Design of an Autonomous Weeding Vehicle
Used in the Agricultural Industry

Simon Axbom and Lisa Ralsgård

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Abstract

This thesis describes the development of an autonomous weeding vehicle for the agricultural industry. It has been done as a project at RMIT University in Melbourne and the aim was to develop a design for the vehicle which could later be used to develop a commercial product.

The current trend in the agricultural industry is larger machines that can benefit from economies of scale. These heavy machines are causing three major problems for farmers; serious subsoil compaction, longer disruptions due to single vehicle failure and an inability to efficiently deal with weeds which have resulted in a rapid increase of herbicide resistant weeds.

This project is an attempt at solving these problems by integrating the already existing stationary farming robot FarmBot with a lightweight, cost efficient, aesthetically pleasing and durable frame on wheels that can operate autonomously on farms and is being powered by solar energy.

The project started by researching the agricultural industry and benchmarking similar products, which gave an understanding of the problem and how it could best be solved. Since many different parts had to be developed, it was decided that the complex problem was to be divided into several sub problems which were then solved parallel with each other. The different concepts were evaluated and a final product was developed visually using CAD.

The finished vehicle was primarily made out of parts that can be ordered off the shelves as well as parts that can be 3D printed. It weighs 154 kg, the parts costs around USD 5300 and it is equipped to be able to operate autonomously for at least a day at a time. It is very easy to assemble and has a modular design, which simplifies further development.

Keywords: Mechanical Engineering, Product Development, Agricultural Robotics, Weeding, Lightweight Vehicle.

Sammanfattning

I denna rapport beskrivs hur en robot för ogräsrensning inom jordbruksindustrin har utvecklats. Examensarbetet har utförts som ett projekt på RMIT University i Melbourne och är ämnat att utvecklas vidare till en kommersiell produkt.

Den nuvarande trenden inom jordbruksindustrin är större maskiner som kan dra nytta av stordriftsfördelar. Dessa maskiner skapar tre stora problem för bönderna; allvarlig komprimering av jorden, långa avbrott på grund av tillförliten till ett enda fordon och en oförmåga att effektivt hantera ogräs vilket har resulterat i en stark tillväxt av ogräs som är resistenta mot ogräsmedel.

Detta projekt försöker lösa dessa problem genom att integrera den stationära farmroboten FarmBot med en lättviktig, kostnadseffektiv, estetisk tilltalande och hållbar stomme på hjul som kan arbeta självständigt och drivs av solenergi.

Projektet började med att granska jordbruksindustrin och benchmarka liknande lösningar, vilket gav en förståelse för hur problemet kunde lösas på bästa sätt. Då många olika delar behövde utvecklas delades det komplexa problemet upp i mindre problem som utvecklades parallellt med varandra. De olika koncepten utvärderades och en slutlig produkt framställdes visuellt i CAD.

Den färdiga roboten är främst uppbyggd av delar som går att beställa samt delar som går att 3D printa. Den väger 154 kg, delarna kostar runt USD 5300 (SEK 47 600) och den är utrustad för att kunna arbeta självständigt på stora fält under minst en dag. Monteringen är väldigt enkel och den har en modulär design, vilket förenklar framtida utveckling.

Nyckelord: Maskinteknik, Produktutveckling, Jordbruksrobot, Ogräsborttagning, Lättviktigt Fordon.

Acknowledgments

This project has been performed at the Divisions of Product Development within Mechanical Engineering at Lund University together with Dr Hormoz Marzbani, lecturer at RMIT University in Mechanical and Automotive Engineering. We would like to thank a few people for making this thesis possible.

This Master thesis has been a great learning experience with many opportunities and challenges. A lot of responsibility has been given to us which has made it possible to create something in the way we wanted it to be and something we are proud of. We would therefore like to give a big thanks to our supervisor Hormoz Marzbani for believing in us and giving us this opportunity to use our technical and creative skills, as well as letting us gain further knowledges within the product design process due to the freedom we had while working.

Another thanks goes to our mentor at Lund University, Damien Motte, who has helped us throughout the project with very quick and helpful responses. We are very grateful for his guidance.

Melbourne, December 2018

Simon Axbom and Lisa Ralsgård

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1 Introduction

This section contains the introduction to the project, such as information about the agricultural industry, goals of the project, delimitations, what has previously been done in the project, and problem description.

1.1 Background

Agriculture in Australia is currently driving the economic growth, with an estimated farm production value of USD 46.4 billion (AUD 62.8 billion) in 2016-2017. The agricultural industry is performing strongly with the fastest growth out of Australia's 19 different industries. Cropping is one of the major contributors, and farm exports were estimated to a USD 35.4 billion (AUD 48 billion) value in the same year, which almost stands for the entire goods and service exports [1].

As the industry gets bigger, the farms get bigger and so does the demand for more advanced technology to maintain the farms. Advanced technology is in the 21st century an essential part of our society. Nonetheless, the agricultural industry has always been early adopters to the new technological innovations due to the demanding environment. Today humans alone could never take care of sowing, watering, removal of weeds, and harvesting and depend greatly on automatic machinery. With bigger farms follow more production costs, and because of the price fluctuations farmers now need more than ever automatic equipment to keep up with the demand [2].

Automatic machinery is needed for many things in order to optimize crop yield. Weeds are a big threat to the natural environment and reduce farm productivity. The agricultural industry, as well as the consumers, are affected by the reduction in both quantity and quality of the crops. The agricultural production loss in Australia alone is estimated to USD 1.9 billion (AUD 2.5 billion) a year and weed control costs the farmers USD 1.1 billion (AUD 1.5 billion) a year [3]. Weeds compete with plants for sunlight, nutrients, space, and water and they are excellent in surviving and reproducing in disturbed environments. With 73% (in 2004-2005) weed control is reported as the most common issue among landowners, in comparison with soil and land issues that 46% of the farmers reported, and 38% reported water issues. It is clear that the farmers spend a lot of money to take care of this countrywide problem [3].

1.2 Problem Description

Detecting and removing weeds is today a big problem among farmers in Australia, as well as the rest of the world. The two standard treatments are to spray the entire field with herbicide, which covers not only the weeds but also the crops, or do nothing at all which makes the weeds uncontrollable and results in a reduction in crop yield potential. In order to optimize the harvest, weeds need to be controlled and removed without harming the crops.

Farmers nowadays use heavy equipment to maintain their farms which results in soil compaction that reduces the crop yield. The bigger the farms get, the heavier the machineries are developed to keep the maintenance as efficient as possible. This however creates a problem with soil compaction, and lightweight yet efficient equipment is therefore required to solve this issue.

There are a couple of already existing solutions to soil compaction, but these machines are often very expensive. Farmers naturally choose the option that is most economically efficient and results in the biggest harvest. There are ways to come up with cheaper solutions to the problem and this is what Professor Hormoz Marzbani, lecturer at Royal Melbourne Institute of Technology, envisioned when he encountered the FarmBot. FarmBot is an open source CNC farming machine that can grow plants and control weeds in private gardens without human interaction, see Figure 1.1. This means that anyone can download and modify the source code, which was very important for this project. Marzbanis idea was to modify and combine this product with a vehicle that can drive autonomously on fields between crops in order to remove weeds on the entire field. It would be cheaper than the existing solutions and would likely be a strong competitor on the market. Marzbani and his team had done the coding and developed the software for the project, but he then needed a vehicle design that put it all together and made it look appealing, without costing too much or having too much of an impact on the soil.

Figur 1.1. The open source FarmBot [38]

1.3 Project Goals

The main goal of this project is to design a lightweight farm vehicle that can detect weeds and remove them on a specific type of crops by spraying a small amount of herbicide. An appealing design is desired where the electronic equipment is attached to the frame in the best possible way. The goal of this project is to make a CAD-file that shows what the vehicle would look like, that in the next phase could be developed to a commercial product. This design will be something that is in between a prototype and a commercialized product. The original goal was to develop a well-working prototype that could show the purpose and benefits of the robot to attract future investors. However there wasn't enough time for this and it was therefore decided quite early that a physical prototype would not be built but that all the documentation required for this step would be delivered by the end of the project. Development will be done by generating different concepts that will go through several evaluations to find a design that is as cheap and lightweight as possible while still keeping it a high quality product.

1.4 Previous Work

This project had already been ongoing for several months before the start of the vehicle design phase, and a lot of development had already been made. Most of the work that had been done was with the software. Code had been written to make autonomous steering possible, the image sensor part of the problem had been worked on and the FarmBot had been reprogrammed for its new purpose.

The team had already made a simple prototype, see Figure 1.2, to test the autonomous steering, and an electric wheelchair had been disassembled and used for the prototype. The parts that were reused were the four wheels, the joystick and the two motors. An Arduino and a developer board had also been brought in to be able to test the prototype.

Figure 1.2. The first prototype

By testing the first prototype it was seen that the autonomous steering worked and the project was ready for its next phase, the design phase. The caster wheels that were used as the back wheels worked well and were therefore going to be reused for the next prototype, however the front wheels were considered too small and needed to be replaced.

1.5 Delimitations

The one requirement that put the most limitations on the robot was the fact that all the materials used for the robot needed to be either off the shelf, 3D-printed, laser cut or something that has already been used for the project. This meant a huge limitation to what parts that could be used for the final design, but it is an understandable requirement when considering the goal of this phase.

Another limitation was how much the total cost of the parts for the vehicle could be, which was set from the supervisor at USD 3000. This budget was excluding the parts that were already used in the prototype as well as the FarmBot. Since it was only going to be a prototype, there could not be expensive design choices. If the prototype attracted investors however, the budget wouldn’t be as limited for further development.

2 Methodology

In this section it is described what methods have been used to solve the problem. It is also described how the time for the project was allocated.

2.1 Plan Timing

This master thesis project stretches over 20 weeks. In Appendix A a Gantt-chart shows how the limited time was allocated for the different stages in the development process. Since it was not necessary to make a prototype, the allocated time for this was very short and would only be done if there was enough time. The chart was estimated in the beginning of the project and was updated throughout the process, it therefore shows planned start and length, as well as actual start and length.

2.2 Approach and Design Process

The problem was approached using the methods presented in the book *Product Design and Development* by Ulrich & Eppinger [4]. This approach was chosen due to the multiple concept generations and thorough evaluations. By using this method, a great amount of concepts can be generated which makes it a promising approach to find an optimal solution. The problems needed to be divided into several sub problems, seeing that the robot has multiple different parts, which would make it easier to approach. In this project several different concept generations and evaluations have therefore been made and in the end the results have been put together.

The different phases in the design process is shown in Figure 2.1. The first step is to identify customer needs, this however was not necessary in this project since the requirements were already given from the supervisor, Hormoz Marzbani, in the beginning of the project. These requirements have been converted into interpreted needs and later established specifications.

Research also had to be done to get a better understanding of the problem as well as benchmarking to see how others have solved similar problems.

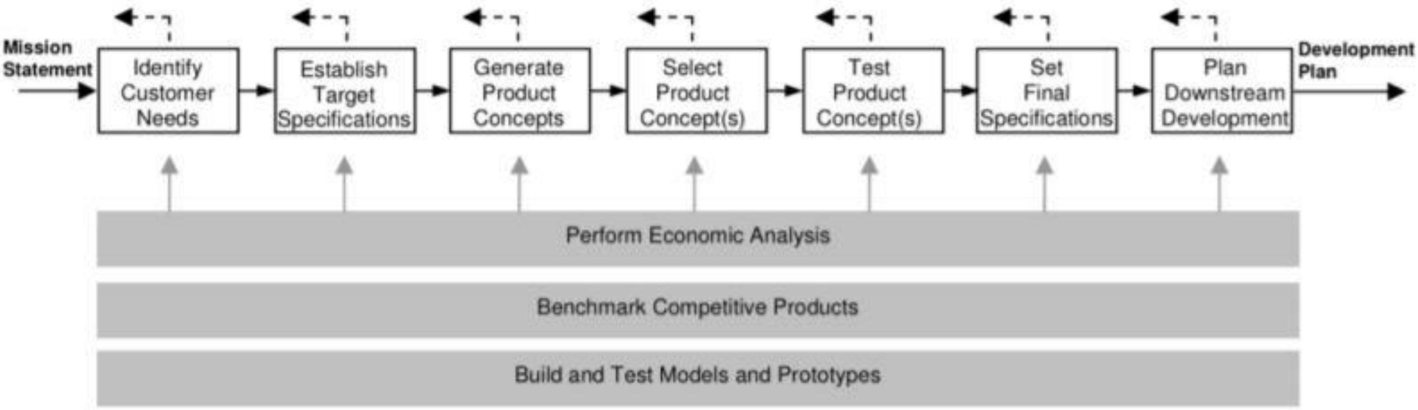


Figure 2.1. The Design Process [4, p. 16]

3 Research

This section shows the research process that was done before the start of the project. It describes what some of the concerns are in the agricultural industry, herbicide usage, weeding vehicles, and the FarmBot.

3.1 Crop production

The world's population is projected to reach 9.8 billion people by 2050 [5], which will require an increase of today's food production by 70% [6]. A decreasing rural labor force with an increasing average age [7] will be tasked with producing more food and fiber to a growing population. More feedstock will be needed for an expanding bioenergy market and the world will need to assist with the development of many third world countries that relies on agriculture. The world's population will get wealthier which means an increase in food consumption [6]. When income rises, the consumer preference shifts from wheat and grain that produces around 0.2 kg of carbon dioxide per kg [8], to legume and then to high energy consuming food like meat which can produce between 22 and 27 kg of carbon dioxide emission per kg [7][9][10]. All this while adapting to climate change and the fact that carbon dioxide emissions need to be minimized.

It is clear that more efficient and sustainable production methods will be needed, especially seeing how 38.6% of Earth's total land area has already been converted to pastureland and cropland [11]. 90% of the needed increase in food production is expected to come from increased intensity and higher yields [6], however the growth in crop production has been steadily declining since the 1950s. The rate of growth in yields of the major cereal crops have gone from 3.2% in 1960 to 1.5% in 2000 [12] and it's clear that this decline needs to be reversed to be able to feed the people of the world in the future.

Over the last decades there have been two clear trends when it comes to how farmers operate. The advancements of technology have introduced a range of new agricultural equipment and methods such as sensors, aerial images, robots and GPS technology [13]. It has allowed farmers to control their operations better and understand what is needed. Drones can be used to spray certain parts of the field or take aerial images that can be used to tell if the crops are ripe or if there is a problem somewhere. Sensors are being used to measure wind speeds, soil conditions, temperatures and even fertilizer requirements. The agricultural technology market is booming, with investments increasing by 80% annually since 2012, and there are even researchers who claim that they think that full scale adoption of these new technologies could mean an increase in productivity that hasn't been seen since the mechanization [14].

Agricultural machines have become bigger and bigger, which is a trend that many equipment manufacturers predict will continue [15]. These larger machines are more useful when taking advantage of the economies of scale; a larger machine usually has a better work rate than smaller machines. It is easy to see how this is an improvement, especially when looking at operator costs, but bigger machines also has some drawbacks. Transporting, turning and positioning becomes harder to do, which has meant that farms have had to become larger to really be able to make use of the bigger machines without having too much downtime. Bigger machines in most cases also means more advanced machines. This can become a problem for farmers when they rely on one machine to handle a lot of the work. If the machine breaks down all field operations might stop and it will most likely be a lot harder to repair than smaller machines.

Another issue with bigger machines is soil compaction which is the issue that is most directly related to the size of the machines. The use of heavy weighted field equipment is one of the reasons for human-induced soil compaction. The heavy weights of tractors, grain carts, combines, trucks, manure spreaders etc., can penetrate down to 60 cm into the soil, which is causing extreme damages on the soil. Soil compaction reduces the pore space, the space needed for air, water and root penetration. It has a negative impact on the aggregate structure due to the crushing of soil aggregates, as well as the soil quality and crop production. The ability for the roots to take up important nutrients and water efficiently is limited and therefore reduces crop yield potential [16]. Figure 3.1 demonstrates the effect of wheel traffic-induced compaction.

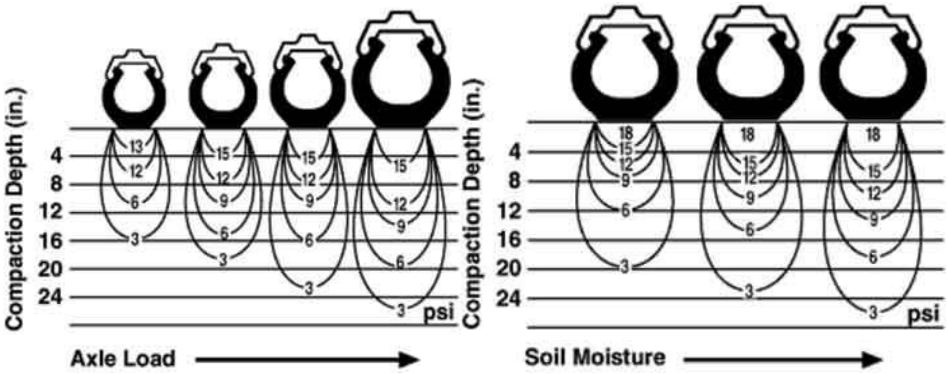


Figure 3.1. Compaction depth due to axle load and soil moisture [16]

In order to minimize soil compaction, the traffic on fields needs to be minimized, especially when the subsoil is wet. The introduction of more light weighted equipment is therefore extremely necessary to avoid great soil compaction.

3.2 Herbicide

Glyphosate, the active ingredient in the herbicide "Roundup", is the most widely used agricultural chemical in history and up until 2016 8.6 billion kilograms had been sprayed globally since its release in 1974 [17]. When first released, it was only used where the land managers wanted all the vegetation to be killed off. This was until 1996 when genetically engineered soybean, maize and cotton, who were all herbicide tolerant, were approved for planting in the US. This led to an enormous increase of glyphosate use, and the usage is increasing even today. 72% of the total volume of glyphosate sprayed globally was sprayed between the years of 2004 and 2014 [17], and it is expected to continue to rise. The efficiency of glyphosate has led to a decrease in the amount of herbicides used, see Figure 3.2, which in turn have led to a rise in glyphosate resistant weeds.

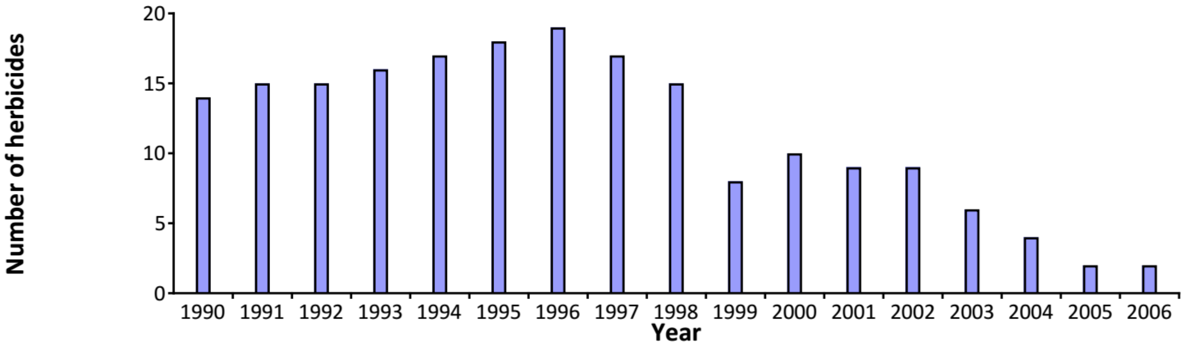


Figure 3.2. The number of herbicides used on over 5% of US soybean crops from 1990 to 2006 [18]

Herbicide resistant weeds are a normal occurrence and a basic part of the evolutionary process [19]. Once a field is sprayed with herbicide, the weeds that are naturally resistant will survive and reproduce. The offspring will also be resistant and with continuous use of the same herbicide the few isolated plants will quickly spread and dominate the weed population and the soil seed bank. Even though it is a normal occurrence, the reliance of just a few herbicides have led to an alarming increase of herbicide resistant weeds with a 23% increase of the number of unique cases discovered between 2010 and 2017 [20], and as can be seen in Figure 3.3 the US (161) and Australia (90) are the two countries with the highest number of unique cases of herbicide resistance in the world. The resistance to glyphosate poses an especially significant risk for agricultural systems due to its widespread use, the effectiveness on a wide range of species, the relatively high safety for users and the environment and its low cost [21].

