as depicted in the figure below. To ensure that the right tolerance for the machining of this part, and hence the right method of manufacturing, we decided to conduct a tolerance analysis on the assembly.

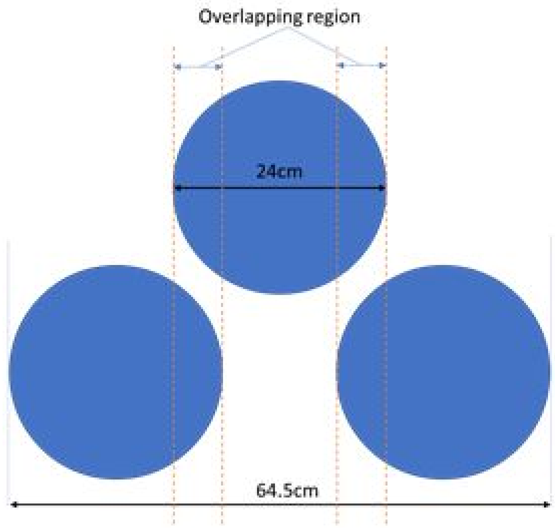


Fig. 5-3 The overlapping region ensures that there are no gaps in between blades

We have adopted the worst case tolerance analysis where a starting and end point is specified and a tolerance is calculated from a worst case scenario where both the Least Material Condition (LMC) and Maximum Material Condition (MMC) are considered.

The tolerance analysis showed a maximum tolerance of approximately ±1.5 cm is allowed for the fabrication of the blades, as calculated in Appendix D. This means that the margin for error is large enough for us to fabricate the blades with hand tools, using a saw to cut off rectangular pieces of aluminium and filing it to shape.

Bending of Acrylic Board

As stated in previous sections, we are extending the chassis using acrylic boards. As acrylic is relatively flexible, we need to know whether the placement of heavy components such as batteries and motors will warp the chassis. The reason to avoid excessive bending is to ensure even cutting height for the grass plots that we are working on.

To calculate the possibility of deflection due to bending, we carried out Finite Element Analysis (FEA) on the chassis (Appendix C). We decided to forgo basic stress analysis calculations because of the shear the complexity of the problem with remote forces and fixed points from different positions. Furthermore, FEA is a convenient tool to utilise.

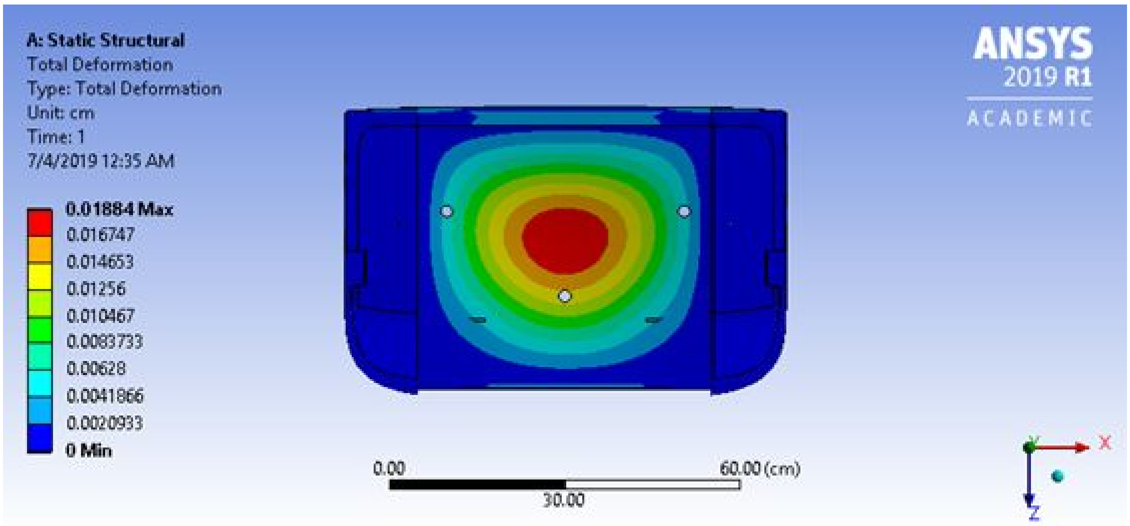


Fig. 5-4 The result of deformation of the chassis. The maximum deformation occurs close to where the battery is located, at a deformation of 0.01884cm

The results of the FEA shows that the maximum deformation that can occur is 0.01884cm or 0.1884mm. This is seen to be not extensive enough to cause any uneven cutting by the blades. However, as discussed in the study, the result only serves as a reference. We still need to take precautions for factors that cannot be input into the study, which includes adhesive strength between polyethylene and acrylic boards, vibration of the chassis in operation etc.

Therefore, we decided to continue to prototype the chassis without reinforcement first, and observe the whole structure's integrity knowing that it may deform way beyond the calculated results of 0.1884mm. If so, we are ready to reinforce it with steel angle bars, to make the chassis sturdier and resistant to violent vibrations.

Gear Torque Calculation

Our robot currently uses the sprocket and chain system, which is a type of gear system that transfers the torque from the motors to the wheels through a chain which links the two sprockets (one at the motor shaft and one at the wheel shaft) together. Before modification, the default ratio set by the manufacturer of the robot lawnmower was 1:1.

In our bid to increase efficiency of the robot, other than expanding the cutting width, we have decided to increase the moving speed of the robot by increasing the gear ratio of the sprockets used from 1:1 to approximately 2:1. However, by increasing the rotational speed of the gear system, the torque produced by the motors to the wheels will be reduced. Hence, there is a chance that, due to this modification, the robot might not be able to move due to the lack of torque from the motors to the wheels.

In this section we will be calculating the force provided by the wheels from the torque of the motors and comparing it with the forward force required to move the whole system.

$$P = F \times v$$

$$P = F \times RPM \times \frac{c}{60}$$

$$F = \frac{P}{RPM} \times \frac{60}{c}$$

$$F_{Motor} = 71N \qquad F_{Wheel} = 47N$$

$$F_{forward\ required} = f \times N$$

$$F_{forward\ required} = f \times g \times mass$$

$$F_{forward\ required} = 65N$$

$$2 \times F_{wheel} > F_{forward\ required}$$

P: power (25W)

RPM: round per minute (28)

F: force

r: radius (12cm)

c: circumference

f: friction coefficient of grass (0.5)

g: gravitational acceleration ($9.81m/s^2$)

Therefore, we can confirm that the reduction in torque will not affect the movability of the robot as the forward forces supplied by both wheels are sufficient to provide a resultant force forwards and backwards

.

Autopilot system specification

Our chosen autopilot system was the ArduPilot open source autopilot. We used a Pixhawk board running Rover v3.4. We also included two ultrasonic sensors into the Grassbot for obstacle avoidance. Our choice was decided by the following factors;

1. ArduPilot was a very well documented software that was actively supported and developed
2. Pixhawk was a established open source board standard, with easily available Chinese boards also conforming to the specifications
3. Rover natively supported skid-steering vehicles, which our Grassbot was.
4. The system was modular; we could pick individual components to fit our design and budget specifications
5. Rover natively supported obstacle avoidance via ultrasonic or lidar sensors.

Thus, we settled on our choice as it was feasible to assemble and debug without having to do hands-on coding, which we were not confident in doing within our project timeframe.

Our choice of GPS module was the Navspark NS-HP-BD GPS board for two reasons; firstly, it supported both the GPS and Beidou Global Navigation Satellite Systems (GNSS). The China-based Beidou GNSS has many regional satellites and increases accuracy and coverage beyond GPS alone. Secondly, the NS-HP-BD board supported the use of RTK. From our research, RTK technology has been becoming more and more accessible in recent years, with prices dropping significantly from thousands of dollars to around one hundred dollars for a compatible GPS board. Our group planned on using an Android phone running Lefebure NTRIP Client, a free app on the Google Play Store, to stream RTK correction data subscribed from the Singapore Land Authority SiReNT network via bluetooth to the GPS board to obtain centimeter-level GPS accuracy, allowing the

Grassbot to move precisely along its predetermined route and completely cover its operation area without the use of boundary wires.

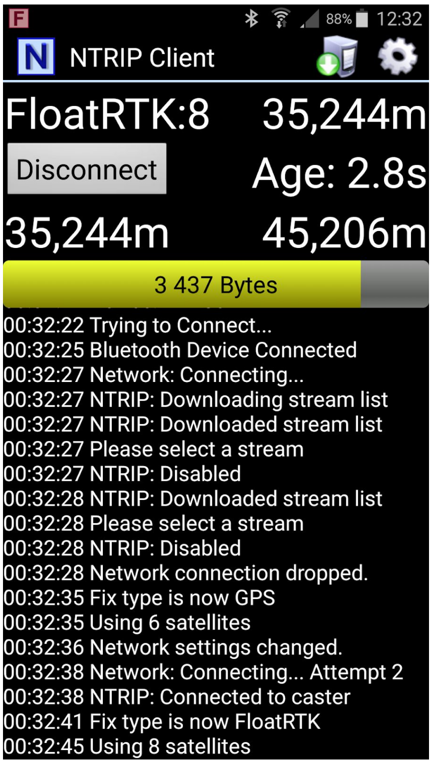


Fig. 5-5 Lefebure NTRIP Client user interface

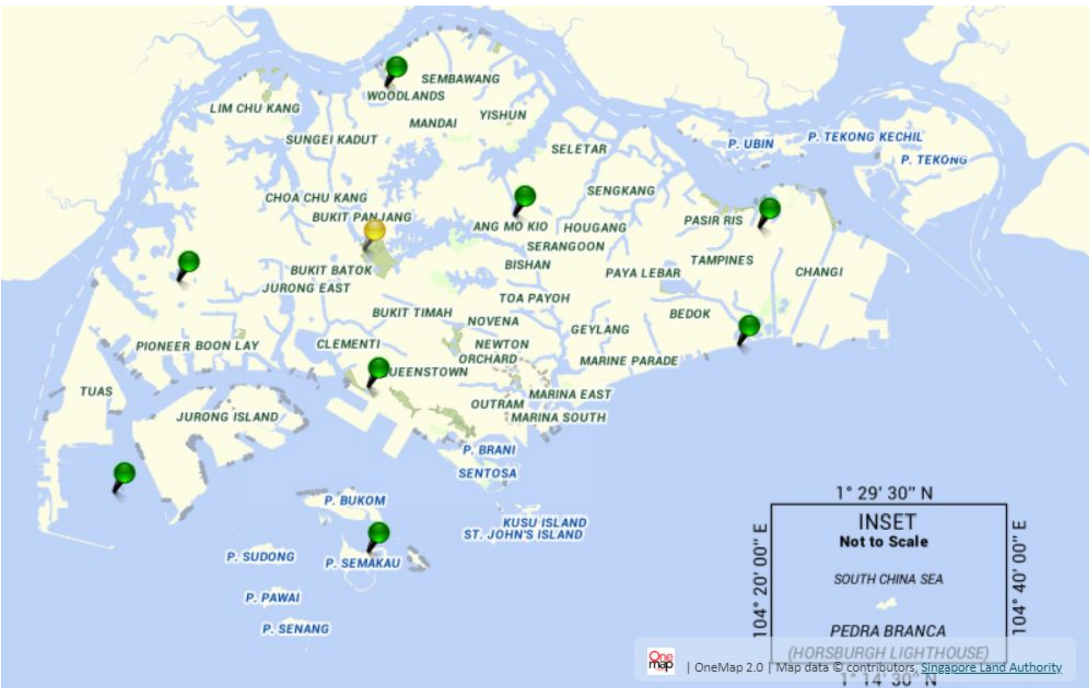
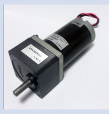


Fig. 5-6 Map of SiReNT base stations. The entire island is well covered by the network.

