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UNIVERSITY OF APPLIED SCIENCES

Novia University of applied sciences

3Dprinted lawnmower

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Thank you all for this flawless semester in Vaasa!

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Abstract

The goal of the project is to create a proof of concept autonomous lawn mower that is charged by the wind turbine to prove that normal objects around the house can be printed at home. The items that were chosen for creation were picked due to their relative complexity and combining them would proof a very useful asset in Finland. During the project multiple setbacks were encountered mainly due to the inexperience of working in Finland. This means that the goals of the project were not met completely, however, conclusions can be made mostly that items with such complexity such as a windmill or lawnmower are not ready for home fabrication due to the lack of experience of the normal consumer, the specialized tools required to complete certain steps and the difficulty of putting it all together.

Abbreviations

3D: Three dimensional

QFD: Quality Function Diagram

EPS: European Project Semester

ABS: Acrylonitrile butadiene styrene

PLA: Polylactic acid

WBS: Work breakdown structure

FDM: Fused deposition modelling

PID: Proportional-integral-derivative

FFF: Fused Filament Fabrication

MJ: Material Jetting

EPS: European Project Semester

FF: Fill factor

LiPo battery: Lithium polymer battery

AC: Alternating current

EMF: Electromotive force

DC: Direct current

SPE: Solid polymer electrolyte

BMS: battery management system

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Table of figures

Table of Contents

1. Introduction

1.1 Rationale

The reason for this project is to create a proof of concept autonomous lawn mower that is charged by the wind turbine to prove that normal objects around the house can be printed at home. The objects that are being printed, the lawn mower and wind turbine, are objects that are useful for normal people to reduce their energy bill and save time on house maintenance. As three-dimensional printing(3D) gets mainstream it is useful to show the general consumers and producers the added value of in house fabrication of small, easy to build machines, tools and products. The hope is that this sparks more enthusiasm within both the consumers and producers so that more items will be developed for in house creation.

1.2 Corporate Design

One part of the EPS is to create a corporate identity, which is generally needed to express the business's brand personality but also sets you apart from the competition. Ordinarily Corporate Identity includes a variety of elements such as name, slogan, logo, packaging, or style and usage of colours and images. Although, for the EPS only name, logo, business card, and website are required.

1.2.1. Team name

After a brainstorming "My Mower" was set to be our official team name.

3D Print	windblade	mowmaker	M O
lawn mower	Ymow	windcut	W E
wind		3dmow	
renewable/regenerative	makemow	treedmow	
sustainable	createmow	lessmower	
home use	makebot	mowitself	U wind mow
	printmow	mowyeah!	
UMOW	3DMOW	mymow	
uMower		MOW	
iMower	mour		ωpdm
yourMower	moe	3Dmower	
doyourmower	3d Moe	windmower	
	mad moe	threemower	
	madowmoe	threecut	
	wind moe		

Figure 1 Name brainstorming chart

1.2.2 Logo

A logo is a graphic mark, an emblem, or a symbol used to aid and promote public identification and recognition. It may be of an abstract of figurative design or include the text of the name it represents as in a wordmark. The task of the logo is to represent the corporate philosophy, ideally, with a minimum input of elements and colours.

There are five logo types – wordmark, letter mark, pictorial mark, combined mark, and emblems.

The wordmark is the simplest type of logo, it is made up only of text, mostly the company's name. Popular wordmark examples are Google and Coca-Cola. This type of logo is common to be used by big companies, which do not need to explain themselves by illustrations.

The letter mark, or monogram logo also is made up of text, but only uses the initials of the company. Famous examples are Electronic Arts (EA) or Cable News Network (CNN). A letter mark can be chosen if the company name is difficult to pronounce or to shorten the name for media and mobile devices.

A pictorial mark consists of a symbol or a graphic. The company name is not inserted, or already removed due to an increased brand awareness. This logo type should only be chosen combined with a good organized market introduction. The success of the pictorial mark relies on the audiences knowing of the symbol meaning. Popular examples are the logo of Apple and McDonalds. The great adventure of the pictorial mark the instant understanding all over the world. As second benefit the viewer will form a psychological connection to the brand.

The combined mark is the most common logo type. Through combination of illustration and type, the meaning of the logo can be guessed rapidly and the awareness level rises. Depending on the medium, illustration and type can be used both together or separately. Mostly it is suitable for mid-sized companies due to a low brand awareness.

The emblem is like the combination mark, as difference the type appears inside the logo. Examples are Starbucks and Burger King.

1.2.2.1 Logo design process

The first step is to make a mind map that lists all terms which are related to the core. Everything that appears in your mind should be written down to serve further brainstorming. Terms seeming more useful than others are highlighted yellow in the following graphic and they create the base for the following step, where paper sketches were made.

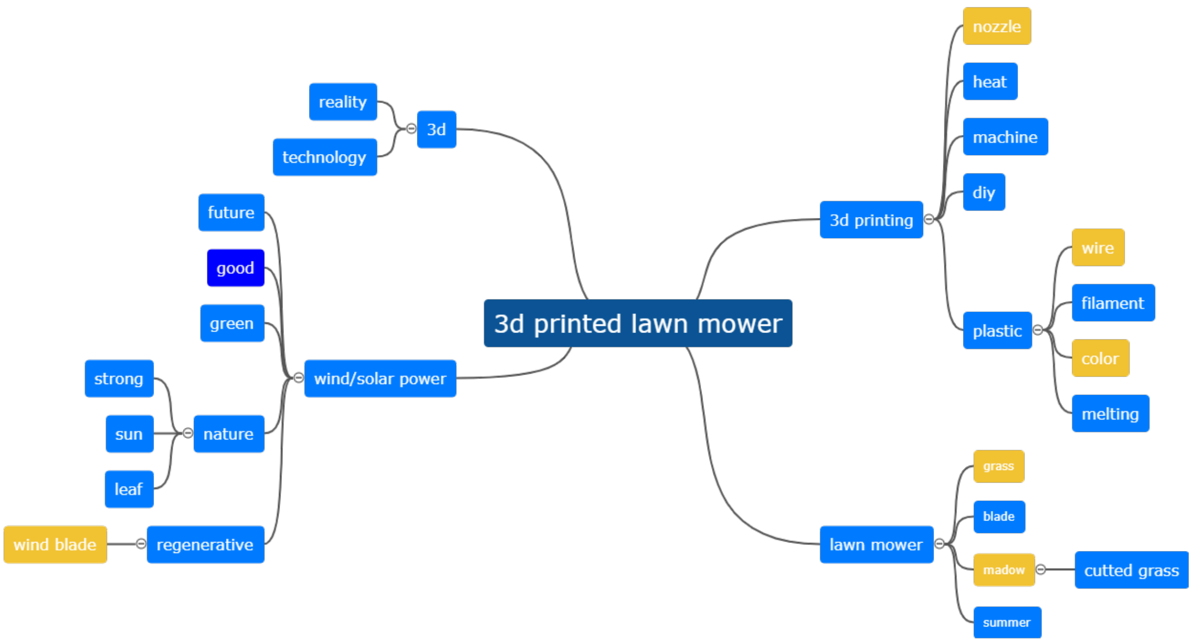


Figure 2 Mind map of logo design

While doing paper sketches, one can try to enforce in a single term or to create combinations between the highlighted terms, but also new ideas should be allowed to emerge. The more variation and ideas, the better the chance creating a meaningful logo. In the image below a small part of the MyMower scribbles can be seen. Trying to combine the terms wind, nozzle, wire, filament and grass.

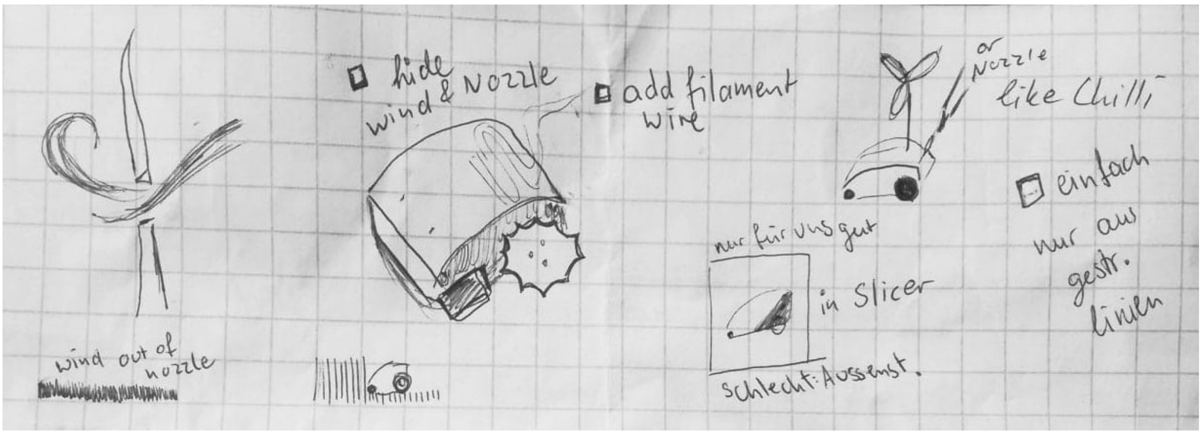


Figure 3 Paper scribbles of logo design

The MyMower logo was created in the vector graphics editor Adobe Illustrator. While the first drafts are just initial attempts to include the idea of the 3d printing wire, you can see in the later drafts a clear selection of elements and the process of redesigning the same elements till a final logo.

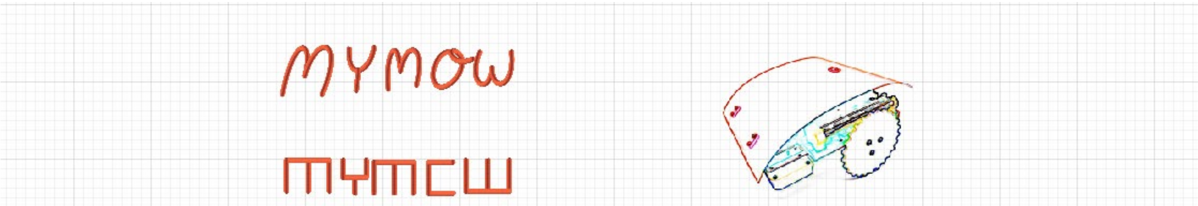


Figure 4 First drafts of logo

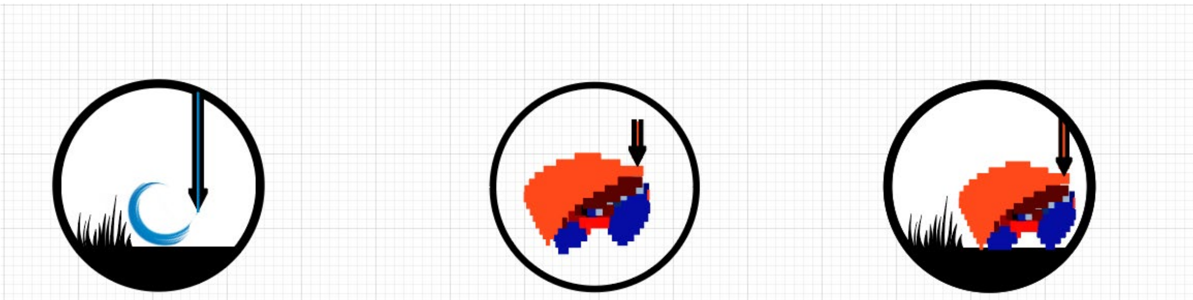


Figure 5 Second drafts of logo

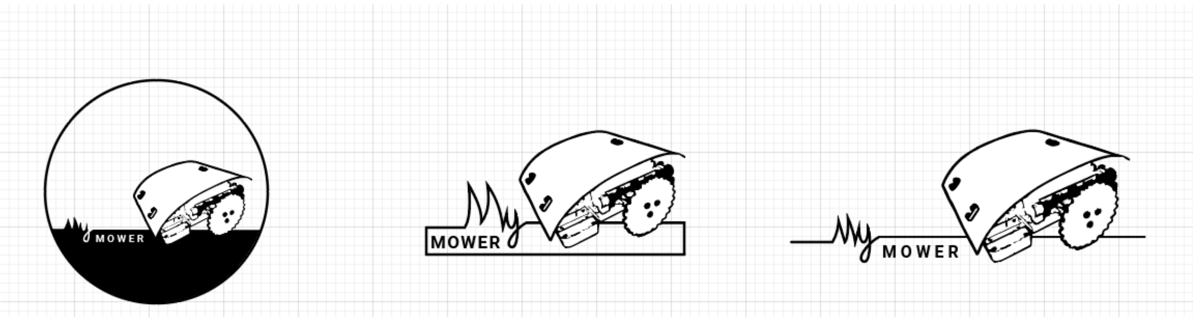


Figure 6 Final drafts of logo

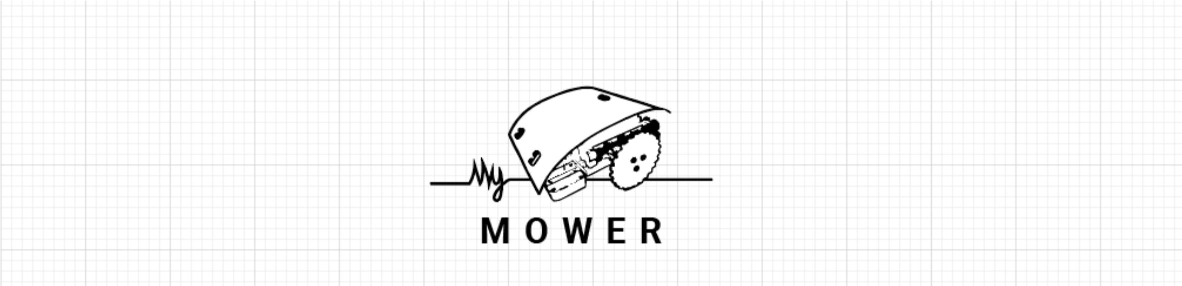


Figure 7 Final logo

1.2.3 Business card

Our double-sided business card enforces on basic information like team names, contact information, and logo. As 3d printing team, we decided to also print a tactile version, which however not will be handed out as our business card but function for illustrative purposes.

Figure 8 Business cards

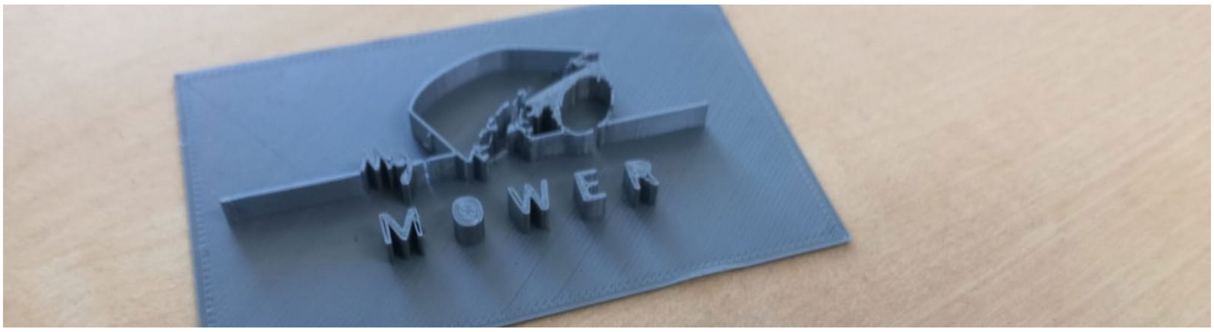


Figure 9 3d print design

1.2.4 Website

The website was built in the source code editor „Visual Studio Code “by using HTML (Hypertext Markup Language), CSS (Cascading Style Sheets) and JS (JavaScript; a high-level, interpreted programming language) – which are the three core technologies of the World Wide Web. Each of them serves different purposes. While HTML creates the semantic structure of the website and defines content and flow, CSS is a powerful tool for styling the existing HTML code and doesn’t contain any content itself. Unlike the other two JS is not a declarative language but a programming language, which is used for interactions on a website like pop-up windows or client-side validation of form elements.

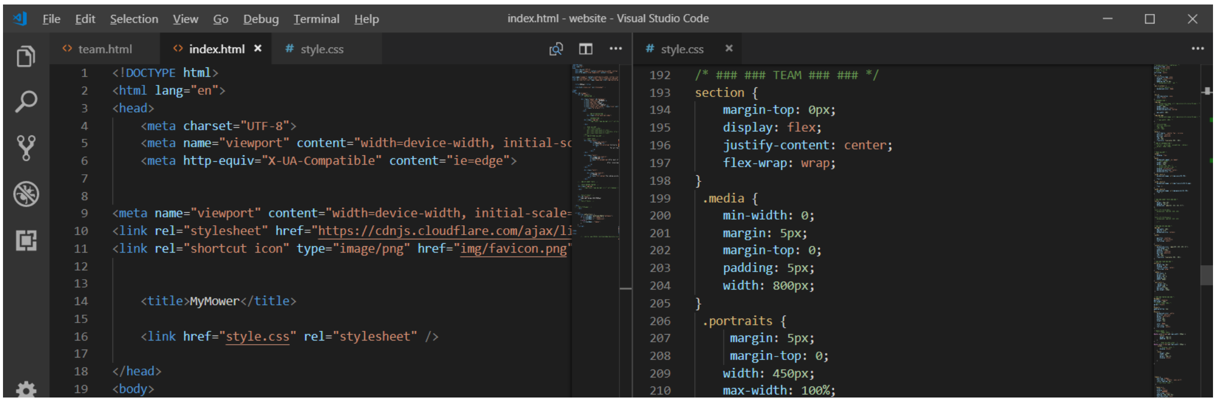


Figure 10 Visual Studio Code

Figure 11 Early version of website

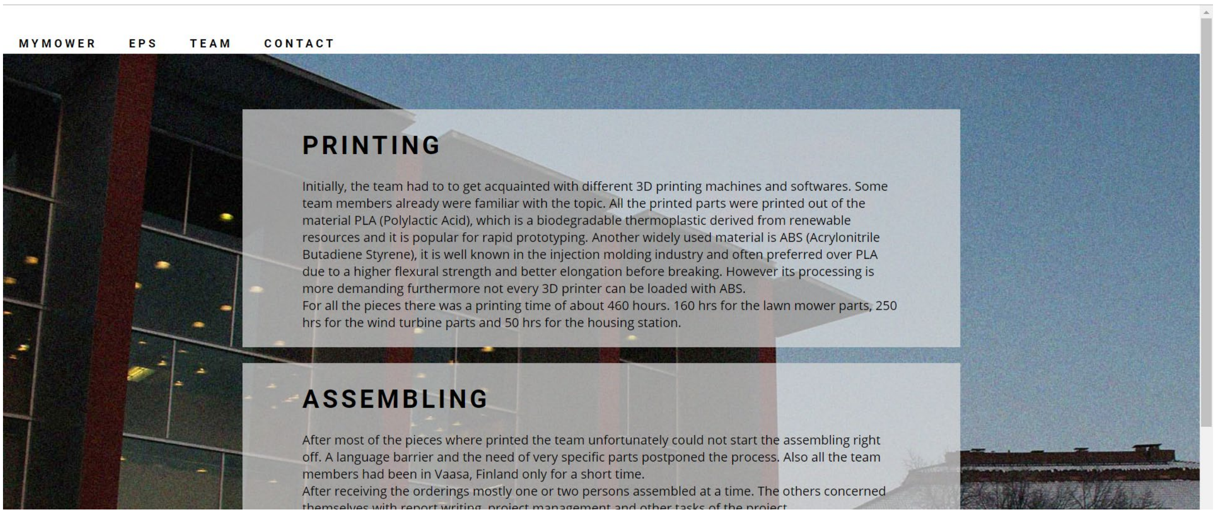


Figure 12 Final version of website

1.3 Team

In this subparagraph the team members will be introduced, each will tell what they study and where. The team members will also tell about their strong points and what they hope to achieve by doing the EPS and by doing this project.

1.3.1 Arno Blekkenhorst (Netherland)

Mechanical engineering student at Saxion in Enschede. Good knowledge on material properties, lightweight engineering, mechanical constructions, 3D printing, sheet metal structures, 3D designing and 2D drawing. With this project I hope to put my 3D printing knowledge and designing skills to the test and learn more about working in a team with international students to develop my communication and English language skills furthermore.

1.3.2 Frederic Bouley (France)

Industrial processing and mechanical engineering at National engineering school of Tarbes, France.

I got strong knowledge on mechanics (fluid, solid), basic programming skills, electrical engineering and knowledges about project management. The mower project will enhance my knowledges on manufacturing, Arduino programming and one of the most important, my English communication skills.

I expect this project to be a first view of working with foreign people in English. I think this will be profitable in my career.

1.3.3 Bart Klaster (Netherland)

Student Advanced Sensor Applications at the Hanze Hogeschool for Applied Sciences Groningen, Netherlands.

The study is a complete international study that focusses on the creation, collection and processing of data in large and small processes. During the course of the study I work in a lot of projects all of which have the final goal of solving a problem with a proof of concept solution. The skills I obtained along the way consist of electrical engineering, problem solving, control systems, programming, project planning, CAD design and multicultural team work.

During the European project semester my goal is to improve my practical problem-solving skills and to complete projects outside of my comfort zone where I know what is reasonable, where parts can be obtained and what tools are available. Therefor the lawnmower project feels like a perfect fit. There is little budget so thinking outside of the box is required, the tools needed for the job are incomplete thus solutions must be found and the parts that are required are not obtainable by known channels.

I hope that these challenges give me the opportunity to grow as an engineer for my future career.

1.3.4 Laura Kohl (Germany)

Media Production and Media Technology at Technical University of Applied Sciences Amberg, Germany

Due to the major which covers a wide range of various subjects, experienced in animating, web and print designing, but also got basic knowledge in programming and electrical engineering. I always wanted to intensify more on technical practices, therefore the lawn mower project seemed as the perfect choice, while working with 3d printers, doing Arduino programming and learning about electronics and motors. Aside from the project I want to learn successful communication within an international team and I hope to develop myself as a person.

1.4 European project semester

The European project semester is a project-based learning solution offered by 18 universities in 12 nations of the European union. [1] The project can be part of a minor or internship for engineering, business and product design students from all over the world. During the project students are placed in groups consisting of students from different backgrounds, studies and nationalities and then having to work together to solve real life problems together with industrial partners and research institutes. EPS is offered to students to students who have at least completed 2 years of study. Mostly for students with engineering background it can be proposed to other students as well. The project must last 15 weeks of work minimum. The project work consists of the project itself worth at least 20 ECTS and 5 to 10 accompanying subjects that focus of team work, project management, teambuilding, academic writing, all knowledges to complete the project itself.

In the beginning of the semester, all available projects are presented to the students. Later, they must sort project by preferences. Thus, they are divided into teams for the different projects. Most of the teams are a good mix of nationalities and competences. The working language is the English

The EPS concept came out in 1995 in Denmark, NOVIA UAS joined the program in 2010 and since the beginning 183 students came from 24 different nationalities. At Novia UAS projects are usually in the fields of renewable energy and robotics but other topics can occur. Many of the projects in EPS are made up out of multiple different kinds of engineering this way the students learn more about how their peers work in a real company and get some basic understanding about different kinds of engineering, their workflow and their bottlenecks.

1.5 Project management

1.5.1 Belbin questionnaire

The Belbin questionnaire is a test based on questions with multiple choices, there is 10 points to divide between each. It is made to find what are your pros and cons by matching with the 8 'Team Roles' [2]:

- **Resource investigator**: Investigate to provide useful information to the team.
- **Team worker**: Create cohesion inside the team, avoid frictions can be undecisive.
- **Coordinator**: Delegate the work all over the team, can be seen manipulative.
- **Plant**: Always ready to solve problems in their proper way.
- **Monitor**: Provide logic to the group, he can be too much critical and long to take decisions.
- **Implementer**: His goal is to be efficient and stick to the plan.
- **Finisher**: Wants to make it on time and with the highest quality.
- **Shaper**: Keeps the team going forward, he can be felt rude by this way.