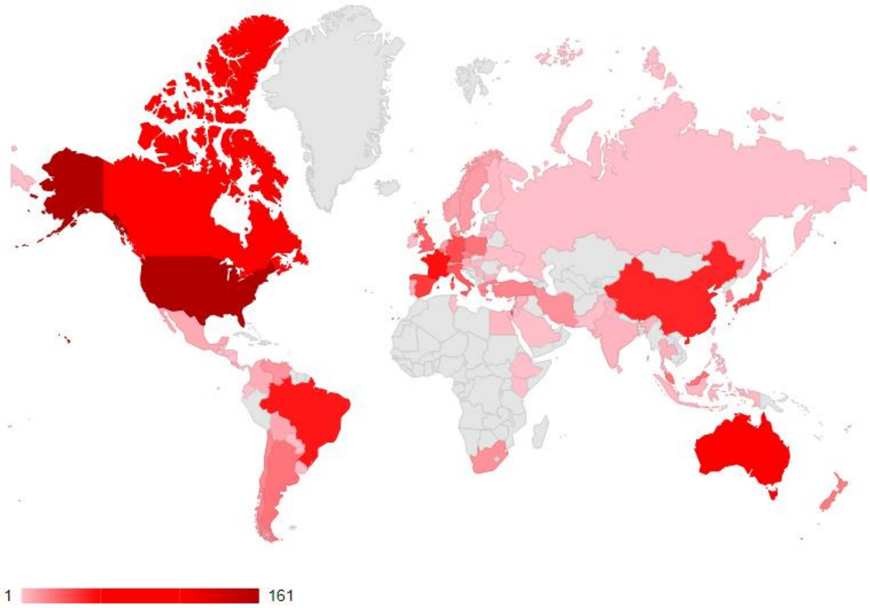


Figure 3.3. Amount of unique cases of herbicide resistant weeds in different parts of the world [22]

3.3 Agricultural Robot Vehicles

The decrease of effectiveness of broadcast-spraying, a very ineffective and expensive way of weeding, as well as the problem with soil compaction have led to an increased interest in robot technology in the agricultural industry. The size of the budding agricultural robot market was USD 817 million in 2013 but this number is predicted to grow to an astonishing USD 16.3 billion by 2020 [23]. Farmers and researchers have started to realize that instead of using heavy machinery and spraying whole fields with herbicides, using lightweight autonomous robots that can do the job of the heavier machines might be a better solution. By making agricultural machines autonomous, hence removing the operator from the immediate control of the system, the economies of scale that applied to the larger systems no longer applies to the smaller systems. This will allow the farmers to deploy smaller units, keeping the work rate high while also removing the threat of having just one point of failure associated with today's bigger machines.

EcoRobotix, see Figure 3.4, is the first completely autonomous robot for weeding of row crops, meadows and intercropping cultures. It is driven by solar energy and therefore does not need any interaction with a human operator. With the help of cameras, GPS RTK and sensors it can follow rows and detect weeds. With two robotic arms it applies a small amount of herbicide on the detected weeds and uses less than 20 times the amount of herbicide used in standard treatments according to the EcoRobotix team [24].

It can work up to 12 h hours per day and batteries don’t need to be recharged manually since it has solar panels. It is controlled and configured with a smartphone, covers up to 3 hectares a day and removes up to 95% of the weeds in ideal conditions according to the EcoRobotix team. With only 130 kg it is classified as a lightweight robot that doesn't have as much effect on soil compaction as heavier machineries. It carries two tanks of herbicide with 15 liters each which is enough for one day of autonomous operation [25].

Figure 3.4. The EcoRobotix weeding robot [24]

Blue River Technologies, a company that was bought by John Deere in 2018, has developed a weeding robot which they call the next generation of smart agricultural equipment. Their See & Spray robot, see Figure 3.5, is currently being used on a limited basis on cotton farms and uses computer vision and artificial intelligence to see every plant and weed and determine what course of action is best for each one in real time. The robot itself is attached to a tractor which is then driven through the field, and can supposedly eliminate 90% of the herbicide volumes sprayed by farmers today [26]. There are some obvious advantages to this compared to a smaller robot like EcoRobotix, but also some disadvantages. By being able to spray a much bigger area simultaneously and not having to move the sprayer to the weed, it is not as limited speed-wise, and will work at a much faster rate than its smaller competitors. However, the See & Spray robot still needs a tractor to pull it, so soil compaction will still be a big problem. It is a step in the right direction, but it definitely doesn’t solve all the problems associated with weeding.

Figure 3.5. The See & Spray robot developed by Blue River Technologies [27]

There are more agricultural robots where weeding is just a part of what they can do. Queensland University of Technology has developed AgBot 2, see Figure 3.6, which is a robot that at the moment can apply fertilizer as well as destroy weeds. It has three ways of destroying weeds depending on what is most efficient; mechanically, by applying herbicide, or by using microwave destruction methods. It is designed to be very modular and in future versions the developers are hoping to be able to add sensors so that it can monitor soil and crop health [28].

Figure 3.6. The AgBot II developed at Queensland University of Technology [29]

The Ladybird, see Figure 3.7, is a solar-electric powered autonomous agricultural robot developed at University of Sydney. It is built specifically for the vegetable industry and other than weeding it can also conduct autonomous farm surveillance, mapping, classification and detection for a variety of vegetables. There is potential for automated harvesting by using the robotic arm that is also used for weeding, but that is something that has yet to be implemented [30].

Figure 3.7. The LadyBird developed at University of Sydney [30]

The startup Deepfield Robotics have together with Bosch developed a robot called BoniRob, see Figure 3.8, which is an agricultural robot with Omni-directional drive as well as adjustable track width. They have taken a modular approach, which has resulted in a robot which can be retrofitted and upgraded with exchangeable application modules. It is built to be a mobile plant lab, able to monitor crop growth and optimize the amount of fertilizer used. It uses a rod to smash weeds, which means it is completely herbicide free, and in areas where hand weeding is still needed it can direct workers to areas that need the most weeding [31].

Figure 3.8. The BoniRob developed by Bosch [32]

3.4 FarmBot

FarmBot is a 100% open source CNC farming robot that takes care of a garden plot without human interaction, see Figure 3.9 and 3.10. It is a precision farming machine all controlled from a computer, tablet or phone after being set up. It is capable of planting seeds with millimeter accuracy, water plants to their exact needs, control weeds before they become a problem and measure the moisture content of the soil [33]. It is available for anyone to buy and is mainly aimed at people with a garden plot.

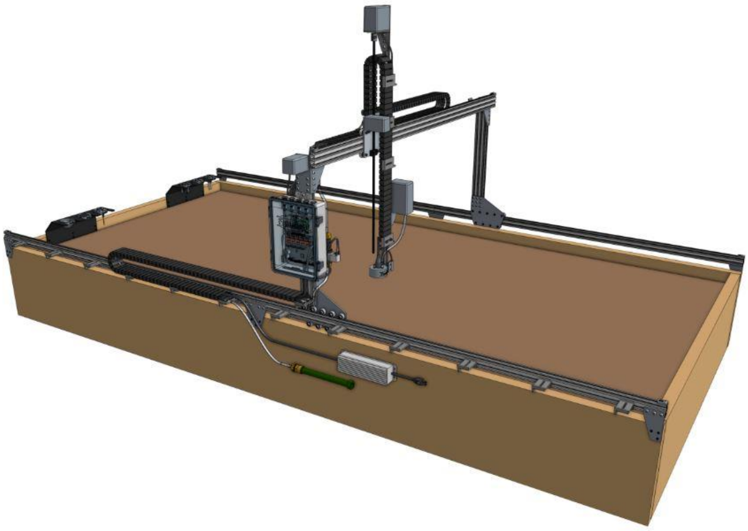


Figure 3.9. CAD-modelling of the FarmBot [34]

Figure 3.10. FarmBot in use [35]

The robot navigates using an Arduino and Raspberry PI in a XYZ direction, which makes it possible to be precisely positioned over the crop or weed for the variety of operations that the FarmBot can do. The gardens can easily be customized and designed using the drag and drop web-based interface from any device, see Figure 3.11, and the plants are ensured to always be watered thanks to the auto-schedule operations. By using the web-based program the user can pick between 33 different common crops to be grown, or choose a customized set up [36].

Figure 3.11. FarmBots Web-based interface [37]

The robot also optimizes the growth with a decision support system that will make sure that the water, fertilizer, pesticide regimes, seed spacing, and timing is automatically adjusted. FarmBot can work in any situation and enables anyone and everyone to build and operate a farming machine thanks to the hardware that is easy and fast to assemble.

The FarmBot comes in two different models, the FarmBot Genesis, and the FarmBot Genesis XL. The price for the FarmBot Genesis is USD 2,595.00 and the FarmBot Genesis XL USD 3,795.00. The FarmBot Genesis has a growing area of 1.4 m x 2.9 m. The Genesis XL model has a growing area that is about 4 times bigger, with a width of 2.9 m and a length of 5.9 m [38], see Figure 3.12.

Figure 3.12. The Genesis XL [38]

The robot is mainly constructed from V-slot aluminum extrusions and aluminum plates and brackets, see Figure 3.13 and Figure 3.14. It has four NEMA 17 steppers motors with rotary encoders, a microcontroller called the Farmduino, as well as a Raspberry Pi 3 computer [39, 40]. See Appendix B for the FarmBot Bill of Materials.

Figure 3.13. Aluminum extrusions [39]

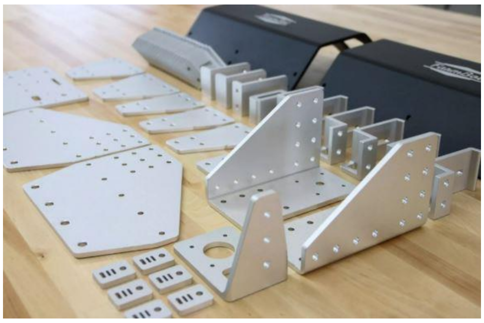


Figure 3.14. Aluminum plates and brackets [40]

What differentiates the FarmBot from traditional wheeled tractors are the tracks. They allow great precision efficiently easily, and can return to the same position repeatedly. However, what makes it superior is that the tracks take up less area than paths for tractor wheels and do not compact the soil.

To bridge the two tracks, a gantry is used which moves in the X-direction via a drive system. It therefore makes up a base for the Y-direction drive system that moves a connected cross-slide across the gantry, see Figure 3.15. The cross-slide then serves as a base for mounting other tools and electronics as well as the Z-direction drive system. Due to the Y-direction motion, planting can be done anywhere in the XY-plane. The universal tool mount is attached to the cross-slide and works in the Z-direction [34].

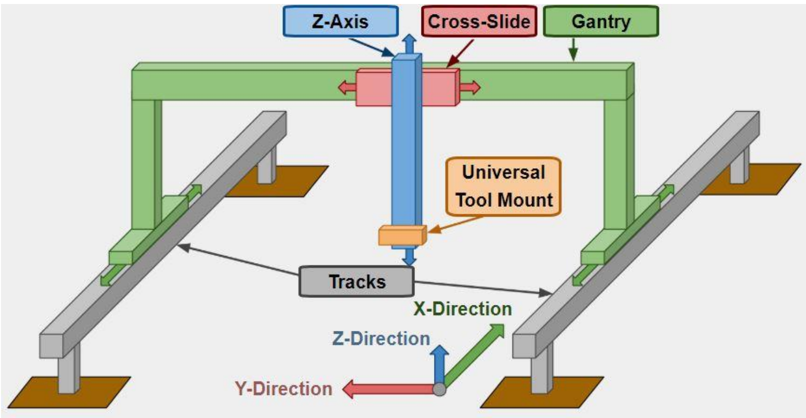


Figure 3.15. The connecting parts [34]

The gantry, cross-slide, Z-axis, and tools must have enough clearance to grow taller plants however. This can be accomplished by using raised tracks and a low profile gantry or using low tracks with a tall gantry, see Figure 3.16. In the FarmBots design, low tracks with a raised gantry is used so that the existing walls in a greenhouse or similar structure could be utilized to support the tracks higher [34].

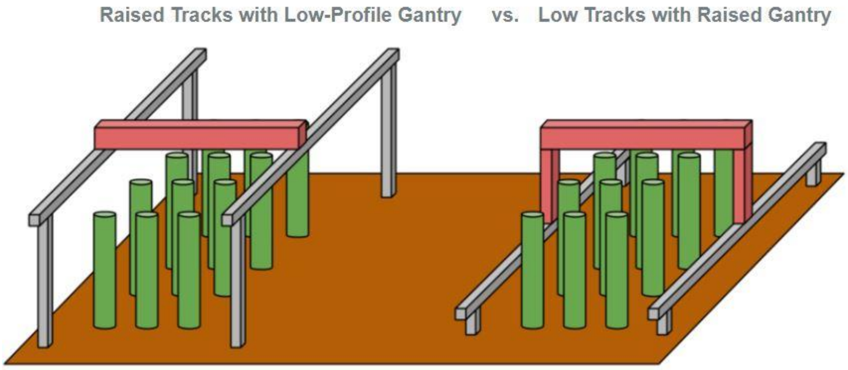


Figure 3.16. Raised tracks vs low tracks [34]

The FarmBot uses a camera to detect weeds, see Figure 3.17, and automatically switches tools for the seeding, watering, measuring of moisture in soil, and weeding actions. The universal tool mount has 12 electrical connections, three liquid and gas lines, and uses a magnetic coupling to pick up the tools, see Figure 3.18. The camera not only detects weeds but also monitors plant growth and there are also hopes that in the future it can be used to detect diseases and pests [41]. The tools included in the tool bays are a seed injector, a watering nozzle, a weeding tool, and a soil sensor which can be seen in Figure 3.19.

Figure 3.17. Camera [41]

Figure 3.18. Universal tool mount [41]

Figure 3.19. The different tools [42]

4 Requirements and Needs

In this section it is described what requirements were given for this project. The requirements have also been interpreted into needs.

4.1 Methodology

In the *Product Design and Development Process* described by Ulrich & Eppinger in their book, the first phase is to identify customer needs. In this project requirements were already given from Hormoz Marzbani in the beginning and there was no need to interview or talk to the farmers because it had already been done. It was therefore possible to go directly to specification establishment from here, however, it was chosen to interpret his requirements to needs to develop a more thorough understanding. It was also important to find needs from research and benchmarking so that the robot could be competitive on the market. There are five steps in the first phase of the design process [4, p. 75]:

1. Gather raw data from customers.
2. Interpret the raw data in terms of customer needs.
3. Organize the needs into a hierarchy of primary, secondary and (if necessary) tertiary needs.
4. Establish the relative importance of the needs.
5. Reflect on the results and the process.

These steps were slightly modified to be suited for this project into the following steps:

1. Get the requirements from the Supervisor.
2. Interpret the requirements in terms of needs.
3. Organize the needs into primary and secondary needs.
4. Establish the relative importance of the needs.

5. Reflect on the results and the process.

4.1.1 Requirements from the Supervisor

The requirements were found through several discussions and meetings with the supervisor and it was understood that he wanted a robot that was:

- Good looking
- Cheaper than the competitors' products
- Better than current methods
- Lightweight
- Driven by solar panels
- Easy to use
- Waterproof
- Weatherproof
- Not harming the crops
- Carrying a joystick
- Carrying adjustable cameras
- Carrying batteries and electronic equipment with minimal cable length
- Carrying modular chemical herbicide containers that can be easily changed
- Not getting stuck while operating

Although EcoRobotix has developed a vehicle that is rather fast it was understood from the many interviews that the supervisor had with the farmers that speed was not of importance. Functionality was more important, as it did not matter to them if it took some extra time to remove the weeds. This was therefore not a requirement, so the fact that the vehicle would be slower than the competitors' was not considered a problem.

4.1.2 Interpreted Needs

The requirements that were given from the supervisor were analyzed and interpreted into needs that can be seen in Table 4.1. Some of the interpreted needs were found by researching and investigating the competitors.

Table 4.1. Interpreted Needs

General	
1.	The robot has an appealing design.
2.	The use of the robot is less expensive than standard treatments.
3.	The use of the robot is more sustainable than standard treatments.
4.	The robot leaves a minimal amount of herbicide on the crops.
5.	All the electronics are easily accessible.
6.	The electronics are protected from water.
7.	The design is weatherproof.
8.	The robot is lightweight to minimize impact of soil compaction.
9.	The robot is durable and mechanically reliable.
10.	The frame is stiff enough so that the FarmBot can operate without any problems arising.
11.	The FarmBot can operate self-sufficiently without any need for recharging by a human.
12.	The FarmBot can operate across the entire crop bed.
13.	The robot is user friendly.
14.	The robot is easy to assemble and disassemble.
15.	The robot doesn’t harm the crops while operating.
16.	The manufacturing of the robot is cheap while still keeping it a high quality product.
17.	The robot is easy to transport by a vehicle for long distances.
18.	The robot can drive over different kinds of agricultural terrain.
Herbicide	
19.	The robot can remove different types of weeds.
20.	The robot is easily able to switch between the herbicides while working.
21.	The herbicide tanks can easily be changed or refilled.
22.	The robot is able to carry enough herbicide to not have to be refilled too often.
Solar panels	
23.	The robot is driven by solar energy.

Wheels

24. There is enough space between the wheels and the crop bed for the robot to operate without harming the crops.
25. The wheels are big enough to not slip and get stuck in the soil.

Joystick

26. The robot is easy to transport by a person for short distances.
27. The joystick is placed so that the driver can easily see in front of the robot while driving.
28. The joystick is placed in an ergonomic position.

Cameras

29. The front camera is able to take pictures that can be used to maneuver the robot.
30. The middle camera is able to take a picture of the whole “working area” of the FarmBot.

Motors

31. The robot can drive on the fields automatically.

Arduino

32. The placement of the sensor allows the gyroscope to measure accurate results.

Board

33. The robot is easy to control.

4.1.3 Organize the needs into primary and secondary needs

In Ulrich & Eppinger’s book the third step is to organize the needs into a hierarchy, however this had somewhat already been done in the previous section and it was therefore chosen to divide the needs into the most important ones (primary needs) and the ones that were not as important (secondary).The reason why this was done was so that it could be easier to know what needs that needed to be most focused on in this project. The secondary needs are needs that might be more important in the future development, for example for a commercialized product and not a prototype.

The interpreted needs were therefore divided into primary and secondary needs. The primary needs can be seen in Table 4.2:

Table 4.2. Primary Needs

1. The robot has an appealing design.
2. The use of the robot is less expensive than standard treatments.
3. The use of the robot is more sustainable than standard treatments.
4. The robot leaves a minimal amount of herbicide on the crops.
6. The electronics are protected from water.
7. The design is weatherproof.
8. The robot is lightweight to minimize impact of soil compaction.
9. The robot is durable and mechanically reliable.
10. The frame is stiff enough so that the FarmBot can operate without any problems arising.
12. The FarmBot can operate across the entire crop bed.
13. The robot is user friendly.
16. The manufacturing of the robot is cheap while still keeping it a high quality product.
18. The robot can drive over different kinds of agricultural terrain.
19. The robot can remove different types of weeds.
20. The robot is easily able to switch between the herbicides while working.
22. The robot is able to carry enough herbicide to not have to be refilled too often.
23. The robot is driven by solar energy.
24. There is enough space between the wheels and the crop bed for the robot to operate without harming the crops.
25. The wheels are big enough to not slip and get stuck in the soil.
27. The joystick is placed so that the driver can easily see in front of the robot while driving.
29. The front camera is able to take pictures that can be used to maneuver the robot.
30. The middle camera is able to take a picture of the whole “working area” of the FarmBot.
31. The robot can drive on the fields automatically.
32. The placement of the sensor allows the gyroscope to measure accurate results.
33. The robot is easy to control.