Budget Breakdown

Below is the cost estimate for manufacturing the product (not the prototype) including assembly and manufacturing costs

Part #	Part Name	Description	Picture	Cost
1	Chassis Fabrication	Chassis, Wheels, Blades		$100.00
2	Blade motors	3x Machifit 895 motor		$23.47
3	Wheel motors	24V 25W Linix DC Motor		$300
4	Sprocket & Chain	Monotaro		$48.96
5	Autopilot Board	Pixhawk 2.4.8		$82.73
6	GPS - RTK Components	RTK board, bluetooth module, GPS antenna, Antenna Cable		$192.22
7	RC Transmitter/Receiver + PPM encoder	Futaba T6L Sport		$150
8	Ultrasonic Sensors	2x LV-MaxSonar-EZ4-High-Performance Ultrasonic Range Finder		$79.18
9	Lipo Battery + Charger	Imax B3 Pro Lipo Charger		$30

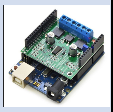
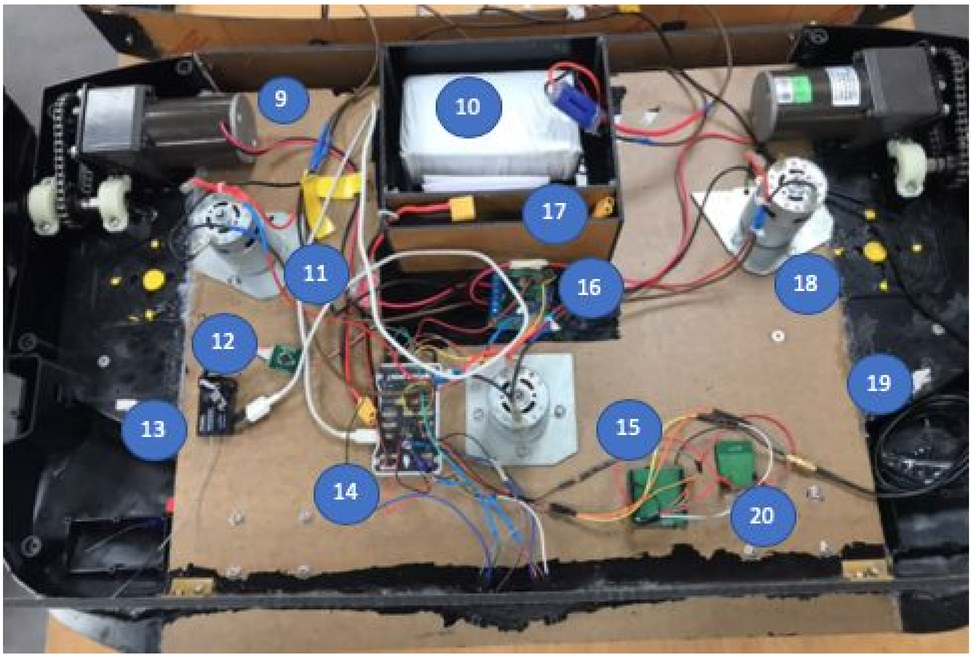
10	Lithium Ion Battery	24V 6.6Ah Lithium Ion Battery		$200
11	Motor Driver	Pololu Dual MC33926 Motor Driver Shield for Arduino		$81.05
	Total			$1287.61

Fig. 6-1 Budget breakdown

Materials Selection

Our choice of materials were majorly based on three factors - Availability for use, material cost and weight. The first two factors were taken into consideration because we have to work on a tight schedule along with an allocated budget. The last factor is also crucial to us because we could foresee the increase in weight in our final product. Coupled with the fact that wheel motors are too expensive outside, we had to ensure that the original wheel motor could still provide enough torque despite the added weight. It became more of a concern knowing that we were going to compromise torque in an exchange for extra speed. Thus, this resulted in choosing acrylic for the extension of chassis and blade bush since it was readily available at zero cost, light and also easy to work with. We decided to support the acrylic board using two steel angle bars because it was also readily accessible and despite being a little heavy, it's purpose was necessary and far outweighed the extra load it contributed. Furthermore, it was still a better option than to extend the whole chassis purely using steel. A thin sheet of aluminium was used for the extended cutting blades purely because we could obtain it with ease and that after some sharpening, it was sure to fulfill its cutting purpose given the speed of the blade motors.

Final Product



1	Ultrasonic sensors	11	Power module
2	Front wheels	12	RC receiver
3	Battery compartment	13	PWM encoder
4	Back wheels	14	Autopilot module
5	Top cover	15	GPS/BDS module
6	Chassis	16	Motor driver
7	Power switch	17	2s Li-Po battery

8	Emergency stop button	18	Blade motor
9	Wheel motor	19	GPS antenna
10	24v battery	20	Bluetooth Serial Link

Fig. 9-1 Labelled diagram of Grassbot showing main components

Testing

In order to determine the success of our final prototype, we ran it through a series of tests; each with a specific task. The initial test was to ensure that our electrical circuits and hardware were operating as intended such as the running of blades, the emergency stop button and switch. We brought it for a test-run around the Pavillion outside the EA Design Lab and controlled it remotely. With the success of its initial test-run, we continued with more task-specific tests.

1. Navigation test

Fig. 10-1 Path set for navigation test

The navigation test focuses on its ability to follow the cutting pattern based on the waypoints set using the GPS and Pixhawk system. The test was conducted on Field 2, opposite the Faculty of Science. While the accuracy of the GPS was limited, the robot was able to locate its first waypoint and followed the path that was set on the Mission Planner. Due to budget constraints and with our project supervisors' approval, we were not able to attain the RTK capability for this project. However, we are able to conclude that the use of RTK would complement the success of this test with improved accuracy.

2. Mowing Capability

Fig. 10-2 Before (left) and after (right) of the grass as the Grassbot mows through

The main objective of this test was to ensure that our blade system would be able to cut grass. Currently, our blades is positioned 2 cm from the ground. However, adjustment of height is relatively easy so less attention was focused on that aspect. As seen from the pictures above, there is evidence of some grass being cut. The test was also conducted at Field 2 and the grass was about 1.5 cm tall, therefore, the full potential of its mowing capabilities could not be achieved. Another successful point to note from the test was that there were no gaps in the cutting stream which confirms blade overlap.

3. Power Management

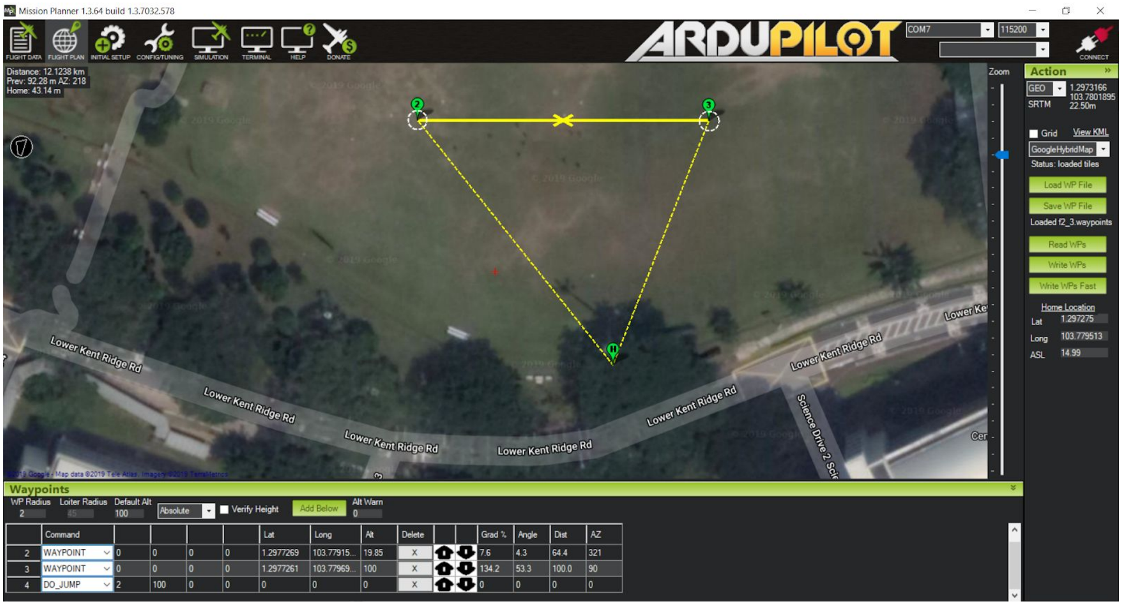


Fig. 10-3 Path for power management test

This test leans more towards the durability of the product. The main purpose is to test how long it can run for in normal operating conditions with a fully charged battery. This test was carried out by setting two waypoints where the robot will run back and forth until it dies out. The target set for this test was 3 hours, our theoretical time taken for the robot to complete our design requirement of half of a football field area. The robot was able to complete this test successfully.

Evaluation

In this section we review the problem statement we had established when we embarked on this project, and evaluate our prototype accordingly.

Our aim was to create a fully autonomous grass cutting robot to solve several problems that are currently faced by the industry.