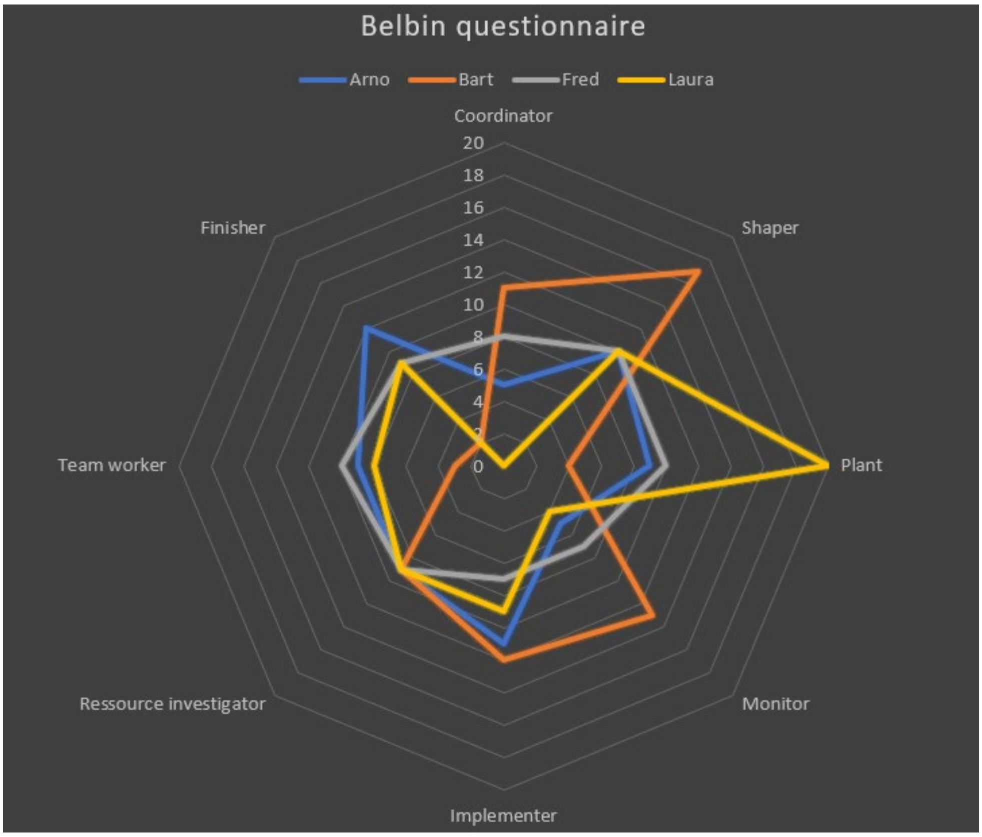


Figure 13 Belbin questionaire results team

The team did the test and the results are summarized above. It show that most of the members are specialised in one or two roles however with whole team combined all posts are fulfilled. With all thoses points on 'Team worker' members should be able to work together. Also, with a 'Shaper' the team may not loose momentum and with a good "Plant" the group should be able to overcome the issues.

1.5.2 Mission and vision statement

Nowadays with all the progress about 3D printing and sustainable energy and the need of automation is our everyday life to save time. Therefore, our mission is to build an autonomous lawn mower connected to static windmill both with mostly 3D printed parts.

Our vision of the project is a lawn mower which can cut grass autonomously inside a restricted area, powered by a static windmill with a docking station and each mostly with 3D printed parts.

1.5.3 Objectives

The objectives of the project are going to be presented through the **SMART** model:

Specific: Have an autonomous 3D printed lawn mower that can sustain with solar panels and a 3D printed static windmill through a charging dock.

Measurable: The mower should be able to cut 200m² in one cycle and cover 500m².

Attainable: The lawn mower and windmill have been made already so this project is about making a charging station and integrate the power solution to the mower system.

Realistic: The current state of 3D printing, electronics and sustainable energy make this project realistic.

Time limited: This project must be completed before December the 17st.

1.5.4 Milestones

In a project a milestone is an achievement, milestones represent steps that are needed to complete the project. Here is the timeline with the milestones for the project.

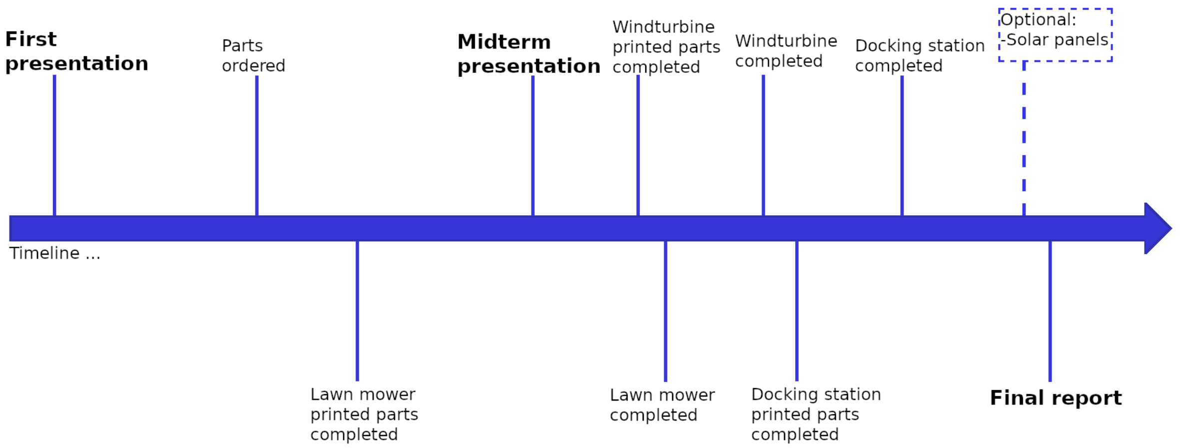


Figure 14 Milestones

At the beginning an inventory was created to visualize what was needed to order and what to print. In this project, the 3D printing time take at least 340h if everything works well and it is often not the case. Therefore, the milestones involving printing are spread out in the timeline. The lawn mower and the wind turbine can be made independently so milestones are close to each other. After completing those, the team is going to focus resources on the docking station, first the design and manufacturing and then testing with the lawn mower and the wind turbine. An optional milestone has been added, if the group find the time to implement it there will be solar panels on the lawn mower.

1.5.5 WBS

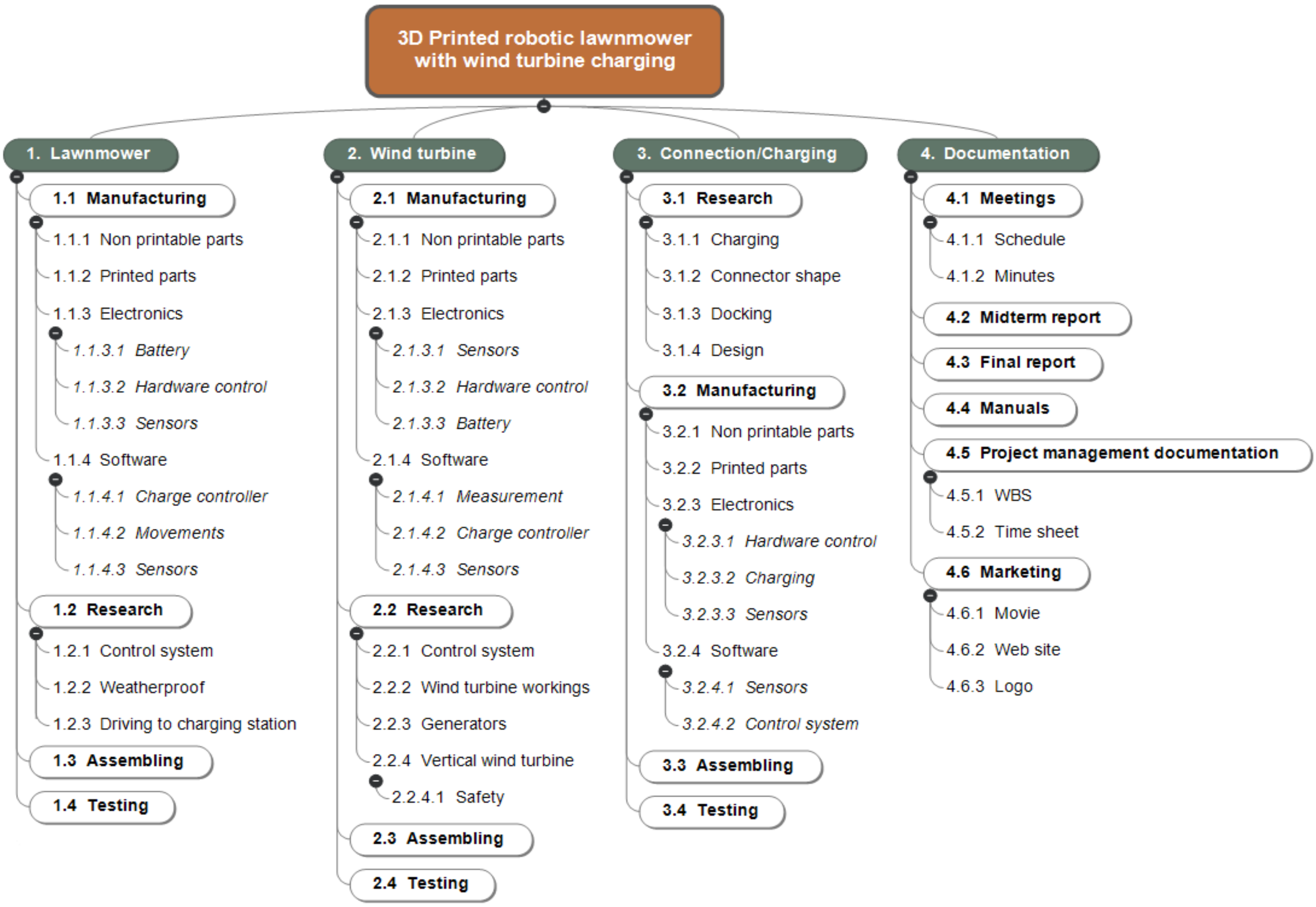


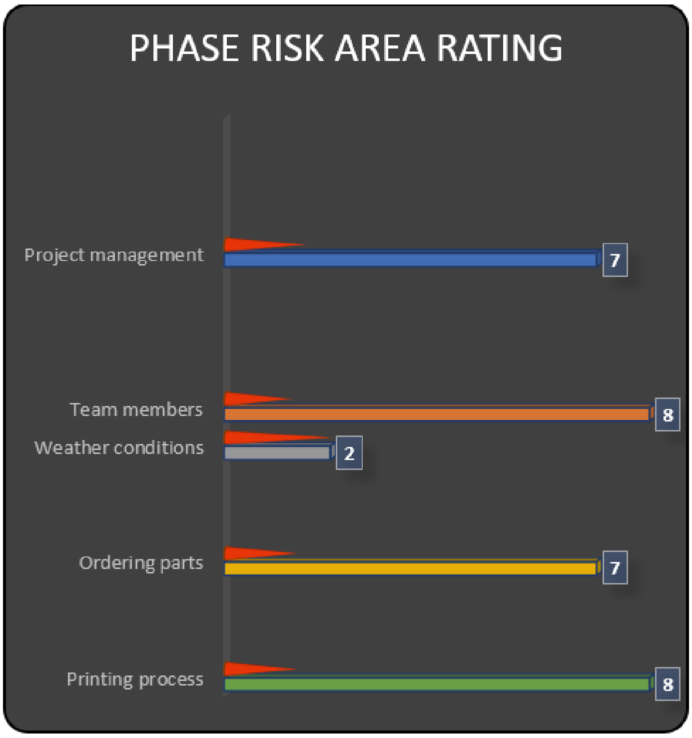
Figure 15 Work break down structure

Creating a WBS is the process of subdividing project deliverables into smaller and more manageable components in a tree structure. This defines the scope of the project and milestones, it can be easily used to create schedule or Gantt chart. To create a WBS some inputs are required and by this way the scope, deliverable and subprojects must be defined before going deeper. The WBS follows the 100% rule, it means that 100% of the work must be in, the sum of the work at the "child" level must represent 100% of the work represented by the "parent" [3].

The four main sections are: Lawnmower, Wind turbine, Connection/Charging and Documentation. Most of the lawnmower is 3D printed and the STL files are finished, for the electronics and the software all the plans and code are also finished. But to implement the charging station some research is required to drive to the charging station and how to control the mower. Almost the same goes for the wind turbine part, in this case research need to be made about the working of a wind turbine and some redesign of the blades are needed. The third part is involving the docking station and its connection to the lawnmower and the wind turbine. For this nothing is given, therefore, the team need to design it. Most of it is going to be 3D printed and some electronics are needed. Moreover, there is a need to order parts that is why in each part there is a section about "non-printable parts". The last section is all about documentation in summary, it is a project management section and some marketing products.

1.5.6 Risk areas

For the project, the team can face many issues in different phases.



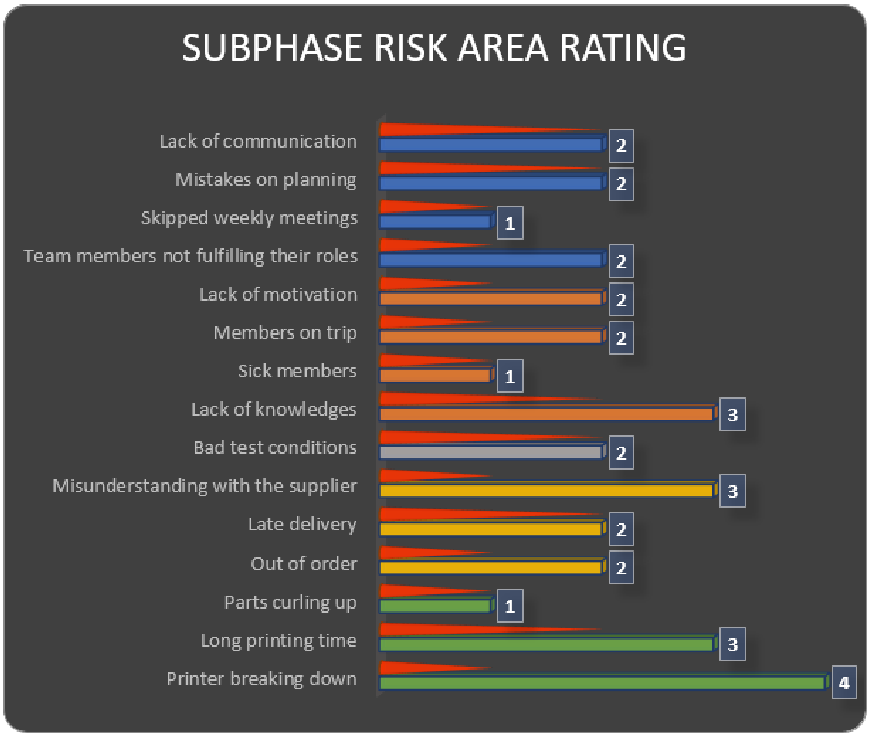


Figure 16 Risk areas

The risk areas of the project are divided in 5 phases divided in different sub phases. This is made from the opinions of the team members. The numbers represent the impact of each phase/sub phase and the red cones represents the probability. This way the team can truly understand the impact of each risk and its probability to complete the project in good conditions.

The phase with the highest chance to happened is the weather conditions because the team is working on a lawn mower in Finland during fall/winter season, the snow or the ice can disturb some testing in the grass. However, this has a low impact on the project, where all the project management, team members and the printing process have a high impact on this project but a low probability of happening.

1.5.7 Budget

The estimated cost of the project begins with all ordered parts. To track this the team has made an inventory list of the parts that were needed to be ordered and the costs. The costs of the parts ordered is close to 480euros without transportation fees.

The costs of the project should also consider the work of the team members. The average salary of an engineer in Finland is 37,000 euros [4] for a cost of 55,000 for the company each year the average hours of work for a week is close to 37,5 a week the same as requested for the EPS. The average working days is 253 per years. This means that with 7:30h in average per day and a cost of 217 euros per day a working hour has a cost of 29 euros for a company. As the project should last 14 weeks with 37,5 hours a week and four team members the estimated labour cost is 60,900 euros if team members were engineers in a company.

In addition to all these costs, the cost of electricity, PLA and depreciation of the 3D printer used should be taken into consideration.

The total weight of the printed parts for the mower is 1,643kg and 3,04kg for the turbine in total this is 4,683 kg PLA we are using. With an average price of €0,0461/gram that is a cost of 216€ for the printing material. This is without the parts for the docking station [5].

The total printing time is about 340 hours, the standard power of a 3D printer is 200W and the Finnish electricity costs are about 0,0655€/kWh. The cost of electricity is then 4,45€ for the project.

The depreciation of the 3D-Printers used is calculated on a standard 1000€ annual depreciation divided by 252 working days. The depreciation is then 3,36€ per days, with 7:30 hours of work per day, the cost of one hour is then 0,448€. With 340 hours of printing this leads to 152€ for the cost of depreciation of 3D-Printers.

1.5.8 Gantt chart

Bar chart or Gantt chart are named because of Henry Gantt developed a complete notational system for showing progress with bar charts. [6] They are simple to construct and to read, it remains the best communication tool for the team members to understand what they need to do within given time frames. Often based on the inputs of the WBS, these charts are composed of bars representing activities, it shows the beginning and the end each task. For large projects, understanding the planning can be hard it is sometime better to show a summary of the Gantt chart. As this project has many tasks the entire Gantt chart is not going to be presented here but only a summary.

Name	Begin date	End date
MyMower	03/09/18	17/12/18
Lawn Mower	04/09/18	16/11/18
Manufacturing	04/09/18	09/11/18
Research	20/09/18	08/10/18
Assembling	18/10/18	07/11/18
Testing	31/10/18	16/11/18
Wind turbine	03/09/18	15/11/18
Research	03/09/18	30/10/18
Manufacturing	03/09/18	06/11/18
Testing	12/11/18	15/11/18
Assembling	01/11/18	14/11/18
Docking station	03/09/18	30/11/18
Manufacturing	03/09/18	14/11/18
Research	02/10/18	06/11/18
Assembling	20/11/18	26/11/18
Testing	26/11/18	30/11/18
Documentation	03/09/18	17/12/18
Meetings	03/09/18	17/12/18
Midterm report	03/09/18	23/10/18
Final report	24/10/18	17/12/18
Manuals	03/09/18	17/12/18
Project management documentation	03/09/18	17/12/18
Marketing	08/10/18	17/12/18

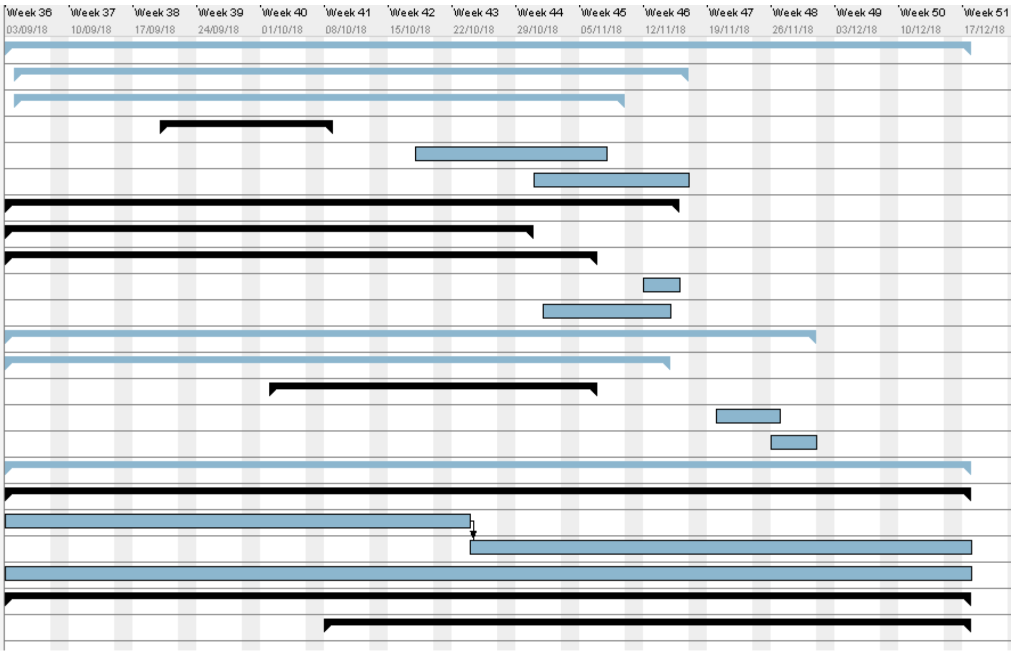


Figure 17 Grand chart of project

1.5.9 Quality management

To make sure that the quality of the project was secured the project group had meetings two times a week. During these meetings the progress of the last two days was discussed, the quality of the printed parts, code and report was checked by the team members. When an item was deemed completed by the group and was of the quality described in the manual for both the windmill and the lawnmower the item would be accepted in a sub-assembly or the report. To recheck the partly-bias views of the team people outside of the team were also asked to comment on the work performed by the team. These people consisted mostly of the project tutor, the staff manning the 3D printing lab and working on the 3D printing robot arm and students who were also present in the working room.

When an item was checked by both the project tutor, the team and one outside evaluator the item would be checked of the list in both the Gantt chart and the WBS.

During the creation of new components, parts and structures outside of the given manuals requirement tables were created. These tables made sure that the functional requirements of the parts were described at a high level and gave test requirements for the final acceptance tests of the newly designed part of the project.

When a part was finished that was not part of the original manuals a reflection was always written about the new parts. In this reflection the test results were discussed and checked of the part was up-to specifications. When this was not the case recommendations for version two would be written out and the old design would be used to create solid base for the new design.

2 Research

2.1 Autonomous lawnmower

An autonomous lawnmower or also called robotic lawnmower is a machine that can cut grass without the help of a human. These autonomous lawnmowers have been around for a good twenty years now and there are mowers available that can cut up to 5000 m^2 of wet grass with slopes of 45° depending on price. In this paragraph different type of autonomous lawnmowers will be featured showing the performance that comes with the different price classes.

2.1.1 Existing lawnmowers

0 - 750 €

Only a few models are available in this price range but getting a lawnmower in this price range means sacrificing a lot in comparison to the more expensive models. Most models in this price range have a cutting time of 60 to 90 minutes and take about 6 hours to charge the lithium-ion batteries. The lawnmowers in this range also have an average coverage area of about 600 m^2 and can cut slopes of about 20°. Lawnmower's weight is about 7 to 10 kg and make about 60 dB(A) of noise, which is about the same as a normal conversation. The average width or the cutting disk is about 15 cm and most carry 3 knives on the disk. [7]

750-2000 €

When looking into the more expensive budget of lawnmowers the immediately noticeable difference is the amount of extra ground the lawnmowers can cover. In this range the area coverage goes up to about 1500 m^2 for the 1000-euro models. The next noticeable thing is the increased slope of 40° the lawnmowers can handle and the wider cutting disk of about 25 cm with 4 cutting knives. The lawnmowers also lost a lot weight and are about 2 kg in this price class. Most lawnmowers in this price class also have a WIFI and Bluetooth connection on it and an app to control your lawnmower [8]

+2000 €

Lawnmowers in this price class can go up to almost 4500 euros which is a lawnmower with 4-wheel drive that does not need any installation at all. But most of the lawnmowers are around 2500 euros and those can cut around 3000 m^2 of grass and cut on 50° slopes but are a bit heavier than the middle-class lawnmowers with a weight of around 5kg. Most of the lawnmowers in this price class also have a smart AI with smartphone app with them so the cutting settings and times can be adjusted to the customers preference. [9]

2.1.2 Docking station

What is common in all docking stations across all price platforms is that it is the place where all the communication happens to the lawnmower since it is the place where the wires lead to. For the most lawnmowers the boundary wire is the way home to the docking station, and there can even be some guiding wires to guide the lawnmower home from difficult to get places or to send the lawnmower to the difficult to get places. These days the modern lawnmowers do not have a roof over the docking station because the lawnmowers are made of good grade plastic that is weather resistant but when robotic lawnmowers where new and not protected against rain they could find shelter at the docking station. The charging happens in most cases through 2 point that connect when the lawnmower is in the docking station.