The secondary needs can be seen in Table 4.3.

Table 4.3. Secondary Needs

5.	All the electronics are easily accessible.
11.	The FarmBot can operate self-sufficiently without any need for recharging by a human.
14.	The robot is easy to assemble and disassemble.
15.	The robot doesn’t harm the crops while operating.
17.	The robot is easy to transport by a vehicle for long distances.
21.	The herbicide tanks can easily be changed or refilled.
26.	The robot is easy to transport by a person for short distances.
28.	The joystick is placed in an ergonomic position.

4.1.4 Establish the relative importance of the needs

The needs were later ranked from 1-5, where 5 is considered extremely important and 1 is considered not as important. If a primary need was given 1 it would however still be considered more important than if a secondary need would be ranked 5. The primary needs were ranked as following, see Table 4.4:

Table 4.4. Ranking of Primary Needs

Needs		Rank
1.	The robot has an appealing design.	4
2.	The use of the robot is less expensive than standard treatments.	5
3.	The use of the robot is more sustainable than standard treatments.	4
4.	The robot leaves a minimal amount of herbicide on the crops.	4
6.	The electronics are protected from water.	5
7.	The design is weatherproof.	4

8. The robot is lightweight to minimize impact of soil compaction.	5
9. The robot is durable and mechanically reliable.	3
10. The frame is stiff enough so that the FarmBot can operate without any problems arising.	5
12. The FarmBot can operate across the entire crop bed.	3
13. The robot is user friendly.	1
16. The manufacturing of the robot is cheap while still keeping it a high quality product.	2
18. The robot can drive over different kinds of agricultural terrain.	4
19. The robot can remove different types of weeds.	3
20. The robot is easily able to switch between the herbicides while working.	2
22. The robot is able to carry enough herbicide to not have to be refilled too often.	4
23. The robot is driven by solar energy.	5
24. There is enough space between the wheels and the crop bed for the robot to operate without harming the crops.	5
25. The wheels are big enough to not slip and get stuck in the soil.	4
27. The joystick is placed so that the driver can easily see in front of the robot while driving.	3
29. The front camera is able to take pictures that can be used to maneuver the robot.	5
30. The middle camera is able to take a picture of the whole “working area” of the FarmBot.	5
31. The robot can drive on the fields automatically.	5
32. The placement of the sensor allows the gyroscope to measure accurate results.	4
33. The robot is easy to control.	3

The secondary needs were ranked as following, see Table 4.5:

Table 4.5. Ranking of Secondary Needs

Needs	**Rank**
5. All the electronics are easily accessible.	4
11. The FarmBot can operate self-sufficiently without any need for recharging by a human.	5
14. The robot is easy to assemble and disassemble.	3
15. The robot doesn't harm the crops while operating.	2
17. The robot is easy to transport by a vehicle for long distances.	4
21. The herbicide tanks can easily be changed or refilled.	3
26. The robot is easy to transport by a person for short distances.	5
28. The joystick is placed in an ergonomic position.	3

4.1.5 Reflection

The needs were interpreted both from the set requirements as well as from research and benchmarking. By analyzing the problem, several more needs were found and this is the reason why the interpreted needs are more than the given requirements. This project contained many preset requirements, for example that the robot had to be driven by solar energy, and that it had to have adjustable cameras. This made it difficult to find secondary needs seeing that all the needs were of high importance.

In order for this to be a successful product it needs to be a strong competitor. Some of the products that are on, or soon to be on, the market, for example EcoRobotix and See & Spray, are already very efficient and innovative so the main focus in this project was to make it cheaper and more lightweight to stay competitive. Thus, the primary needs that were given a 5 were either musts or something that was needed to differentiate the product from existing products.

Having a lot of limitations made it difficult to work freely with the design concepts. That the design had to be appealing was very important, however everything needed to be off the shelf which made this requirement a lot harder to fulfill. In the CAD-file any design could be made however, so it would still be possible to meet the requirements with the 3D model, but if a prototype were to be made then some design features might not be possible to have.

Seeing that the final prototype won't be a commercialized product some requirements like "The electronics are easily accessible" and "The robot is easy to assemble and disassemble" were set as secondary needs. These were needs that might be more important for the commercialized product, but not something that is as important for the prototype since it won't be used for a long time.

Some of the requirements, such as "The robot leaves a minimal amount of herbicide on the crops" and "The FarmBot can operate across the entire crop bed", is outside the scope of this project and can therefore not be improved or modified, however they do need to be taken into consideration while making the design so that it can operate the way it needs to.

5 Establish Target Specifications

In this section the specifications that were established are presented. They were used to make sure that the requirements were met.

5.1 Methodology

After identifying the needs, target specifications were established to describe what the product has to do. This was by done using the three steps below [4, p. 95]:

1. Prepare the list of metrics.
2. Collect competitive benchmarking information.
3. Set ideal and marginally acceptable target values.

In order to set the specifications the needs were analyzed and information about the competitors' products was collected. This made it possible to establish specifications so that the product could either match or outperform the products on the market. Some of the specifications were given with the requirements in the beginning of the project. The specifications that could not be established by investigating competitors' specifications, or that were not given with the requirements, were estimated and are therefore approximated.

5.2 Specifications

The specifications that were established from the needs can be seen in Table 5.1.

Table 5.1. Specifications

General	
1.	There is a reduction in overall weeding operating costs by at least 70%.
2.	There is a reduction of herbicide use by at least 90%.
3.	Less than 5% of the herbicide lands on the crops.
4.	All the electronics can be accessed within 1 minute.
5.	The robot is designed so that none of the parts are damaged by rain or dust.
6.	The robot operates in winds of up to 14 m/s.
7.	The robot weighs less than 200 kg.
8.	The frame has a maximum displacement of 5 mm.
9.	The FarmBot is self-sufficient enough to operate for 24 hours per day.
10.	The FarmBot can have an operating area of at least 1300 x 1500 mm.
11.	The FarmBot has a 100 mm ground clearance from the crop bed at its lowest point.
12.	The FarmBot has a possible ground clearance of 400 mm from the crop bed.
13.	The robot has a height of less than 1650 mm.
14.	It takes a maximum of 10 mins to set up the robot for operation.
15.	It takes a maximum of 4 hours to fully assemble and disassemble the robot.
16.	The total cost for the parts needed, excluding the FarmBot, is USD 3000.
17.	It takes a maximum of 5 minutes to load the robot onto a vehicle.
18.	The width of the robot is less than 2.5 m.
19.	While operating, the robot never gets stuck or slips in non-rainy conditions.
Herbicide	
20.	The robot has a minimum of two chemical herbicide containers.
21.	It takes a maximum of 10 minutes to refill or change the herbicide containers.
22.	The robot is able to carry at least 30 liters of herbicide.
Batteries	

23. Accommodates four batteries of model TDRMOTO 6DZM20 [43], which had already been chosen earlier on in the project by the supervisor.

Solar panels

24. Accommodates two solar panels of model 327W SunPower E20 [44], which had already been chosen earlier on in the project by the supervisor.
25. Accommodates two solar panel charge controllers of model 12V/24V Solar Panel Battery Regulator Charge Controller [45], which had already been chosen earlier on in the project by the supervisor.

Wheels

26. There is at least a distance of 1500 mm between the insides of the wheels.
27. There is a maximum distance of 1900 mm between the outside of the wheels.
28. The robot has two caster wheels as back wheels.

Joystick

29. Accommodates a joystick taken from an electric wheelchair of model Jet 3 Ultra, made by Pride Mobility Products Corp [46]. This model had already been chosen earlier on in the project by the supervisor.
30. The placement of the joystick enables the driver to have full vision of at least one front wheel.
31. While using the joystick the angle of the wrist should be in between 0 and 20 degrees.

Cameras

32. The angle of the front camera is adjustable by 45 degrees.
33. The middle camera is adjustable in height by at least 10 cm.
34. The middle camera is installed in the middle of the robot, with regards to width.

Motors

35. Accommodates two motors taken from an electric wheelchair of model Jet 3 Ultra, made by Pride Mobility Products Corp [46]. This model had already been chosen earlier on in the project by the supervisor.
36. The robot has front-wheel drive.

Arduino

37. Accommodates an Arduino of model Mega 2560 [47], with a sensor mounted on top, which had already been chosen earlier on in the project by the supervisor.
38. The sensor is placed in the middle of the frame, as far to the front as possible.

Board

39. Accommodates a developer board of model Nvidia Jetson TX2 Developer kit [48], which had already been chosen earlier on in the project by the supervisor.

6 Concept Generation

In this section the concept generation process is shown. Brainstorming, benchmarking, and the decomposition into sub problems are presented.

6.1 Method

Since the vehicle consists of several different parts, a *problem decomposition* was done where a complex problem is divided into simpler sub problems and can therefore be tackled in a more focused way. The four-step concept generation method, described in Ulrich & Eppinger [4, p.120], was used in this project to solve the problem:

1. Clarify the problem.
2. Search externally.
3. Search internally.
4. Explore systematically.

After clarifying the problem, the sub problems were found and the following steps were performed in parallel with each other since they all depend on each other and new discoveries in one sub problem can lead to new concept generations in a different one.

6.2 Sub problems

The problem of this project was to design a frame to a robot which consisted of several parts. The design development has therefore been divided into following sub problems:

1. Solar Panels and Charge Controllers
2. Frame and FarmBot
3. Wheels and Motors

4. Middle Camera
5. Front Camera
6. Batteries and Charge Controllers
7. Herbicide tanks
8. Board
9. Arduino
10. Joystick
11. Cover

For each and every sub problem, different concept generations or solutions were found where the most critical problem was the frame and the FarmBot. Most sub problems depended greatly on how this sub problem was solved. The solar panels didn't depend much on the frame and FarmBot, rather the opposite, and it was therefore set as the first sub problem.

6.2.1 Solar Panels and Charge Controllers

Which solar panels and charge controllers that were to be used were already decided before this phase of the project but the main problem was how and where to attach them to the frame.They needed to be connected to the batteries with minimum cable length and placed in a way that would be most energy efficient. The solar panels were waterproof but if they could be placed in a way to protect the other equipment from water, that would be desirable. From an energy efficiency point of view, the solar panels had to be placed on top of the robot.

6.2.2 Frame and FarmBot

This problem was the biggest and most critical problem and had most effect on the end product. The design of the frame decides how big the vehicle is, how lightweight it is, how appealing it looks and so on. During this concept generation it was therefore extremely important to make sure that all the requirements and needs were met. The other problems were developed at the same time but were often changed if the frame was changed. The main concern was to not make it too heavy and it was therefore important that the frame was as small as possible while still keeping it durable and making sure it wouldn't harm the crops. The FarmBot was already built but could be modified in many different ways. The Z-axis and the Gantry could be shortened and the electronic equipment could be moved.

There were already some requirements of where the wheels, the FarmBot and the solar panels were to be placed before the start of the design phase which would all affect the design of the frame.

The wheels were to be placed so that the distance between them was around the same as the average distance between the middle of one track to the next one, which was 1728 mm. This meant that the robot had as much room to operate as possible with enough space on both sides of the wheel.

The FarmBot was to be placed in the middle of the robot and it had both a length and a width of 1500 mm. There were no requirements as to what height it was placed at, but there were requirements as to how low it was able to go and how much clearance it had to have.

The solar panels were to be placed on top of the robot.

6.2.3 Wheels and Motors

The main requirements for the wheels were that they decrease the soil sinkage and wheel slip to a level where the robot can operate freely without getting stuck in non-extreme conditions. The front wheels on the first prototype, which was made before this phase of the project, had a diameter of 10 inches and a tread pattern not specifically developed for off road or agricultural purposes, which can be seen in Figure 6.1. There was a problem with slip sinkage when the first prototype was tested, so this needed to be improved upon.

Figure 6.1. Front wheels used in the first prototype [46]

The requirement for the back wheels was that they were caster wheels, so that the robot behaved the same way as when the first prototype was tested.

The motors that were to be used were already decided, and the only problem was regarding how to attach them to the frame.

6.2.4 Middle Camera

The middle camera needed to be adjustable in height by 10 cm so that the image of the crop bed could be adjusted. It was important that the whole crop bed was shown but also that the picture was as close to the crop bed as possible to get a detailed view. Even though the camera needed to be adjustable in height, it was important that the mount remained as short as possible so that the whole frame did not have to be unnecessarily big.

6.2.5 Front Camera

The front camera needed to be angularly adjustable from a horizontal position to 45 degrees below horizontal. The reason for this was so that the camera wouldn’t get blinded when the sun met the horizon at sunset, which would happen if it is always in a horizontal position. When the sun is higher up the camera should be pointed straight forward to better be able to analyze the tracks and also to be able to detect the end of a lane early enough.

6.2.6 Batteries

What batteries to use and how many were already decided before this phase of the project and what needed to be figured out was where and how to attach them to the frame. They needed to be accessible and close to other electronic parts of the robot so that the cable lengths could be kept to a minimum. They were also going to be attached close to the charge controllers.

6.2.7 Herbicide tanks

There needed to be at least two herbicide tanks so that the robot could carry at least two different kinds of herbicides. This was important due to the fact that many weeds are resistant to some herbicides. It also needed to be able to carry at least a total of 30 liters of herbicide so that it could operate at least one day without needing a refill.

6.2.8 Board

A developer board was already decided before this phase of the project and the problem was where and how to attach it to the frame so that it could be easily accessible if modifications needed to be made. The board in itself was not waterproof, so it was very important to make sure that no water could get to it. Most of the electronic devices were connected to the board, so it would need to be placed in a strategic location.

6.2.9 Arduino

A gyroscope sensor was to be attached to an Arduino, and the sensor and the Arduino was decided before this phase of the project. It was known that it had to be placed in the middle of the robot as close to the front as possible so that it could perform correctly. The main problem was to figure out how to attach the Arduino to the frame, but it also needed to be made sure that no water could get to it.

6.2.10 Joystick

The joystick is used to transport the robot for short distances, to set up the robot so that it can drive autonomously on the fields and to calibrate and improve the algorithms used. The joystick model was already decided before this phase of the project but a decision regarding how to attach it to the frame in an ergonomic position and so that the driver easily can see in front of the vehicle while driving needed to be made.

6.2.11 Cover

The supervisor wanted the vehicle to look appealing and “futuristic” to attract investors. However, it was important that it didn’t look too extraordinary seeing that it also needed to reflect the simplicity of the machine. It was desired that a cover was designed for the different parts and the frame so that it would look more professional and hide what was behind it. There weren’t really any restriction for the design part seeing that it would only be shown in the CAD-file for now and wasn't going to be made for the actual prototype.

6.3 External and internal search

6.3.1 Solar Panels and Charge Controllers

Since the solar panels and the charge controllers were already determined, there wasn't really any need for internal and external search. How they would be placed was still to be decided however. For this decision information mainly came from external search, especially by analyzing EcoRobotix design since they too have two solar panels that the vehicle is driven by, see Figure 6.1.

Figure 6.1. The placement of EcoRobotixs solar panels [49]

The two solar panels on EcoRobotix are placed close together at the very top of the robot with the short sides in the front and back and the long sides on the side. This makes it a little bit wider than it is long, however if they were placed with the short sides together, it would be a lot longer than it would be wide. This type of placement therefore seemed most reasonable from an aesthetic point of view, since it would look more compact. It would also make it possible to hide the electronic equipment on the sides of the robot. Another important thing to consider was the oversize light vehicle requirements so that it didn't exceed the measurements which are 2.5 m in width [50].

The solar panels had the dimensions 1559 x 1046 x 46 mm and if placed with the long sides together the full dimension would be 2092 mm in the front and back and 1559 mm on the sides. They could also be placed with the long sides in the front and back, and the short sides on the sides. In this case, the solar panels would stick out in the front and back instead of the sides.

The other problem was how to attach the solar panels and the charge controllers to the frame, and to figure that out it had to be known what they looked like underneath. The distributer was therefore contacted and it was told that the panel frame is an aluminum angle with a gap of around 40 mm between the cells and the frame which could be utilized for mounting purposes if the mounting kit would be obtrusive. It was told that it could easily be bolted directly to a frame or they could be attached by using aluminum angles. The solar panels could either be fixed to the frame or have a mechanism where they could be folded up for an easy access to the electrical parts. It would be convenient if they could be fixed but if the parts couldn't be accessed due to for example the height of the vehicle, then it would be necessary to be able to somehow open them.

The solar panels each have one junction box with the dimension 32 x 155 x 128 mm which are placed in one of the corners, see Figure 6.2.

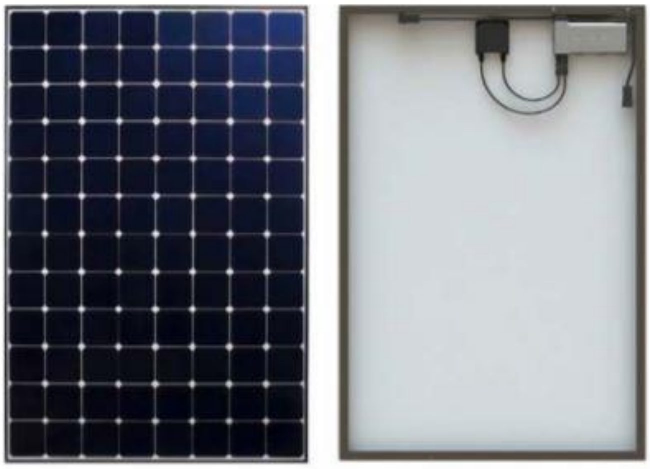


Figure 6.2. The 327W SunPower E20 Solar Panels from SolarOnline seen from above and below [51]

Due to the minimal cable length requirement, the charge controllers needed to be placed close to the junction boxes. If the solar panels were placed with the long sides together, one junction box would be in the front corner and the other one in the middle in the front. It would therefore be most reasonable to attach the charge controllers to the frame in the front as close to the junction boxes as possible. They also needed to be close to the batteries for a minimal cable length, further development of the placement and mounting of the charge controllers was therefore done together with the batteries.

6.3.2 Frame and FarmBot

An early discovery when searching for off the shelf parts that could be used to build the frame was the discovery of t-slot aluminum extrusions. T-slot aluminum extrusions have a t-shaped track along the extrusion, see Figure 6.3, where you can attach a t-nut and a bolt, see Figure 6.4.

Figure 6.3. A t-slot aluminum extrusion [52]

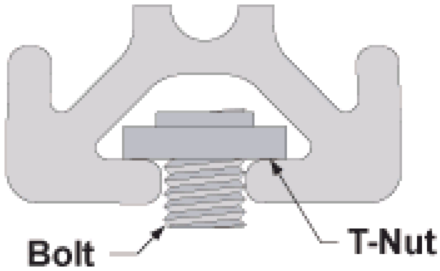


Figure 6.4. Attachment of a t-nut and a bolt to the t slot extrusion [52]

This design makes the extrusions very easy to work with due to the flexibility and versatility that they offer while also eliminating the need for welding, clamping or similar bonding methods. If something in the structure needs to be changed, it is a lot easier to just untighten the t-bolts and move the parts than it is to cut something up and reweld. There already exists a lot of t-slot accessories and connectors to make it possible to build structures that fit the needs of the constructor. On top of this, they exist in a variety of dimensions which makes it very easy to change the design depending on how much load it will have to bear. These extrusions are generally made out of aluminum due to a number of factors, where the two main ones are the high strength to weight ratio and its good corrosion resistance [53].

The frame was heavily dependent on the design of other parts, the FarmBot needed to be able to operate freely without anything being in the way. The frame would have to be modified depending on how all the other parts were to be attached, which meant that the frame was a work in progress throughout most of the project. This was not too much of a problem seeing how it is very easy to add extrusions when using t-slots. The first step in designing the actual frame was to make a sketch, see Figure 6.5, which marked the places where parts such as the wheels, attachment points for FarmBot etc. needed to be attached to the frame. This sketch was then used to come up with many different ideas on how the frame could be designed.