1. Large number of foreign labourers required
2. Foreign labour's deployability in sensitive locations
3. Noise pollution and emissions by handheld grass cutter
4. Reliance on perimeter/ guide wire by existing grass cutting robot
5. Cutting capacity and efficiency of existing grass cutting robot

Our prototype strives to tackle the above-mentioned problems.

Strengths

Navigation

We had done extensive modification on the Grassbot. We replaced all the circuitry from the original setup with the Pixhawk Autopilot Board and Pololu dual mc33926 motor driver shield. A GPS module had been installed as well. We are now able to fully customise the route planning of the Grassbot with the autopilot board. The GPS module has enabled the Grassbot to know it's own location. Hence the Grassbot will be able to navigate on it's own moving to designated location and follow all the waypoints set to carry out the grass cutting work.

Obstacle Handling

The obstacle avoidance function had been revised. The original design was an analogue system, using bumpers that send signals to the motherboard for redirection when the robot physically bumps into obstacles. The revised design uses ultrasonic sensors to detect obstacles. This provides the Grassbot to re-orientate itself to avoid obstacles before colliding with them. This feature enhances the Grassbot's current level of safety.

Movement

The Grassbot's movement speed is increased. After analysis of the drivetrain, we modified the gear ratio of the chain final drive. By changing the motor sprocket from 15 to 26 teeth, we managed to increase the wheel speed from 28 rpm to 42 rpm, a 50% increment. This is a good improvisation as we made good use of mechanical advantage without increasing our expenditure to procure another pair of motors.

Cutting Capability

The cutting width of the Grassbot had been doubled from 32cm to 64cm. This is a major improvement in our Grassbot grass cutting capability. This directly increases the cutting efficiency while still utilising the 3 existing blade motors.

Power Management

With the extension in chassis, we are able to house double the size of the original battery. As the capacity of the battery is doubled, the Grassbot will be able to run almost twice as long as before.

Area for Improvement

Mass

With the extension of chassis, we had increase mass of the Grassbot from 14 kg to 13.2 kg. This will increase the load on the wheel motors and may affect the performance of the motors in the long run. The bulk of the mass increment comes from the acrylic boards and steel angle bars used. We had to use thick acrylic boards due to the large increase in bending moment at the centre of the Grassbot. We were constrained to using resources that are easily available to us for the construction of the prototype. If this prototype is adopted for manufacture, plastic injection moulding with appropriately-placed ribs will shave away the excess mass and avoid the need for steel reinforcement.

Stability

With the new extension, there is much more empty space at the front of the Grassbot. The centre of mass is now shifted more to the rear. This has decreased the stability of the Grassbot when it is moving up a slope. The risk of wheelstanding is increased. However, since our main objective is to mow a football field and similar flat terrain, we decided the decreased stability an acceptable compromise to increase the cutting capacity.

Wheels

It was proven with the final product that despite the reduced torque and added weight, the Grassbot still had ample power to move around. It was even able to climb steep slopes of at least 35 degrees. Despite all this, one potential problem we foresee is the lack of wheel grip, as it was struggling to climb up the slope in areas with thick and long grass. A simple solution would be to change the wheels with grippier off-road wheels. However, we did not make this modification as the ability to traverse steep slopes in low grip conditions was outside of our project scope.

Ultrasonic sensors

Our choice for selection of ultrasonic sensor, the Maxbotix LV-MaxSonar-EZ4 was based on online research on the ArduPilot forum, where it was agreed that a sensor with a narrow, well-aimed beam was ideal for autonomous vehicles as an overly sensitive sensor would tend to cause the robot to stray from its intended route excessively due to interference from objects in its surroundings. However, during our testing, we observed that even when the sensor was optimally aligned, the sensor beam was too narrow to allow the Grassbot to avoid obstacles that were at its sides. In retrospect, we could have selected a sensor with a wider beam to avoid this problem, such as the Maxbotix LV-MaxSonar-EZ0 sensor from the same family, which had good sensitivity but poor side object rejection.

Project Management Plan & Gantt Chart

With six members in the team, it was important to delegate tasks to each person to ensure full utilization of the team’s potential. The research and conceptualization phase of the project was a team effort, with each member working individually to cover a wider scope and view the problem from their own perspective. This allowed us to explore more viable concepts, and we eventually settled on our final concept in a timely manner. However, after the concept for the grassbot had been finalized, we split the team into sub-teams to work on separate aspects of the robot. They are:

- Aqil, Haziq, Hilman and Jasper for hardware development
- Hazim and Wei Shi for software development

respectively. We further split the hardware development team to specific tasks that were able to be more effectively handled by one person; in our case, Hilman was put in charge of blade development and Jasper was tasked with drivetrain upgrades. This allocation of manpower allowed the group to develop the separate parts of the grassbot in parallel and reduce waiting times. FIgure 11-1 shows the recommended product development timeline from the department, while our actual progress is represented in figure 11-2 and 11-3.