2.2 Wind turbines

A wind turbine is a machine that converts the kinetic energy of the wind into electrical energy. This happens when the wind hits the rotors which will make the hub spin on the gearbox. The hub is connected to the generator generating electric energy, though there are turbines without a direct drive to the generator, but these are generally costlier or less efficient. Turbines are available in 2 types, the vertical turbine and the horizontal turbine. In this paragraph the two types of turbines will be explained where they are generally used and their advantages and disadvantages [10].

2.2.1 Vertical Turbine

The vertical wind turbine gets its name from the fact that the axis on which the generator is attached stands vertical. The wind can hit a vertical wind turbine from every angle to power it, so the turbine does not need a rotation system to adjust to the wind direction. This means that vertical wind turbines can be placed more closely to each other than horizontal wind turbines. A vertical wind turbine can start up with less power from the wind, but it is also more stable at high wind speeds. Some more technical advantages of a vertical wind turbine are that they can be built close on the ground and only have one moving part, which makes it robust and easy to maintain. In comparison to the horizontal wind turbine, the vertical one generates less energy, especially the turbine with straight rotors seen in Figure 19. Another disadvantage is that on the ground, where a vertical wind turbine normally is placed, the wind speeds are generally the lowest. The old designs of the vertical wind turbine used to suffer a lot from vibrations and a pulsing torque on the axis which would shorten the life expectancy of the turbine drastically, the new designs however use helical rotors (Figure 20) or scoops (Figure 18) to lessen the vibrations and pulsing torque.

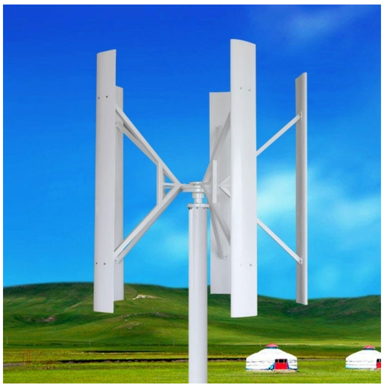


Figure 19 Vertical widnmill design

Figure 20: Helical Darrieus turbine

Figure 18 Vertical windmill design

2.2.2 Horizontal turbine

The horizontal wind turbine gets its name from the fact that the generating axis lies horizontal in it. There have been many different versions of it but the most popular one is the three-rotor turbine because it has the best efficiency to cost ratio. This is the best because the efficiency of the turbine jumps from 38% to 45% going from the two rotors to three rotors and the efficiency of a four-rotor turbine is 47%. This means that adding an extra blade will increase the cost of the rotors by 33% and results in only 2% increase. The three-rotor turbine are also a favourite because it creates a better load on the hub. To get a higher efficiency than a vertical wind turbine, the modern horizontal turbine (figure 21) has rotors that can turn on the hub to get a better angle in the wind and to make it go faster, slower, or stop the turbine in a storm. But to get a higher efficiency than a vertical turbine a horizontal turbine must be placed higher in the air which makes maintenance harder. Furthermore, a horizontal turbine takes up a lot more space than a vertical turbine because a horizontal one must turn around the vertical axis to get the best wind angle.

Figure 21: 3-rotor horizontal wind turbine

2.2.3 Power generation with a wind turbine

The aim of a wind turbine is to convert kinetic energy of the air into electric energy. The kinetic energy is first converted in a spinning motion on a rotor with oppositely charged magnets surrounded by coils. Thus, an electromagnetic induction is created, and this generate electricity between two oppositely charged magnets. The magnitude of the voltage inducted depends directly on the speed of the rotor and the number of the coils turns. To produce higher voltage magnets can be connected in series. Furthermore, to increase the power output this circuit can be replicated in parallel. The voltage output created is AC, to charge a battery, it is needed to convert it to DC voltage this can be done by a rectifier.

2.3 Guiding systems

Almost every fabricant of a good selling autonomous lawnmower uses a wire system that sends out a frequency that the lawnmower can pick up with the sensors mounted on it. This is a basic system that has been around for quite some time now and is very reliable to keep the lawnmower in its boundaries. The wire needs a one-time installation on or in the ground which is mostly done with some herrings, the ends of the wire mostly come together at the charging dock which is also the point of return for the lawnmower. To return to the docking station the lawnmower will find the boundary wire and follow it back to the docking station for a general 60 to 90 minutes charge. Guide wires are sometimes needed as well to make it easier for the lawnmower to find its way back to the station or to get the lawnmower to the most difficult places. Some modern docking stations are also sending out a radio signal to the lawnmower to communicate with it.

Some robotic lawnmower producers also have a system to let the lawnmower know if it is cutting grass or if it is cutting nothing. This can be done by sensors that can differ cut from uncut by an electric signal, here the cut grass will produce a higher signal because it is more damp than uncut grass. Another technique used is to measure the resistance on the cutting motor, because when the motor is not cutting grass there will be less resistance on the motor. Some more expensive lawnmowers also use a GPS signal to decide the location where the lawnmower is and has been. Though most lawnmowers still make a random pattern because all the grass will be cut eventually, and the lawnmowers can be made simpler and cheaper without the tracking systems. What almost every lawnmower does have is a bump detector to recognise if the lawnmower runs into something unknown, for example a person or a chair, and then the lawnmower can turn around to find another path to mow. The bump detector is in most cases the front of the chassis that can be pushed back into a switch that, when pressed, will turn the lawnmower around like it is hitting a boundary wire.

2.4 Solar panels

Figure 22: Solar panels mounted on a flat roof

Solar panels absorb sunlight to generate electricity through the photovoltaic effect. It is composed of photovoltaic cells made of wafer-based crystalline silicon cells or of thin-film cells, but the basics of solar panels are made of p-n junctions. Each module is rated by its DC output and the power produced, one module ranges from 100W to 350W. Due to limitations on DC output, modules can be connected in series or parallel to provide the desired current capability. Solar panels are often connected with battery pack, inverter to convert DC current to AC or solar tracking systems to increase sun exposure [11].

2.4.1 Equivalent circuit of solar cells

The equivalent circuit is a current source parallel with a diode, a shunt resistance and a series resistance. By using the Kirchhoff law, the current produced by the cell can be determined $I = I_L - I_D - I_{SH}$
The voltage output can be also determined using Kirchhoff law $V = IR_S - I_{SH}R_{SH}$

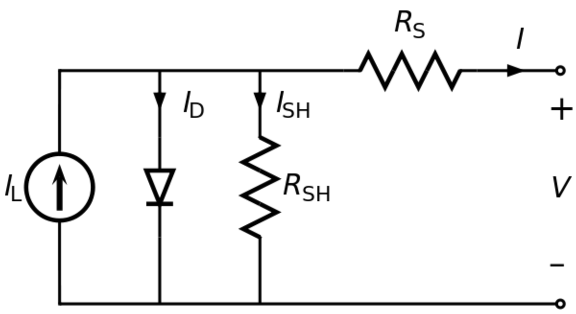


Figure 23: Equivalent circuit of solar cells

The current through the diode is given by the Shockley diode equation $I_D = I_0\left(e^{\frac{V_J}{nV_T}} - 1\right)$ with V_J the voltage through the shunt resistance $V_T \approx 0{,}0259\,V$ at 25°C and n the diode ideal factor(1 for an ideal diode)

Those equations lead to the characteristic equation of solar cell:

$$I = I_L - I_0\left(e^{\frac{V_J}{nV_T}} - 1\right) - \frac{IR_S + V}{R_{SH}}$$

2.4.2 P-n junctions

A p-n junction is an interface between two semi-conductors materials, a p-type(positive) with a lack of electrons and a n-type(negative) with an excess of electrons this allow current to pass in only one direction. By stimulating the n-type with a photon which is the case for solar panels, the electrons in the n-type go in an upper state of energy and by this way the electron migrate to the p-type, this create an electric field which can be used to create a current. Thus p-n junctions quality has a major role in solar cells efficiency.

2.4.3 Efficiency

Solar panels efficiency is mainly related to his cells efficiency if sun exposure and stacking the cells are not taken into consideration. The scale efficiency of solar panels available in commerce is up to 24% right now but studies tends to rise it. Solar cells efficiency is ratio of how much energy is harvested with how much the sun send to the surface. In a sunny day at the zenith with an orientation of the panel perpendicular to the light, a panel can receive 1kW/m² by this way, a 15% efficient solar panel with a size of 1m² produce 150W. Many factors affect solar cells efficiency such as reflectance efficiency, thermodynamics efficiency, charge carrier separation efficiency (p-n junctions) and conduction efficiency. [12]

2.4.3.1 Reflectance efficiency

The reflectance of a material is his ability to send back the energy received through radiations. The reflectance efficiency can be measured with a quotient: $R = \frac{\Phi_r}{\Phi_i}$ with Φr the radiant flux reflected and Φi the radiant flux received. The smallest this quotient is the highest the efficiency of the cell is going to be.

2.4.3.2 Thermodynamic efficiency

Given by the Carnot heat engine formula, the maximum efficiency produced with a source of heat temperature Ts and cooler heat sink temperature Tc is $\eta = \frac{1-Tc}{Tf}$ By this way Alexis de Vos and Herman Pauwels showed that efficiency up to 95% could be achieved with an infinite stack of cells. However, this is not achievable cause this case is not considering that the stack is going to emit radiation because it has a non-zero temperature and it should be considered that the sun only emits in a little part of the sky. With all these considerations the maximum thermodynamic efficiency drops to 68.7%

To achieve the maximum efficiency on a solar panel the maximum power point P_m must be found. This can be made by increasing the resistive load to a very high value on the cell when it is illuminated. This point is reached when the product $V \times I$ is at his highest value. On large enough solar installations, a maximum power point tracker can be used, it measures constantly the current and the voltage and it adjust the resistive load to keep the solar panel as close as possible of the maximum power point.

With the maximum power point value, the fill factor (FF) can be calculated with the formula:

$FF = \frac{P_m}{V_{OC} \times I_{SC}}$ With V_{OC} the open circuit current (I=0) and I_{SC} the short circuit current (V=0).

This factor is a measure of the quality of the solar cell and trying to maximize it equate to taking the solar cell close to his theoretical maximum. It can be made by decreasing the value of the series resistance and increasing the value of the shunt resistance. Typical fill factors range from 50% to 82%.

2.4.4 Maintenance and recycling

Solar panels can face climatic hazard, which may result in a huge drop of efficiency. Threats like dust, pollen and everything that can accumulate on the solar panel can reduce efficiency up to 30% [13]. The rain cleans it in most of the case in rainy region, to take benefits of it, panels should be tilted for more than 5 degrees. In the case of small systems, it has been proved that it is not worth it to clean solar panels.

Recycling solar panels is a challenge. Most of it can be recycled, up to 80% in weight. But the fact is solar panels contains precious and scarce metals that are worth it. Issues on how properly treat solar panels recycling have only raised recently but regulations tend to force private organizations to do researches about it. However, investments are not valuable due to the small amount of waste right now, but considering the average life-time, 27 years it is going to raise a lot in the next decades.

2.5 Electric battery

For the project, Li-Po battery is used the reference used is Multistar High Capacity 5200mAh 3S 12C Multi-Rotor LiPo Pack. Though this section, the basics about batteries and the characteristics about the one used are explained.

2.5.1 Battery theory

2.5.1.1 Principle

The principle of a battery is converting chemical energy to electric energy. It is made of two half cells, each composed of an electrode, a negative one and a positive one bathing in a conducting solution called electrolyte. It is always detached but the separator allows ions to flow between each half cells. The chemical principal involved is redox reactions, a reduction for the cathode and an oxidation for the anode during charging. This is inverted during discharge. Thus, a power output is generated, it can be calculated with the electromotive force (EMF) of each electrode. The power output is $\Delta V = \varepsilon_2 - \varepsilon_1$ with ε_1 and ε_2 the EMF of each electrode. [14]

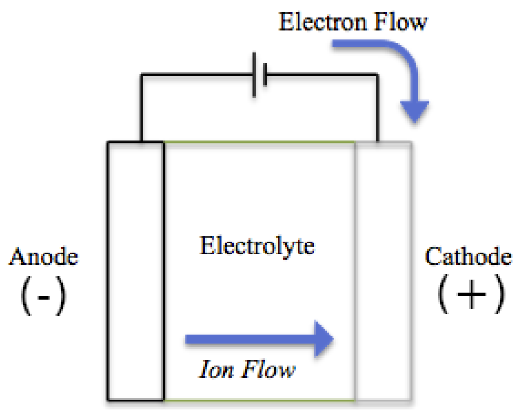


Figure 24: Schematic of a battery during discharge

There are two types of batteries using this principle: primary battery and secondary. The difference between them is that the primary one is not able to be charge, the chemical reaction cannot be reverted because of the consumption of active materials. The secondary can be reverted but not indefinitely because of the dissipation of active materials and the internal corrosion.

2.5.1.2 Characteristics of a battery

The characteristics of the battery are, the voltage output in volts, the current output at the rated voltage in amps, the C-rate and the capacity in amp-hour (Ah). The capacity is the current that the battery can deliver for 20 hours multiplied by 20. For example, in the project the capacity is 5200mAh which means that it can deliver 260mA for 20hours. For the project this is not useful because the battery will not be used 20 hours without charging and because in the working time, the mower will require more current. A characteristic which is useful in this project is the C-rate.

The C-rate is a measure of the rate at which the battery can discharge relative to its maximum capacity. The battery in the mower with a capacity of 5,2Ah and a C-rate of 12C, voltage output of 11,1V the battery can discharge in 5 mins with a current output of 62,4 A for a peak discharge. But for a charge at 10,4 A it will take 0,5 hours to charge the battery. All of these can be calculated with two formulas: $I = Cr \times Er$ and $t = \frac{Er}{I}$ with Er the capacity of the battery in Ah, Cr the C-rate, I (A) the current of charge/discharge and t the time of charge/discharge in hours.

Another thing about batteries is the self-discharge. Every battery not actively being used will lose power for a normal battery it with lose 5% to 20% of its power per year at room temperature the reason for this is because the reaction will still occur because of the internal load.

The last thing to explain about batteries is the S and P, the S state for series and P for parallel. In this project the battery used is a 3S1P which means there is 3 battery cells in series and not in parallel. So, each battery cell has a voltage output of 3,7V but the battery pack has in total 11,1V for the voltage output.

2.5.2 Lithium polymer battery

Figure 25: The LiPo battery used in the mower

For the project the Lithium polymer battery often called Li-Po battery is used to power the mower and it will be charged at the docking station. These batteries are used in application where the weight is a critical aspect and Li-Po batteries provide a higher specific energy than other lithium-based batteries. [15]

The Li-Po battery is a battery with an electrolyte composed of a solid polymer electrolyte (SPE), electrodes are composed of 3 parts of metal, polymer and lithium and the separator may also be composed of polymer.

Due to its lightweight and high-power density the Li-Po battery is mainly used in radio-controlled aircraft/cars, drones or helicopters. The C rate can reach 95C in continuous discharge and 120C on short time burst. The power it can reach and the low weight the prices justify the price.

Following all these pros the Li-Po battery has some safety problems. Overcharge, over discharge overtemperature, pressure on the battery may results in failure such as lowering drastically the lifetime of the battery, electrolyte leaking or even worst, fire.

3 Theory

3.1 Additive manufacturing

Additive manufacturing is a way of creating items by adding material as opposed to other methods that remove material from a block of material and carve out the object. 3D (three dimensional) printing in one of the most well know systems out there for the public and it is the focus area of the project. When creating an object with 3D printing the original design that is created on a computer with 3D modelling software like Autodesk Inventor or Solidworks is exported to another piece of software called a slicer. The slicer takes the model of the object analyses it and adds supportive material where necessary. When the support material is added the slicer proceeds to slice the object in layers with a thickness that is appropriate for the printer that is being used for the project. When all slices are created the slicer creates a tool path in G-code, a language created in the 50's to make a standardized method of talking to machines from computers and saves the G-code to a file. This file is then send to the 3D printer either over USB, ethernet or with removable media like an SD card or USB stick. With the instructions the 3D printer starts running a program. The start of the program generally consists of "*homing*", finding the end points of the machine, and calibration of the machine, finding out where the printer head is in relation to the print bed and levelling both to each other. With these steps completed the machine proceeds to print the object in layers. There are multiple methods of how this is done, and some materials have different methods corresponding to different printer designs.

3.1.1 Stereolithography (SLA)

Stereolithography or SLA in short is the oldest way of 3D printing with the first research in this way of additive manufacturing being conducted in the 1970. In the early 1980 Chuck Hill named it this way when applying for a patented. Since then the system is used extensively in the medical industry. The system prints with polymer resin.

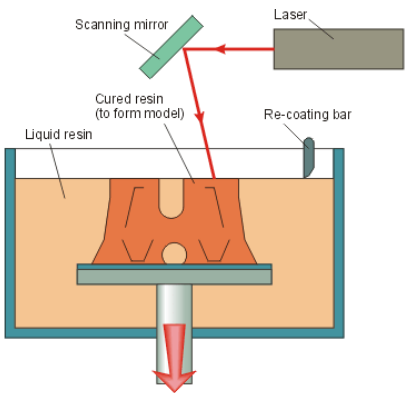


Figure 26: Stereolithograpy printing (source:https://uni.edu/~rao/rt/major_tech.htm)

This way of printing can be very accurate as the layer of the resin can be carefully controlled by the movement if the z-axis and the recoating bar. Also, be having the laser or in some cases even a project tracing or projecting the layers and them having a very small focal point high resolution prints are obtainable.

The system works with ultraviolet light that is being projected in a vessel filled with a polymer resin. When the polymer resin is exposed to the ultraviolet light is hardens the layer between the top of the vessel and the build plate or 3d printed item below. With the layer hardened the z-axis is dropped and the polymer liquid will fill the cavity left behind with the help of a re-coating bar. After this a new image is projected with the new layer. This process is repeated until the desired object is complete.

3.1.2 Fused deposition modelling (FDM)

Fused deposition modelling or FDM for short is one of the most well-known and widely used types of 3D printing. The technology was developed by a company called STRATSYS LTD in the 1980's. Other companies like MAKERBOT or ULTIMAKER use the same technique and changed the name when they started producing these printers and called the technique Fused Filament Fabrication (FFF).

FDM is so widely used and know because of the advantages this system provides. The FDM technique can be used to print materials like concrete, plastics, nylon, Kevlar, food like items such as sushi and pancakes, flexible materials and soft metals. Because the filament can be basically anything the system can be used to create concepts, prototypes or even production models of parts and objects. With the advantage of having the large amounts of materials that can be printed with this system is widely used by hobbyist as the cheapest possible materials for printing start at less than 10 euros for a kilogram.

Due to their popularity FDM printers are also cheap. Reasonable hobbyist printers start at 300 euros, with at the time of writing the cheapest with a clear upgrade path being 130 euros. The higher performance models that could be counted as semi-professional range from 600 to 1500 euros. Professional models start at 1500 euros and continue up to millions however these machines may have features to make them either good enough for professional prototypes in the car and aerospace industry or features that make them useful for full scale production of parts and products.

Figure 27: FDM printer printing a house (source: Apis cor)

Some companies and research centres, one of them being the Technobothnia centre in Vaasa (FI), also experiment with robotic arms with FDM printing attachments as claws. This makes it possible to create more intricate shapes and depending on the size of the arm even houses can be printed as can be seen in Figure 27.

FDM printing works on the concept of having a printing head that gets to a desired temperature to partially melt the filament. With the correct temperature the filament will then either by direct drive (filament driver next to the nozzle) or indirect drive (filament is pushed through a tube to the nozzle) is pushed through the nozzle. Next the material is deposited on the work surface. For the project mostly, a heated bed for plastics. The printer will move the head in the X and Y direction over the bed depositing the material extruding support material where needed with FDM this can be a very loose structure of the to print material or a different material that is solvable in water or that can be melted away at low temperature. When the complete layer is printed the printer will move in the x direction with a step that is appropriate for the project and material and will start to print the next layer.

Figure 28: PLA part curling up during a print

Common problems for FDM printers especially for materials that print on a higher temperature is curling on the edges. Due to the long print times earlier layers of the print can cool down so much and thus contract so that the edges of the print pop loose of the printing surface and start to curl up. In Figure 28. A part that was printed for the lawnmower had this problem. The part should have been of uniform thickness however due to shrinking of material on one side the part flattened and thus became a non-functional part. Another common problem for FDM printers is that the nozzle can be blocked. This can happen when the material is not heated properly or when the curling from the previous example starts to happen and as a result puts more pressure on the material extruding from the print head. When this happens, the printer can be damaged, or a fire could start due to excessive heating of the material. During test printing for the project another common error found with the printers available for the project, especially the cheaper ones, is that the material can come loose of the printing bed resulting in a large ball of loose filament extrusion.

3.1.3 Material Jetting (MJ)

Material jetting is the third method that was used in this project. MJ printing can be compared to traditional inkjet printing. In theory Material Jetting is a combination of an inkjet printer and Stereolithography printing as the printing head disperses tiny droplets of a heated (40-60 degrees Celsius) photosensitive polymer on the work area these droplets are then hardened by an ultraviolet light source directly following the printing head. This makes sure that everything dries directly and makes it possible to get smooth, high detailed prints (sub 25 µm resolution is possible), and very intricate parts from the printer. Material Jetting printers do however need support material. Often this material is a special paraffin wax that due to is low melting point (37 degrees Celsius) can be printed with the same head. The wax is also ultraviolet light sensitive and will harden after the light passes.

Figure 29: Medical model of a head printed with an MJ printer (Source: Stratasys)

When printing with an MJ printer the same benefits apply as using a normal inkjet printer. As an inkjet printer can rapidly swap the colour of the inked being printed so can an MJ printer rapidly and effortlessly change colour or material type of the printing medium. This makes the MJ printers very useful for multi coloured and multi material applications. Having this capability makes it also possible to make" *digital materials*" these materials are a combination of two or more of the loaded printing materials resulting in different colours, hue or material properties. These advantages are clearly shown in Figure 29 where a medical model of the human head is printed with multi materials, colours and high detailed. Another feature of the MJ printers is that all surfaces that not encounter support material get a glossy appears. This makes it possible to make glossy and matte approach of the print.

There are however also some downsides of material jet printing. Most of the materials that can be printed with this method are brittle and not that temperature resistant.

3.2 Electronics

For the project multiple electronic components are being used. These electronics can be found in all part of project and consist of complete modules bought from suppliers or home build electronics on perfboard, a special substrate that consists conductive material and can be used to create circuitry, or custom printed circuit boards. From the basic components sensors and senders are created for the boundary wire system, charging circuits for the batteries and for the control of the robot.