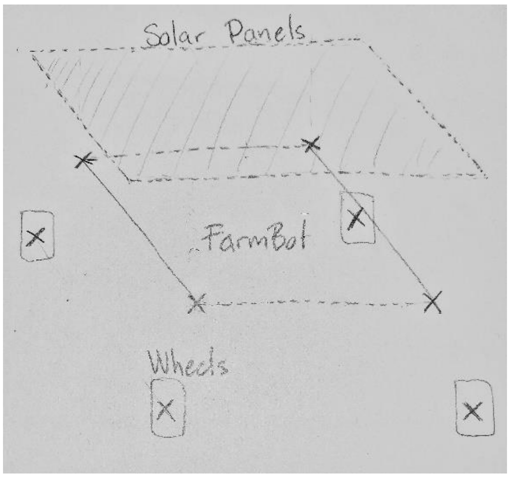


Figure 6.5. A very early sketch that was used to visualize where the frame needed to connect to certain parts

Two of the requirements that needed to be kept in mind when working with the frame and the FarmBot were the clearance requirements and the total height of the vehicle. Two things that needed to be changed with the FarmBot was the height at which the Y-axis on the gantry was placed, and the length of the Z-axis. The placement of the FarmBot as well as the height of the Y-axis would affect the clearance and the length of the Z-axis would affect both the clearance and the total height of the vehicle. See figure 3.15 for the definitions of the x-,y- and z-axis.

To find out at what height the FarmBot could be placed the original range of movement of the Z-axis arm were measured. In its normal configuration the lowest part of the Z-axis, the universal tool mount, was able to get 100 mm below the tracks in its lowest position and 470 mm above the tracks in its highest position. As mentioned earlier the arm needed to be able to have a clearance of 400 mm from the crop bed and be able to get as close to the crop bed as 100 mm. The fact that the Z-axis could only reach 100 mm below the tracks meant that tracks could not be placed so that there was a 400 mm clearance in the original configuration, since the arm then wouldn't be able to get as close as 100 mm. It was discussed if the tracks could be placed lower, but the conclusion was that it was not a good idea mainly due to one reason. The tracks will be attached to an extrusion that will also be used to stabilize the vehicle, which can be seen in Figure 6.6. To stabilize the vehicle the extrusion needs to be placed at a height of at least 600 mm. This is the height of the crop bed, which was the height of the specific crop bred where the prototype would be tested, added to the 400 mm clearance. What this meant was that the Y-axis needed to be lowered by at least 200 mm to be able to get as low as 100 mm from the crop bed. This is the minimum distance it needed to be lowered, before shortening of the Z-axis.

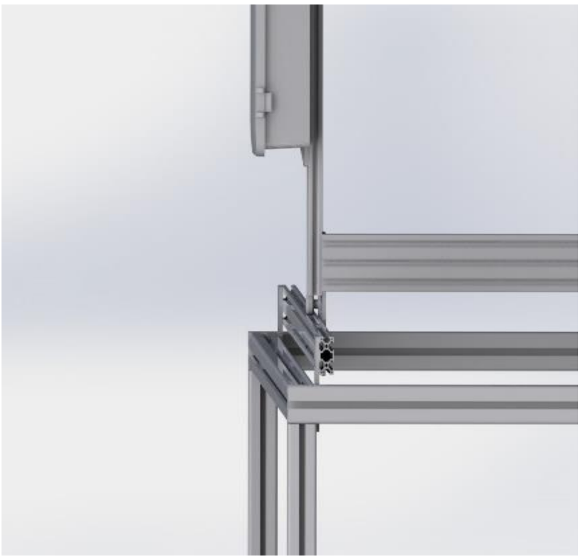


Figure 6.6 The tracks of the FarmBot are placed higher up than the horizontal part of the frame, which is due to the way they are attached to the frame

To meet the height requirement some calculations were made to see how much the Z-axis needed to be shortened. A maximum total height of 1650 mm had been decided, but an optimal height of 1600 was preferred. An assumed length of 150 mm was used for the middle camera, and a 10 mm gap between the FarmBot and the middle camera was used in the calculations. These calculations showed that the Z-axis needed to be shortened from 1000 mm to in between 694 mm and 794 mm to meet the preferred height, which can be seen in Figure 6.7 and Equation 1.

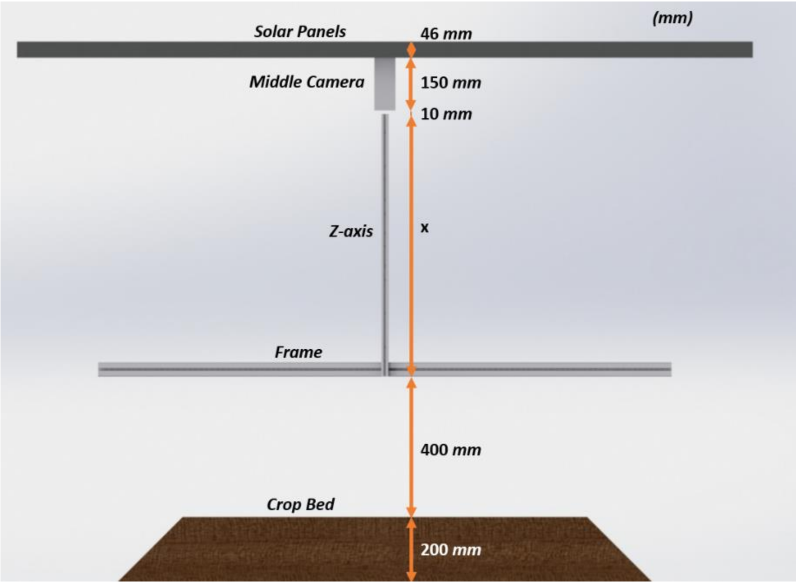


Figure 6.7. Measurements used to find out how much the z-axis needed to be shortened

$$1600 - 200 - 400 - 10 - 150 - 46 = x = 794$$

Equation 1

To be able to calculate exactly how much the Y-axis needed to be lowered, both the clearance and the shortening of the Z-axis needed to be kept in mind. The clearance requirements meant that the Y-axis had to be lowered by at least 200 mm and the height requirements meant that the Z-axis had to be shortened by 206 to 306 mm. However, the Z-axis could only be shortened from below, which meant that on top of having to be lowered 200 mm it also needed to be lowered by as many millimeters as it was shortened. The total millimeters of lowering needed therefore ended up being 406 to 506 mm. This could be achieved by moving down the Y-axis and attaching it to the wheel bearing connector that was connected to the tracks, see Figure 6.8.

Figure 6.8. The y-axis was attached to the wheel bearing connector so that it could be lowered as much as was needed.

With the lowering part done, calculations needed to be done to see how much the Z-axis could be shortened by. As calculated earlier, to meet the height requirements it needed to be shortened by 206 to 306 mm, and as much shortening as possible was positive as it would result in a lower total height of the vehicle. With the Y-axis lowered the distance between the lower part of the frame and the upper part of the Y-axis was 180 mm, and with the Z-axis in its lowest position it was 260 mm above the top of the Y-axis, see Figure 6.9. To determine the length the Z-axis could be shortened by, these two values as well as the 300 mm that was needed below the lower part of the frame were deducted from the length of the Z-axis which was 1000 mm, see Equation 2. This meant that the Z-axis could be shortened by a maximum of 260 mm and it would still satisfy the total height requirements of the robot as well as the clearance requirements.

$$1000 - 260 - 180 - 300 = 260$$

Equation 2

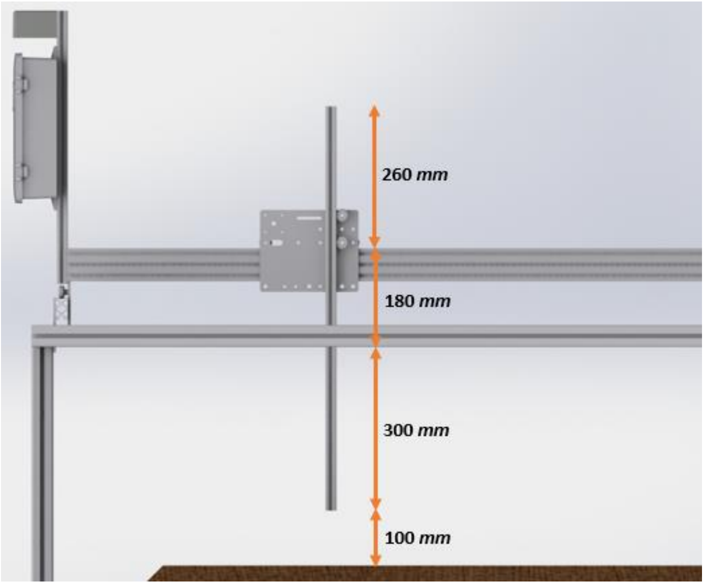


Figure 6.9. The measurements used to be able to calculate how much the Z-axis could be shortened by

The placement of the electronics box and the combined length of the solar panels needed to be kept in mind when designing the frame. It was decided that the electronics box was to be kept on the Y-axis since most of the cables in the electronics box leads to the Z-axis arm, making it very handy to keep the box attached to the moving gantry. By keeping the electronics box attached to the gantry, it would be wider than the gantry itself. This would affect how the frame could be designed, see Figure 6.10.

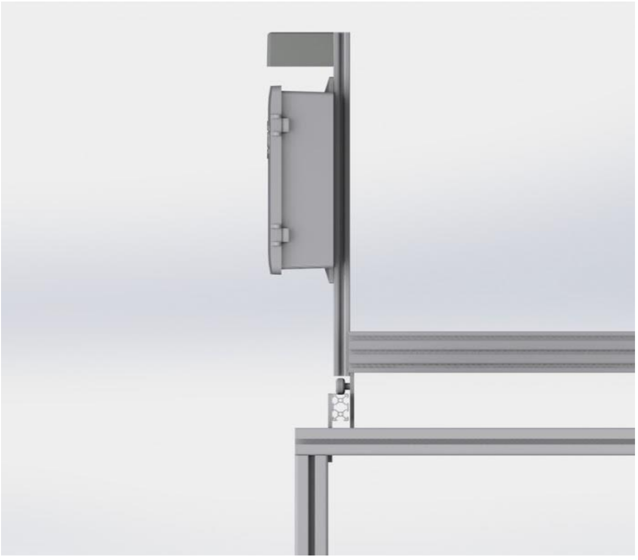


Figure 6.10. The electronics box is protruding further than the frame, which meant that the frame had to be designed with this is mind if the electronics box were to be kept on the FarmBot

The combined length of the two solar panels were wider than the 1500 mm of the FarmBot, which meant that the frame needed to extend further out than the FarmBot. With these two things in mind different designs were discussed within the team but also with the supervisor to find the design which would make the robot not only sturdy but also look as good as possible from a design point of view. Some of these designs can be seen in Figure 6.11.

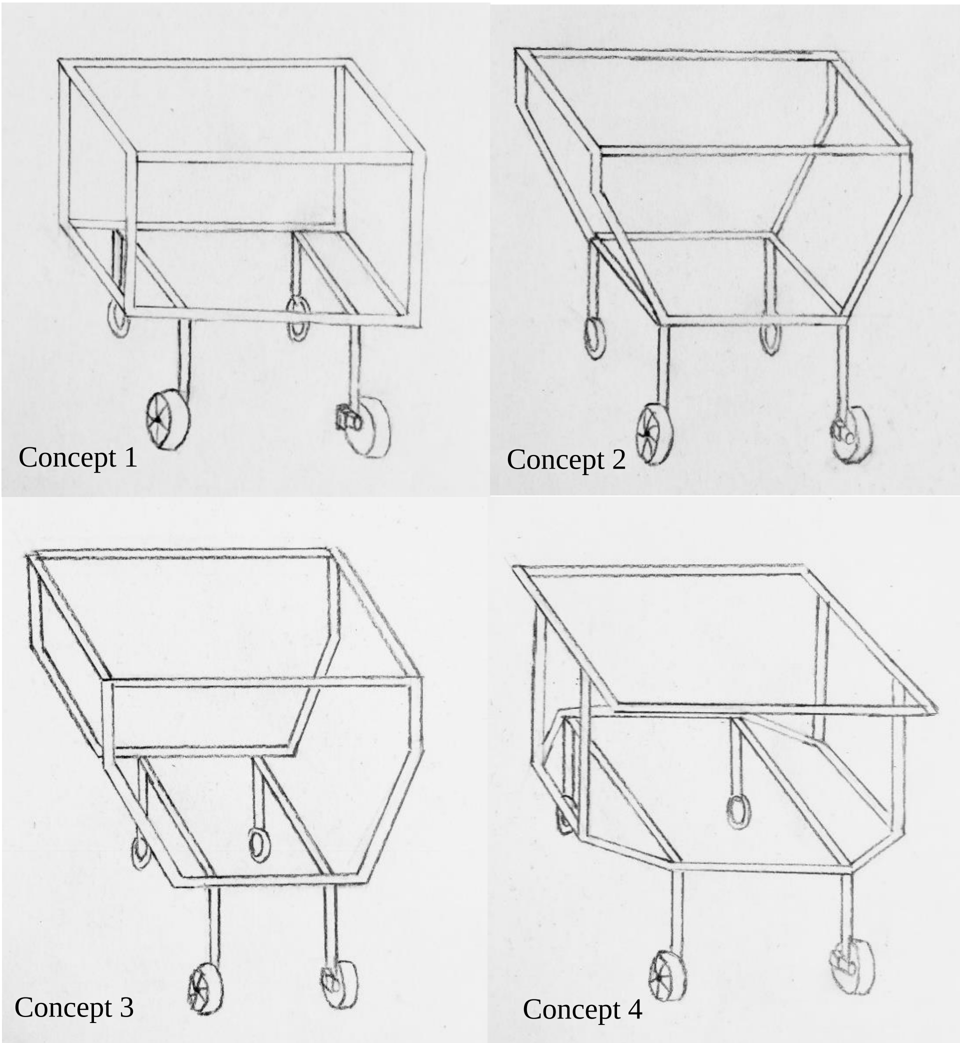


Figure 6.11. The first generated frame concepts

Concept one would be the easiest to manufacture since there would be no need for special angled connectors or angled extrusions, which could prove to be hard to manufacture. There are a variety of 90, 45 and 135 degree off the shelves brackets that are used for connecting the extrusions together but finding other types can be hard. Concept one also require fewer parts which is always positive since it simplifies the assembly. Concept two, three and four were considered to be better from a design point a view. They are more aesthetically pleasing, and it would also be easier to create a nice cover for the robot considering there were some angles incorporated and the robot would therefore not look like just a box. Concept two and three are very similar, with the only difference being how long the bottom horizontal extrusion is. Concept four was considered very good from a design point of view, but it might prove to be less stable than the other designs due to the way the loads will be distributed.

All the tubes and cables that enters the FarmBot enters from the same side. This side could be placed either in the front or in the back of the robot. Depending on how the other parts were placed, this would be decided to make sure that the tubes and cables were as short as possible.

Supports are something that might be needed for the final prototype, and it was decided that this would also be something that was to be investigated during the Finite Element Analysis (FEA). If the prototype was not sturdy enough supports could be added to make it sturdier.

Most of the cables are very likely to be attached to the frame in some way. This can either be done by treading them through the extrusions, or some kind of cable clip can be designed. The cables are of varying sizes and some of them are quite big, so a solution that will work for all of them are needed.

6.3.3 Wheels and Motors

There are many variables that affect how well an off road tire functions in agricultural conditions, but four of the main ones are the size of the tire, tire width, the tread design and the compounds [54]. It has been observed that an increase of the wheel diameter decreases slip sinkage, slip velocity and motion resistance which leads to better performance [55][56] . A decrease of the wheel diameter does give higher traction force but it also increases the slip sinkage which might lead to the wheel getting stuck in the soil. The angle of the tire lugs also affects the performance of the wheels, see Figure 6.12, with a decrease of the lugs angle resulting in an increased traction force and increased slip velocity. This is especially true with wheel slip below 30% and the common wheel slip for agricultural machines are between 5% and 25%. However, a low angle also results in higher slip sinkage which decreases the performance of the wheel. A lug angle of 45% is recommended for agricultural purposes, because it gives a good balance of traction and low slip sinkage [56].

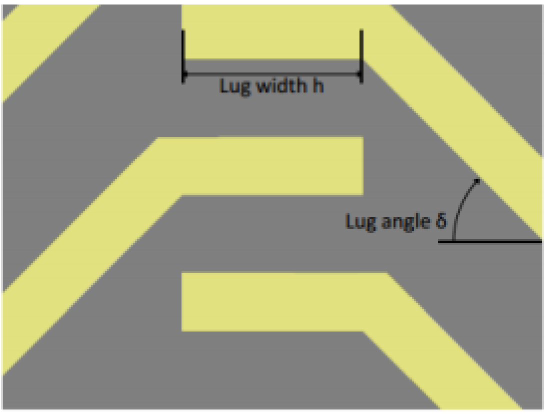


Figure 6.12. Lug angle. Here with a straight middle part, but it also works without the middle part. From the thesis, page 74. "Combined lugs-pattern parameters" [56, p.74]

Since the back wheels needed to be caster wheels, it meant that traction force and slip sinkage were not considered to be of much importance. The main criteria for the back wheels were that they were big enough to not sink when it was muddy.

The wheels used on nine similar agricultural vehicles were evaluated, and seven out of the nine used tires with a lug angle of around 45 degrees, while the two others used another kind of off road tire. In Figure 6.13 Digital Farmhand from University of Sydney can be seen, which shows what kind of tire pattern the seven vehicles used. This information was later used in the concept selection phase when deciding tires.

Figure 6.13. Digital Farmhand is a small robot, but it still uses the same type of tread pattern used on many bigger robots [57]

It’s not just agricultural robots that use this tread pattern, it’s also being used on bigger vehicles that have been used for a long time for example tractors, which can be seen in Figure 6.14.

Figure 6.14. The same tread pattern that is used on smaller vehicles is also used for larger machinery [58]

Wheels usually come in standard sizes, and different tire sizing formats are used for different types of tires. For smaller off road vehicles the sizing format seen in Figure 6.15 is commonly used.

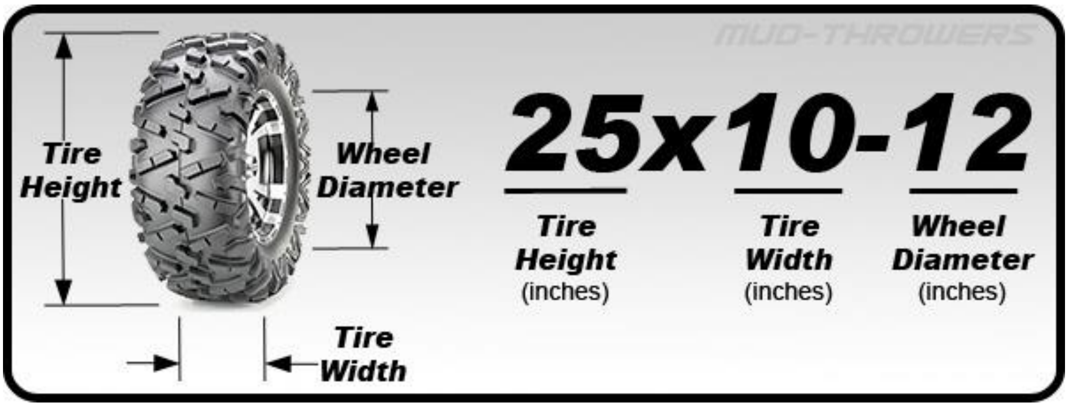


Figure 6.15. Commonly used format for smaller off road tires [59]

It was known that the tires previously used didn’t work well enough, so a bigger tire size than 10 inches was needed. The two bigger standard sizes were 13x5.00-6 and 16x8.00-7. After a group discussion involving Hormoz Marzbani, who had experience of how well the previous wheels worked, it seemed as if a tire of size 13x5.00-6 would be appropriate to use. The increase in diameter and width but also the off road tire pattern was predicted to be enough for the wheel to work well without sinking. If it turned out to be too small, it wouldn’t be too hard to change to a bigger wheel. A search resulted in two wheels that matched the three criteria of being the right size, have the right tire pattern and also being cheap. Tire option one can be seen in Figure 6.16 and tire option two can be seen in Figure 6.17.