Fig. 11-1 Recommended product development timeline

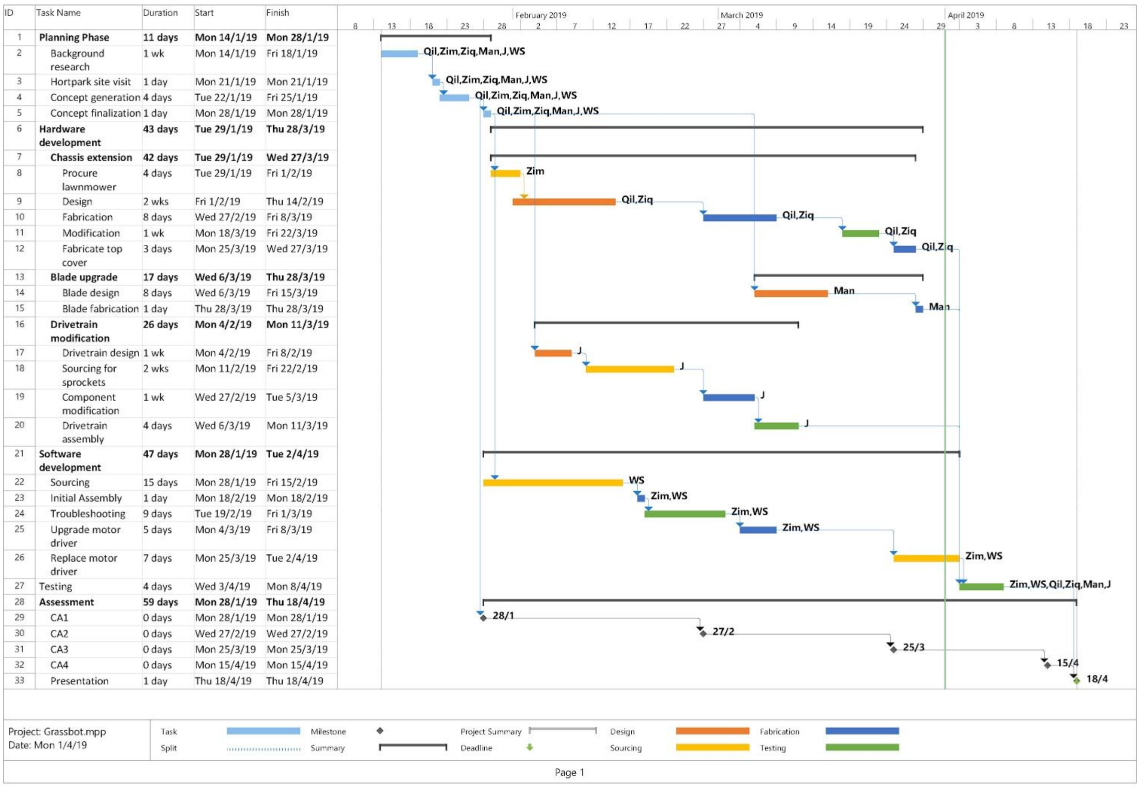


Fig. 11-2 Actual progress

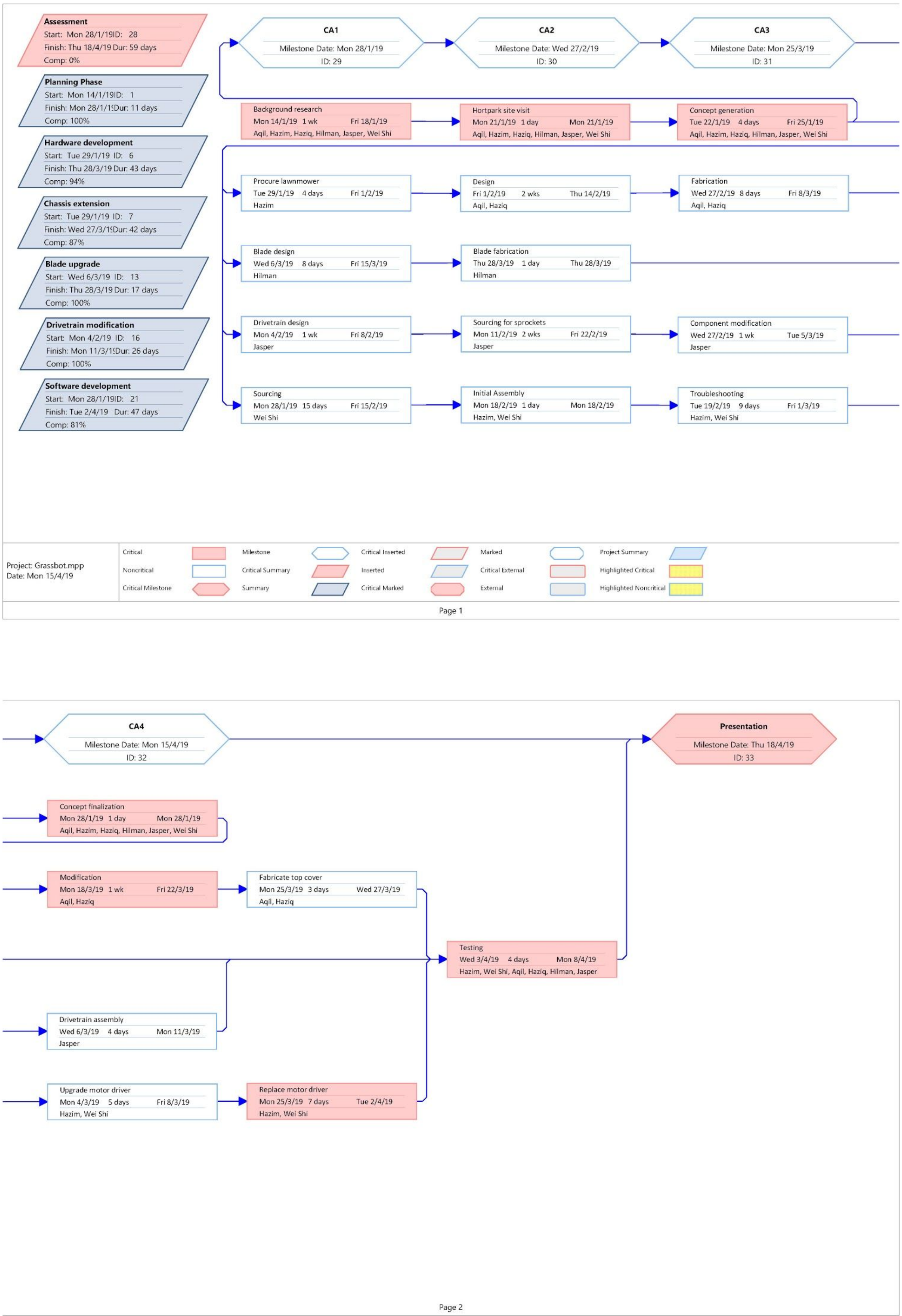


Fig. 11-3 Network diagram

From our project Gantt chart, it is evident that splitting the tasks amongst the team members was more effective than tackling one component at a time. There were several aspects of the project that involved sourcing and waiting for component delivery; we were able to use this time to advance other parts of the project instead of wasting it unproductively. Another notable point was the timing of the Chinese New Year holiday. We ordered our components on 29 January, a week ahead of Chinese New Year, to avoid having delivery of our Chinese made components being delayed by the extended break. However, we were unfortunately still affected by the holiday break, as our software components were delayed by two weeks.

Comparing our actual progress with the recommended schedule, we observe that we were mostly on time even though each design component had its own timeline and duration, and sometimes involved multiple iterations of testing and modification. However, there were some points for improvement. Firstly, while the chassis upgrade was completed as scheduled, we could have allocated more resources to it to complete it sooner, as the other design components were already completed and were waiting for the rolling chassis to be ready for testing. Furthermore, we overlooked the amount of time needed for software debugging. Thus we spent much of the later weeks of the project without any promise of a working product. Also, we did not leave sufficient allowances for unforseen circumstances. We suffered unfortunate malfunctions of our motor driver and GPS board before we could finish testing, and ended up with very little time to tweak our system after testing, limiting our options.

Conclusion

Through the course of this design project, we have developed a working prototype for an autonomous lawnmower. We believe that our design was an adequate proof of concept, and can be scaled up readily to meet future needs and improved specifications. These consist of upgrades to hardware components including battery, motors and motor drive, to increase operation speed and range. We believe that with appropriate component selection, such a system is viable and able to be commercialized.

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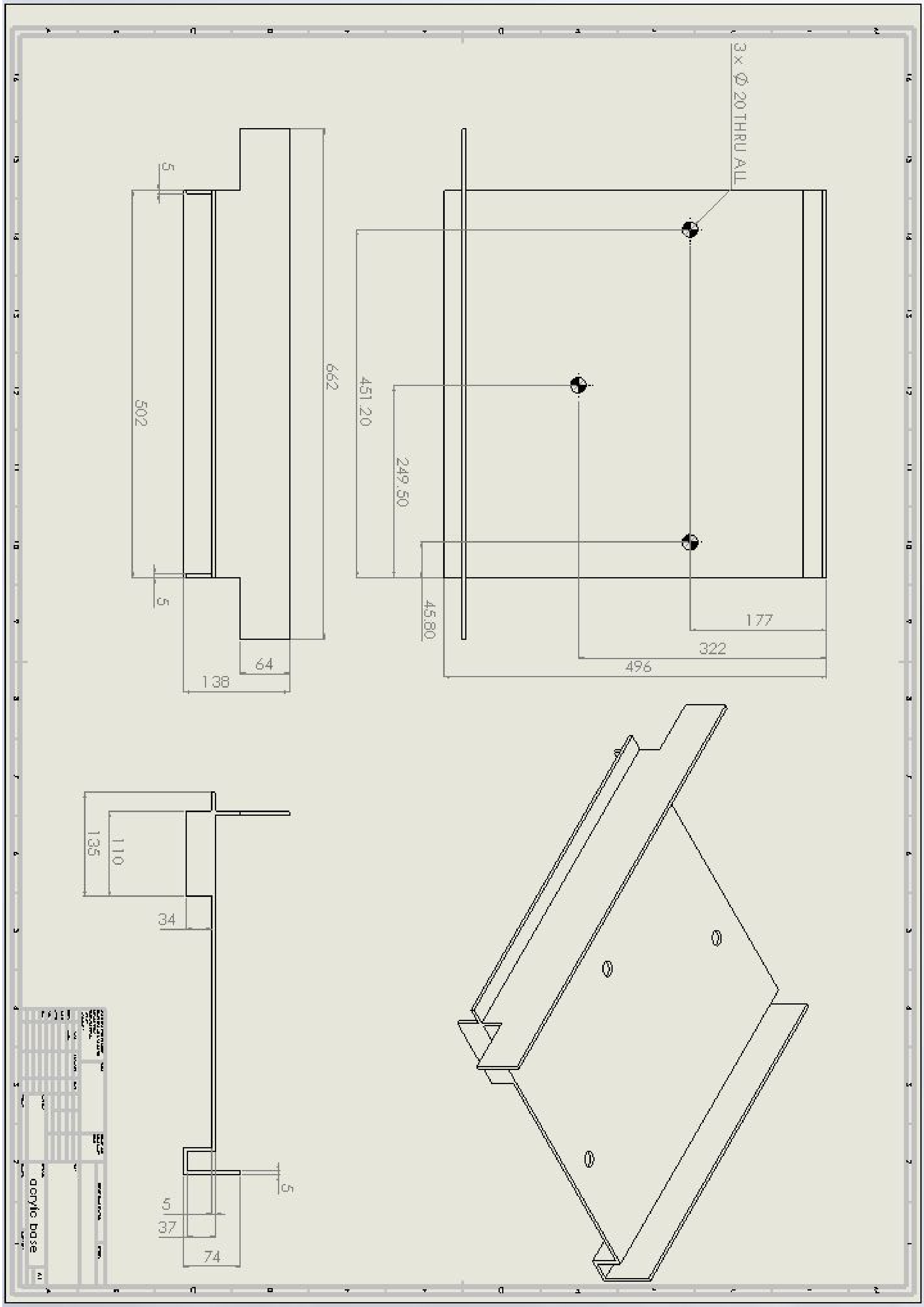
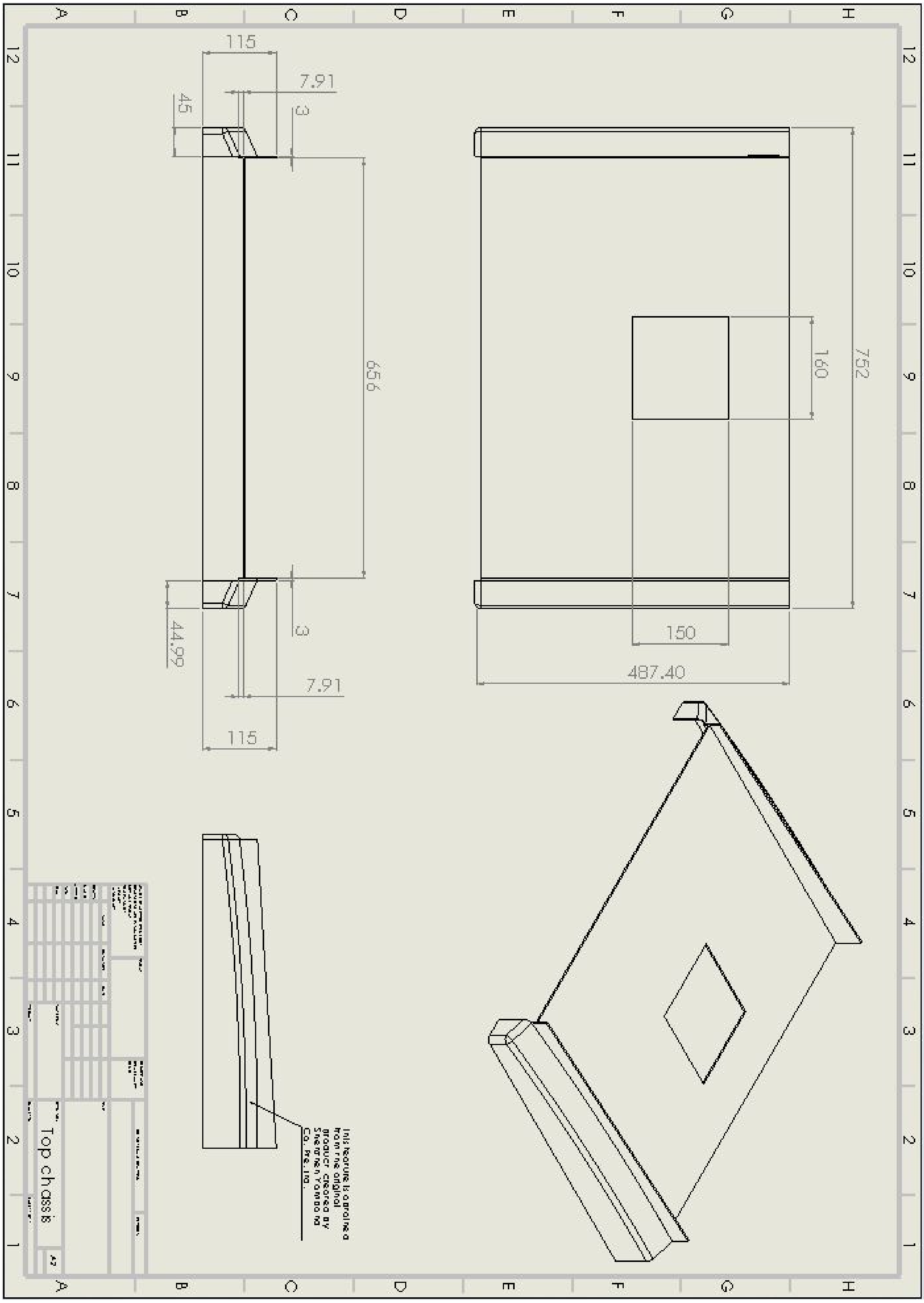
Appendix A: Drawings