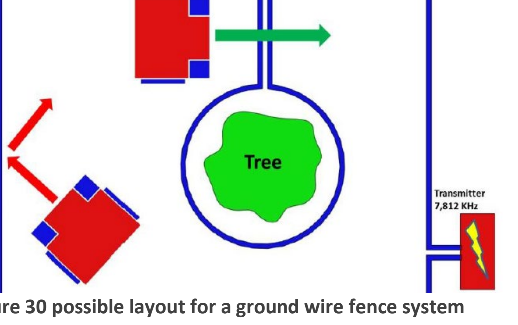


Figure 30 possible layout for a ground wire fence system

To make sure that the lawnmower will stay within the area designated to be mowed a boundary wire fence is used. The fence uses a wire buried in the ground to transmit a low power electromagnetic signal. This signal is generated using a 4MHz quarts oscillator crystal. Quarts has the property of stable oscillation under pressure therefor the signal produced is constant. This signal is fed into a binary counter that on reaching a reset position triggers a wave to travel over the wire. The power of the signal is regulated by the value of the resistors within the circuitry. With the use of the ground boundary wire it is possible to fence of an area of land for the lawnmower to cut as is shown in Figure 30. When this area has obstacles, islands can be created, wires are parallel to each other when running to and from the island and thus the electromagnetic pulse is cancelled out and the lawnmower can cross the wire.

To detect the ground wire, a resonance circuit is being used. This circuitry has a resonance frequency, a frequency at which it starts to produce a small voltage, at the same 7.841KHz of the ground wire fence. Whenever the circuit comes in range of the wire fence the voltage being generated is used as input for the directional controls of the robot. This is possible by using two sensors, so the direction and position of the wire can be determined. Each of the two sensors in the system uses two parallel sensing circuits on one sensor plate. These circuits are placed in 90-degree angle opposed to each other. When the signal is generated in the resonance circuitry it is not high enough for information collection in the rest of the system. To overcome this problem the voltage is fed into an operation amplifier circuit. This piece of hardware has two inputs and one output and amplifies the incoming voltage by a certain amount of "*gain*". This gain is produced by the difference between the input and the output. In Figure 31 one of the most basic op-amp circuits is shown and the formula to calculate the amplification (Av) is: $Gain(Av) = -R2/R1$. By amplifying the signal, it is measurable with the Arduino microcontroller that controls the machine.

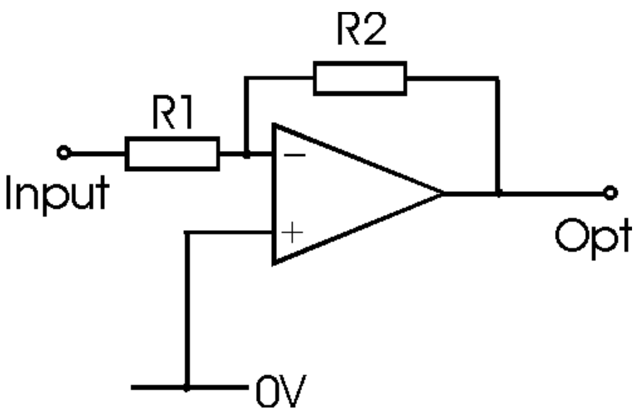


Figure 31 basic inverting op amp circuit (source: Radio-Electronics.com)

The brain of the machine is an Arduino Uno. Arduino is an open-source software and hardware company and project. When the Arduino was conceived in 2003 Hernando Barragán as the development platform Wiring as master's thesis to replace the BASIC Stamp microcontroller board with a cheaper alternative. After the thesis was finished Massimo Banzi and a team of other students forked the project and called in the Arduino.

The Arduino software is widely adapted and can run on a large variety of devices, microchips and other hardware solutions. Most commercial boards however and the board that is being used in the lawnmower project are based on the Atmel 8-bit AVR microcontroller family. Depending on the Atmel chip being used the amounts of system memory, flash memory, pins and features that are supported on the board differs. During the project an Arduino Uno is being used with an ATmega328P chip. This gives it the specifications shown in **Error! Reference source not found.**. Next to these general specifications the chip that is used has support for the Serial Peripheral Interface(SPI), Two wire interface(TWI), external analogue reference, serial interface and external interrupts on pins 2 and 3.

Operating voltage	5
Input voltage	-7 to +20 V
Digital I/O pins	15, 6 with pulse width modulation
Analog input pins	6(10-bit resolution.1024)
DC current per I/O pin	20 mA
Flash memory	32KB
Sram	2KB
EEPROM	1KB
Clock speed	16MHz

Table 1 Specifications Arduino Uno

The Arduino bootloader for the chips accepts a multitude of programming languages and styles. However, for this project the main language being used is the Arduino C language this is a fork of the C language with special rules for code structuring. Software written for the Arduino boards are cyclic this means that when the initiation of "*setup*" has been performed the code between the "*loop*" brackets will loop continuously until the device is reset. The loop can also be interrupted so that the code will start to run at another

3.2.1 Control systems

In the project, control systems are being used for all the movements of the lawnmower and for charging of the batteries. Control theory can be split up in two large groups, open loop control and closed loop control. Both are used in the project. Open-loop control systems are systems that have no feedback loop. For example, a microwave, the microwave is set at a 1000 W for 40 seconds and runs the program. It however does not check if the to be warmed item is heated up to specification and thus can be burned or frozen after the 40 seconds. The original lawnmower is based on open-loop systems.

Closed-loop control systems are systems that work on the feedback from sensors within the system to confirm that the desired outcome is achieved. This can be done with multiple different techniques the simplest of which is an on/off system that switches off and on parts of the plant (the system that is controlled) to stay between set margins. An example can be found in a thermostat which needs to control the temperature within an area, so it is near a known setpoint and can have some deviation (2) from this point. There are, however, more complex control systems for more demanding systems for example, cruise control in cars or climate control in greenhouses. These systems make use of control systems based on proportional control most of which are proportional-integral-derivative(PID) control systems. Systems like these will try to make sure that a specific setpoint for the plant will be reached with as little error as possible. They will also result in less hysteria, higher stability and a rapid response to external inputs.

3.2.1.1 Proportional control

Proportional control is a type of linear feedback that creates a controller output proportional to the error signal generated by the plant. This is the difference between the setpoint(SP) and the process variable(PV). The output can be mathematically stated as $P_{out} = K_p e(t) + p0$ where p0 is the controller output with zero output; P_{out} is output of the proportional controller; K_p is the proportional gain, a calculated value by the engineer; *e(t)* is the instantaneous process error at time *t*. $e(t) = setpoint - process\ variable.$ When implemented there are some constraints that are created by the limitations of the actuators of the process. These can make P_{out} a bounded variable.

One of the disadvantages of proportional control is that proportional control cannot eliminate the offset error that is created by the difference between the desired value and the set value. This is because SP – PV error needs as a requirement an error to generate an output error. The offset error can be accounted for in the original design of the plant however when an outside error is added to the plant this error will always be present in P_{out}.

The clearest advantage of the proportional control system is the analogue instead of digital control. It is not on or off, but power can be applied at percentage. This that the plant is not overly stressed and thus decrease service life. Another advantage of the proportional control system is that the system is cheap and easy to implement.

3.2.1.2 Proportional-integral-derivative (PID)

Proportional-integral-derivative(PID) is the third and final evolution step of the proportional control system. The first, proportional is described in 3.2.1.1. The second one is I, integral and this part integrates the error found in the P value (Setpoint(SP) – measured process value(PV) at e(T)). This means that it sums all errors of the previous steps in one and integrates this and makes sure that the residual error of P is accounted for. This term will cease to grow or decline when the error is 0 and thus will make sure that the control system is stable at 0 error. The problem with only having P and I in the controller is that the I term makes the controller sluggish

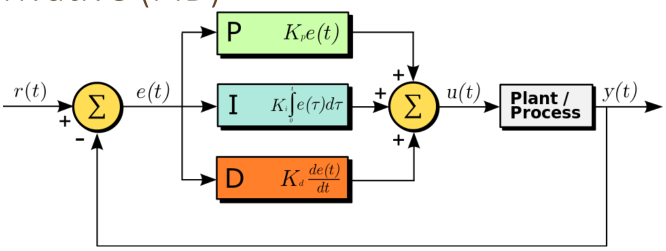


Figure 32 Block diagram of a PID controller. [22]

when the I value is set low or when set to a higher value makes the changes faster and makes the plate overshoot the setpoint and thus risks damaging the plant. The third and final step in the PID controller is the addition of the derivative part(D). It uses the future trend of the SP-PV error. This part anticipates the error for the next tick of the system and seeks to exert control influence generated by the rate of change in the system. This helps the controller to make more rapid changes that would not be possible by the P and I controller alone. The D part also makes sure that whenever there are big changes in a short duration of time the controlling or dampening effect will be greater in response.

4 Lawnmower

The lawnmower build for this project is based on the RepRap Lawnmower plans sold by Digital River GmbH. The first iteration was designed in 2009 by Andreas Haeuser to be built from aluminium, steel and other materials requiring a large well-equipped workshop to recreate as a hobbyist. With the rise of 3d printers Andreas changed the design to be printed on simple do-it-yourself 3D printers. With this design change the electronics where also simplified to work with the Arduino board. This makes the system nice to print, easy to use and simple to operate. This model is designed to within the following conditions:

- Lawn size of 500 m2
- Central European climate
- Fertile soil that is not being fertilized by the owner.
- Wavy uneven ground

The machine is not used to cut long grass however the main usage of the machine is to trim the overnight growth of the grass the following day thus maintaining a constant grass length over time. The original design was tested for 6 years.

It is powered by two 11,1V 5200 mAh LiPo batteries. Which can power the device for approximately 90-120 minutes for one charge. During this time the lawnmower will randomly drive around cutting the grass while also looking out for boundary wires. During this time little to know logic is applied to the system, the system just drives and turns a random amount of degrees when a boundary wire is found and depending on the intensity and coil that picked up the signal a turn is made left or right. When the lawnmower control system notices that the battery of the system is 75% depleted the lawnmower will find the nearest boundary wire and will follow it back to the base station. This is done by using the coil parallel to the mowers body of the left or right sensor. The signal is used as an input for an PID controller that controls the wheel speed for the left and right wheel. Whenever the second parallel coil picks up the signal the machine will be trying to stay as parallel as possible to the surrounding ground wires. The ground wire connect to the base station and the machine will thus drive to the charging dock. When the dock is reached two copper plates will touch the charging points of the dock and start charging the machine. The machine stops and in case of an emergency has an override button in the front to make sure it does not damage the charging bay by driving against the back wall.

Next the lawnmower monitors will charge the level of the battery whenever the battery level reaches 80% it will move out of the shed and starts mowing again. This is done due to the increased degradation of cell life in deep cycle (100% → 0% charge) applications of LiPo batteries [16]. When the device is charged it will start mowing again.

4.1 Battery mounts

To save money on the budget another battery was used, the new battery has the same capacity but different dimensions. Therefore, new battery mounts had to be made. After measuring the batteries on the chassis of the lawnmower the conclusion was drawn that the old holes of the LiPo batteries could be used. The old battery mounts were also not really a good design for a battery mount because if the lawnmower experiences a crash than the batteries could come lose. Before starting a design, a dummy was made by measuring the batteries, this was done so the 3D model will be an accurate view of how the batteries will be mounted in real life.

For the new design it was preferred that the batteries would be fixed into the lawnmower, so the design started by making a clam type of case for the back because those can be identical. To get a tight fit a tolerance of 0.2 mm was applied to the caps of the mounts. The holes in the mounts, to fix the cap as well as fixing to the chassis, were made to drill out with a 2.2 mm drill and then to be threaded with a m3 tap. The back mounts had to get a slot out in the bottom because of how the chassis was designed. The front mounts needed a hole in the front for the cables. Because one battery had to have the cables on the right and the other one on the left the mounts had to be mirrored to each other.

The back mounts are shown in Figure 35 Battery mount back side and Figure 36 Battery mount back side (2), the front mounts are shown in Figure 34 and the mounts on the lawnmower are shown in Figure 33 Battery mounts on the lawnmower

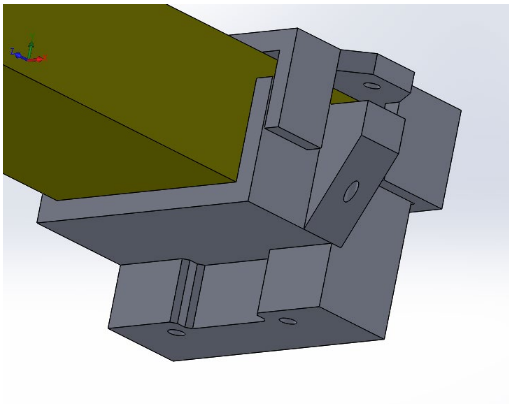


Figure 35 Battery mount back side

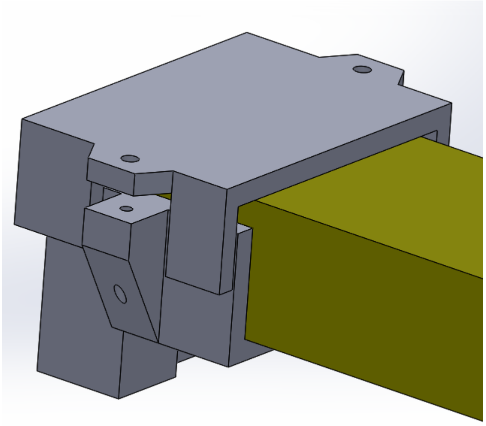


Figure 36 Battery mount back side (2)

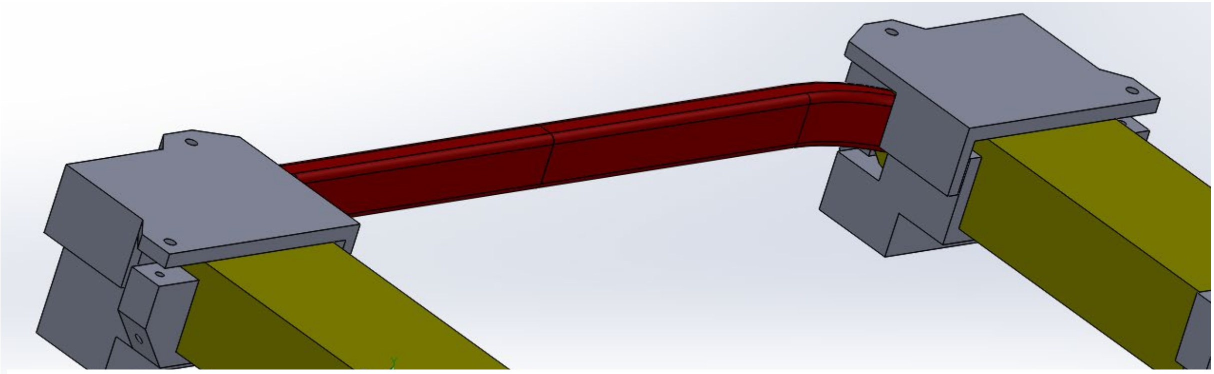


Figure 34 Battery mounts front side

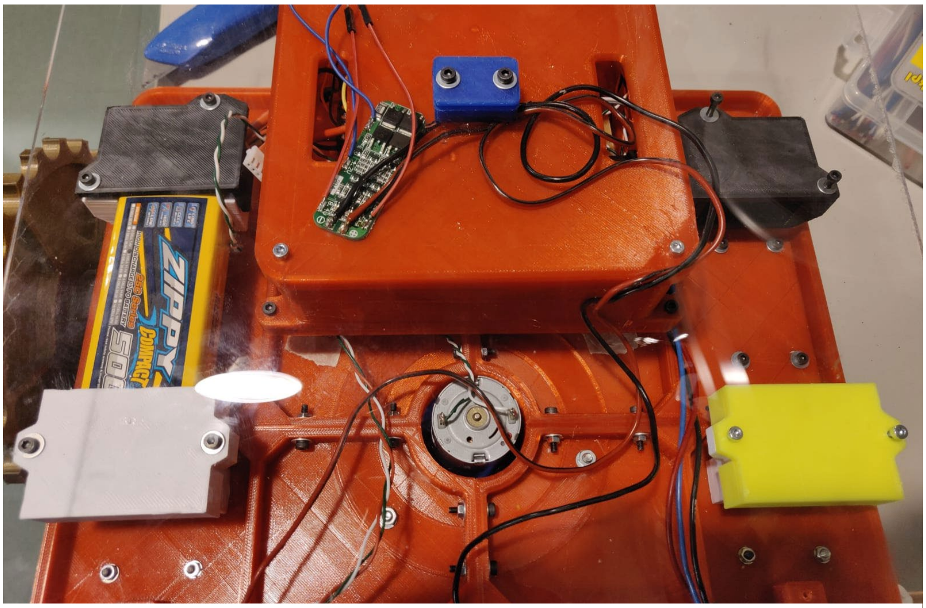


Figure 33 Battery mounts on the lawnmower

4.2 Charging points

To charge the robot in the docking station a solution was designed to connect to the charging pistons shown in the concept part of chapter 6. The solution that was designed is shown in

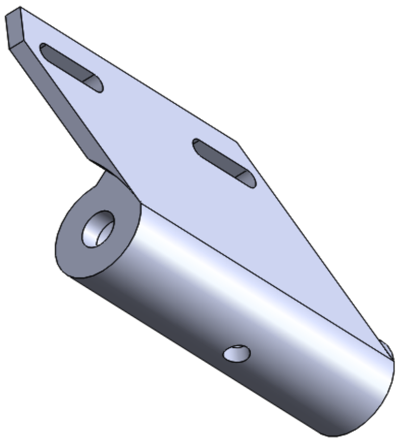


Figure 37 Left charge point

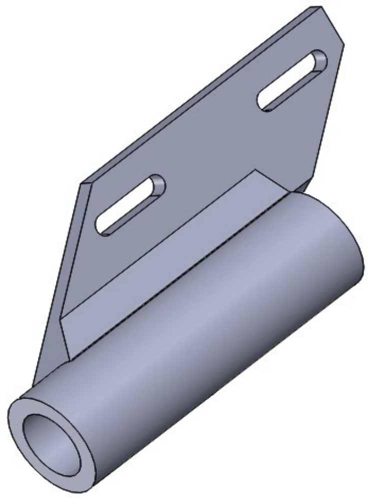


Figure 38 Right charge point

Figure 37 & Figure 38 this is only part of the result because in the round opening a copper tube will be inserted that makes the actual connection. The mounts were designed in Solidworks and exported as an. STL file when completed. The elongated slots are used to attached and position them correctly on the NiMH battery holder slots on the original design of the lawnmower. These are solid pieces with no shock absorbing mechanism as this is part of the charging dock.

4.3 Lawnmower construction

The construction of the lawnmower is based on "The 3d-printed „Robotic lawn mower"© by A. Haeuser" [17]. This document describes the correct steps to make to replicate the original lawnmower. The changes made within the project are described within this section and refer to where in the construction manual the deviations where made.

To make sure a solid start was achieved an inventory was made of the available parts and the to order parts. The part list can be found in the references. The parts that were not available in Technobothnia were order by the suppliers listed in the parts list. Next an inventory was made on all assemblies and subassemblies of the lawnmower and the parts that needed to be printed with time and estimated material usage. This inventory would act as a guideline for printing the components in the correct order. When printing the following tactic was used: check printer availability → find first component that fits printer size and fits in the time slot available for printing → slice part in correct slicer → check weight of part, if under 100 grams and bed space is available add more parts → print parts → check if parts are correct, if not restart print with resliced model or less parts on the bed

During the printing a parallel development track was opened this track was used for research in the device, mostly charging, and verifying the integrity of the provided code. During the research part the decision was made to use the LIPO battery technology in favour of the NiMH battery technology due to the increased power density and the need for a battery management circuit that could be used for data collection and service life of the batteries within the lawnmower system. The second part of the parallel track, checking the code, was performed after the research in the lawnmower. During this part all code was placed in the editor and checked if it would compile correctly with the control hardware found at Technobothnia. Next an inventory was made of the pins that were in use within the code and this was used to check if there were pins available for measuring the battery voltage or getting inputs from the BMS chip.

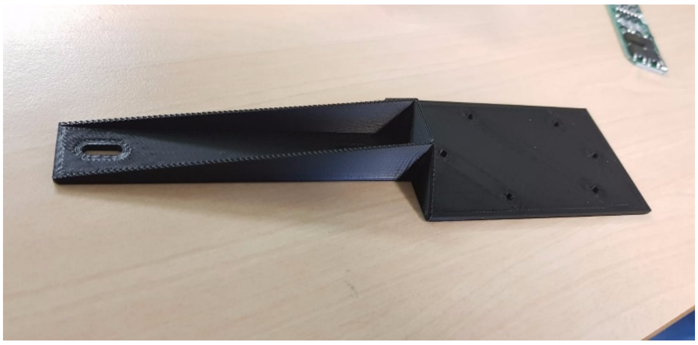


Figure 39 Replacement part for part #55

With the first parts printed the building of the lawnmower started. This was done according to the manual. Changes made during the build process are described in this paragraph and all chapters refer to the build manual "The 3d-printed „Robotic lawn mower "© by A. Haeuser" [17]. Up until chapter 3.6 "*the sensor housing*" small changes were made due to part availability. The aluminium profile to make parts #55 was not available so the decision was made to redesign the part to an 3d printed part shown in Figure 39. The design of the part was realised in Solid works and the files can be found in the references. In the next chapter 3.7 "*batteries and battery holder*" the LiPo battery holders were modified slightly due to different dimensions of the available batteries. The. STL files for this can be found in the references. Chapter 3.8 "*the electronic housing"* deviated on two small parts for the construction manual the changes made were leaving out the protective mesh and not installing the LEDs within the housing. Reasoning for this is that during testing easy access to the components and a clear line of sight were necessary to measure the temperature within the box and show the LEDs without having to open the protective cover.

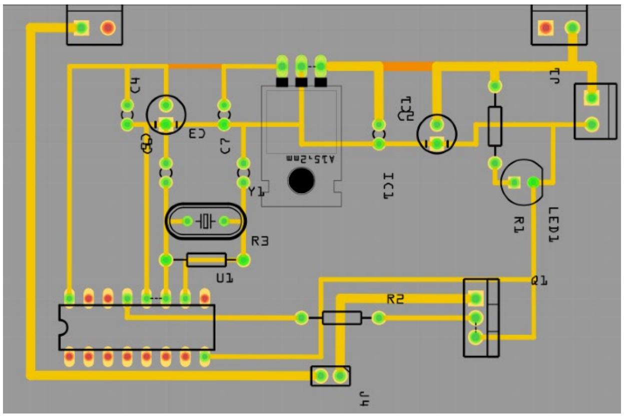


Figure 40 Sketch of the wiring of the transmitter board

When building the electronics, a lot of changes were made due to the poor documentation in the manual. All parts of the electronics were explained in a wiring, diagram, however this diagram does not show the connection on the template boards provided by the designer. To overcome this problem that first arose at chapter 4.1 "*The transmitter*" the schematic was transferred to a Fritzing sketch (Figure 40). After this the design was soldered on to the breadboard as shown in the manual. When testing the completed circuitry, the circuitry blew up. After bug tracking it was found that the power supply lead cables were switch during the weekend and shorted out the circuit. While checking the components on defects after the failure it was found that components VR1 and C6 were broken and needed replacement. These fixes resulted in a stable 7.841KHz signal on the cable while testing.