Figure 6.16. Tire option one [60]

Figure 6.17. Tire option two [61]

The motors had two attachments points, one swivel point and another point to stop it from rotating, see Figure 6.18. A 3D printed connector was most likely to be used seeing how it would be very unlikely to find an off the shelf attachment for this specific motor.

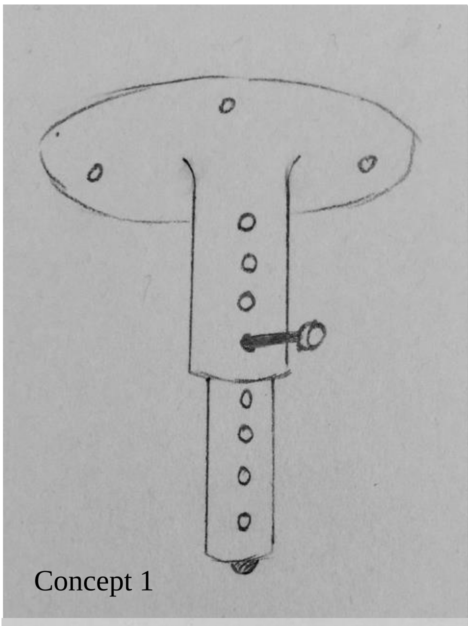
Figure 6.18. The two attachment points for the motor

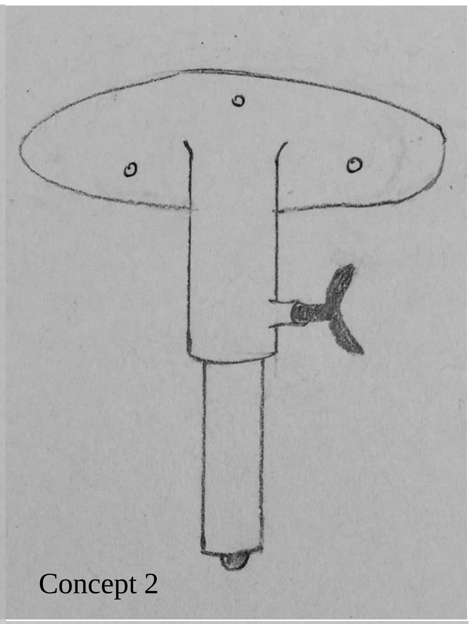
6.3.4 Middle Camera

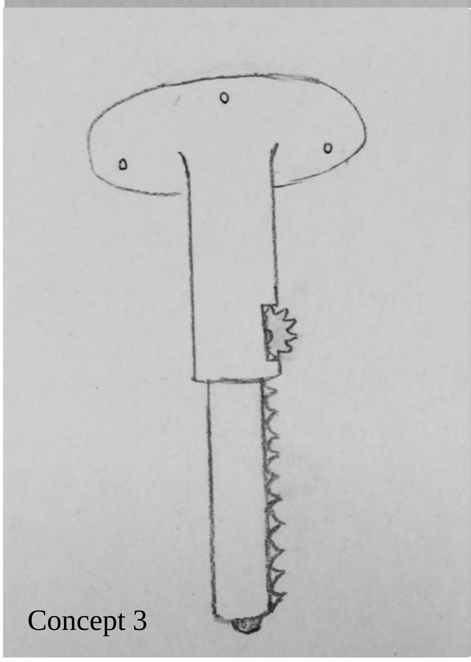
The middle camera needed to be adjustable in height by 10 cm and the main concern while generating concepts was how to make this possible without making the whole frame unnecessarily high. To find a concept that was as compact as possible, external search had to be done to see how similar problems had been solved. Seen in Figure 6.19 are some of the inspiration that was gathered while searching the web.

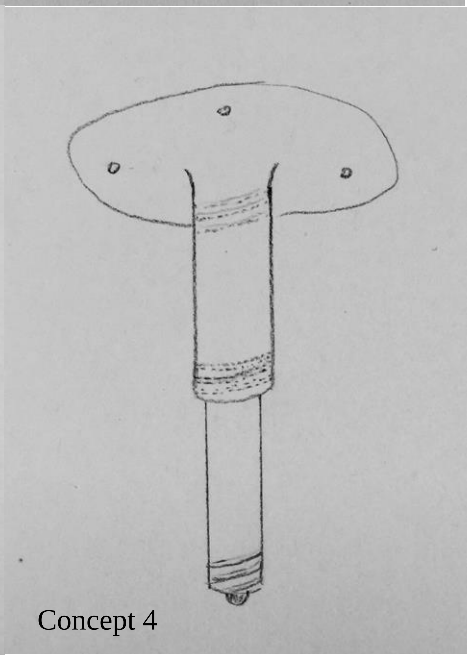
Figure 6.19. Height adjustable products [62, 63, 64]

The first figure in Figure 6.19 is showing a table that is adjusted by untightening the handle, setting the table in the desired height, and then tightening the handle to lock it in place. This is a common function to use while adjusting in height. The second figure is showing a very compact solution where the arms can be folded down and then extended out for a full length. The third figure shows how a product can be adjusted by using pins in holes to lock it in place. With inspiration from these solutions and through brainstorming, several concepts were generated which can be seen in Figure 6.20.


Concept 1


Concept 2


Concept 3


Concept 4

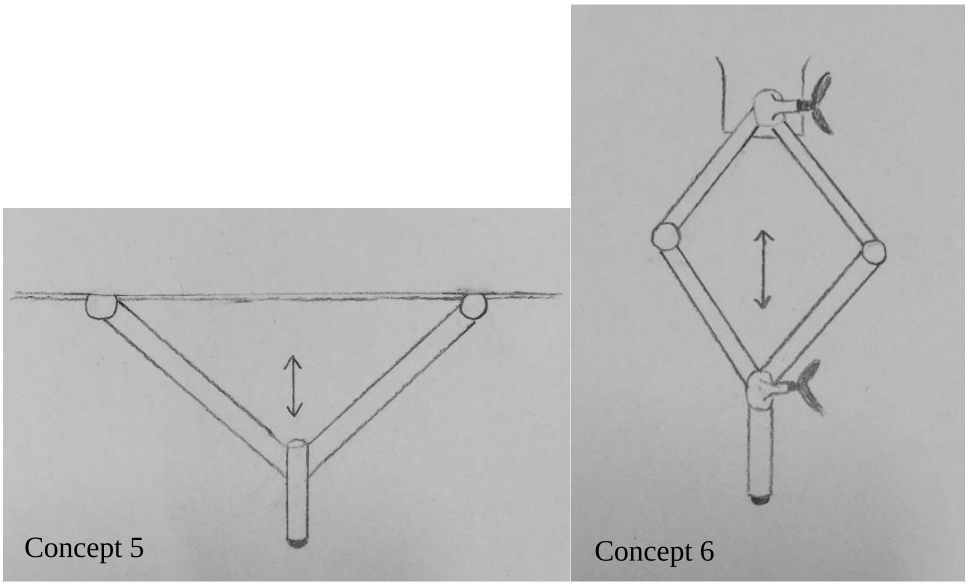


Figure 6.20. First Middle camera concepts

Concept 1 is adjusted using holes and a pin, concept 2 is an untighten, adjust, and tighten function, concept 3 is using gears to pull the camera up and down, concept 4 is using threads to loose and tighten in place, concept 5 is using tracks along the sides that can make the camera go up and down and concept 6 uses arms that can be folded and extended.

With only 7 mm in diameter and a length of 43 mm, the camera is very small and it would be suitable to find a solution for the mount that was not a lot bigger than the actual camera, but also not too small so that it would be difficult to adjust the height. It was also important to find a solution that was as simple as possible seeing that the camera will not be adjusted that often. The mount and camera also need to stay stable and sturdy at all times to avoid blurry images. Some solutions, for example concept 5 and 6, might not be stable when they are in the most extended position and these solutions were therefore not further developed since it was a priority to make it as stable as possible. It was also important that the mount could be adjustable to any height and not only a few different positions. This would be difficult to make with concept 1 and 4. It seemed early on that the easiest solution would be something similar to concept 2, which could be further developed in many different ways.

The camera could be attached to the mount in several ways. The most discussed ones were to bolt two pieces of the mount together and therefore creating enough friction for the camera to stay in place or to glue it to the mount. Depending on which solution was chosen, the camera mount would look differently. If it was bolted together the mount would need to be a lot bigger than the camera so that there was room for the bolts, but this solution would be a very stable and safe solution. Smaller mounts could be used if the camera was glued to the mount. Gluing the camera to the mount would mean that if the camera broke, a new mount would also have to be manufactured.

6.3.5 Front Camera

The front camera needed to be manually adjustable between the angles 90 degrees (horizontal position) and 45 degrees due to the positioning of the sun in the sky. A simple and stable solution was wanted that would not stick out under the solar panels and risk getting impacts during transportation. It was also important to find a solution that had an appealing design.

The inspiration for the generated concepts mainly came from an external search for products that are angle adjustable. Pictures of these are shown in Figure 6.21.

Figure 6.21. Angle adjustable products [65, 66, 67, 68, 69]

All these products have a similar angle adjustable function (except the last one), where pressure from a screw or bolt is used to lock the adjustable part in place. It seemed as this would be the easiest way to adjust the camera, however it could still be mounted in several different ways. The ball head function, as seen in Figure 6.21.2, is very good if the camera needed to be not only adjusted up and down, but also sideways. This is however not necessary and would therefore not be very useful. In Figure 6.21.3, a sort of case is covering the camera which would be useful in situations where the camera could get an impact from for examples tractors, trees etc. In Figure 6.21.4 a very easy screw with a knob is used to tighten the mount. The last mount, Figure 6.21.5, is using a pin to be locked in place and would require the use of two hands.

6.3.6 Batteries and Charge Controllers

Since the batteries needed to be close to the charge controllers it was decided that an attachment for both of them would be developed together. This attachment would ideally be placed in the front corners to be close to both the junction boxes and the motors. For the prototype it was desired to only use off the shelf parts, but it was difficult to find something that would look appealing and something that could hold both the batteries and the charge controllers. It would be much easier to design an attachment with form-fitted sheet metal. It was therefore decided that two different designs were to be developed, one for the prototype, which would be made only from off the shelf products, and one for the CAD model that could be manufactured from form-fitted sheet metal.

For the off the shelf design it was easiest to use t-slot extrusions and connectors since the rest of the frame was most likely going to be constructed by them. They would in that case form a box that would hang down from the top of the frame and comprise the batteries using a strap to hold it firmly in place. The charge controller would then be attached to an extrusion on the outside of the box. This type of design can be seen in Figure 6.22.

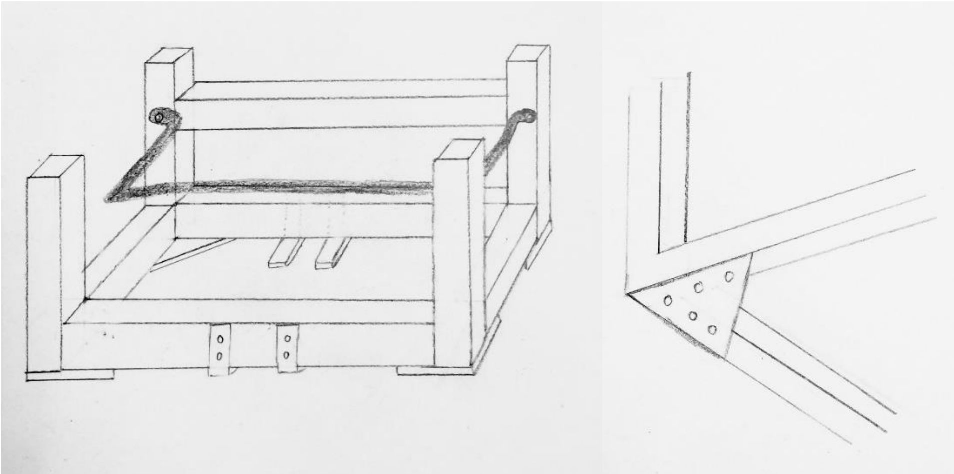


Figure 6.22. The battery holder made from off the shelf parts

By only using bent or welded sheet metal, a more sophisticated design could be made that would efficiently hold the batteries and charge controllers, see Figure 6.23. In this design the charge controller could sit on the outside of the box, or if the box was made bigger it could be placed next to the batteries for extra cover.

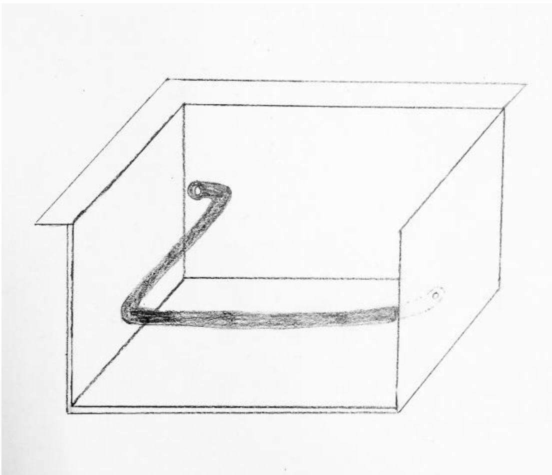


Figure 6.23. The battery holder made from sheet metal

Another solution would be to use both t-slot extrusions and sheet metal to form a box, see Figure 6.24. Just like in the previous designs, the charge controller could be placed both on the outside and on the inside.

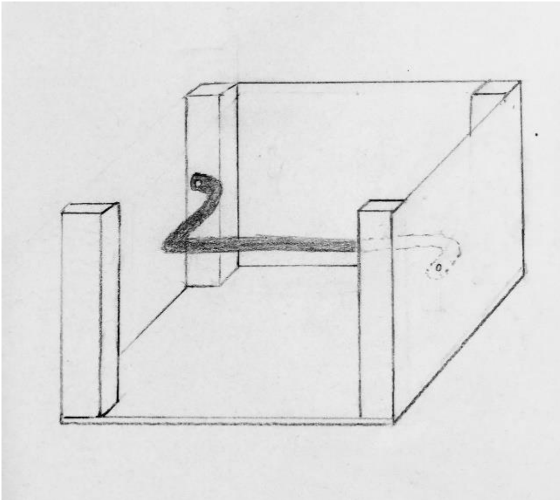


Figure 6.24. The battery holder made from a combination of off the shelf parts and sheet metal

The batteries were already waterproof and the charge controllers were humidity proof, so there was no need to design something that would cover the parts completely from water. However some protection was needed to make sure that they wouldn’t be damaged. The designs above could easily have a wall that protects the parts from rain, except the one with only t-slot extrusions.

6.3.7 Herbicide tanks

Most of the tanks that could be bought off the shelf came in 5 liters increments (5, 10, 15 liters). The more herbicide that could be stored the better, however more herbicide also meant that the robot would get heavier which would mean more soil compaction as well as making it harder for the robot to operate in muddy conditions. It would also be beneficial to have more than two tanks so that more varieties of herbicides could be used. If this was not something the farmers wanted, they could still use more tanks filled with just one kind of herbicide. There were a number of different options for how many herbicide tanks that could be used, which can be seen in Table 6.1. It was decided that only one type of tank and an even number of tanks were to be used due to weight and symmetry reasons.

Table 6.1. Herbicide tank size options

Option	Herbicide tanks	Total volume (liters)
1	6 x 5 liters	30
2	2 x 15 liters	30
3	8 x 5 liters	40
4	4 x 10 liters	40

The four types of herbicide tanks that were found that could be used can be seen in Figure 6.25, 6.26, 6.27, and 6.28. Tank number 2 and 3 were both much cheaper than number 1 and 4, but the quality also seemed to be a bit lower. Tank 2 had its attachment points perpendicular to the outlet which would make it harder to mount and there were also some concerns about the shape of the tank, that it wouldn't fit as well as the others. Both tank number 1 and 4 are built so that accessories can be attached to them, which does make them a bit heavier than the other options and the accessories are not something that will be needed for this project.

Figure 6.25. Tank option 1 [70]

Figure 6.26. Tank option 2 [71]

Figure 6.27. Tank option 3 [72] **Figure 6.28. Tank option 4 [73]**

The obvious place for the herbicide tanks were on the sides of the robot below the solar panels. This is the only place on the robot where there is a lot of space to place the tanks and it would make it easy for the herbicide to flow since the tanks would be placed higher than the FarmBot. The placement of the herbicide tanks depended on the placement of the batteries. Since the weight of the filled herbicide tanks would be 17-22 kg per side and the weight of the batteries would be 11.52 kg they needed to be placed so that the weight was evenly distributed. On top of this, it would be preferable if the herbicide tanks were placed close to the side of the FarmBot where the tubes from the herbicide tanks enter. All of the herbicide tanks found had a way of connecting them to the frame using t-nuts and bolts. They all needed at least four connecting points, which for tank number 1, 3 and 4 could be solved by adding extra extrusions just below the solar panel that the tanks could be attached to. For tank number 2 the extrusion would have to be added on the side instead. When attaching the tanks, it was important to place them so that they only stick out from the frame as much as necessary, to not make the robot bigger than it had to be.

6.3.8 Board

The developer board needed to be placed so that no water could get to it and placed strategically since many of the electronic parts were going to be connected to it. However, the board would preferably not be placed in the middle since both cameras and the Arduino were going to be placed there. There would also be a slit between the solar panels which could allow water to seep through which needed to be avoided. It would be reasonable to place the board in the back since the cables from the FarmBot would come from there.

It was desired to find a waterproof junction box that would be easy to open and that was big enough for all the incoming cables, but not too big. The developer board dimensions were 180 x 180 x 47 mm. By searching the web with these requirements two products were found, box 1 and box 2, which can be seen in Figure 6.29 and Figure 6.30.

Figure 6.29. Box 1 [74]

Figure 6.30. Box 2 [75]

Box 1 could be ordered with the dimensions 200 x 200 x 80 mm, 255 x 200 x 80 mm, and 300 x 250 x 120 mm. Since there needed to be room for the cables, the first two options where either one or two sides were 200 mm, were probably too small. It already came with 12 holes which would be enough holes for all the cables that needed to go into the box. Box 2 had the dimension 280 x 280 x 130 mm which would be enough room for both the box and the cables. It didn't have any premade holes for the cables but this could easily be done by drilling the exact amount wanted and the exact sizes needed.

The cover of the box would be mounted to the top of the frame and the developer board would be attached to the bottom of the box. Box 2 could easily be opened thanks to the hinged cover but it wouldn't be as easy with box 1 seeing that it had two separate parts. Some sort of angled brick that would rest between the box and the frame would ideally have to be installed behind the box in order to keep it still when it was opened. A stopper like this was made in CAD, see Figure 6.31, but seeing how not all measurements are available for the boxes the design has to be finalized when the box arrives. It was discussed how the board could be easily accessed, and some of the ideas were to have a box that could be opened as a drawer or to be folded down in a way that a big toolbox can be opened. However, since only a prototype was to be made where the board wouldn't need to be accessed that often, it was rather unnecessary to develop a concept with these functions. For a commercialized product however, this would be necessary to consider in the design.