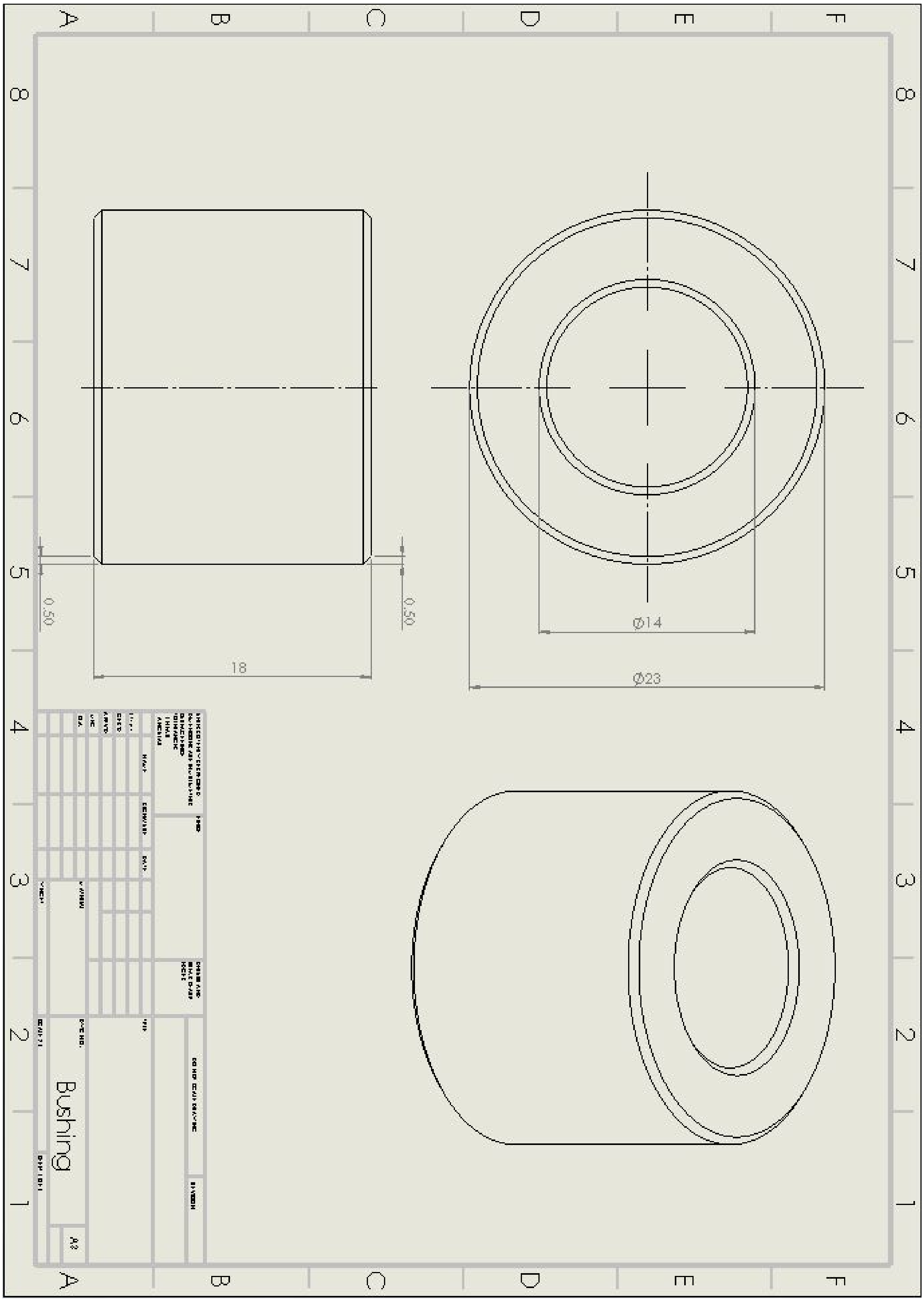
1. Chassis



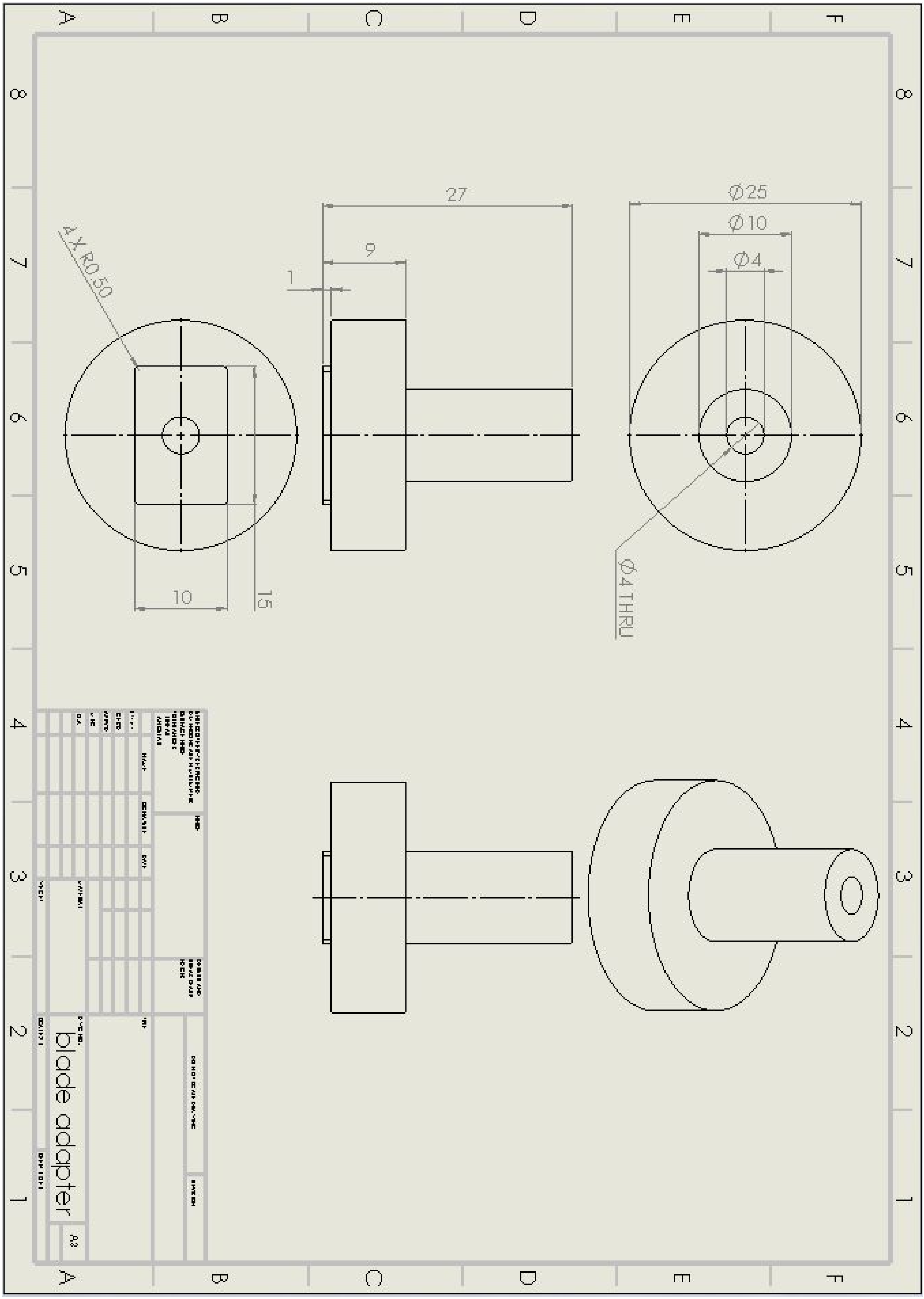
2. Top Cover



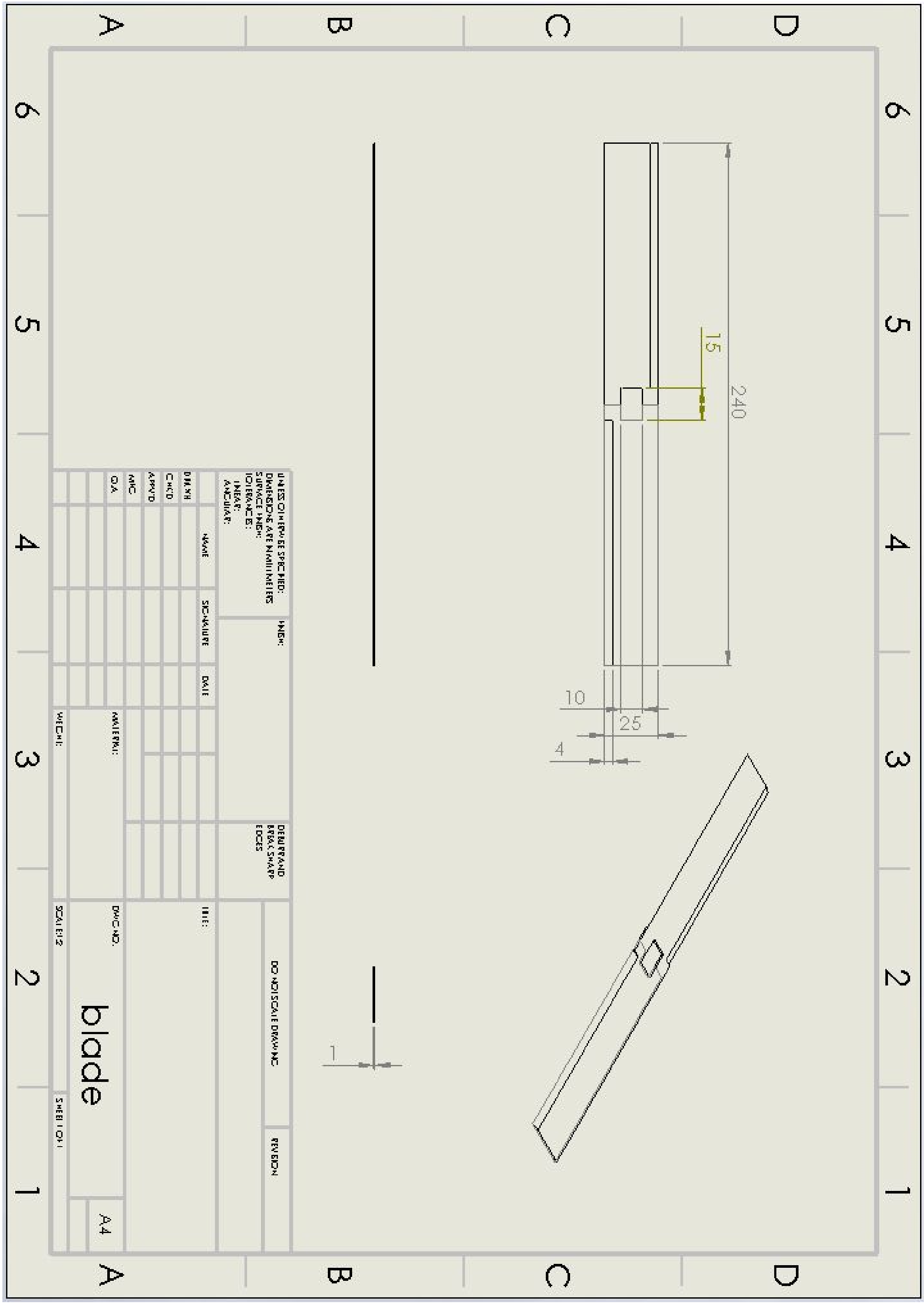
3. Blade Bushing



4. Blade adapter



5. Blade



Appendix B: Specifications of Purchased Components

Yomband YB-M13-320

Certification	CE, RoHS from TUV
Product Exterior Size	590*580*230mm
Package Size	740*600*280mm
Cutting Power	130W
Gross Weight	17kgs
Working Voltage	24V
Battery Available	7AH Lithium Battery
Working Time	2.5-3H(Average)
Charging Time	5.5H
Max Cutting Scope	3000sqm
Max Cutting Width	32cm
Max Cutting height	14cm
Blade Type	3/4/5cm (3 options)
Walking Speed	18-20m/min
Noise	<70db
Rotate Speed	5000rpm
Hill Capability	45 degree
Wireless Remote Control	Within 10m
Warranty	1 year

Pololu Dual MC33926 Motor Driver Shield for Arduino

Dimensions

Size:	1.90″ × 2.02″ × 0.38″[1]
Weight:	10 g[1]

General specifications

Motor driver:	MC33926
Motor channels:	2
Minimum operating voltage:	5 V[2]
Maximum operating voltage:	28 V[3]
Continuous output current per channel:	3 A[4]
Current sense:	0.525 V/A
Maximum PWM frequency:	20 kHz
Minimum logic voltage:	2.5 V
Maximum logic voltage:	5.5 V
Reverse voltage protection?:	Y[5]

<u>Pixhawk 2.4.8</u>

Specification:
The board integrates with PX4FMU+PX4IO
Pixhawk is with new 32 bit chip and sensor technology

Processor:
32 bit 2M flash memory STM32F427 Cortex M4, with hardware floating point processing unit
Main frequency: 256K, 168MHZ RAM
32 bit STM32F103 backup co processor

Sensor:
L3GD20 3 axis digital 16 bit gyroscope
LSM303D 3 axis 14 bit accelerometer /magnetometer
MPU6000 6 axis accelerometer / magnetometer
MS5611 high precision barometer

Interface:
5* UART, 1*compatible high voltage, 2*hardware flow control
2*CAN
Spektrum DSM/DSM2/DSM-X satellite receiver compatible input
Futaba SBUS compatible input and output
PPM signal input
RSSI (PWM or voltage) input
I2C
SPI
3.3 and 6.6VADC input
External USB MICRO interface

Features:
- Advanced 32 bit CortexM4 ARM high performance processor, can run RTOS NuttX real time operating system;
- Integrated backup power supply and failure backup controller, the main controller can be safely switched to backup control;
- Provide redundant power input and fault transfer function;
- 14* PWM/ actuator output;
- Bus interface (UART, I2C, SPI, CAN);
- Provide automatic and manual mode;
- Color LED lamp;
- Multi tone buzzer interface;
- Micro SD to record flight data;

Package included:
1 x 2.4.8 Pixhawk main control
1 x Safety switch
1 x Flight control shell
1 x Buzzer
1 x 6pin to 6pin line
1 x 4Pin to 4Pin line
1 x 3pin DuPont line

Navspark NS-HP-BD : GPS/BDS RTK Receiver

TECHNICAL SPECIFICATIONS

Receiver Type	GPS L1 + BDS B1 + QZSS + SBAS L1 C/A code, 167-channel
Accuracy	Position: 2.5m CEP autonomous mode; < 1m DGPS mode; centimeter-level RTK mode
	Velocity: 0.1m/sec
	Time: 10ns
Time to First Fix	1 second hot start under open sky (average) 28 second warm start under open sky (average) 29 second cold start under open sky (average) 90sec to 1st ambiguity fixed solution at 7Km baseline for example*
Reacquisition	1s
Sensitivity	-148dBm cold start -160dBm tracking
Update Rate	

	S2525F8-BD-RTK model suffix		-5	-10
Update Rate	RTK cm-level accuracy (Hz)	1	1 / 2 / 4 / 5	1 / 2 / 4 / 5 / 8 /10
	normal meter-level accuracy (Hz)	2 / 4 / 5 / 8 / 10 / 20	8 / 10 / 20	20

Operational Limits	Altitude < 18,000m or velocity < 515m/s
Serial Interface	3.3V LVTTL level
Protocol	NMEA-0183 V3.01 GPGGA, GPGLL, GPGSA, BDGSA, GPGSV, BDGSV, GPVTG, GPRMC 115200 baud, 8, N, 1 RTCM 3.0, 3.1 or SkyTraq raw data binary 57600 baud, 8, N, 1
Datum	Default WGS-84 and user definable
Input Voltage	3.3V DC +/-5%
Current Consumption	70mA
Dimension	25.4mm L x 25.4mm W
Weight:	3g
Operating Temperature	-40°C ~ +85°C
Storage Temperature	-55 °C ~ +100°C
Humidity	5% ~ 95% non-condensing

*****_Note: This time to first RTK fixed solution is dependent on number of satellites available, usable satellite geometry, signal strength, distance from base-station…etc. May take 1 ~ 10 minutes under open sky within 10Km baseline._

ELECTRICAL SPECIFICATIONS

ABSOLUTE MAXIMUM RATINGS

Parameter	Minimum	Maximum	Condition
Supply Voltage (VCC33)	-0.5	3.6	Volt
Backup Battery Voltage (VBAT)	-0.5	6.0	Volt
Input Pin Voltage	-0.5	VCC+0.5	Volt
Input Power at RFIN		+5	dBm
Storage Temperature	-55	+100	degC

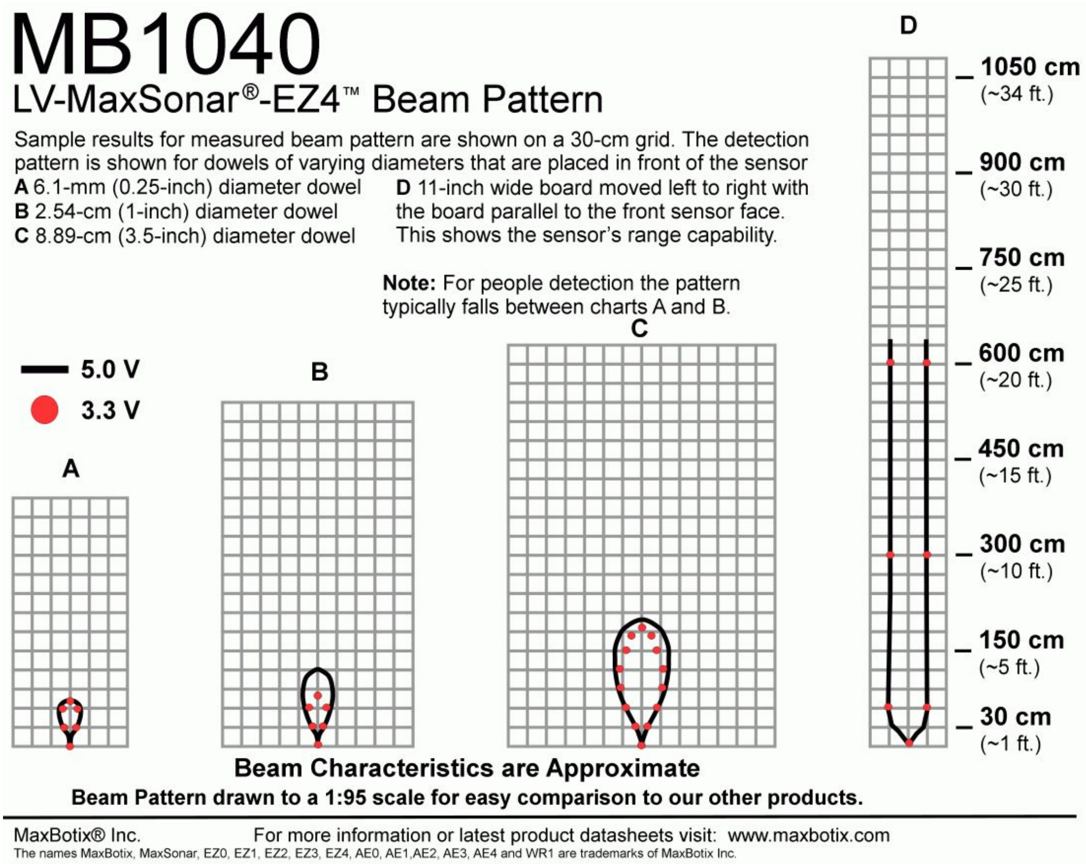
OPERATING CONDITIONS

Parameter	Min	Typ	Max	Unit
Supply Voltage (VCC33)	3	3.3	3.6	Volt
Acquisition Current (exclude active antenna current)		70		mA
Tracking Current (exclude active antenna current)		50		mA
Backup Voltage (VBAT)	2.5		3.6	Volt
Backup Current (VCC33 voltage applied)			1.5	mA
Backup Current (VCC33 voltage off)			10	uA
Output Low Voltage			0.4	Volt
Output HIGH Voltage	2.4			Volt
Input LOW Voltage			0.8	Volt
Input HIGH Voltage	2			Volt
Input LOW Current	-10		10	uA
Input HIGH Current	-10		10	uA
RF Input Impedance (RFIN)		50		Ohm