The next part that was created was the sensor system. The layout design was made in similar fashion for both the left and right version. It was decided not to go with a manufactured PCB or a homemade

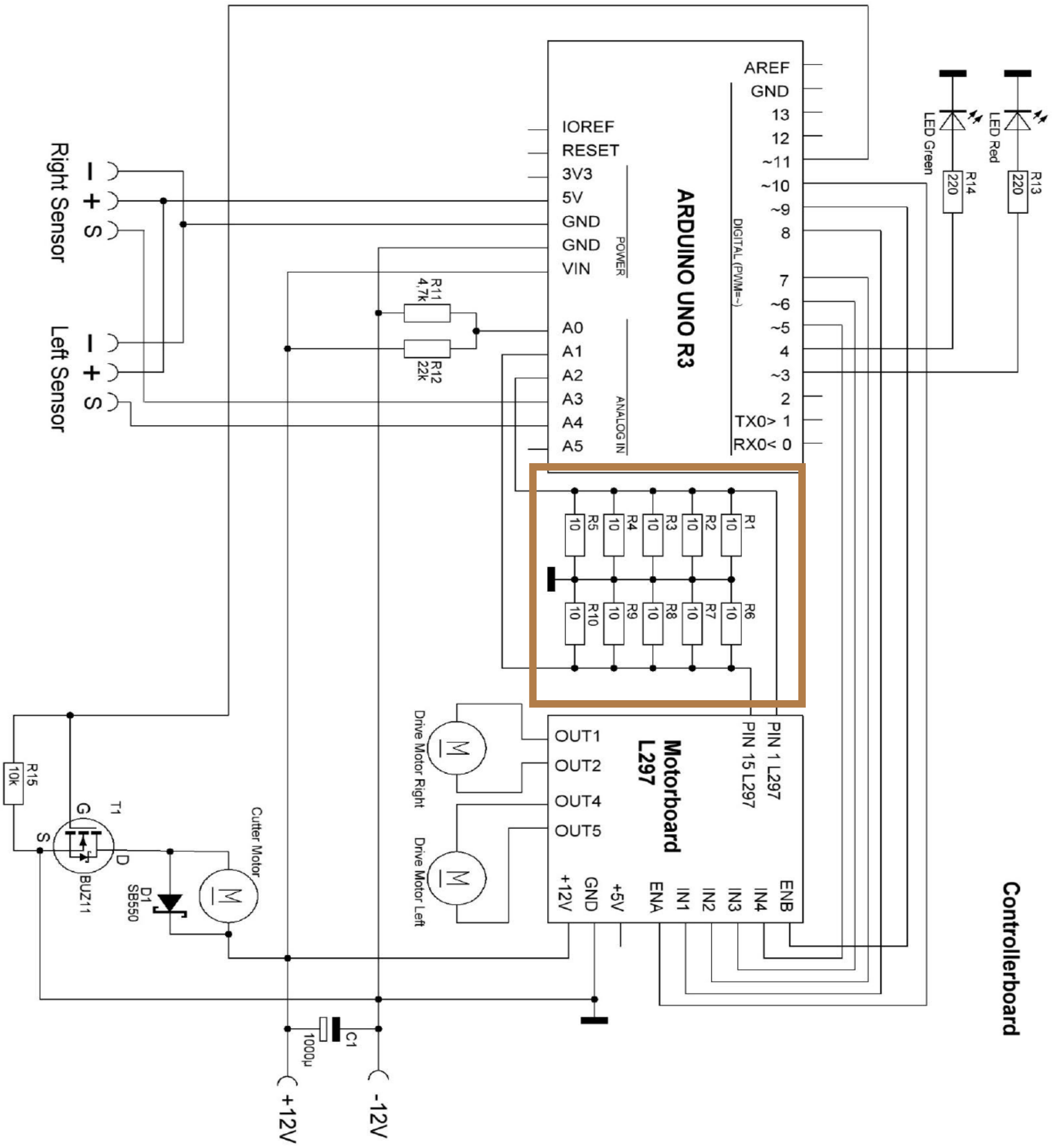


Figure 41 schematic control board

PCB to stay true to the mission objective of the project. The left sensor was manufactured first and during testing a fault in the design was found. This resulted in a small rework of switching around the wires on pin 8 and 1 and after extensive testing the system was installed. Next the right sensor was created in a similar way. With the fix already in place the system second sensor completion was fast and easy.

After securing the sensors, the main board was build and one modification to the original instructions was made. The only thing that was changed was the value of the resistors r1 to r10 shown in Figure 41. The resistors are outlined with the brown box. These values were changed to 14 Ohm instead of 10 due to availability problems.

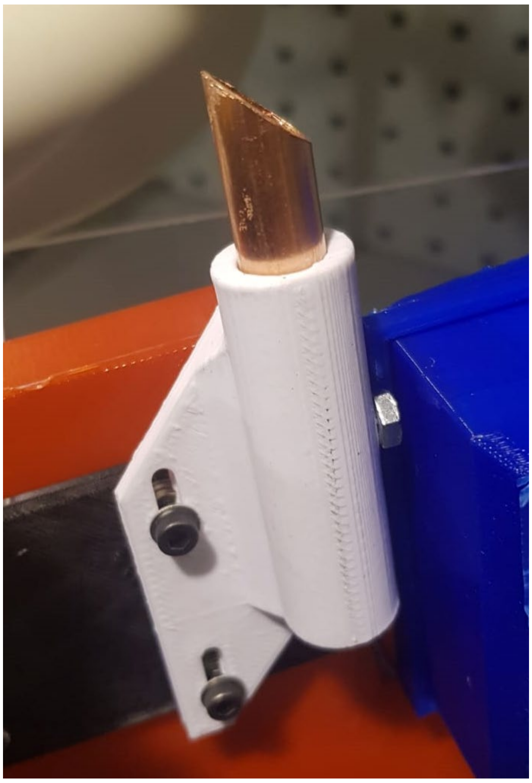


Figure 42 charging point on robot

Next the charge controller was installed in the same housing. The charge controller is basic charge controller that accepts dc power on one side and charges each of the cells. This charge controller has a control chip on it and thus no coding was required. Only one battery was installed in the final iteration of the project. This was done so one spare battery was available for testing the windmill. The charge controller was attached to the housing with tape and the battery wires were soldered on. Next the copper tubes that make the connection with the charging dock were prepared. This was done by soldering two wires in the inside of the tube and then placing the tube in the 3d printed mount. These sub-assemblies were mounted on the robot and the wires were soldered on the charge controller this can be seen in Figure 42. The attachment holes for the charging points are the old NiMH attachment points from the original design.

Next a Bluetooth controller was added. This controller was connected to pin 12,13 and the 5 volt and ground bus. The controller made it possible for us to control the robot with a phone and collect telemetry data while driving.

After this the control board was installed in the system and the code was uploaded to the Arduino for testing of the device and integration with charging bay, windmill and supporting equipment.

4.4 Testing

Testing of the lawnmower went as follows. First all the testing steps from the manual were completed this mend that all the hardware components and circuits were tested. First the ground wire fence was tested. This was done by hooking up the system to an oscilloscope to the system at the following points shown in blue in Figure 43. The top point is the large resistor that leads to the wire and the other point being the ground of the system. Next it was turned on and the following wave Figure 44 form was observed on 7.876 KHz. The wave form was as expected. The next part of testing the system was testing the heat production of the system and seeing if this was being safety limits given by the manual. An infrared thermometer was used for this. The temperature was measured after 40 minutes

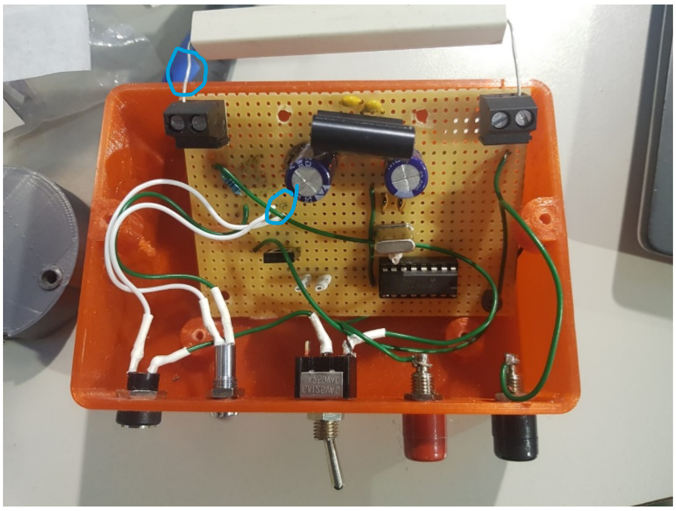


Figure 43 Ground wire transmitter

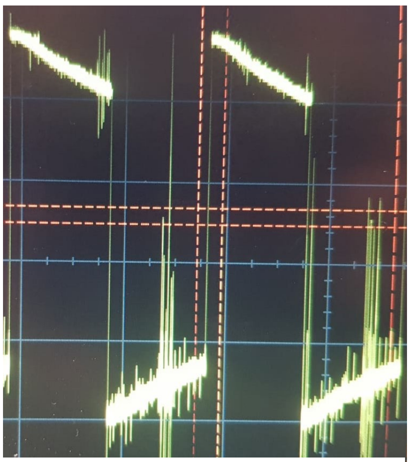


Figure 44 Ground wire wave

and the resistor was 62.1 degrees Celsius and the MOSFET was 87.4 degrees Celsius. This is within limits.

The next part tested were the sensors. To make sure that everything was up to specification and could work in a PID controller for the line following part of the project. The first sensor(left) was tested with a sign generator running at 7.812 KHz. Next both the side and front coil were measured separately with the oscilloscope and the output of the combined signal after the op-amp was collected in the Arduino. Both coils were measured with a wire power of 0.5 amps at 5 volts and 8 cm directly under the wire. The table below shows the results. The average of 20 measurements was taken by the scope and the Arduino sketch

Table 2 Measurements of sensors

Coil	Measured voltage	Arduino ADC measurement
Side_left	0.072	86
Top_left	0.121	143
Side_right	0.143	187
Top_right	0.89	101

The results gathered at the left sensor do not bode well. The recorded difference of 57 steps between the two represents a difference of approximately 40% for the output of the sensor. This is a large constant error that could not be used in a PID controller. To make sure this was not a fault in the sensor the other sensor was tested in the same way the results are shown in the same table as top right and side right. The results showed that this was a design fault in the sensor board. However, for the original design it works. The following tries have been made to fix the problem or make the deviation lower.

- Make the traces equally long, or as close as possible with the tools at hand
- Make the traces thicker
- Make traces out of wire instead of perfboard
- Change out resistors to 1% resistors instead of 5% resistors

None of the above-mentioned methods made a difference. A variable resistor in the line was also tried this had limited success however the resistors available were too large and not precise enough to be workable.

Continuing in the manual the next part to test is the main board. The mainboard circuitry controls all the motors and thus those can be tested as well. First item check was the mainboard itself. It was power on by a lab bench power supply. The power supply started at 5V 1A and was connected to the power input of the board. Next all the power points were measured, and it was checked if all the lights turned on and the power and status LED's were burning and could blink. Next the power level was raised to the voltage of the battery when fully charged (12.2V) and all points were checked again. The system was turned on for 1 hour to check if it still worked after a longer time and if power regulation components got excessively hot.

Next the motors were tested. Testing of the motors was done by hooking them on to the lab bench power supply this and to the motor wires. The power supply was set to 14V 3A, a higher voltage than ever encountered in the working life of the lawnmower. All the motors had their respective sub-assemblies attached to their shafts and were turned on for 1 hour. To make sure that the highest load and most dangerous part of the lawnmower, the cutting blade, was strong enough for the high loads heavier screws and nuts than the normal blade were attached to the blade and the blade was turned on a higher RPM than in normal operations for 24 hours. To make sure this was done in a safe environment a cardboard box lined with acrylic and wooden sheets was placed over top and over the top of the box a sheet of fake grass was placed. After the 24 hours the blade was inspected, and no damage was found.

At this point the whole system could be tested. A ground wire fence was placed around an area of 4x 2.5 meters and the voltage of the battery was measured at the start of a 30-minute test run. This was 11.8 V. After the 30-minute test run the voltage of the battery was 10.2 V. this mend a 1.8 V drop in 30 minutes.

The voltage was also measured every three minutes to get an accurate representation of the voltage drops. The results are visible in the graph on the left.

Based on the test and the discharge characteristics of LIPO batteries. The robot should be able to cut at least one hour before returning to the docking station on one battery.

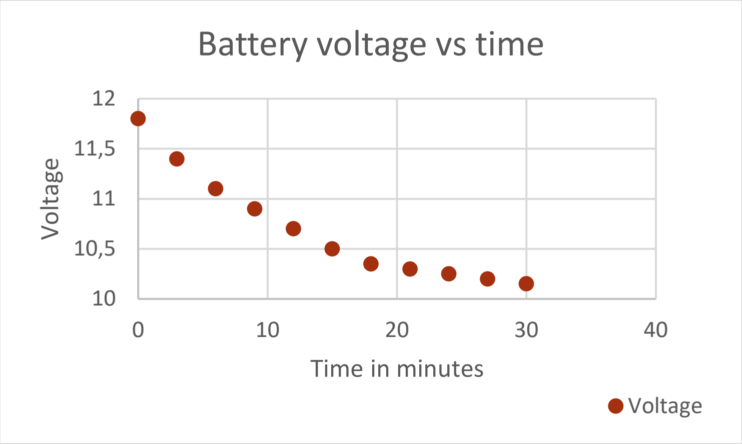


Figure 45 Voltage vs time

Next part to be tested was if it was possible to charge the battery with the BMS circuit. This was done by hooking up the BMS circuitry to a stable 12V DC power supply and getting a partly discharge battery connected to the system. When this was done the voltage was measured after 4 hours and the thickness of the battery was measured to compare if it increased in thickness by agitated LIPO cells. This resulted in a charged battery and no increase in thickness.

4.5 Conclusion & recommendations

In the end the robot worked as expected with the provided code given by the manual. It drove around between the boundary wire and stopped when it reached a too low battery voltage. The redesigned parts did not interfere with normal operations and the addition of the Bluetooth module makes it easy to see what is happening from a distance.

If the lawnmower would be built again the following items should be considered as high priority changing points.

- Improved sensors, the reasoning behind this is that better designed sensors can be calibrated between the sensors on each of the side. Improvements that would improve the quality of the lawnmower a lot can be:
    - Variable resistors between the coil and the op-amp to make sure that the sensors output can be the same between both coils
    - 4 sensor outputs instead of combining the coils left and right to one output. This give greater control and makes it possible to follow the line properly resulting in a more even edge of the lawn and easier tracking to the station
    - GPS, GPS and a rudimentary position algorithm can be implemented for a low price (sub 5 euros) and can increase the efficiency of the lawnmower. It will also result in not needing the wire fence resulting in lower cost overall as roll of wire big enough to encompass the complete edge of a yard would cost between 80 and 150 euro's
    - Cutting blade sensor. This can be made by measuring the resistance of the blade turning motor over time. When a sharp drop is noticed, not cutting the grass so less drag) the blade can turn slower and thus decrease energy usage.
- Improved design, the current design of turning wheel. The current caster wheel design works however the way it is attached to the lawnmower is not great and causes it to turn chaotically and get stuck occasionally this can be improved.
- Change of Arduino UNO to Arduino Mega micro, the mega micro is more power efficient and can handle more inputs. This makes it easier to upgrade the lawnmower over time and can also enable the use of multiple lawnmower by having three instead of one serial connection. This increase gives the user the capability to add WIFI, Bluetooth or other low power wireless solutions set up a mesh

network and thus make the system more efficient. It would also give a cheap and easy method to connect it to the charging station and the internet to make the lawnmower smarter and give the possibilities to track statistics of the lawnmower over time that could be valuable for the consumer or researchers to improve the system even more.

5 Wind turbine

In this paragraph the choice of wind turbine is explained based on the information that was gathered in the research paragraph. There are two options of turbine available, a vertical and a horizontal wind turbine. There will be an environmental sketch of the circumstance in which areas the lawnmower will be used and by which people, this will help decide which turbine will fit better in which environment. The horizontal turbine will be printed because the design was already ready for use, the only thing that needs to be changed are the rotors because they do not have the right aerodynamic for a wind turbine rotor.

5.1 Choice of turbine

Both turbines will be listed below in Table 3 with their advantages and disadvantages, these advantages and disadvantages will then be given a score between 1 to 5 to mark how important they are. The total sum should then give an outcome of the better turbine.

Table 3

Horizontal turbine				Vertical turbine			
Advantage	Score	Disadvantage	Score	Advantage	Score	Disadvantage	Score
High efficiency	5	Must be placed in a high place for good efficiency	2	Can be placed on the ground	3	Low efficiency	5
Cost efficient	3	Needs more area	2	Takes up less area	2	Pulsing torque	1
Has already been designed	2	Need proper balancing to have a good lifespan	2			Vibrations	1
Total	10		6		5		7

Table 3 shows that the advantages of the horizontal turbine outweigh the disadvantages in the scenario of this lawnmower project and that the disadvantages of the vertical turbine outweigh the advantages. This means that for this project the power source will be from the horizontal turbine. But some slight adjustments will be applied to the horizontal turbine design that is provided for this project. At first the rotor will be redesigned into a more efficient rotor design than the aluminium sheet that was used before. As second the wind vane will be redesigned so it can be laser cut on the machines provided by Technobothnia.

5.2 Redesigning the rotor

An efficient turbine is all about the rotors, looking at the modern big megawatt turbines the rotors have a slim body, airplane wing design twist outwards to the tip. The original producer of the 3D printed windmill used a simple aluminium sheet and bend it once to create a rotor, this is not an efficient rotor design therefore a new one will be made that can be fully 3D printed.

5.2.1 Tip Speed Ratio

The first step to designing a lift-based turbine rotor is to decide on a Tip Speed Ratio (TSR). [18] The TSR refers to the ratio of the speed the blade tips to the wind speed. TSR is important because if the blades spin too slow at a given wind speed, then most of the wind will pass through without being harnessed. And if the blade spins too fast, then the blades will 'blur' and act like a wall blocking in the wind. The TSR required for a rotor depends on the average speed of the wind and if the wind is laminar or tubular. A low TPR is used for turbines that need more torque than speed and a high TPR is used for turbines that need to generate a lot of electricity like in this case. However, a high TPR also has some drawbacks like excessive noise, vibrations or erosion from the air, so it is important to let the TSR not exceed the structural threshold. In this project there are three blades in the hub so the optimal TSR lies between 5 and 7, so for this project a TSR of 6 will be used because 3D printing is not the strongest form of building.

5.2.2 Wind power equation.

Harnessing energy from the wind all comes down to the size of the rotor, also known as swept area, the wind speed, the air density and the efficiency of the turbine. This energy can be calculated by the following formula.

$$P = \frac{1}{2} * p * A * V^3$$

In which

P = power (W)

p = air density (kg/m^3)

A = swept area (m^2)

V = wind velocity (m/s)

This formula does not contain the efficiency of the turbine itself but in general a DIY made turbine can achieve an efficiency of about 20 to 40%. The most important thing that this formula shows is that the most power can be made in high wind speeds, but since this is a location-based input the next things that influence the power the most are air density and swept area. Air density depends on the temperature of the air, because as air gets colder it also gets denser, so the only input left is swept area. And the swept area is something than can be increased by making the rotors bigger. So, for this project the rotors will be made 50 mm bigger to get more power out of the turbine. This is almost a 15% increase in rotor length, which could be even bigger. But to stay within printable dimensions for now is easier and safer because bigger rotors also mean bigger loads. With an air density of 1.23, kg/m^3 a swept area of π m^2 and a wind velocity of 8 m/s the turbine should be able to make 989 Watt of power. About 30% of that would be left after the loses of mechanical and electrical components and that should leave the whole turbine with almost 300 Watt of power.

5.2.3 Blade design.

For this project the most effective way to design a rotor design would be to use the blade element moment theory (BEMT) because in this project group lacks the time, programs, and knowledge to design a professional rotor design. First the rotor diameter must be decided, which will be increased from 840 mm to 1000 mm which comes with the exact swept area (A) of π m^2. The number of blades (β) is 3 and the angle of attack (α) of the wind will be 5°, and the average wind speed (V) in this area is 8 m/s. The lift coefficient (CL) is approximately 85% for the aero foil profile that is being used, how this profile works when the winds hit it is shown in Figure 46.With this data the chord width (Ci), thickness (Cti), and the pitch (σi) can be calculated per element. The rotor will be made from 9 chord elements which almost all will have 50 mm between them. The only thing that must be modified in the formula different per element is the radius in which the element lies.

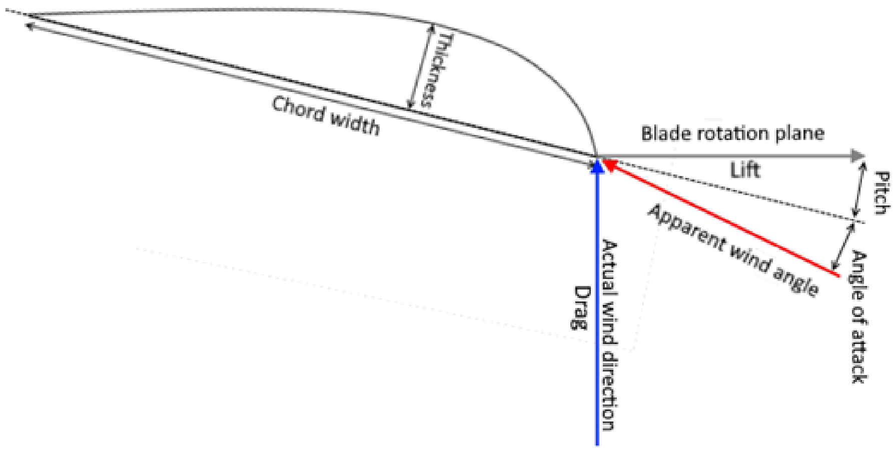


Figure 46 Aero foil profile using drag

First chord:

TSR per element

$$\lambda i = \lambda\left(\frac{r}{R}\right) = 6 * \left(\frac{0.120}{0.500}\right) = 1.44$$

Relative wind angle per element

$$\varphi i = \frac{2}{3} * tan^{-1}\left(\frac{1}{\lambda i}\right) = \frac{2}{3} * tan^{-1}\left(\frac{1}{1.44}\right) = 23.19°$$

Pitch per element

$$\sigma i = \varphi i - \alpha = 23.19 - 5 = 18.19°$$

Chord width per element

$$Ci = \frac{V * R * 2}{\beta * CL * r * \lambda^2} = \frac{8 * 0.500 * 2}{3 * 0.85 * 0.120 * 6^2} = 0.13617\,m = 136.17\,mm$$

Chord thickness per element

$$Cti = \frac{1}{8} * Ci = \frac{1}{8} * 0.13617 = 0.01702\,m = 17.02\,mm$$

With this data the chord in Figure 47 was made in Solidworks.