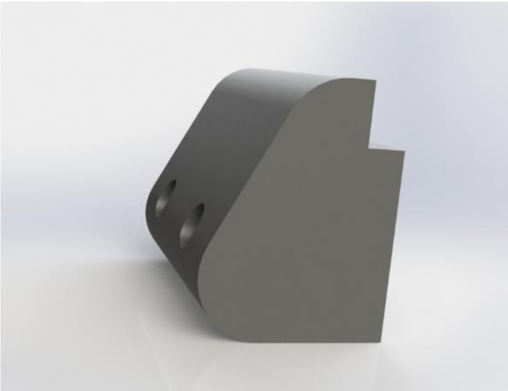


Figure 6.31. A stopper that will keep the box in place when accessing the developer board

To make sure that no water would get to the board, waterproof cable glands could be used. These can be ordered in a variation of different sizes, and can be mounted directly to the box after holes are drilled. To connect to the board by using a computer an Ethernet cable is used. This cable won't be attached at all times, and it would be optimal to not have to open the box to connect the computer. To solve this a special waterproof Ethernet cable gland can be used which has the Ethernet connector on the outside of the box, see Figure 6.32.

Figure 6.32. Waterproof cable gland designed specifically for Ethernet cables [76]

The board will produce some heat, so ventilation was also required. Depending on the placement of the board, it can be shielded from most water from above by the solar panels and from the sides by the cover. This makes the upper part of the box optimal for ventilation holes. Most likely no water will get through the top but there are products that allow air to pass through while blocking water and dust, such as an IP Rated Porex Virtek PTFE Vent by Porex [77], which is basically just an adhesive tab that you place over a hole, and Gore Vents by Gore [78]. These do not only ventilate the case, but they also make sure that there is no condensation within the case as well as protecting against pressure changes which can damage the electronics if the box is completely sealed.

6.3.9 Arduino

A sensor was attached to an Arduino Mega 2560 and the Arduino needed to be placed in the middle of the robot for the gyroscope to work properly, preferably as far to the front as possible. It also needed to be made sure that no water would get to the Arduino as that could destroy the hardware. There are many cases for Arduinos, however most of them are not waterproof at all and it is especially hard to find a case that will fit when there is a shield attached to the Arduino. There are many bigger cases where both the Arduino and the shield will fit, but they will most likely be a bit bulky since they are not custom-made for this. If both the case and the front camera were to be attached to the front frame there also wouldn’t be too much room to place the case. On top of this the case required a way of being attached to the frame. A good way to overcome these problems is by 3D-printing the case. It can be custom-made so that the Arduino fits very well in the case and it can also be made sure that it is designed so that no water will get to the Arduino, as well as providing enough ventilation if needed. It makes sense to place the Arduino underneath the solar panels to provide some cover from the rain, but even then some water will most likely leak through the slit between the solar panels and down onto the Arduino. Arduinos does not produce much heat so ventilation might not be necessary, but ventilation holes with protective covers can be used to make sure that there is some ventilation. If this is not enough the IP Rated Porex Virtek PTFE Vent or the Gore Vents by can be used, however these can be a fairly expensive solution. To protect the cable entrances from water getting in, a grommet with a gasket could be used, see Figure 6.33.

Figure 6.33. Grommets [79, 80, 81]

6.3.10 Joystick

Since only about 15% of the world's population is left-handed [82], the placement of the joystick would naturally be suited for right-handed drivers. The drivers also need to be able to see in the front of the vehicle while driving, so another obvious placement would be on the side in the back and in this case on the left hand side so that the driver can use its right hand and walk on the side with a clear view. It could also be placed in the middle to suit both right-handed people as well as left-handed ones, but then the FarmBot would most likely be in the way of a clear view.

The natural and ergonomic wrist and hand position is when the wrist is straight and unbroken [83]. The wrist should also be in line with a straight forearm so that the force can be exerted in the same direction. The joystick should therefore be placed in a way where the wrist does not require flexion, extension or deviation, but is instead in a natural, straight position [84].

The average man in Australia is 175.6 cm tall [85] and since there is a majority of men working in the agricultural industry, this height was used to determine where to place the joystick so that the forearm could be in a straight horizontal line. The average height from the floor to the elbow of a

175.6 cm tall man is 109 cm [86] and it would therefore be appropriate to place the joystick around that height.

It was necessary to do some measuring of the joystick and the mount it had for the wheelchair in order to design a new mount that would fit the frame. The joystick that was going to be used can be seen in Figure 6.34, its attachment points in Figure 6.35 and the mount in Figure 6.36.

Figure 6.34. Joystick

Figure 6.35. Attachment points

Figure 6.36. Original mount

The joystick was attached to the mount using two M4 screws and the distance between the centers of the holes was 40 mm. A similar mount needed to be designed that could be firmly attached to the frame.

6.3.11 Cover

How the cover could be designed depended greatly on the shape of the frame since it was going to be attached to the frame. Brainstorming sessions were done to gather inspiration, and the inspiration mainly came from sports cars, robots and modern buildings. Using curves that can be seen in sports cars was discussed which would make it look impressive and luxurious. It could also be designed with straight lines which would make it look clean, sophisticated, and futuristic, like a modern building. Another idea was to work with layers and angles to give it a more dynamic look and more depth, like many other robots. Seen below, Figure 6.37, are some of the early designs that were generated.

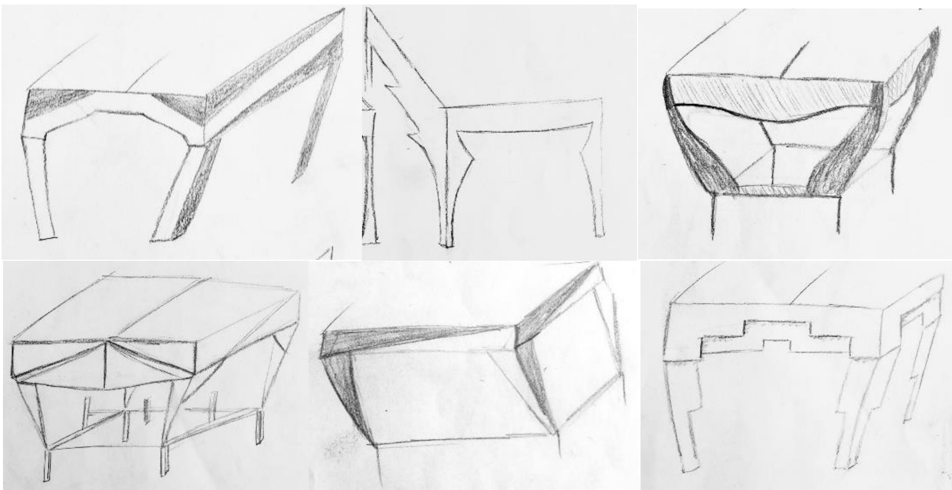
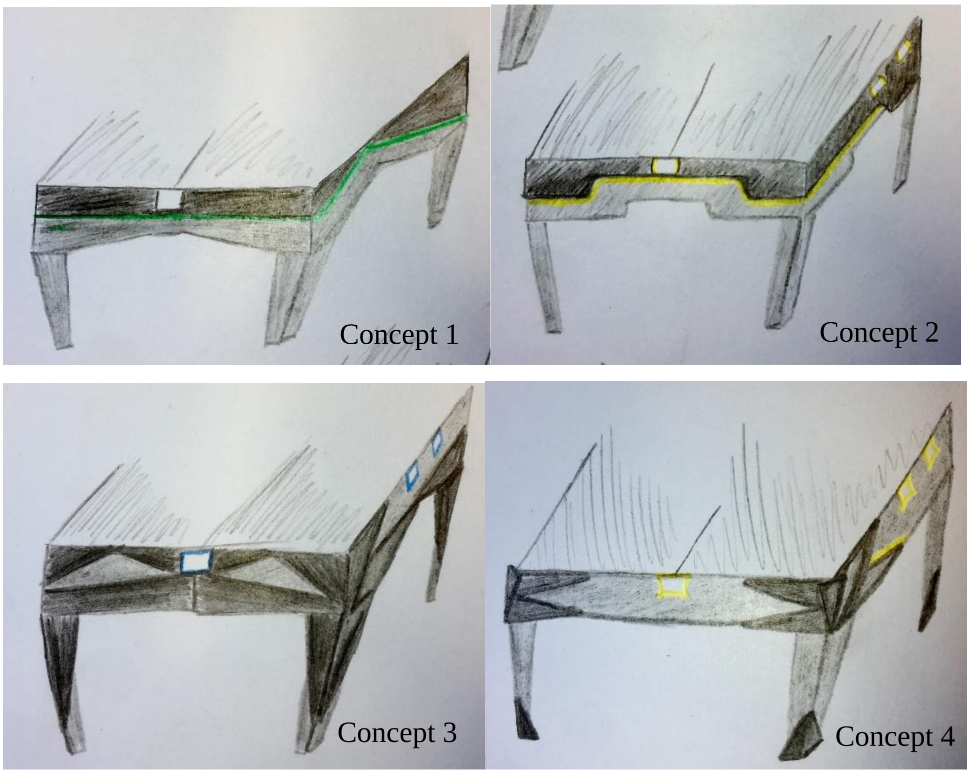


Figure 6.37. First cover concepts

It was mainly discussed to use dark colors, like gray and black, but with different materials. One could be matte and one could be shiny to make them stand out more. Combining white or light gray with black was also considered, but the problems with lighter colors in the agricultural industry is that when the vehicle gets dirty it shows a lot more than with dark colors. Adding some colorful details could make the design a lot more interesting and it would be enough with a few lines or a logotype because it still needed to be a simple and clean design.

The electronic parts needed to be easily accessible and most of the parts were going to be attached to the upper part of the frame, which meant that the cover shouldn’t cover the whole frame. The cover could therefore cover the upper part and parts of the legs. If the frame was going to be angled then a design could be made utilizing that to avoid making the vehicle look like a big box or a tent. With a design similar to what is shown in Figure 6.37, the only thing that would be shown from the outside would be the FarmBot, the front camera and the joystick. The herbicide tanks would most likely be covered, however the taps needed to stick out so that they could be refilled easily.

With these things in mind, some further concepts were generated with more details. These design can be seen in Figure 6.38.



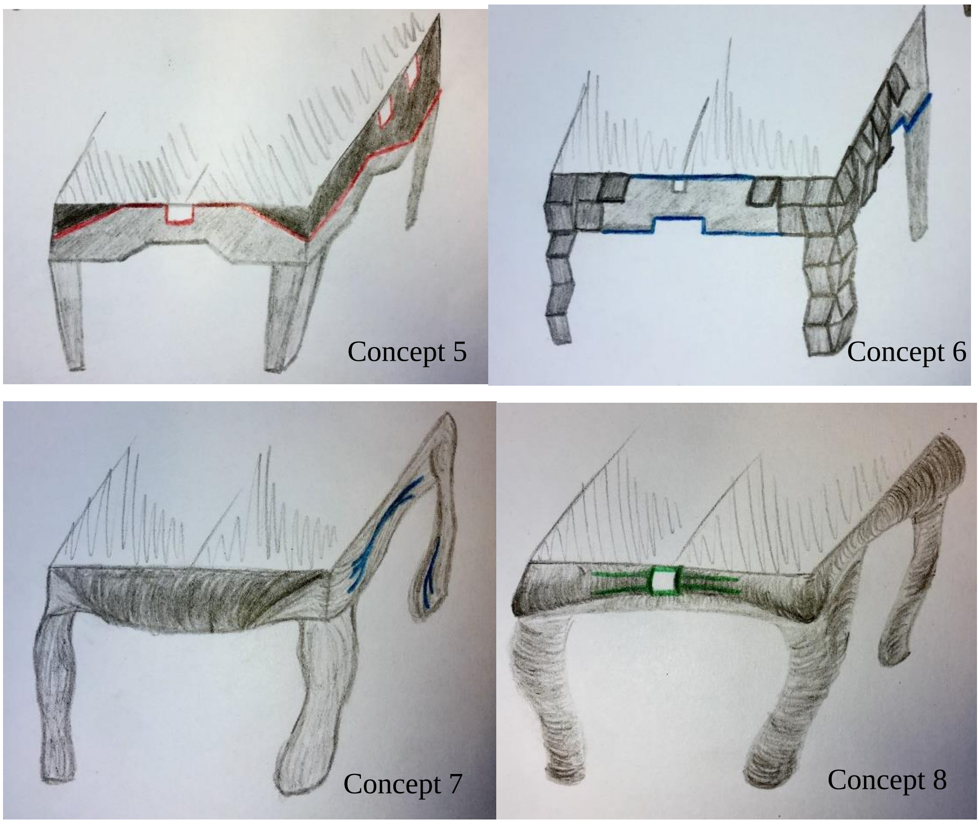


Figure 6.38. Design concepts of the cover

Some of the concepts are completely flat, some have layers or curves and some have protruding parts. Concept one with a green line has flat parts with triangles used in the design. Concept two has two layers but can easily be made as one layer. It has straight lines with a little bit of curves. Concept three has angled triangles so that some of the parts stick out a little bit. Concept four, with red lines, is also flat with the use of triangles in the design. Concept five uses more angled triangles and also has some details on the "feet". Concept six has squares going out in small angles with a very futuristic look. Concept seven and eight are curvy with inspiration from sports cars.

After discussing the concepts together with the supervisor it was decided that it would be benefitting to have a flat design so that there wouldn't be any unnecessary production complications for the prototype stage. A design that was easy to manufacture and assemble was desired. The flat concepts were concept number one, two, four and five and all of these were promising designs but needed some further development with a few more details. The general favorite among the team members was the second one but it could be designed using different colors and details.

7 Concept Selection

This section contains the selection of the final concepts. This part shows how they were selected and why.

7.1 Methodology

The most thorough methodology for selecting a concept is according to Ulrich & Eppinger's book to use two stages of Decision matrices, where the first one is Concept Screening and the second one Concept Scoring. In both of them the concepts are rated against prespecified selection criteria in a five-step process [4, p. 149]:

1. Prepare the selection matrix.
2. Rate the concepts.
3. Rank the concepts.
4. Combine and improve the concepts.
5. Select one or more concepts.

This method was not necessary to use on all sub problems seeing that most of them had to be designed in a certain way due to the restrictions, or some of the concepts were obviously better and were therefore chosen by intuition. However, the camera concepts needed to be evaluated using Decision matrices seeing that there was not any one concept that was obviously the best and most concepts seemed equally good. The selection of the camera concepts therefore started with Concept Screening so that some of the concepts could be eliminated. The final concepts were then evaluated with Concept Scoring so that one final concept with the highest score could be chosen.

The other parts of the robot were as mentioned selected through intuition, it was discussed what concept would be the best and that one was chosen. Some of them were chosen by making pros and cons lists to get a better overview of the concepts weaknesses and strengths.

7.2 Concept Selection

7.2.1 Solar Panels and Charge Controllers

Since it was already decided in the beginning which solar panels and charge controllers that were to be used, there was no need for a concept selection for anything other than the placement of them.

First of all, it was chosen to place the solar panels at the very top seeing that it was an obvious solution from an energy efficiency point of view. This would also make it possible to hide all the electronic equipment underneath. Since the FarmBot tracks were 1500 mm wide, and the front wheels would stick out on the side a little bit due to the attachment of the motors, it was chosen to place the solar panels with the long sides together and on the side, with the dimensions 2092 x 1559 mm where the total longest sides would be in the front and back. With these dimensions it wouldn't be classified as an oversize light vehicle. The idea was to make it look compact and to make the robot as small as possible, and by placing the solar panels in that way it would look the most compact because everything would be in a boxed shape. It would also be benefitting to have the electronic equipment hidden under the solar panels on the sides for an evenly weight distribution, and for the minimization of cable length from the motors.

The solar panels were going to be fixed and bolted to the frame on the sides and in the middle. Since the vehicle would be rather tall the electrical part could be easily accessed from underneath and it was therefore not necessary to be able to fold the solar panels up.

It was decided to place the charge controllers underneath and in the front sides close to the junction boxes and the batteries. They would be attached to the frame together with the batteries.

7.2.2 Frame and FarmBot

For a design that is to be something in between a prototype and a commercialized product the t-slot aluminum extrusions are great to use, since it will be easy to make modifications further down the line. The high specific strength and the corrosion resistant properties of aluminum were two more reasons why the aluminum extrusions were chosen. The dimensions of these extrusions were chosen to be 40 x 40 mm, but a FEA had to be done later on to make sure that this would be enough.

Two designs were considered to be the most viable ones. Option one, see Figure 7.1, and option two, see Figure 7.2.

Figure 7.1. Frame option one

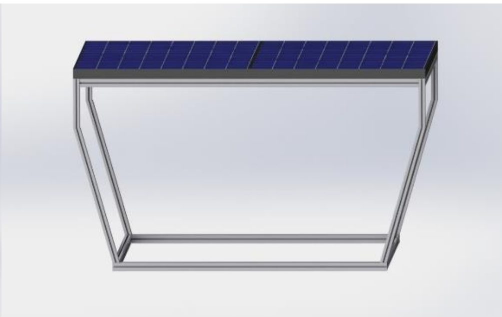


Figure 7.2. Frame option 2

The angled type of frame one was chosen as the design, mainly due to the fact that it was more aesthetically pleasing than the one with straight extrusions. The design was prioritized over the fact that it would be harder to manufacture and assemble. To connect the extrusions together four different types of connectors will be used; L-type 90 degree brackets, small 90 degree brackets, big 90 degree brackets and special 3D printed connectors. 3D printed connectors will be used where the extrusions are angled, big brackets will be used to attach the extrusions connecting to the wheels, L-type 90 degree brackets will be used to connect the extrusions that will hold up the tanks and the board and small brackets will be used everywhere else.

The Y-axis of the FarmBot was decided to be moved down and attached to the wheel bearing connector, while the Z-axis was decided to be shortened by 260 mm from below. The tracks were going to be connected to an extrusion that also had the purpose of stabilizing the robot. The FarmBot was going to be placed so that the tubes and cables entered from the back of the robot, so that they could be as short as possible. It was extra important that the herbicide tubes were as short as possible so that the herbicide could easily flow through them.

A cable clip was seen to be the easiest solution to fixing the cables to the frame, and a 3D-printed cable clip was designed. It solves the problem of different sized cables by using a zip tie to tie them to the cable clip. The cable clip has a t-slot attachment so it is easy to attach to the extrusions, see Figure 7.3.

Figure 7.3. The cable clip

The final frame can be seen in Figure 7.4.

Figure 7.4. The final design of the frame

7.2.3 Wheels and Motors

Both of the wheels from the concept generation matched the three criteria listed and were therefore viable, however tire option one looked very similar to what all the other robots from the external search had used and were chosen mainly due to this fact. It was a tried and tested tire pattern that had been used for many agricultural vehicles, and seemed like an appropriate choice. See Figure 6.16 for the chosen wheels.

The motor will be attached using a 3D-printed connector, which can be seen in Figure 7.5.

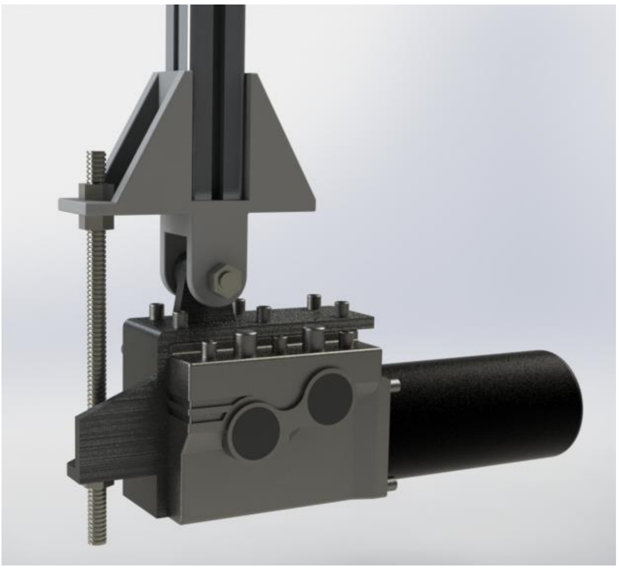


Figure 7.5. The final design of the motor attachment

7.2.4 Middle Camera

From the brainstorming session it was decided to develop a camera mount for the middle camera with a function used in concept number two, see Figure 6.20. The reason why this was chosen was because of its ease of use, the sturdiness and stability and because it can be adjusted in every height within those 10 cm. However, it needed to be further developed and a new concept generation therefore begun.