LV-MaxSonar-EZ4-High-Performance Ultrasonic Range Finder

Product Specifications

- Resolution of 1 inch
- 20Hz reading rate
- 42kHz Ultrasonic sensor measures distance to objects
- RoHS Compliant
- Read from all 3 sensor outputs: Analog Voltage, RS232 Serial, Pulse Width
- Virtually no sensor dead zone, objects closer than 6 inches range as 6 inches
- Maximum Range of 254 inches (645 cm)
- Operates from 2.5-5.5V
- Low 2.0mA average current requirement
- Small, light weight module
- Designed for easy integration into your project or product
- Narrowest beam of the LV-MaxSonar-EZ sensors
- Best for large object detection applications



Futaba T6L Sport 2.4GHz T-FHSS Mono 6-Channel Air System

Transmitter Specifications:

Type:	2-stick, T-FHSS Mono Directional 2.4GHz System
Transmitting Frequency:	2.4GHz band
Channels:	6
System:	T-FHSS (Mono Dircetional), no telemetry
Power Supply:	4 "AA" cells (required)
Low Battery Alarm:	Yes
Mixes:	Elevon, V-Tail, Flaperon
Modulation:	Futaba T-FHSS Mono AIR
Receiver:	R3106GF (Included)
Switches:	1
Telemetry:	No
Trainer Connector:	Student Only
Trims:	4 Analog
Dials:	1
Frequency:	2.4GHz

Receiver Specifications:

R3106GF 2.4GHz T-FHSS Air (Mono directional)

Type:	T-FHSS Air (Mono directional)-2.4GHz system, no telemetry
Power requirement:	4.8V-7.4V battery or regulated output from ESC, etc.
Dimensions:	1.7 x 0.98 x 0.35 in (43.1 x 25.0 x 8.8 mm)
Weight:	0.3 oz (7.8g)

Appendix C: Finite Element Analysis on Chassis

Description of Study

A Finite Element Analysis study is done on the chassis to know the maximum deformation that can occur to the chassis. We agreed within the group that the maximum allowable deformation should be 1mm.

Firstly, the chassis is modelled using Solidworks and a STEP file is produced, before being imported into Static Structural on Ansys. The materials for the prototype (acrylic and polyethylene) are matched to the individual parts.

Next, fixed support were inserted to locations where it is supported by the wheels (location A, D, H and I in figure X) whereas battery and blade motors forces were exerted onto the location that we intend to place it (location B, G, F and E).

The mesh size is set to be 1cm.

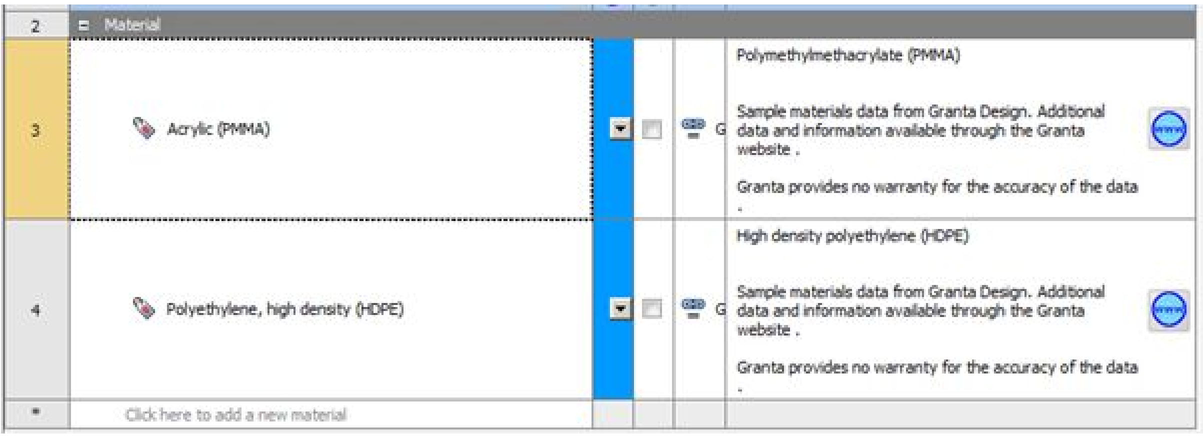


Fig. C-1 Acrylic and HDPE materials set to respective parts

Calculations on Remote Forces

Mass of battery = 1.057kg

Remote force of 24V battery on chassis = 1.057 * 9.81 = 10.369 N

$= 1.0369 \times 10^6$ dyne

Mass of blade motors = 0.210kg

Remote force of Blade Motor on chassis = 0.210 * 9.81 = 2.0601 N

$= 2.06061 \times 10^5$ dyne

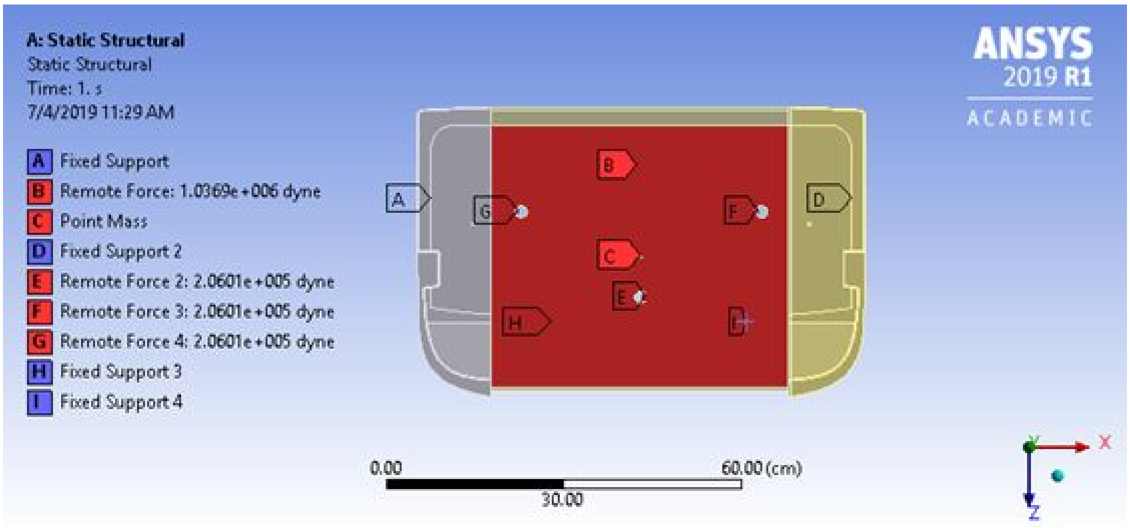


Fig. C-2 showing fixed support locations, point mass and remote forces of battery and motors

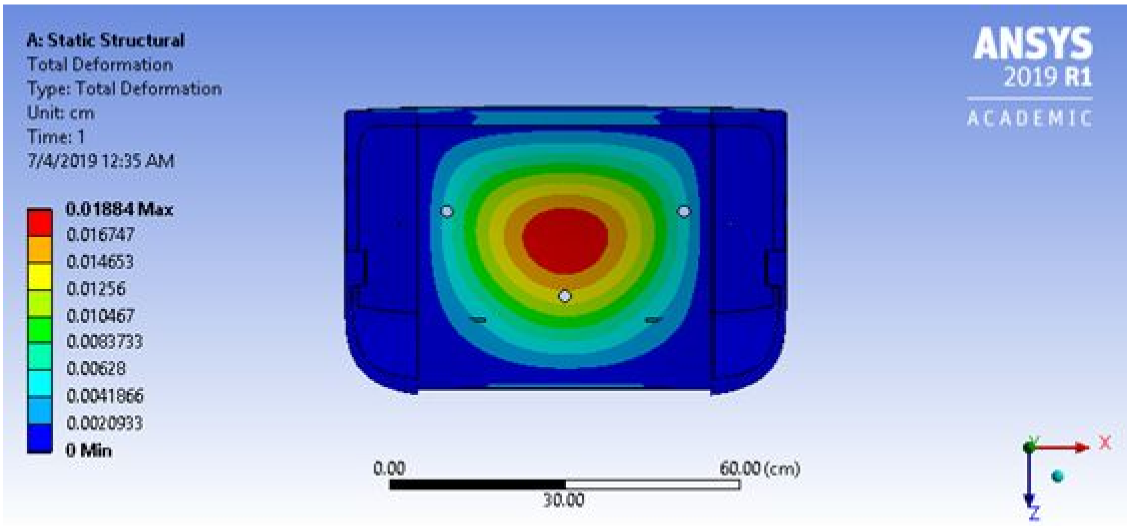


Fig. C-3 showing total deformation of the chassis

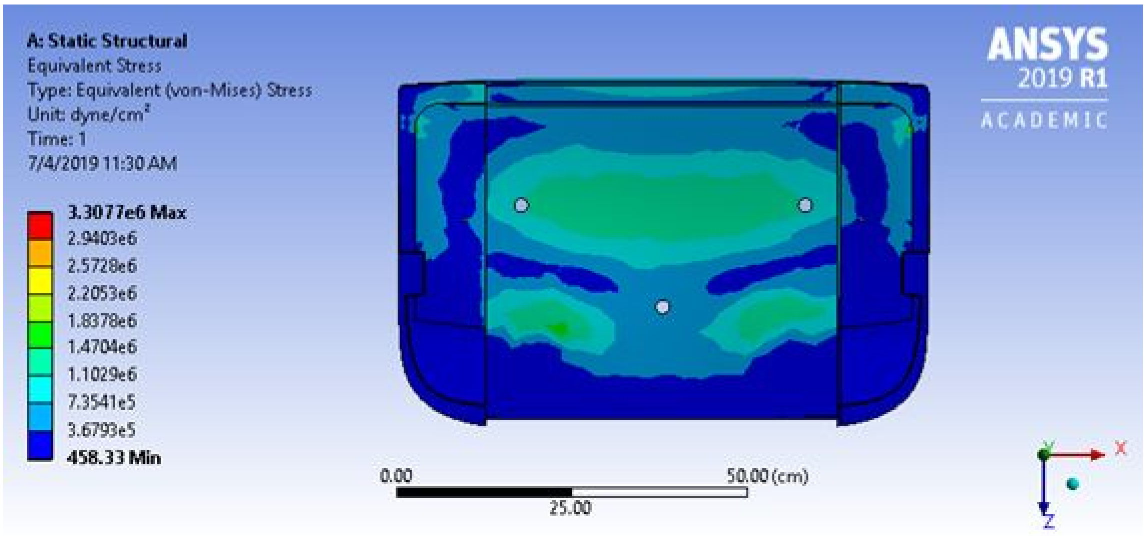


Fig. C-4 showing equivalent stress on the chassis

<u>Results</u>

Maximum deformation was found to be 0.01884 cm or 0.1884 mm in deflection. Therefore, in theory, we do not need reinforced support to the base of the chassis. However, there are other limiting factors that may contribute to the weak structure of the chassis that cannot be included in this study. These factors include, the gluing strength between the contact points of the acrylic and plastic and also the other weight that is assumed to be negligible, such as wires and other electronics.