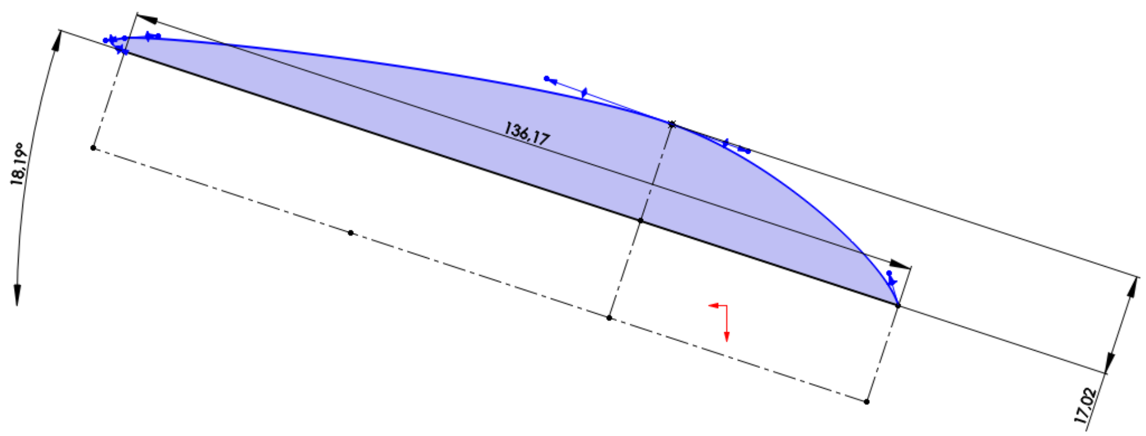


Figure 47 First chord of the blade

All these calculations were done in excel, Figure 50, to create a clear sheet on what the width, thickness, and pitch of each chord element should be. All the elements can be seen as sketches on each other in to see how the blade turns from bottom to top. The full blade that has been made using the loft feature in Solidworks can be seen in Figure 51. [19]

Diameter rotor	1
Swept area	3,141593
TSR	6
Blades	3
Wind speed	8
diameter hub	0,18

Chord element ↓
1
2
3
4
5
6
7
8
9

	1	2	3	4	5	6	7	8	9
CL	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85
Ci	0,136166	0,096117	0,074272	0,060518	0,051062	0,044162	0,038904	0,034766	0,03268
Cti	0,017021	0,012015	0,009284	0,007565	0,006383	0,00552	0,004863	0,004346	0,004085
σi	18,18522	12,40928	8,83072	6,434948	4,73105	3,461777	2,481639	1,70289	1,308215
ϕi	23,18522	17,40928	13,83072	11,43495	9,73105	8,461777	7,481639	6,70289	6,308215
λ	6	6	6	6	6	6	6	6	6
λi	1,44	2,04	2,64	3,24	3,84	4,44	5,04	5,64	6
R	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
r	0,12	0,17	0,22	0,27	0,32	0,37	0,42	0,47	0,5
V	6	6	6	6	6	6	6	6	6
A	0,785	0,785	0,785	0,785	0,785	0,785	0,785	0,785	0,785
a	5	5	5	5	5	5	5	5	5
β	3	3	3	3	3	3	3	3	3

Figure 50 Calculations of chords

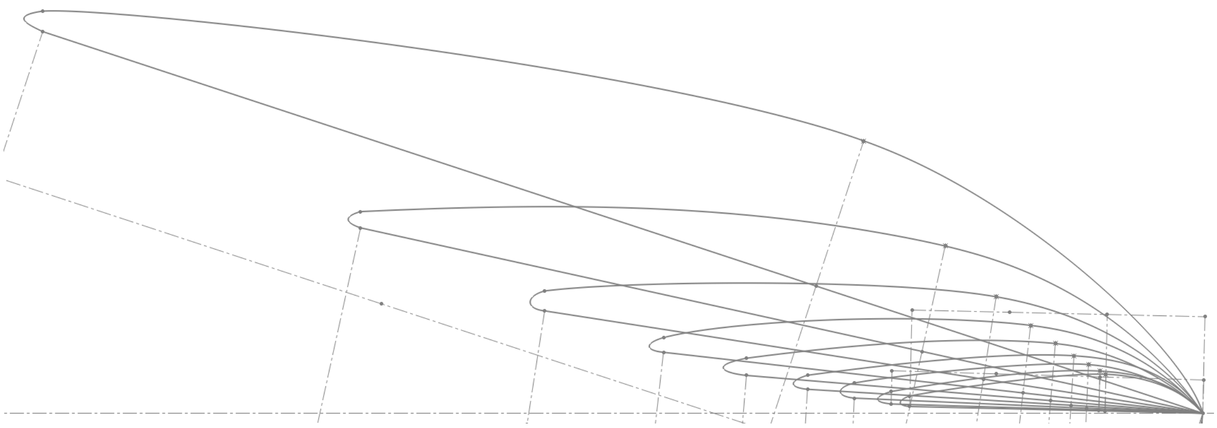


Figure 49 All blade stations

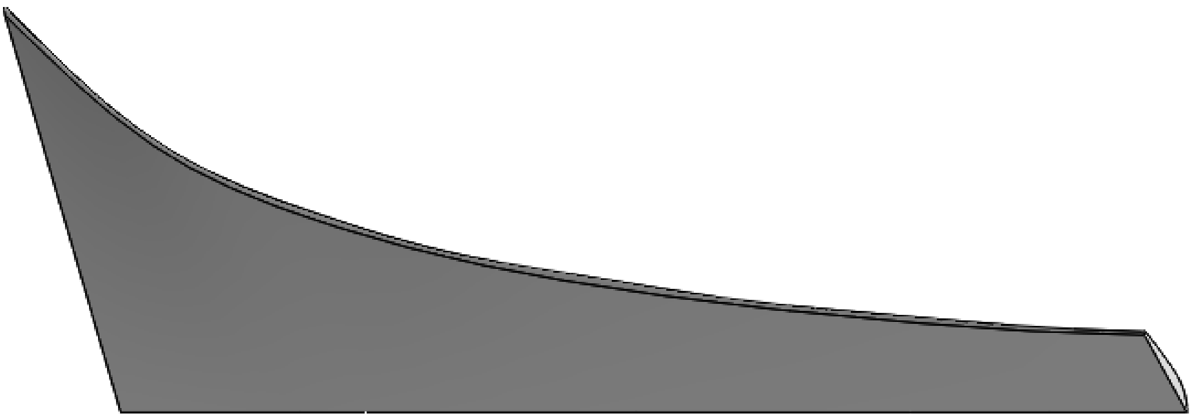


Figure 51 Blade

The only thing missing from the new blade is an attachment piece to attach the blade to the hub. This was made by sketching a smaller aero foil profile under the biggest chord and then lofting in back 30 mm to a chord with a length of 60 mm and a width of 15 mm. This profile was then extruded straight down for 20 mm and then the attachment holes were cut into that extrusion. All of that will conclude in the blade shown in figures Figure 52, Figure 54 and Figure 53.

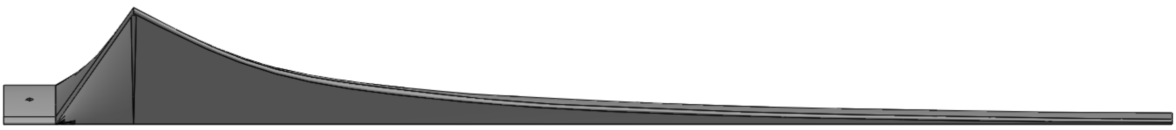


Figure 52 Side view blade

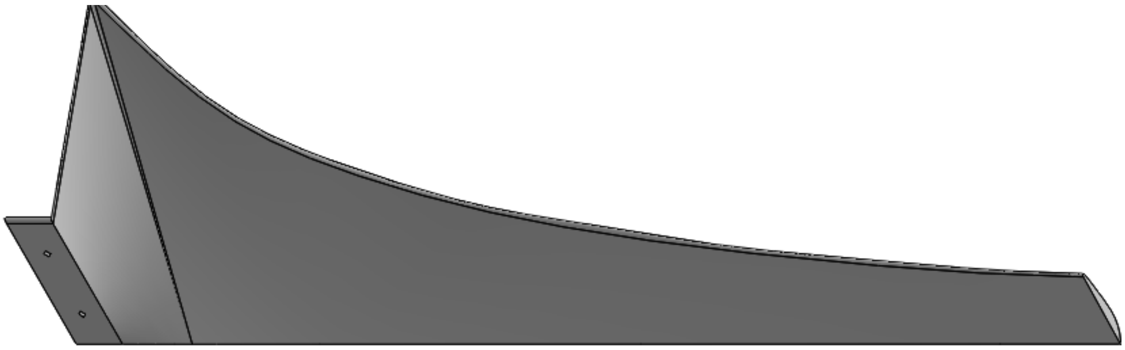


Figure 54 Side view blade

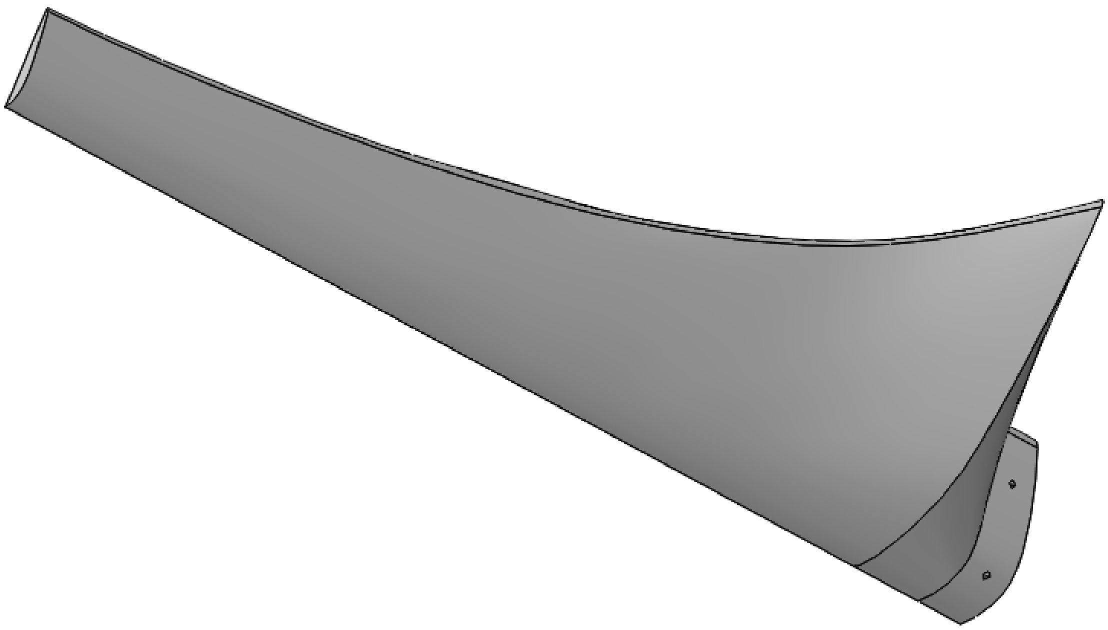


Figure 53 Top view blade

5.2.4 Printing

Because the blade has a length of 450 mm the blade must be printed in the Wanhao, which is capable of printing about 600 mm vertically. The blade was sliced with the WanhaoMaker software. The blade has a shell thickness of 1.6 mm and a bottom and top thickness of 1.25 mm with a layer height of .25 mm. this means that all the walls have a 5-layer thickness. The blade is printed with a 30% infill, and even though there was no testing on the blade it is still strong at the bottom and flexible enough at the top. The blade is printed with volcano PLA, this is a PLA which requires a printing temperature between 220°C and 255°C which will make it stronger like ABS but still maintains the less warping qualities like PLA. This is important because the Wanhao does not have a heated bed, so the blades cannot be printed in ABS. The blade does require to be printed with support because the first chord overhang is too much to print without support.

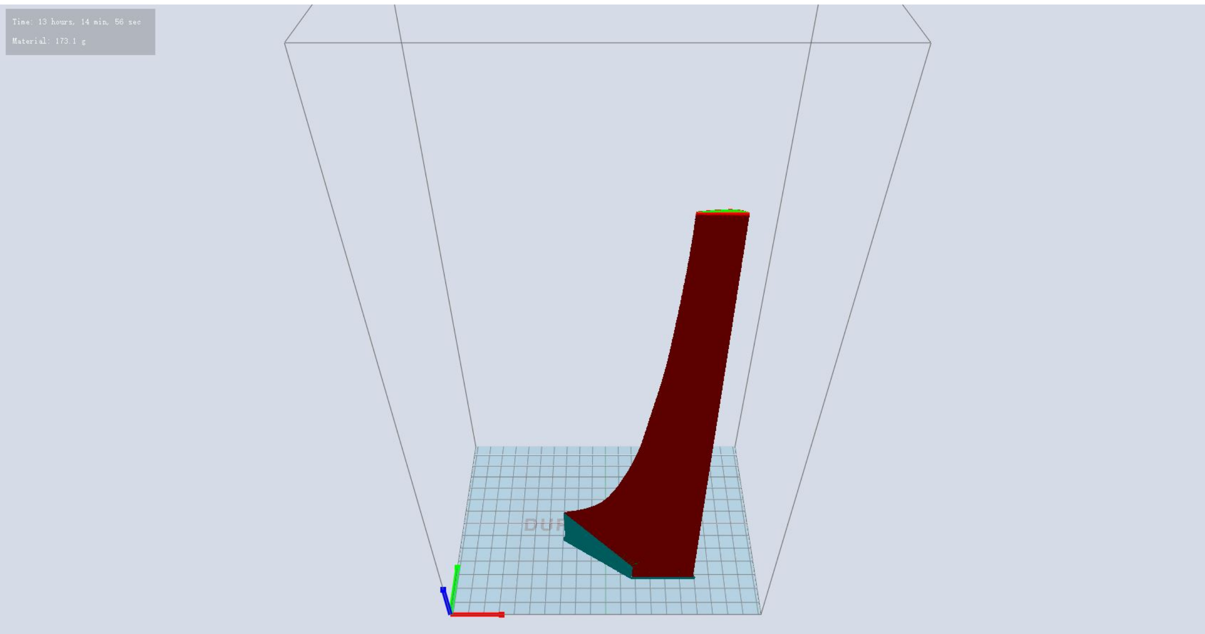


Figure 55 Blade model in slicer

Figure 52 shows how the Blade is placed in the Wanhao printer, the blade is put slightly off-centre because the build plate of the Wanhao was slightly damaged in the middle. The time it takes to print is estimated at 13 hours and 15 minutes and the amount of material that is needed is estimated at 180 grams. When the support is broken off after the print is done, a blade of 140 grams remains.

5.2.5 Fixes.

Soon after the rotors were printed some flaws were discovered which could be solved quite easily. The first fault is that the attachment holes had 30 mm between the centres of the holes and the attachment holes on the hub have 36 mm between the centres of the holes. This fault is a human fault made while constructing the blades but can be solved quite easily as well by making an attachment piece. The attachment piece has a tight fit to the sides of the hub and the sides of the blade. The attachment piece can then be adjusted with the key holes to get a tight fit with the outer walls of the hub as well. This attachment piece was printed with an 80% infill to make it at least a strong as the hub. The attachment piece can be seen in Figure 53 and for the assembly check the next paragraph.

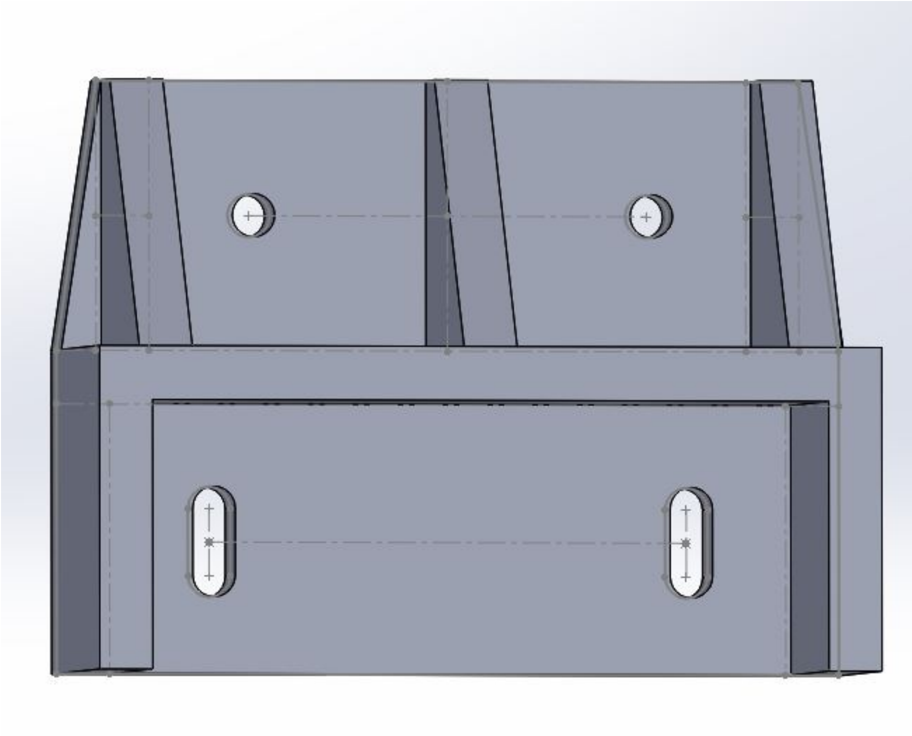


Figure 56 Adapater

5.2.6 Assembly.

The assembly of the turbine is the same as in the instruction manual except for the rotors, the rotors require 6 m3x40 bolts, 6 m3x20 bolts, 12 m3 nuts, and 24 m3 rings. The easiest way to attach the rotors is by first assembling the attachments pieces to the rotors, see Figure 54 and Figure 55.The next part is putting the rotors on the turbine hub, see Figure 57 and Figure 56 , this is best done by first assembling the hub according to the manual and then fixing the axle in a workbench. Make sure the hub can still turn in the workbench and that it has enough space to turn with the rotors on.

Figure 58 front side rotor and attachment piece assembly

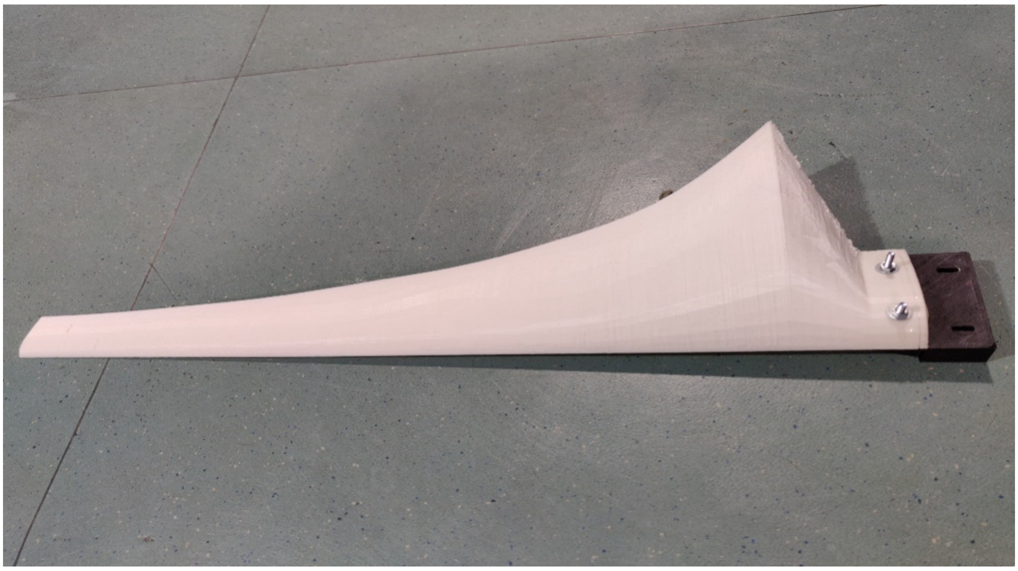


Figure 57 back side rotor and attachment piece assembly

To balance the hub with rotor out the key slots in the attachment piece can be shoved out further to make the centre of gravity of a blade go out further. Extra m3 rings can also be added to the attachment pieces to balance the rotors out. It is also preferred to put on a m8 spring ring and a normal m8 nut instead of a locknut, because the tension on the bearings can be adjusted more precise than with a locknut. This will result in a smoother running hub and less tolerance on the bearings.

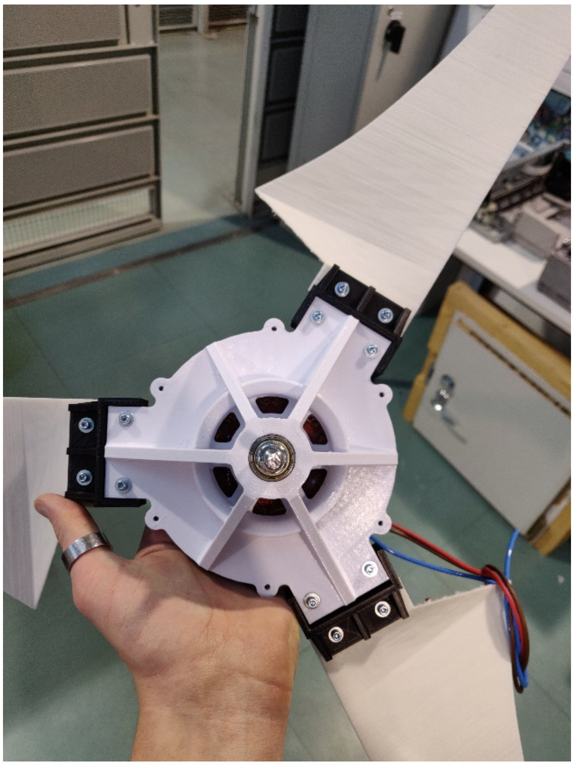


Figure 60 Front of hub

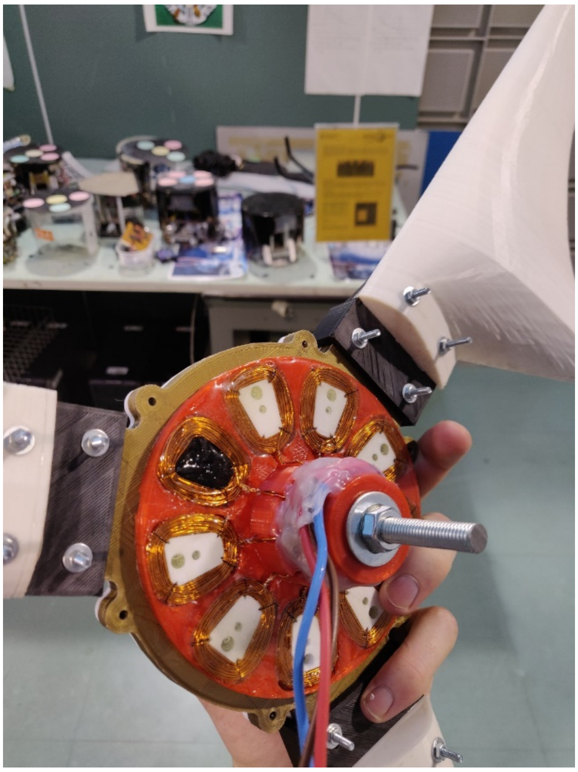


Figure 59 Back of hub

The rest of the turbine can be assembled as instructed by the manual made by the original designer.

5.3 Rectifier

To charge the Li-Po battery with the wind turbine, the 3-phases AC power must be rectified into DC power. In the original design, the rectifier used is a **DB35-04 manufactured by DIOTEC**.
As it is quite simple to build, the team decided to make it. It's a basic used of solid-state diodes, the electrical scheme can be seen below.

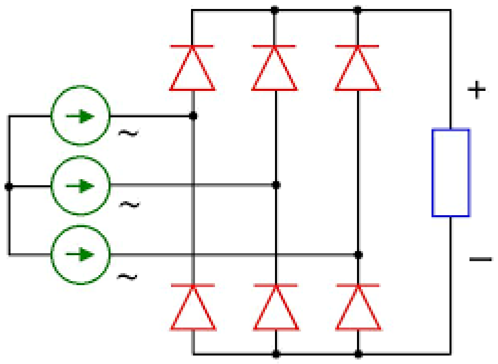


Figure 61 Electrical scheme of the rectifier

The diodes used to build it are the PH4148. It can easily be found in electric store around 5cents for 10 diodes. Diodes can be soldered on a perfboard. By making the it, the budget is lowered by more than 10 euros as a 3-phases rectifier cost around 10 to 15 euros.