7.2.4.1 Concept Screening

Three different concepts were generated after developing concept number 2 from the first concept generation. The generated concepts were very similar, but the camera is mounted differently in each one. In the first one it is bolted together on both sides, in the second one it is bolted together on one side, and in the last one the camera is attached to the mount using glue. These were designed using CAD and can be seen in Figure 7.6, Figure 7.7 and Figure 7.8.

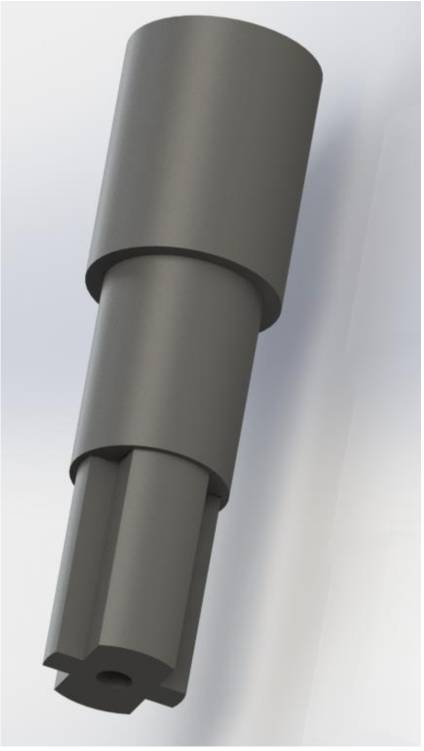


Figure 7.6. Concept 1

Figure 7.7. Concept 2

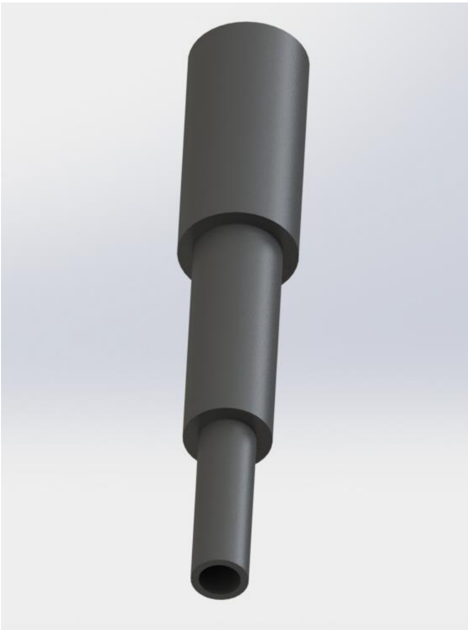


Figure 7.8. Concept 3

To decide which one that was going to be developed further, it was necessary to evaluate the concepts using the decision matrices. The three concepts first went through Concept Screening and the results can be seen in Table 7.1. A concept was given a + if it was better than the rest of the concepts in that criteria, a 0 if it was average, and a - if it was worse than the rest. It is normal to have a reference concept that is given a 0 in all the criteria, and the concepts are then compared to that reference. In this case there was no reference concept however and they were therefore compared to each other.

Table 7.1. Decision matrix for middle camera concepts

Selection criteria:	**Concept 1**	**Concept 2**	**Concept 3**
Ease of use	0	0	-
Ease of switching camera	+	0	-
Appealing design	0	-	+
Stability	+	+	0
Sturdiness	+	0	0
Size	-	0	+
Sum +’s	3	1	2
Sum 0’s	2	4	2
Sum -’s	1	1	2
Net Score	2	0	0
Rank	1	2	2
Continue?	**Develop**	**No**	**No**

7.2.4.2 Concept Evaluation

Concept 1 was the clear winner in the concept screening and it was therefore not necessary to continue with Concept Scoring. It was chosen to develop this concept further since it is easy to use, has a nice and simple design, and most of all is stable and sturdy. However it still needed to be further developed and the lock function needed to be integrated in the design.

7.2.4.3 Further Development

In order to be able to adjust the mount in different heights, there needed to be room for a screw on the side that could be loosened and tightened. By adding this, the mount would be longer but it was still important to keep it as short as possible.

In the previous design a slot was set in the end of each part and around it, which made the whole design wider. A small design was wanted seeing that the camera was very small and it would be unnecessary to make it a lot bigger. It was therefore chosen to use a different way to hold the parts in place. A slot was integrated on the side instead, with a carved cut on the upper part of the mount, which made the mount slimmer, see Figure 7.9 and Figure 7.10.

Figure 7.9. The final middle camera concept

Figure 7.10. The final middle camera concept seen from the other side

The figures above show how the concept was further developed with the new functions. It had two threaded holes for screws, one on the middle part and one on the upper part. It was not possible to use only one screw to adjust the height since the mount was made out of three parts, which it was so that it would be as compact as possible. The screws that were to be used to fix the camera in place can be seen in Figure 7.11.

Figure 7.11. Screws used for the middle camera [87]

Two brackets were added at the top so that the mount could be attached to the solar panels. There also needed to be room for the cord, and a hole was therefore added at the top of the camera mount.

7.2.5 Front Camera

After gathering inspiration from the external search it was decided that the concept would use pressure from a screw or bolt to tighten the camera. Further concept generations began to find the best way to do this and some of the concepts generated can be seen in Figure 7.12, 7.13, 7.14, and 7.15.

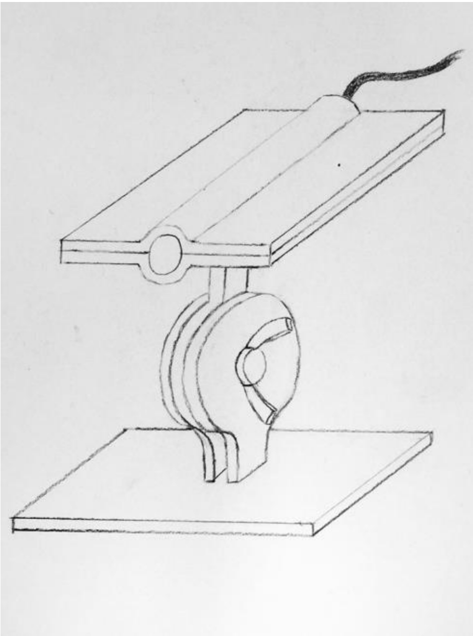


Figure 7.12. Concept 1

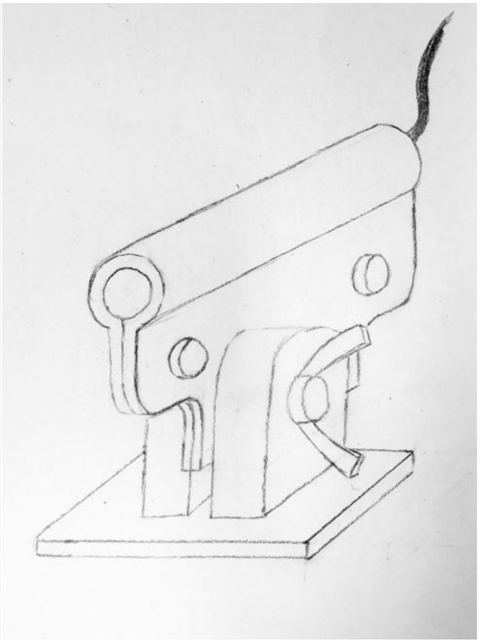


Figure 7.13. Concept 2

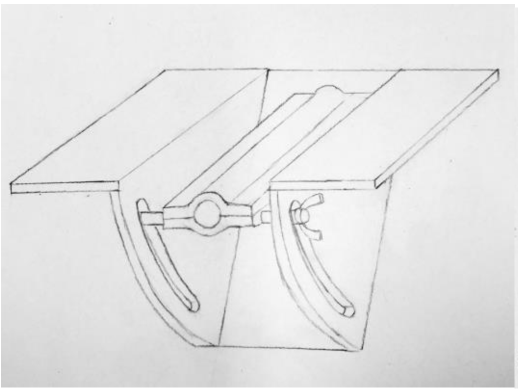


Figure 7.14. Concept 3

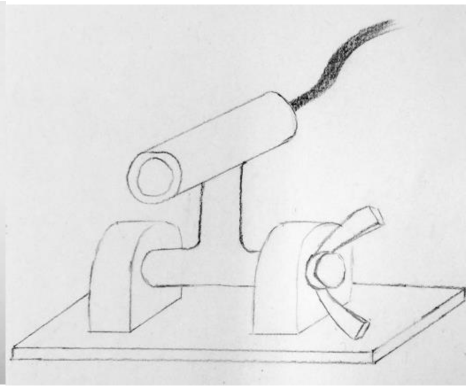


Figure 7.15. Concept 4

In concept 1-3 the camera is bolted to the mount. This makes the whole mount slightly bigger but the camera will be firmly attached. Concept number 4 is mounted using glue which makes it as small as possible but the camera can never be changed to another camera if needed.

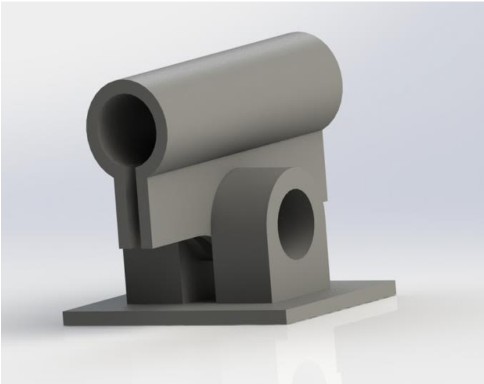
7.2.5.1 Concept Screening

All the generated concepts were very similar and were based on the same solution. They would all work well with the robot and were discrete and small. It was therefore difficult to decide which one would be better than the others and they therefore needed to be evaluated with decision matrices so that a final concept could be found. The first stage in the decision matrices process was Concept Screening, which can be seen in Table 7.2.

Table 7.2. Concept Screening of the front camera concepts

Selection criteria:	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Ease of use	0	0	+	0
Ease of switching camera	+	0	+	-
Appealing design	-	0	0	+
Stability	0	+	0	0
Sturdiness	-	0	+	0
Size	-	0	-	+
Sum +'s	1	1	3	2
Sum 0's	2	4	2	3
Sum -'s	3	0	1	1
Net Score	-2	1	2	1
Rank	4	3	1	2
Continue?	**No**	**Yes**	**Yes**	**Yes**

By rating and ranking the concepts it was decided to further develop concept number 2, 3 and 4. It was also decided that more detailed sketches would be made using CAD to get a better understanding of what the final design would look like, see Figures 7.16, 7.17, and 7.18.



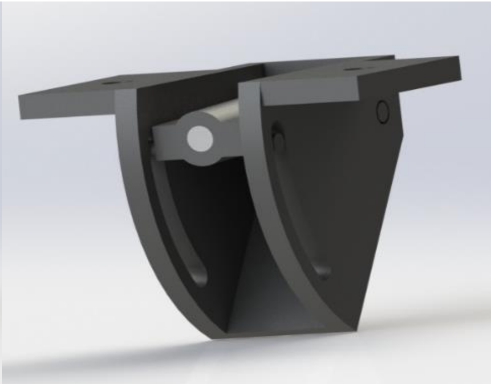


Figure 7.16. CAD model of concept 2 **Figure 7.17. CAD model of concept 3**

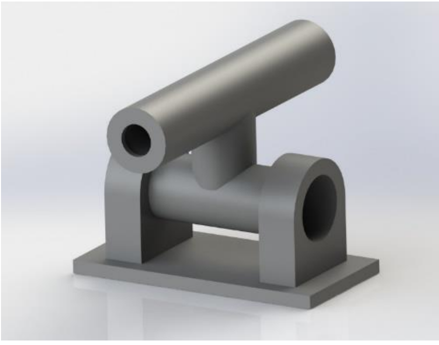


Figure 7.18. CAD model of concept 4

7.2.5.2 Concept Scoring

After sketching the concepts in CAD, they were evaluated through Concept Scoring, the second and last stage in the decision matrices process. See Table 7.3 for results.

Table 7.3. Concept Scoring for front camera concepts

		Concept 2		**Concept 3**		**Concept 4**	
Selection criteria:	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Ease of use	15%	3	0.45	4	0.60	3	0.45
Ease of switching camera	5%	3	0.15	4	0.20	1	0.05
Appealing design	25%	3	0.75	3	0.75	4	1
Stability	30%	4	1.20	3	0.90	3	0.90
Sturdiness	20%	3	0.60	5	1	3	0.60
Size	5%	3	0.15	2	0.1	5	0.25
	Total score	**3.3**		**3.55**		**3.25**	
	Rank	2		1		3	
	Continue?	**No**		**Develop**		**No**	

7.2.5.3 Concept Evaluation

From the decision matrices it was understood that the most suitable concept for this purpose would be concept number 3. It got the best score in both Concept Screening and Concept Scoring and it was therefore chosen for further development. This concept is stable, sturdy, and easy to use.

7.2.5.4 Further Development

The concept needed some further development and a more detailed design had to be made. The final design of the concept can be seen in Figure 7.19 and 7.20.

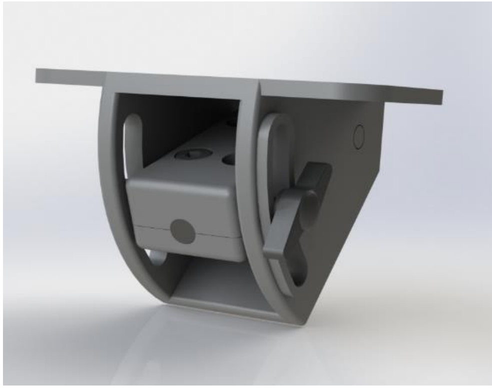


Figure 7.19. Final design of the front camera

Figure 7.20. Final design of the front camera seen from the front

The part that holds the camera in place had to be made bigger so that there would be room for the screw that locks the camera in place in the desired position. The camera is bolted together using four bolts and attached to the frame using two screws. The adjustment is done by using a track where the screw slides and it can be adjusted between the angles of 90 degrees and 45 degrees. It rotates in the back using a stick that connects the camera to the mount. The screw that is used to fix the camera in place is the same one used for the middle camera, see Figure 7.11.

7.2.6 Batteries

For the prototype it was chosen to use the design with t-slot extrusions seeing that this would be the easiest to build. However for the CAD-file the design with only sheet metal was chosen so that it would look more appealing when presenting the vehicle for investors and others. The final extrusion design can be seen in Figure 7.21 and the final sheet metal design can be seen in Figure 7.22.

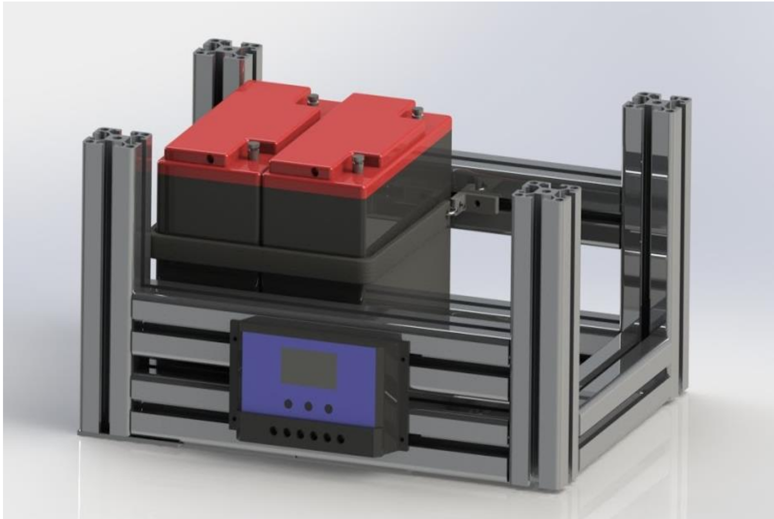


Figure 7.21. The final battery holder made out of extrusions

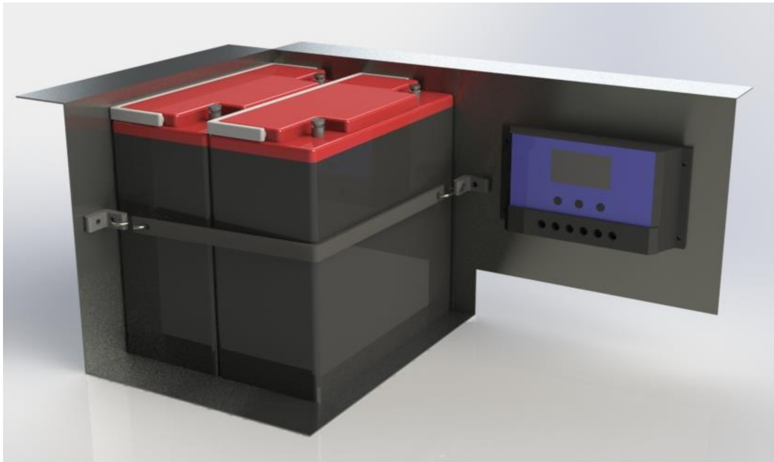


Figure 7.22. The final battery holder made out of sheet metal

7.2.7 Herbicide tanks

The herbicide tank chosen was tank 3, see Figure 6.27, due to the fact that it was easy to attach to the frame, lightweight, of a good shape and also very cheap. Extrusions will be added to the frame that the tank can be attached to, see Figure 7.4.

7.2.8 Board

It was decided to use box 2, see Figure 6.30, to cover and mount the board to the t-slot extrusions on the frame on the left side. This box would be the easiest one to handle if the board needs to be accessed and was a good size to fit both the board and the cables. The holes for the cables would be drilled so that suitable cable glands could be used. For the Ethernet cable, a waterproof cable gland specifically designed for Ethernet cables will be used, see Figure 6.32. Ventilation holes will be drilled at the top, but it has to be closely monitored if water can get it in which case IP Rated Porex Virtek PTFE Vents should be used to solve the problem.

7.2.9 Arduino

A custom designed Arduino case was made using CAD and was then going to be 3D-printed. It was made so that the Arduino could be attached to the case while also having enough room for the cables. A rubber seal was used to seal the cable entrances and the case was designed with a specific rubber seal in mind that can be used for 4 mm cables. The combined parts can be seen in Figure 7.23 and the bottom part alone can be seen in Figure 7.24, which shows how the rubber seals are squeezed in between the two parts. Three ventilation holes with covers were designed on the bottom of the case, see Figure 7.25, but if the Arduino gets too hot or condensation forms inside the case it is recommended to remove the ventilation holes and use an IP Rated Porex Virtek PTFE Vent to solve the problem. The screws that are used to screw the two case parts together are screwed on from the top. This will make it so that you need to remove the whole case from the frame to open it, but it will prevent the screws from falling off due to vibrations.

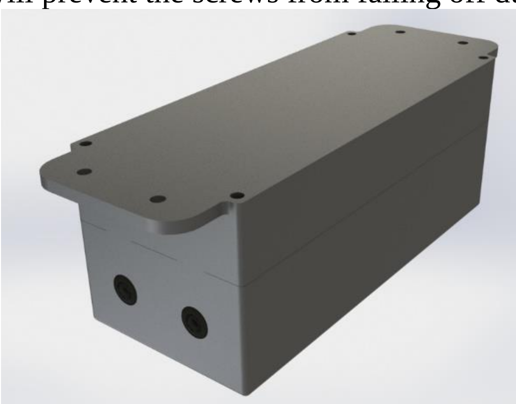


Figure 7.23. The finished case with rubber seal

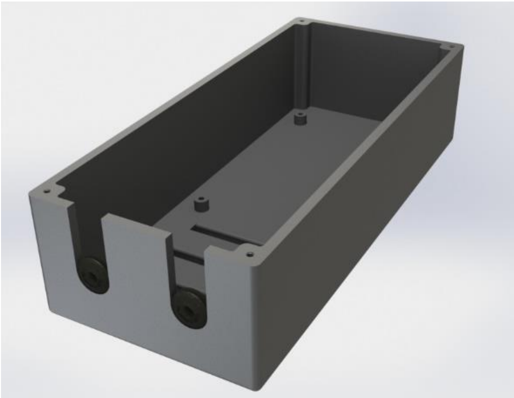


Figure 7.24. The bottom part of the Arduino case

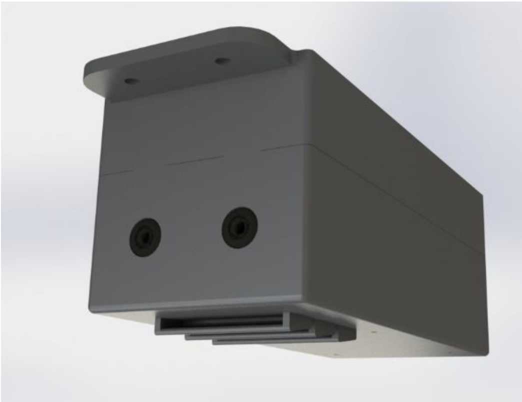


Figure 7.25. Ventilation holes for the Arduino case with cover

7.2.10 Joystick

It was decided to place the joystick on the left side in the back of the frame with a mount that was similar to the mount used for the wheelchair. The joystick will lie on a mount that is attached on two sides of the frame for extra support. It also has a hole for the cable to go through so that it will stay close to the frame. The new mount can be seen in Figure 7.26.