Furthermore, the rigidity of the acrylic is not input into the study as seen below. This lack of information means that the study cannot be fully relied on. But it does provide us with a good gauge of the chassis deformation in which it helps us decided whether to reinforce the base with steel angle bars.

Properties of Outline Row 3: Acrylic (PMMA)

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	1180	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
5	Isotropic Elasticity				
11	Tensile Yield Strength	6.24E+07	Pa		
12	Tensile Ultimate Strength	6.71E+07	Pa		

Fig. C-5 A table of properties that in set into the FEA for acrylic parts. It shows that only density, tensile yield strength and tensile ultimate strength is considered in the calculations

Appendix D: Tolerance Analysis on Cutting Blade Placement

The purpose of this study is to investigate the tolerance needed for the fabrication of the aluminium blades. This is to ensure that there exists an overlapping region that ensures the coherent cutting by the cutting system at a specified height. The procedure of the Stack-up analysis is as illustrated in the Technical Training Consultants guide for Stack-Up Analysis[2].

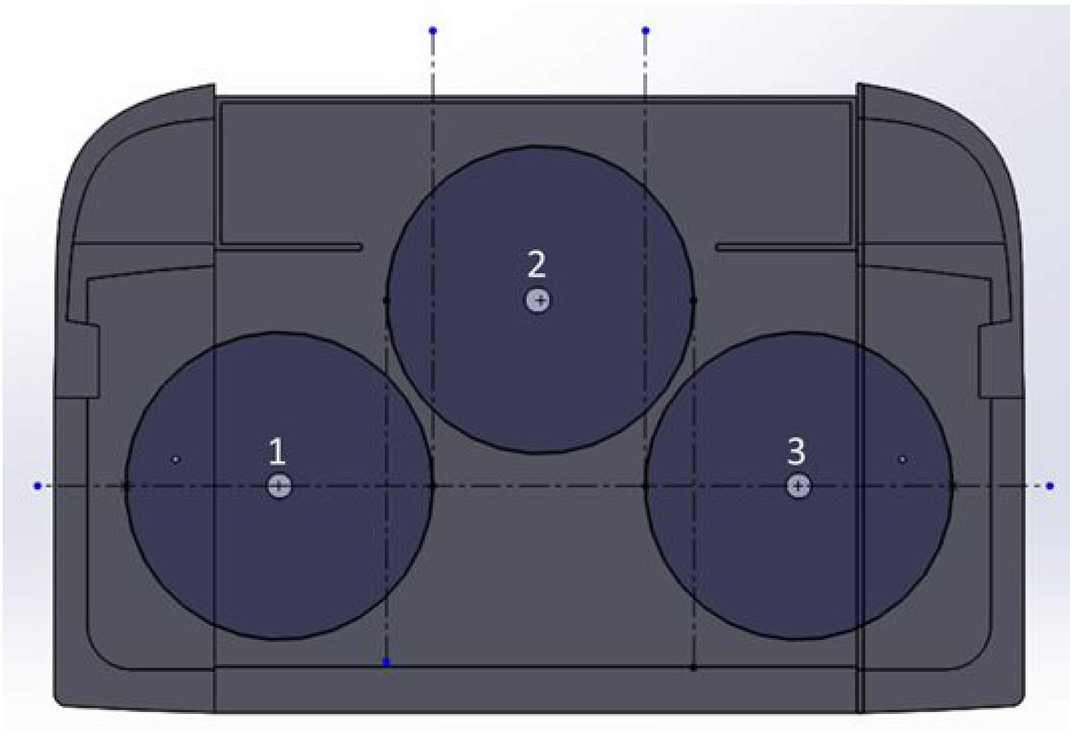


Fig. D-1 Bottom view of the chassis showing the numbering of the blades (1, 2 & 3)

[2] Technical Training Consultants. "Tolerance Stack-Up Analysis." Retrieved Feb 2019. http://www.ttc-cogorno.com/Newsletters/140117ToleranceAnalysis.pdf

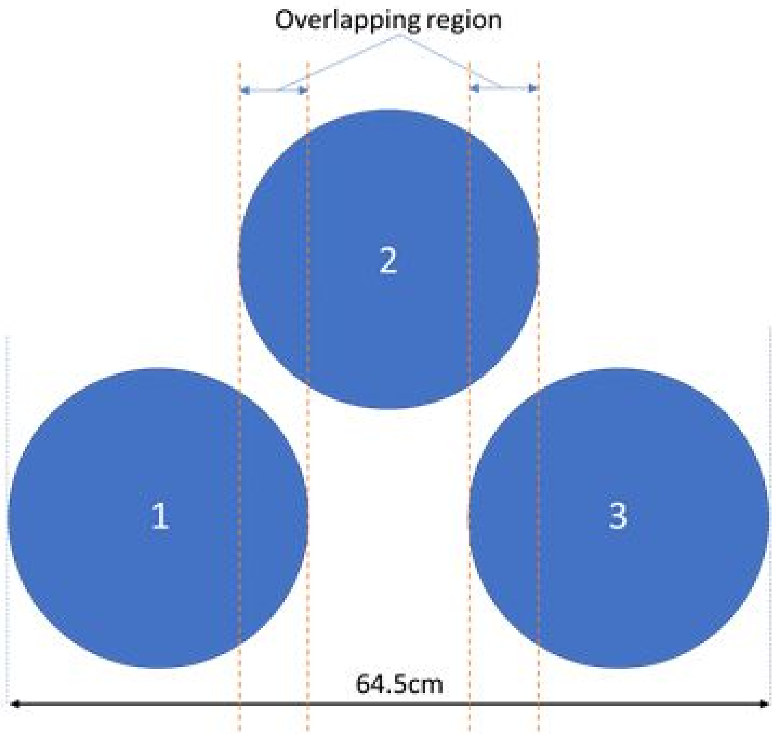


Fig. D-2 Illustration of the blades showing the overlapping region that we trying to achieve

In this analysis, only blades 1 and 2 are analysed, and assuming symmetry, all three blades will have the same tolerance values. We will consider the x-axis values for the tolerance stack up.

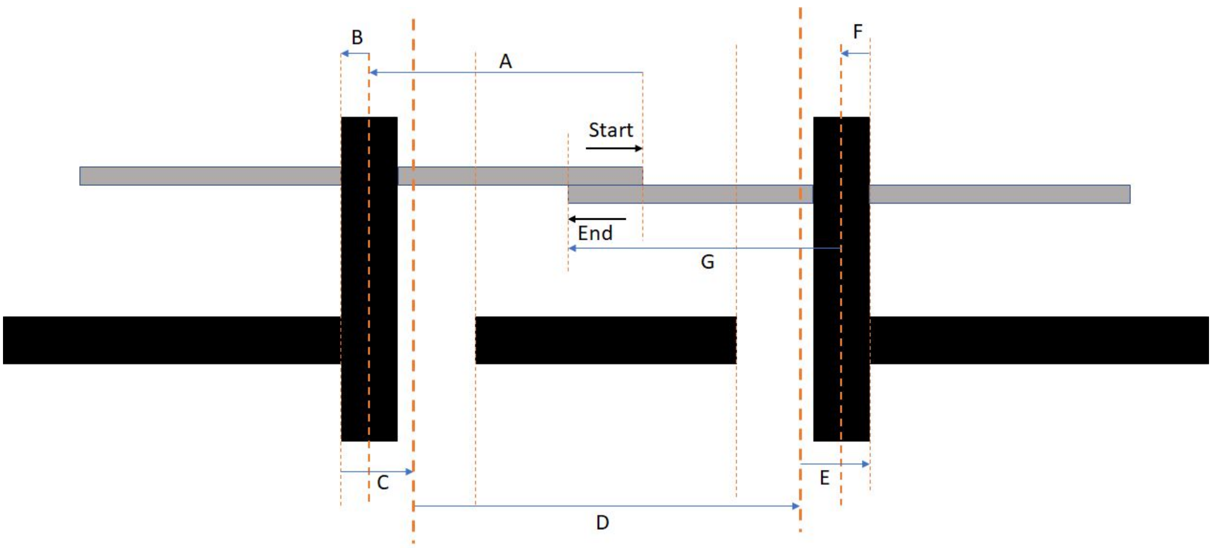


Fig. D-3 Exaggerated depiction of the assembly of the blades (in grey) and chassis (in black)

Dimension Label	Vector Dimensions		Tolerances	Part
	-	+	+/-	
A	120		x	Blade Dim.
B	6		0.03	Shaft Radius
C		10	0.03	Hole Radius
D		200	2	Basic Dim.
E		10	0.03	Hole Radius
F	6		0.03	Shaft Radius
G	120		x	Blade Dim.
Total	-252	+220	2x + 2.12	Total

Fig. D-4 Table of dimensions and tolerance that is used to find the sum of vector dimensions of the dimensions that contribute to length of overlapping region. Tolerances are obtained from the Air Force-Navy Aeronautical Standards for standard drill sizes, AND10387[3].

Conclusion of Analysis

Nominal length of overlapping region $= -252 + 220$

$= -32$ mm

Minimum length of overlapping region $= 32 - (2x + 2.12)$

$= (29.88 - 2x)$ mm

The negative value of the overlapping region denotes that the blades overlap one another when seen from the y-direction. It's tolerance is stated as $(2x + 2.12)$, where x is the unknown that we are trying to solve.

For there to be an overlapping region, the minimum length of overlapping region has to have a value of more than zero. Therefore, equating $(29.88 - 2x)$ to zero:

$$29.88 - 2x = 0$$

$$x = 14.94 \text{ mm}$$

Hence we conclude that the required tolerance for the fabrication of blade is 240 mm ±14.94 mm.

[3] Engineers Edge. "Machinist Drilling Mechanical Tolerance Capabilities Chart" Retrieved Feb 2019. https://www.engineersedge.com/manufacturing/drill-mechanical-tolerances.htm