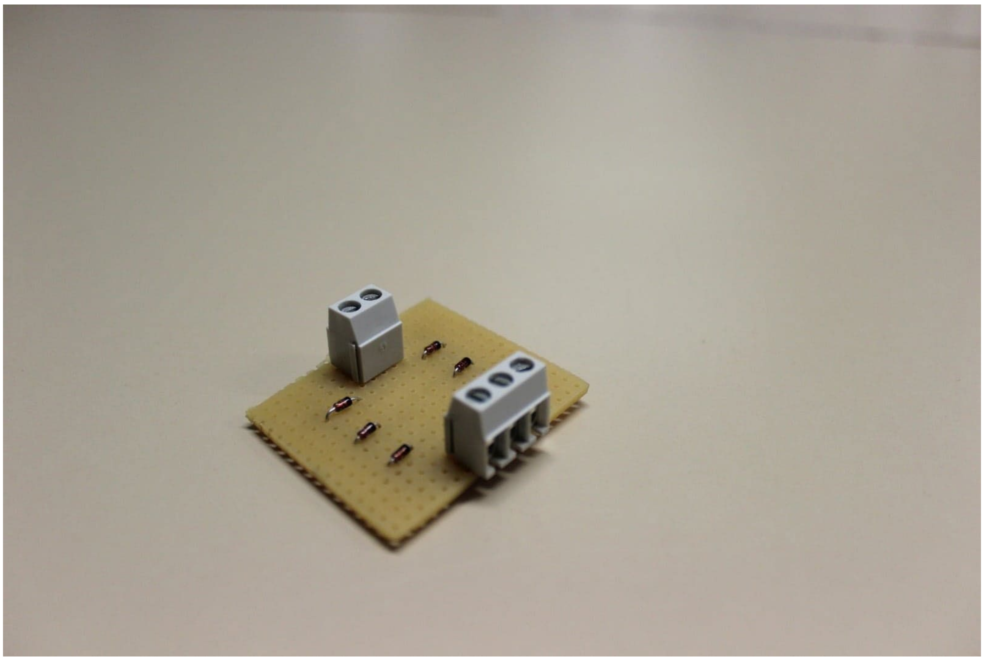


Figure 62: The rectifier

After testing this rectifier showed a relatively stable DC signal. Improvements were made by adding capacitor between the plus and minus points of the rectifier. Next this signal was fed into a BUCK-BOOST converter to get a stable voltage to charge the battery

5.4 Conclusion.

This paragraph will conclude, reflect and provide suggestions for improving the wind turbine. The biggest bottleneck for this project was getting all the non-printable parts. Some of these parts were hard to get because they are not common to get in Finland as they are in Germany, where the original designer is from. Some other parts were difficult to get because they were ordered later because they were thought to be found at Technobothnia. For example, the carbon brushes, which came in the latest, could not be found at 2 of the biggest hardware stores of Vaasa and not at a power tool specialist repair shop. In the manual of the wind turbine it is also written in the part list that part number 74, a ball bearing, is needed once but later two are needed. This mistake will run up into extra cost and into extra time waiting on a part.

The improvements that could be applied to the turbine in general is that the original designer does not have an optimal design at all. Because this product needs a lot of drilling, threading and glue to fit together and 3D printed products do not go well with drilling, especially small holes for m3 bolt that are used a lot. Same goes for threading because the plastic is very fragile the thread can be threaded dead very fast and then a new part must be printed. The original designer also used glue to put everything together which is not necessary at all for most of the products, which will save weight, money and creates exchangeable parts which can be replaced when broken. And exchangeable parts will be needed because the new rotors are so efficient that the bearings will probably be the first parts that need to be replaced.

An extra generator could also be used at the back of the turbine if it was redesigned for that, this would result in an extra load for the rotor, but the rotor would turn slower then so would expand the lifespan of the bearings. This would also create a better weight balance, because the turbine now has more weight at the rotor end than at the vane end. Redesigning the holes for the carbon brushes to rectangle holes instead of square holes would open a lot of variety for using different carbon brushes. This is because most power tools use square carbon brushes.

6 Docking station

This paragraph will show the trajectory of designing and building the docking station for the lawnmower. There are a couple of things that need to be thought out well to design a good docking station, with the first being the wire placement in the station because the lawnmower will guide itself home through the boundary wire. The second thing that needs to be thought out is the charging points and the placement of these points in the docking station. The controller board and all other components will get a place in the docking station where there is room or where room can be made for it.

6.1 Requirements

The first thing that is done is making a requirements package for the docking station, this is a list of the fixed requirements, the variable requirements and the wishes for the docking station. This list is made to check if the product fits all requirements when it is done. In table 4 down below is the requirements package shown for the docking station, this table has requirements in different categories to make them more specific.

Table 4 Requirements docking station

Nr.	Category	Requirement	Description	Fixed	Variable	Wish
1.1	Mechanical	Force lawnmower	Withstand the lawnmowers power	X		
1.2		Force rain	Withstand up to 3 hours of hard rain		X	
2.1	Dimensions	Print size	The parts need to be able to be 3D printed	X		
2.2		Lawnmower	The lawnmower needs to fit in completely in the dockings station	X		
3.1	Durability	Lifespan electrical components	Lifespan of 3 years		X	
3.2		Lifespan mechanical components	Lifespan of 3 years		X	
4.1	Power	Sustainable Power	Connection to a sustainable power supply	X		
4.2		Power outlet	Connection to a power outlet	X		
5.1	Communication	Returning and sending	Must communicate with the lawnmower	X		
6.1	Manufacturing	3D printing	Use a 3D printer to manufacture the parts	X		
6.2		Price	Maximum cost of 100 euros		X	
7.1	Usage	Interface	User friendly interface			X

6.2 Function analysis

To get a clear image of what the docking station must do a function analysis will be made. This exist by specifying the main function and splitting it into sub functions. These sub functions will then be used in the morphological overview, seen in the next paragraph. In a function analysis a noun will be put together with a verb to make a function about what the docking station should do. The main function of the docking station will be charging the lawnmower, so the noun is 'lawnmower' and the verb is 'charging'. All the functions will be shown in table 5.

Table 5 Functional analysis

Main function	Lawnmower	Charging
Sub function	Lawnmower	Guiding
	Lawnmower	Protecting
	Power	Controlling

6.3 Morphological overview

A morphological overview is made by crossing the sub functions with methods to achieve the sub function. Then a line can be drawn from top to bottom through each method and those methods will then be used to make a first concept. There will only be drawn one line because time is short and working out more concepts will be too much time consuming, so each method will be thought out carefully. The morphological overview can be seen in Figure 63

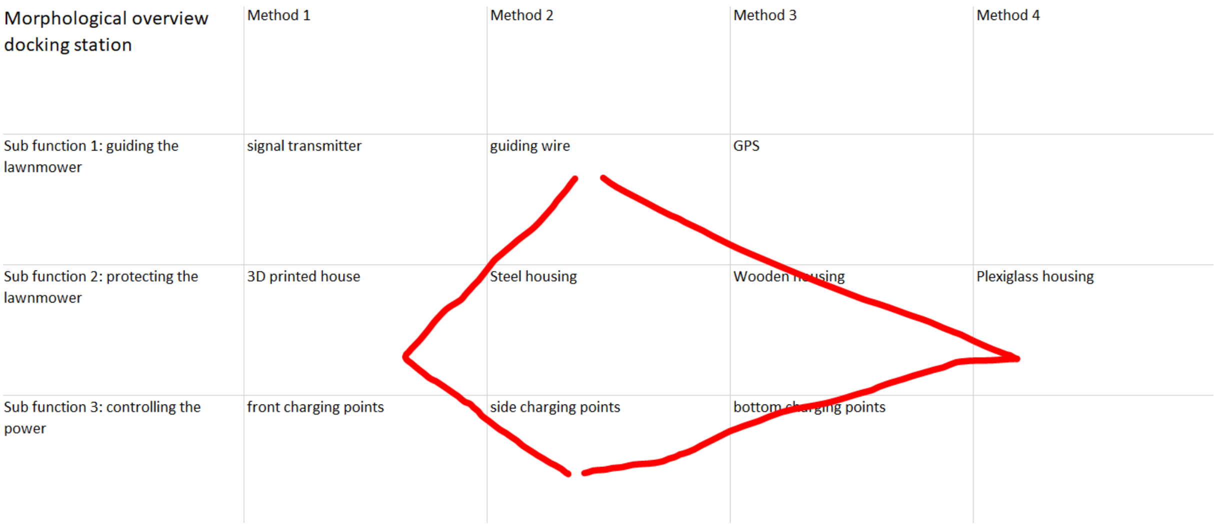


Figure 63 morphological overview

After discussing all the methods, the red line seems to be the best option. It is split in two because for protection a combination of plexiglass and 3D printed parts will be used because those are easily accessible parts for the project. It would take a lot of time to get wood and steel parts in the right size as to plexiglass which can be laser cut in technobothnia. The guiding will be done by mounting the guiding wire, which the lawnmower already uses, into the housing so the lawnmower can follow it home. Charging will be done by the side of the lawnmower and the housing because there are mounting holes free from a battery holder on each side. Also, because charging from the front would interfere with the crash system that is built into the lawnmower.

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6.4 Concept

This paragraph will show the designing of the housing based on the methods chosen in the morphological overview. At first the housing of plexiglass and 3D printed parts will be shown followed by the charging point and at last the guiding system will be explained.

Because printing the whole housing is a waste of time and material the housing will be a combination of plexiglass and 3D printed parts to keep the plexiglass together and give it a tight fit. The plexiglass will be cut on a 30W laser cutter, which will read the DXF files created through Solidworks. The 3D printed parts will be made on any available printer and will all consist out of PLA with an infill of 66%, walls of 1.6 mm and a top and bottom fill of 1 mm.

Before the designing of the housing started a dummy of the lawnmower was made into a 3D model. This was done to get an accurate picture in 3D to model around. The model also had the holes that were still free in it to design the charging point around. The first part that was designed for the housing were three plexiglass panels, one for the bottom, one for the side, and one for the back. Because the available laser cutter only has a cut area of 600x300 mm the bottom panels had to become 2 separate panels. They were made identical to make cutting and designing easier. The bottom panel can be seen in Figure 64, it has four holes on the top for connecting to the side panels and three holes at the bottom for connecting to the other bottom panel. The slots are for the guiding wire parts.

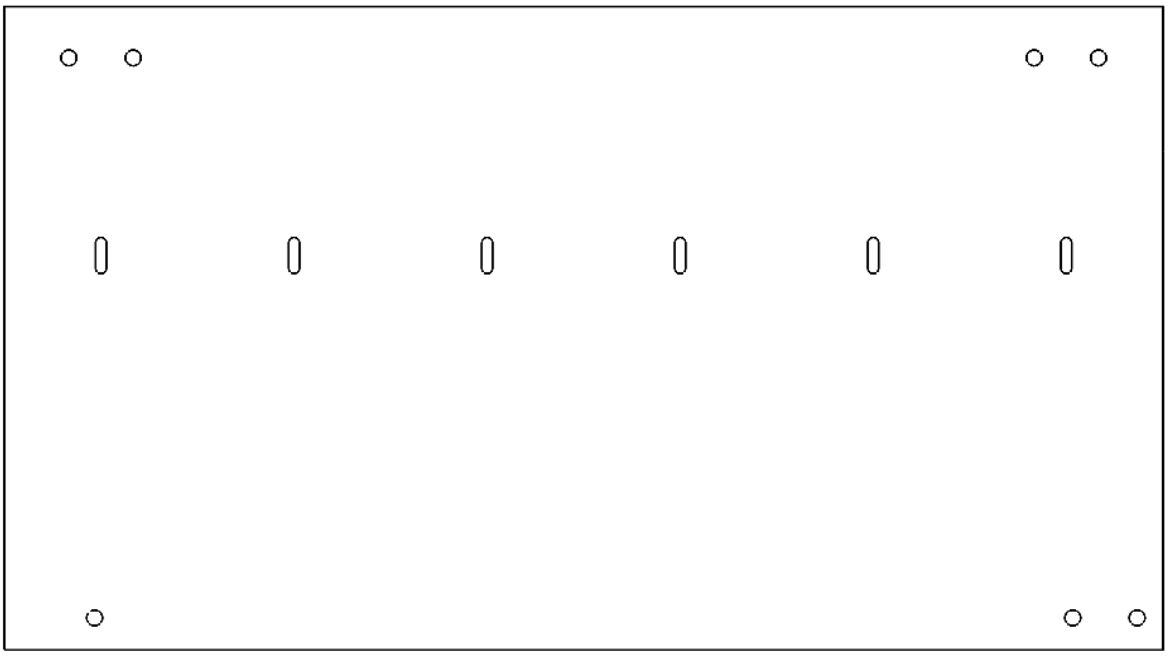

Figure 64 Bottom panel

The Side panel, seen in Figure 65, has four holes at the bottom for connecting to the base plate and six in the top for connecting to the roof. The panel also has two holes at the right side for connecting to the back panel. The slots in the middle are for attaching the charging module and to adjust it.

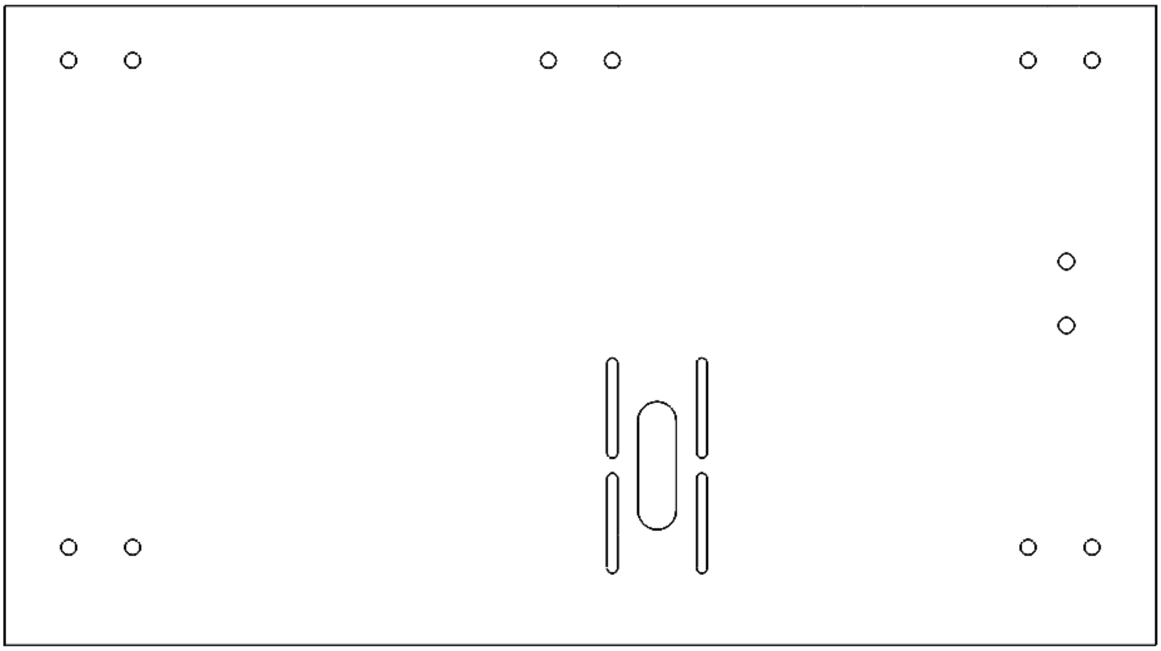

Figure 65 Side panel

The back panel, seen in Figure 66, has two holes at both sides for connecting to the sides. The two small holes in the middle are mounting points for the lawnmower transmitter and the two bigger holes below are for connecting to the base panel. The two 4 mm diameter holes left are for connecting the wire guides.

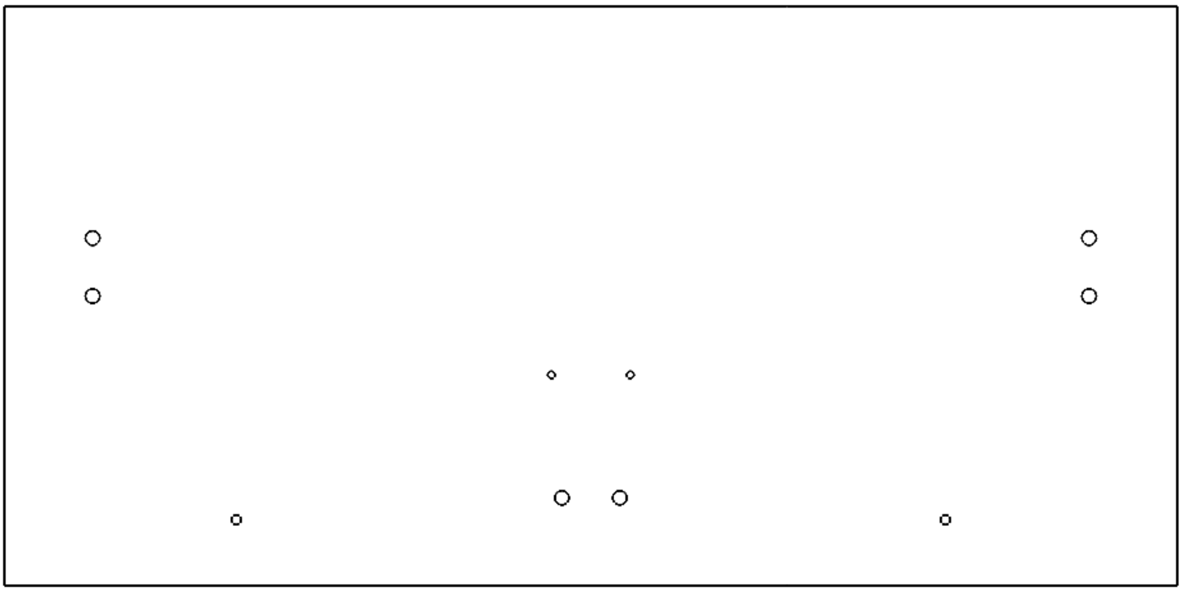

Figure 66 Back panel

The roof panel, shown in Figure 67, has two rows of holes. The upper row is for connecting to the other roof panel through the roof corners and the lower row is for connecting to the side panels.

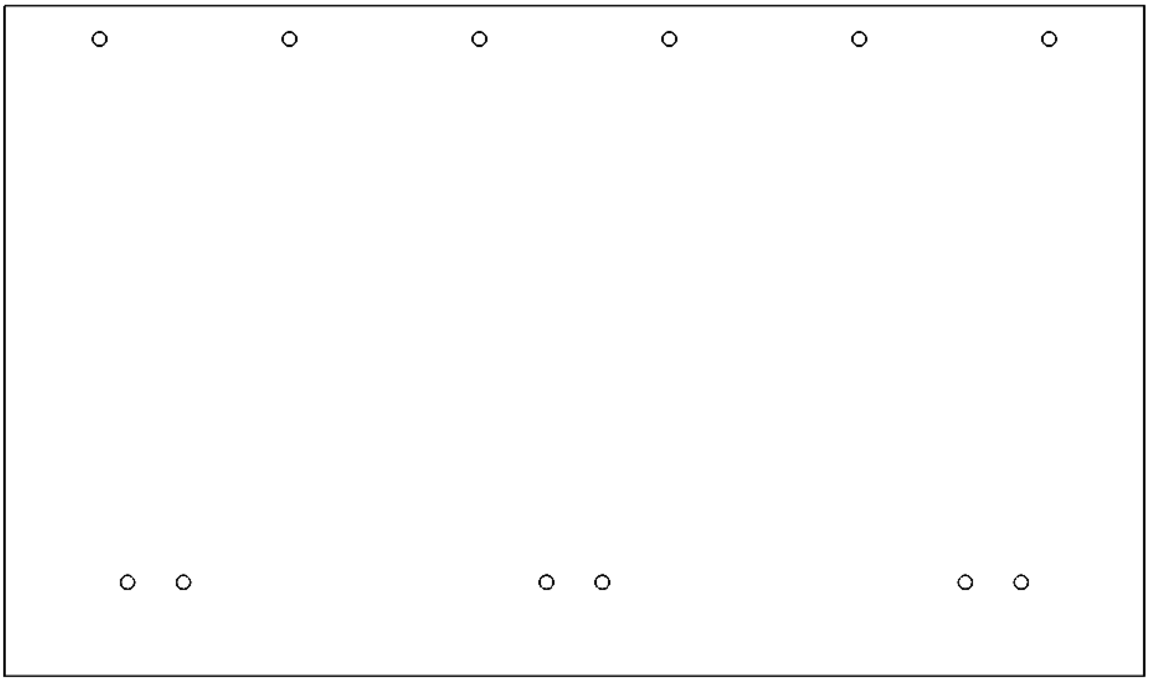

Figure 67 Roof panel

For attaching the two base panels together the drive-in plate and a 45-degree corner piece is needed. These parts are shown in Figure 68 and Figure 69 and both need m6 bolts.

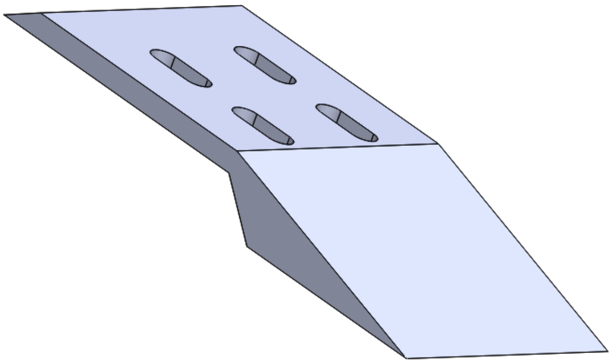

Figure 69 Drive in plate

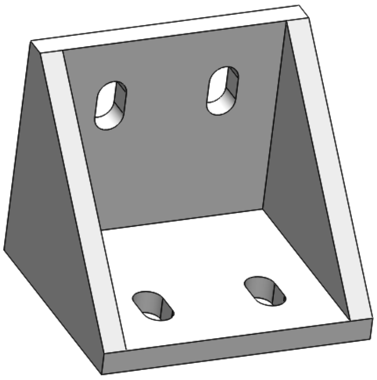

Figure 68 45-Degree corner piece

A 60-degree corner piece is needed to attach the side panels to the base panels, this part is shown in Figure 71. To attach the roofs to the side a 120-degree corner piece is needed, shown in Figure 70. These pieces also need m6 bolts.

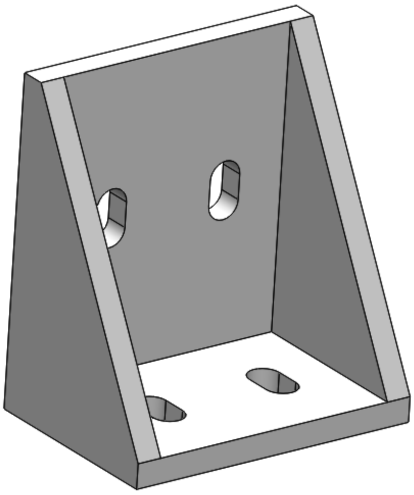

Figure 71 60-degree corner piece

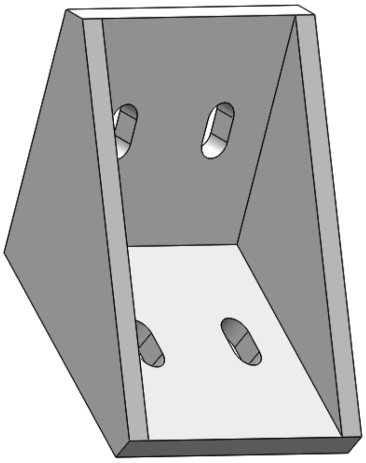

Figure 70 120-degree corner piece

The roof panels are connected to each other through the roof corner pieces, shown in Figure 72, and need m6 bolts.

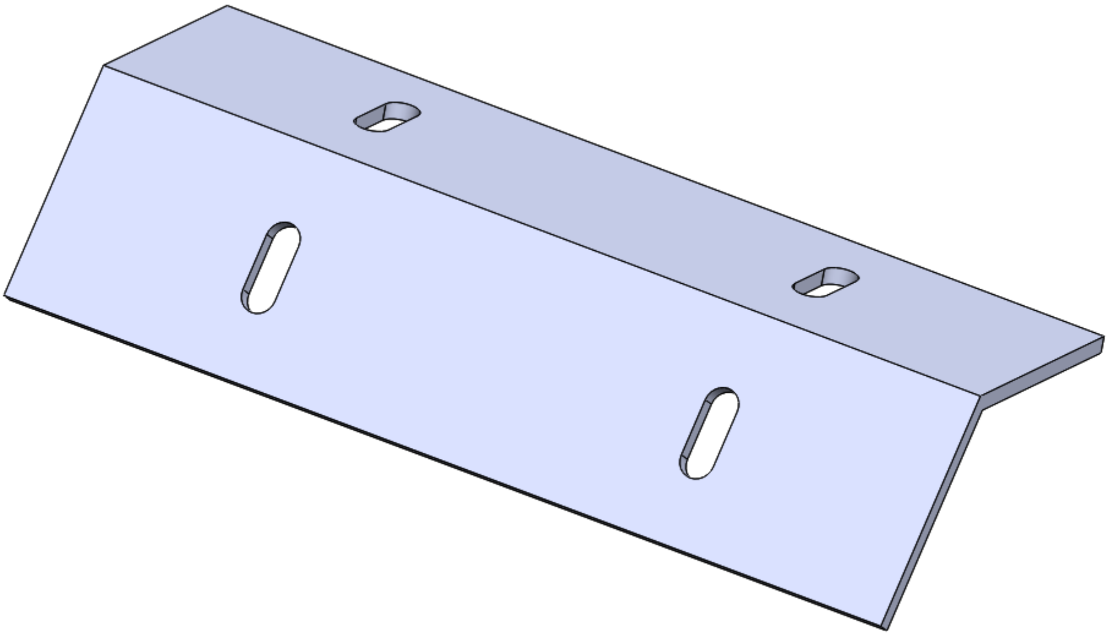

Figure 72 Roof corner piece

For charging the lawnmower a spring powered piston was designed. It consists out of a piston chamber, which is attached to the side panel, and through that chamber the piston can be pushed back. The piston has a rib on it so when it is in the chamber it cannot turn around, so the copper plate will stay in horizontal. The piston can move about 20 mm back into the chamber so even when the lawnmower goes in in a weird position it has room enough to adjust. The chamber has four hexagon slots for nuts to fall into, this makes adjust easier because only one end of the bolt needs to be turned to fix and loosen.

The piston must be inserted through the back, so it will stop on the side panel as shown in Figure 74 . The copper plate holder and copper plate can then be attached to the piston with an m3 bolt. The copper plate can be made from any piece of copper by cutting it to 65x25 mm and drilling a hole on the middle. The spring goes over the chamber and pushes on the copper plate holder shown in Figure 75.

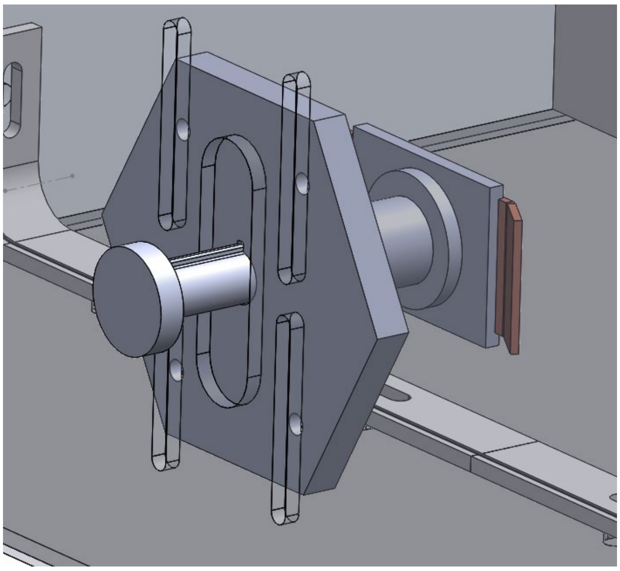

Figure 74 Assembly back side 3D

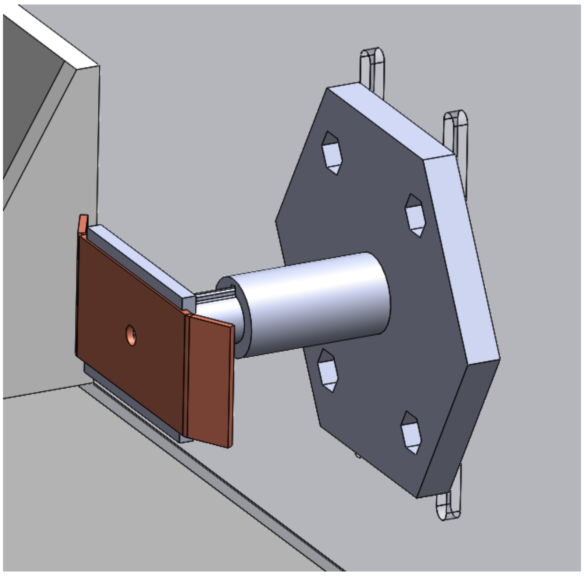

Figure 75 Assembly front side 3D

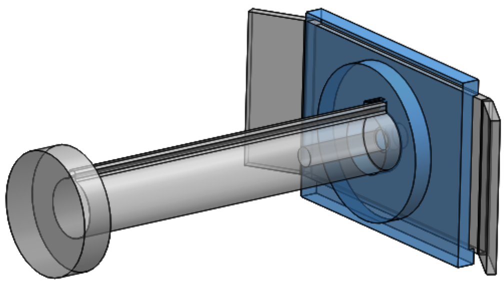

Figure 73 Attaching copper plate to piston

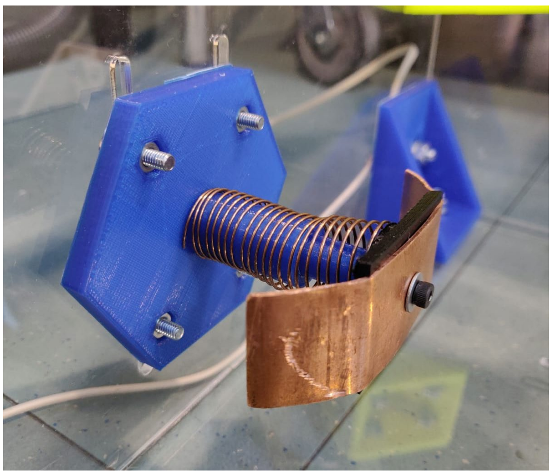

Figure 76 Assembly whole charging point

The guiding wire has to be inserted into the holes of the guide wire parts shown in Figure 77.The wire guides and the bottom panel both have slots so the wire guides can be adjusted to make sure the wires will guide the lawnmower in as accurate as possible.

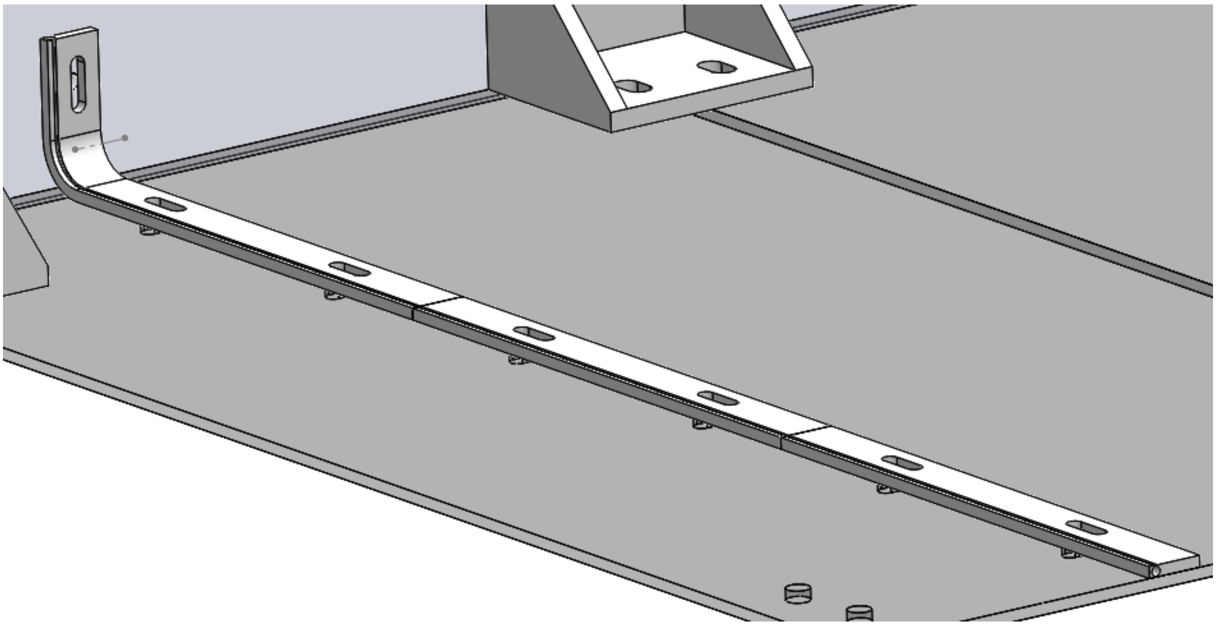

Figure 77 Wire guides

The full assembly can be seen in Figure 78

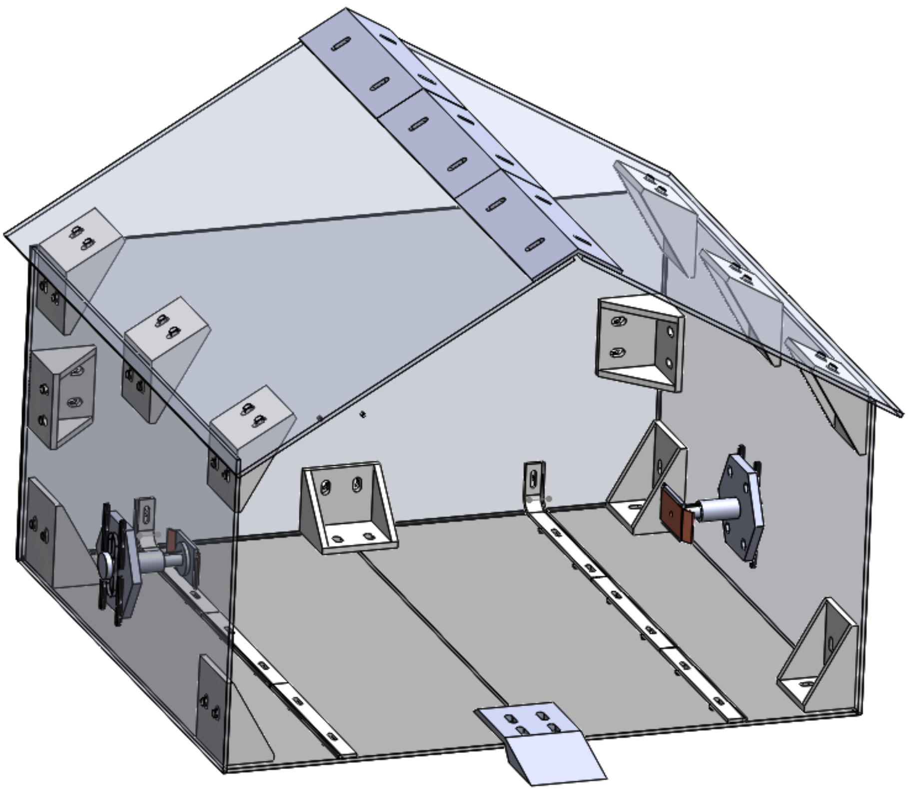

Figure 78 Full assembled Docking station

6.5 Part list

The 3D printed parts can be seen in Table 6 with the specifications next to it. The laser cut parts and other parts can be seen in Table 7 and the bolt, nuts and rings needed can be found in Table 8.

Table 6 Parts printed

Part number	Part name	Quantity	Infill (%)	Wall thickness (mm)	Top and bottom thickness (mm)
1.1	Base to Side	4	66	1.6	1
1.2	Side to Roof	6	66	1.6	1
1.3	Side to Back	3	66	1.6	1
1.4	Roof corner	3	66	1.6	1
1.5	Drive in plate	1	66	1.6	1
1.6	Piston chamber	2	66	1.6	1
1.7	Piston	2	66	1.6	1
1.8	Copper plate holder	2	66	1.6	1
1.9	Wire guide	4	66	1.6	1
1.10	Wire guide back left	1	66	1.6	1
1.11	Wire guide back right	1	66	1.6	1

Table 7 Parts to order

Part number	Part name	Quantity
2.1	Plexiglass baseplate	2
2.2	Plexiglass backplate	1
2.3	Plexiglass roof	2
2.4	Plexiglass side panel	2
2.5	Copper Plate 65x25x2 mm	2
2.6	Spring D 20 mm	2

Table 8 Nuts and bolts

Type	Size	Quantity
Hex Socket Bolt	M6	68
Hex Socket Bolt	M4	22
Hex Socket Bolt	M3	2
Nut	M6	68
Nut	M4	22
Ring	M6	136
Ring	M4	18
Ring	M3	2

6.6 Conclusion

This paragraph will conclude the docking station and is about the looking back on the requirements made earlier in this chapter and the improvements that can be done in the future.

Even though plexiglass will not rust or rot outside it is not the perfect material for this. The problem with plexiglass is that it cannot stand heat that well and it is not a stiff material. To make the docking station completely water proof the faces where the panels touch each other must be glued or purred together. Even better would be to use steel if there is access to a machine capable of cutting that, because of the ability to weld threads on it so the whole housing would not stand on bolt heads. Therefore, the housing would be standing on the ground and the base plate could be grinded at an angle at the front, so the drive-in plate would not be needed either. Cutting the bottom plate out of one piece is also preferred as it offers more stability to the docking station.

The charging point on the docking station would work even better if it were to be at a slight angle towards the lawnmower. This would mean less power is needed to push the piston down the chamber and that would result in a longer life span of the docking station. The recommended angle to print at would then be 60 degrees to maintain a good quality print.

Looking back at the requirements, that were put up at the start of designing the docking station, a lot of were accomplished. However, a few important ones were not achieved. The connections to the wind turbine was not made yet because there was not enough time yet to finish the turbine and lawnmower for that connection. A connection to communicate with the lawnmower was also not made yet. Some requirements are not yet ready to be tested because they require time, like the lifespan, and that can only be tested by using the docking station. In table 9 the requirements are shown again but now with a green cross if they were accomplished, a red cross if they were not yet accomplished and a black cross if they are still unknown.

Table 9 Realized vs goals

Nr.	Category	Requirement	Description	Fixed	Variable	Wish
1.1	Mechanical	Force lawnmower	Withstand the lawnmowers power	X		
1.2		Force rain	Withstand up to 3 hours of hard rain		X	
2.1	Dimensions	Print size	The parts need to be able to be 3D printed	X		
2.2		Lawnmower	The lawnmower needs to fit in completely in the dockings station	X		
3.1	Durability	Lifespan electrical components	Lifespan of 3 years		X	
3.2		Lifespan mechanical components	Lifespan of 3 years		X	
4.1	Power	Sustainable Power	Connection to a sustainable power supply	X		
4.2		Power outlet	Connection to a power outlet	X		
5.1	Communication	Returning and sending	Must communicate with the lawnmower	X		
6.1	Manufacturing	3D printing	Use a 3D printer to manufacture the parts	X		
6.2		Price	Maximum cost of 100 euros		X	
7.1	Usage	Interface	User friendly interface			X

7 Merging the projects

The second goal of merging the project failed due to time constraints and missing parts. In this chapter however, the missing parts are described and solutions for found problems are suggested.

The first problem that was encountered for the merging of the system was the problem of the low accuracy of the lawnmowers sensors. The sensors on each of the boards are currently not calibrated between each other as described in chapter 4.4 This means that the values cannot be entered in a PID controller. The values would be too different when nearing a corner that the system would tip over due to an unstable error. This is caused by “noise in derivative” [20] errors where large amounts of error change can cause noise in the output of the controller. This results in unwelcome behaviour in the motors and excessive turning to the point that it cannot stability follow the ground wire fence.

To fix this first problem multiple solutions were stated in chapter 4.5. These solutions all revolve on getting either separate streams of data that can be used in the controller of changing out the wire and going on a GPS based system.

The second problem that was encountered in the merging process was that it is driving straight in the charging dock without forward facing sensors is hard. Especially without the aid of a good guide wire. To overcome this problem ideas were pitched for ultrasound and infrared sensors on the front of the machine. This would give the robot the opportunity to see ahead and to the sides to straighten itself out before entering the shed. From the two-suggested solutions infrared would be the better solution due to the echo chamber effect in the charging shed.

Problem number three that was encountered was the lack of carbon brushes. These brushes had an unexpectedly long lead time and could not be replaced by other brushes. To overcome the problem multiple approaches were suggested. First one being getting carbon brushes from small electro motors from scrap. These carbon brushes did not come with springs attached and soldering wires or press fitting a cable to it proved to be unstable. The carbon broke off when soldering and the press fit did not have a secure enough fit to make a reliable connection even when slotted in a custom designed bracket and pressed against with a pen spring.

The last problem that was encountered was the fact that the language barrier between the project group and the local population was large. Due to this the metal parts for the wind turbine were hard to get a hold off. The first attempt to secure the metal rings for the project was by utilizing the resources in Technobothnia. This was done by asking the metal shop next to the 3d printing lab to create the rings after a technical drawing was made. However, the students forgot to make the rings and after a few days a second solution was tried. The second solution involved the metal shop downstairs in Technobothnia however the staff available in this metal shop did not speak English and an appointment was made with a local person to go back at another time. This was again a fruitless endeavour since the metal shop did not have the metal and did not want to create items for non-VAMK students. A third solution that was tried was laser cutting smaller sheets of metal from the used electronics bin on the laser cutter. This plan did not work due to the low power of the laser cutter. The last plan was finding a metal shop nearby to create the metal parts. The effort to find a suitable place was substantial and still then took a long time to get due to the small order. In the end workshop 60 kilometres outside of Vaasa was found that would accept the order.

The reason that the metal parts could not be made in Technobothnia was the lack of metal working tools available to the project group.

8 Conclusions

To answer the original research questions found in the rationale of the project starting from the first one creating an autonomous lawnmower that is charged by the windmill. This part of the project failed due to multiple reasons. First one lacking time and experience in getting parts in Finland. This was exaggerated by the language barrier in part suppliers and the complete project group.

Another reason why this part of the project failed was that the second research question had to be kept in mind mainly that it should be buildable in a DIY home factory. Thus, the project was focused on the using of the shelf components and buildable with tools that are found around the house and a 3D printer. Due to this limitation the sensors were not accurate enough to follow lines and other sensors could not be added before testing the system in its original configuration. Therefore, making a connection and driving into and finding the charging dock is difficult. This makes it virtually impossible to make the system truly autonomous.

However, the system is now setup and documented in a way that in the future people can relatively easy integrate the charging dock with little modifications to the overall system. This can be seen as a success. The docking station does require access to a laser cutter, or plasma cutter if steel is chosen as panels. This does not make the docking station DIY at all.

Integration of the windmill is straight forward however due to long lead times on parts the windmill is not completely finished. However, the power generation part could be tested. The test concluded that the power generation of the system is insufficient in low winds. In higher winds the power generation 24/7 generation should be possible. But in higher winds the turbine turns so fast that vibrations will be a big problem. And because of how late the wind turbine is finished no extensive testing in high winds was done. The blades that were printed for the windmill are also not available for everybody because they require a printer that can print 500 mm in at least one axle. The blades were also printed with volcano PLA which gives them stiffer and harder qualities over normal PLA.

The main question was if items like these are able to be created at home by someone who has access to a 3D printer and has hobbyist tools available. The result is no. Items like this are too complex and take too much time to create for the average person, especially if the lawnmower, wind turbine and docking station need to be combined. The design of the lawnmower and wind turbine is in general too much 3D printed focused which, from an engineering perspective, is not the best choice for every part.

9 Recommendations and suggestions

A few things can be improved about the lawnmower, wind turbine, and docking station to make them more DIY. The lawnmower could be made more DIY by lessening the amount of useless 3D printed parts and use stronger, easier to make, and cheaper parts. For example, the base of the lawnmower could have been made out of a wooden plate because the base only needs holes which can easily and quite accurately drilled by the average hobbyist. The cutting disk could also be made out of a thin piece of sheet metal, which if sharpened properly would not even need blades.

But by simplifying those parts to wooden or steel parts the problem rises of the availability of those parts. In Vaasa it was quite hard to just get some steel sheets. This however depends on the city where the project is fulfilled and the contacts available to get those parts. The availability of those parts would most certainly rise if there was access to someone who could speak Finnish and has knowledge about the project.

It would have also been nice if there was access to more professional machinery. A lot of drills broke off because the 3D printed parts could not be fixed properly, or the drill did not have enough power, so for that scenario a drill press would have been perfect.

To make the lawnmower actually work and make it able to return a GPS tracker would be needed instead of the guiding wire. A GPS tracker will not only make it able to return to the docking station, but it will also lower the cost of the whole lawnmower by getting rid of a few hundreds of meters of guiding wire. A GPS tracker for Arduino usually only cost about 3 to 15 euros. The area of where the lawnmower has to stay in still has to be set up like with the guidewire, but it would then be much easier by just walking the boundaries of the area with the lawnmower once. It would also allow the user to track where the lawnmower has exactly been. In future project that might even lead to a lawnmower that knows where it has already mowed. In addition to GPS, infrared sensor can be installed in the front of the lawnmower to aid in the guiding in the dock. This would make the device less likely to break the current shed and would make for a longer lasting design. Another improvement for the lawnmower would be a change from the Arduino UNO to an Arduino Mega Micro, the footprint is the same however the addition processing power and ports on the Mega would make precision guiding and control of the robot easier and the tripling of ports would make it easier to expand on the project by adding features as wireless communication to let more lawnmowers work together with one base station more control by the user due to the possibly of data storage and collection, more sensors for environmental measurements and multiuse capabilities like fertilization or resowing of grass.

10 Appendices

All the files and codes that are referred to in the report can be found in the file folder that goes with the report. The folder is called “EPS Lawnmower autumn 2018 appendices”

The STL files for the Battery mounts can be found in folder “Battery mounts”

The STL files for the Lawnmower charging point can be found in folder “Charging point”

The STL files for the Rotors and the attachment pieces can be found in folder “New blade design”

The STL & DXF file for the wind van can be found in folder “Wind vane”

The STL & DXF files for the docking station can be found in folder “Docking station”

The STL file for the aluminium sensor mount can be found in folder “Replaced parts lawnmower”

The DXF file for the cover plate of the lawnmower can be found in folder “Replaced parts lawnmower”

All coding can be found in the folder “Coding”

The STL and manual for the wind turbine can be found in the folder “Wind turbine”

The STL and manual for the lawnmower can be found in the folder “Lawnmower”

The link to the website is: http://wp13240685.server-he.de/index.html

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