Figure 7.26. The final design of the joystick mount

7.2.11 Cover

It was decided that further development were to be done on a flat version of concept 2. This concept was designed in CAD to get a better understanding of what it could look like. This can be seen in Figure 7.27.

Figure 7.27. A first CAD model of concept 2

By analyzing the result it was easier to see what changes that could be done for a more appealing look. The colors of the design were slightly changed and some details were added in the final design, which can be seen in Figure 7.28 and 7.29.

Figure 7.28. Final concept of the cover shown from the front and side

Figure 7.29. Final concept of the cover shown from the back and side

The first layer had a shinier grey material and the second was a matte black material. The details were made with a bright orange color to make it a bit more interesting. It was decided to use orange instead of yellow since it is a more subtle and not as distinctive color. Legs for the lower part of the vehicle were also added to cover the extrusions and the electronic parts as much as possible. This also made it look more professional and complete. The reason why this concept was chosen was due to the fact that it is a simple design with no protruding parts, but still nice and elegant which makes it look like a futuristic robot which was desired. It would also be easy to manufacture, which was something that was desired by Hormoz Marzbani. The final design was chosen through discussion within the team and with Hormoz Marzbani.

8 Concept Testing

In this section it is described how the vehicle was tested using Finite Element Analysis to see if the design worked. The results from stress- and displacement analysis are presented.

In order to see if the vehicle could stand the loads from the solar panels, batteries, herbicide tanks, and the rest of the parts, it had to be analyzed using FEA. The analysis were done in the same program as the CAD drawings, SolidWorks, and a static simulation with a rather coarse mesh of 8 mm, was run. This was due to the fact that the computers available couldn’t handle a finer mesh of such a big product. The material assigned to the extrusions and solar panels was aluminum 6061 T6, and the material assigned to the connectors was ABS plastic. These are the correct materials for the extrusions and the connectors, but it was only known that the solar panels were made of aluminum. To simplify the analysis in order to make sure the computer could handle it most parts were excluded, and forces were used to mimic the load from those parts. A downward force from where the solar panels, the batteries, the board, and the herbicide tanks would act on the extrusions were set. The load from the solar panels was acting on top part of the frame, as if it was pushing the extrusions down. The load from the herbicide tanks and the board was set as pulling the extrusion down, and the load from the batteries was set on the battery holder. Since the parts not included were small, lightweight or didn’t have a great impact on the vehicle, they were disregarded in the simulation. There were connection set between extrusions and extrusions, extrusions and connectors and extrusions and solar panels. These connections were all set as rigid, once again to simplify the analysis so that the computer could handle it.

The results from the simulation can be seen below. In Figure 8.1 the displacement is shown from the top. In Figure 8.2 it is shown from underneath and it can be seen that the maximum displacement is on the top inner extrusions which is displaced 7.627 mm. The parts with the highest displacement hold the herbicide tanks, the board, and the batteries. It is not surprising that the greatest displacement is there seeing that the biggest load is on those extrusions and that they are not that supported. Since these extrusions are not of great importance to the overall function of the vehicle the displacements were deemed to be acceptable, however it would be very easy to change these extrusions to bigger ones if needed, for example 60 x 40 mm, since the design is very modular. The rest of the model has small displacements and it was considered to be acceptable.

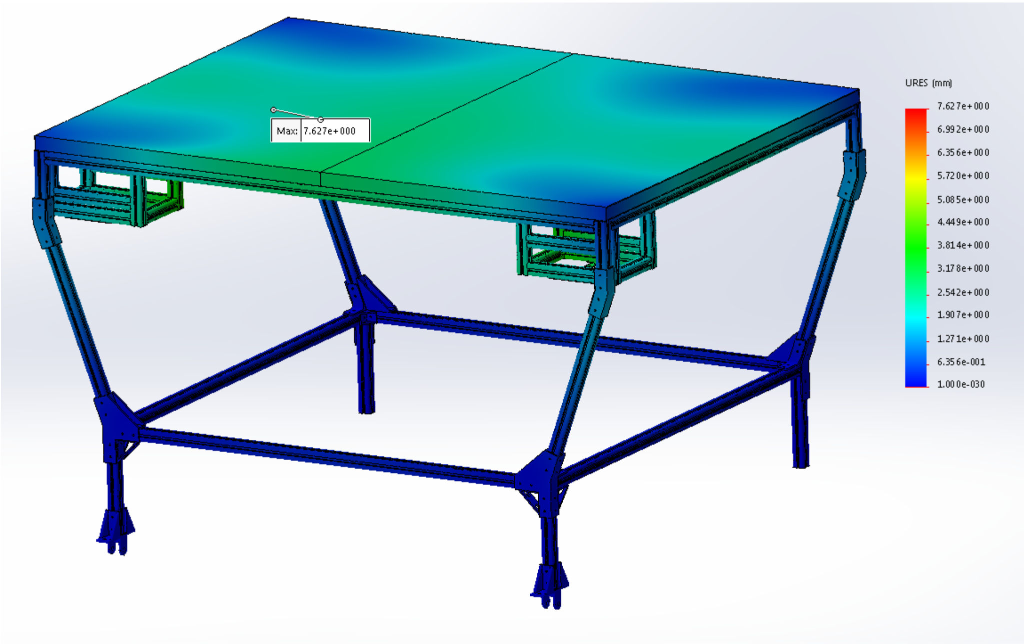


Figure 8.1. The displacements of the frame

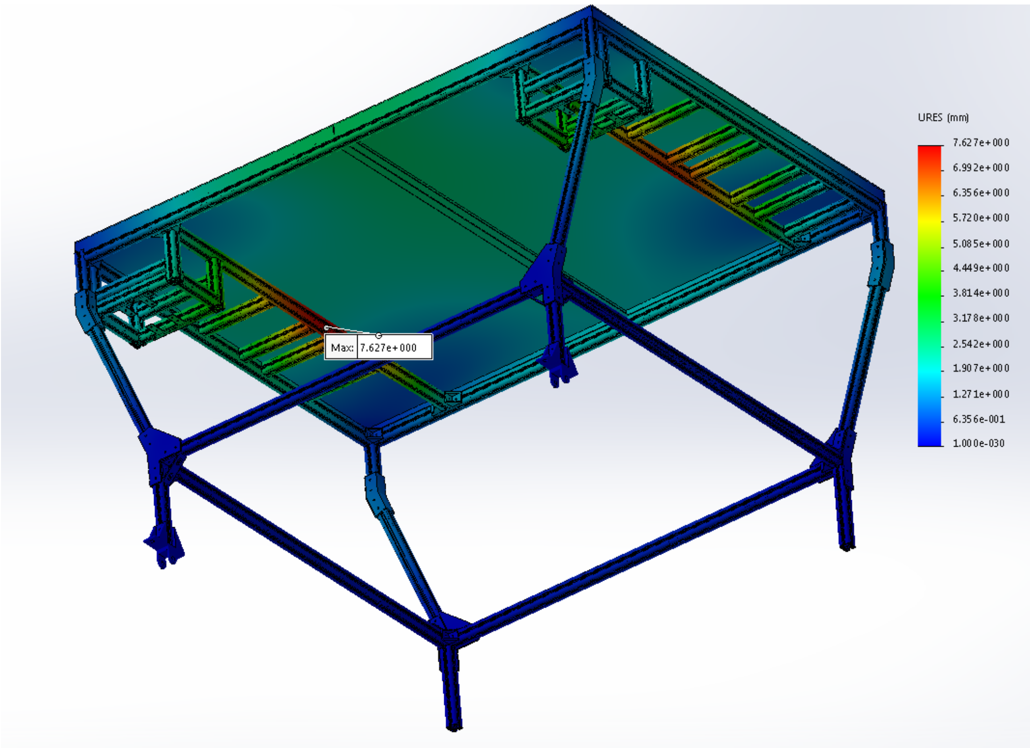


Figure 8.2. The displacements of the frame seen from underneath

In Figure 8.3 the stresses in the model are shown. The maximum stress of 250.2 MPa was in the angled extrusions, under the 3D-printed connectors. The yield stress for Aluminum 6063 T6 is around 170 MPa and with a safety factor of 2, the maximum stress was set as 85 MPa in the charts to better see where the higher stresses were located and if it can stand the safety factor.

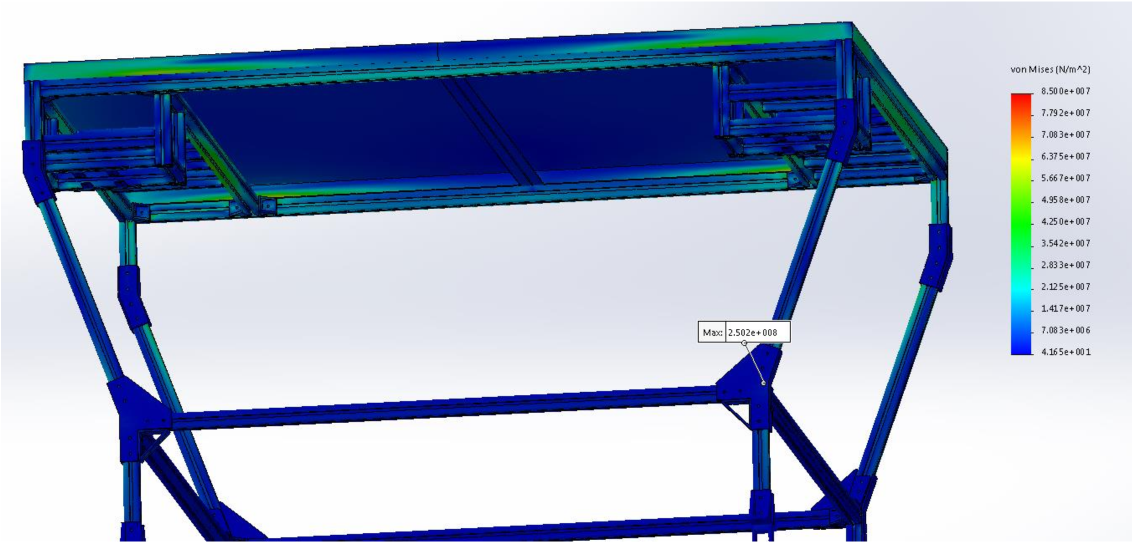


Figure 8.3. The stresses in the frame with a chart set to a safety factor of 2

In Figure 8.4 and 8.5 the point of the maximum stress is shown up close, where the stress is 250.2 MPa. There were some suspicions that this high stress was due to the big mesh size, which was confirmed when looking closer. In Figure 8.5 it can be seen that the mesh has some problems where the maximum stress is located, and that the stresses around that area are very low.

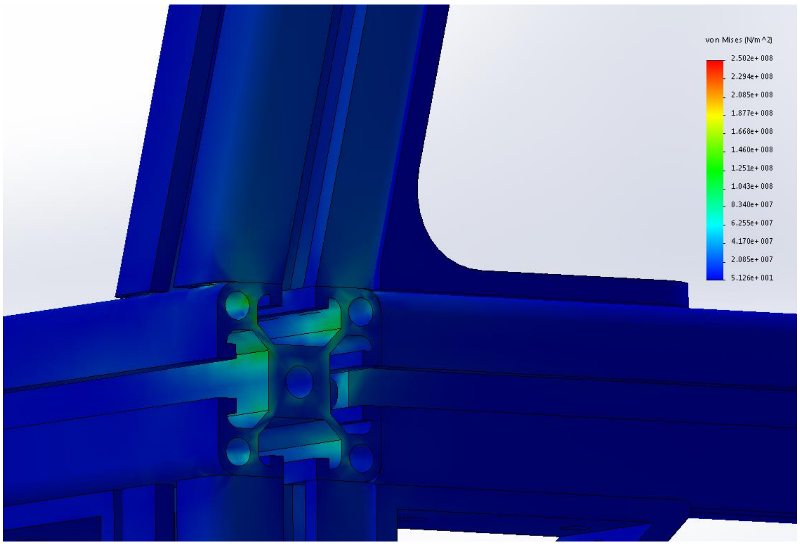


Figure 8.4. The maximum stress was in the angled extrusion

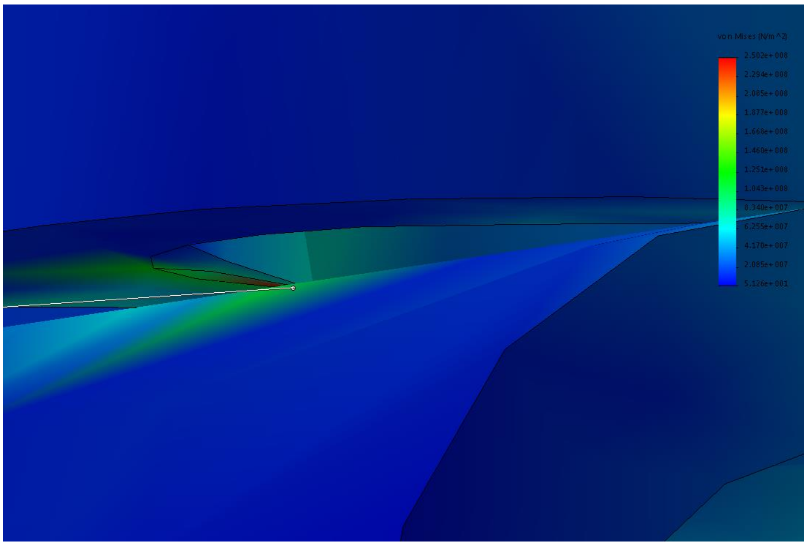


Figure 8.5. A closer look at the point of the maximum stress shows that the mesh is deformed

The results show that there are small deformations and low stresses in the model which means that there will most likely not be any plastic deformation. There are however some extreme points in the stress analyses where the lower angled extrusions meet the horizontal extrusion, but these were deemed to be due to problems with the mesh rather than problems with the design. If more resources were available, a more accurate FEA would have been done with a smaller mesh size. The rest of the model can stand a safety factor of at least 2.

Seeing that the results from the FEA shows that the design of the vehicle will not be plastically deformed it was decided to not do further testing and developments. However, when the prototype is made there needs to be real life testing to see if the theory is correct. If those testing show that it needs to be more stable, modifications can easily be made in the design such as adding extra supports or different connectors.

9 Results

This part of the report shows the final design of the vehicle. CAD-modeling renders of the vehicle with and without the cover are presented. The total cost and weight of the vehicle is also presented.

The final design of the frame can be seen in Figure 9.1 and in Figure 9.2. The final design of the complete vehicle with the cover can be seen in Figure 9.3, Figure 9.4 and Figure 9.5.

Figure 9.1. Final result of the frame shown from the back and side

Figure 9.2. Final result of the frame shown from the top

Figure 9.3. Final result of the complete vehicle shown from the front and side

Figure 4. Final result of the complete vehicle shown from the front

Figure 5. Final result of the complete vehicle shown from the back and side

The final cost for the autonomous weeding vehicle, excluding the costs of parts that were already obtained, was USD 2075.38. Including the Nvidia Jetson TX2 Developer Kit (USD 569), Arduino Mega 2560 (USD 38.50) and FarmBot Genesis (USD 2595) the vehicle costs were USD 5277.88. Parts not included in this due to unknown costs is the front camera, the joystick and the motor. Costs for the individual parts can be seen in Appendix B.

The total weight of the autonomous weeding vehicle including the FarmBot was 154.38 kg. With 40 liters of herbicide in the tanks it will weigh around 194 kg. Weight of the individual parts can be seen in Appendix B.

10 Discussion and Summary

In this section the project is discussed. It is discussed how it could have gone better or worse, pros and cons about the vehicle, general problems, and future possibilities. A conclusion of the project and the results is also presented.

10.1 Discussion

The goal of this project was to design a robot that could detect and remove weeds. A CAD-file showing the vehicle and all its parts was wanted and an appealing and lightweight design was desired. The final product that was developed meets the requirements that was given in the beginning. By using aluminum extrusions as the base of the design, it was possible to make it lightweight yet sturdy and durable. It is also a cheap design that is easy to manufacture and build seeing that most of the parts will be ordered and not custom-made.

The hardware of the vehicle has been created with the assumption that the software will work. Hence, requirements like "The robot doesn't harm the crops while operating" has been slightly disregarded when it comes to how the FarmBot operates, but has been highly prioritized when the placement of the extrusions have been decided upon. Therefore, if everything works as it should with the coding, then the requirements will be completely fulfilled. This has to be tested however and will not be known until the prototype is ready. Unfortunately there wasn't enough time to make a prototype in this project due to the fact that it takes up to two months to receive some of the parts that needed to be ordered. Some of the testing has to be done at a later stage and if needed the vehicle must be modified so that the requirements are met. However, the CAD model shows what the robot can do and what it will look like which still makes it possible to demonstrate it for the farmers.

Seeing that the prototype wasn't made, the only testing that could be done was FEA to see if the structure could withstand the forces applied to it. These analyses were done in SolidWorks which is a program that is not specifically designed for these kind of simulations and therefore doesn't give the most precise results, however it does give an understanding of how the vehicle will behave under the impact of loads. Other programs that are designed for this type of work, such as Ansys and COMSOL, couldn’t be used due to the fact that they have a restricted amount of mesh elements for the version that was available. The design is quite big, and required more elements than allowed even with a really coarse mesh. The results from the simulations showed that the vehicle most likely will not be plastically deformed but there were a few extreme points in the stress analysis that had a higher stress than the yield strength of the material. This is a little worrying but was most likely the result of a too coarse mesh. It would have been better with a finer mesh to get a more accurate portrayal of the stress distribution but the computer allocated was unfortunately not advanced enough for this. If a program developed specifically for structural analysis could have been used, isosurfaces could have been created to get a better view of high stress areas. A modal analysis as well as a buckling analysis could also have been completed, but wasn’t due to the same reason.

Even though it is believed, and supported by the FEA, that the design will be sturdy there are still some concerns that the vehicle might be a bit unstable while operating due to the slimmed down design approach needed to minimize the weight. The good thing about using t-slot extrusions is that it is very easy to add parts, so if the robot is considered to be unstable while testing the prototype, several supports can easily be added. Adding more supports would make the robot less aesthetically pleasing and heavier and should only be done if it is really needed. There was not enough concern to actually change the design, but it is something that should be observed while testing the prototype.

The final design is very slimmed down and with a weight of 154.38 kg it only weighs 24.38 kg more than EcoRobotix, which is a very similar robot. Considering the fact that the FarmBot weighs approximately 25 kg the weight of the final design has to be considered very good. It will definitely be a big improvement in terms of soil compaction compared to the heavy machines that are currently being used in the agricultural industry. The weight could be decreased further by using parts specifically designed for this type of vehicle, such as lighter motors and better batteries, but this would also result in higher costs and seeing how the vehicle is already very light it is most likely not worth it.

The fact that everything had to be off the shelf made it difficult to be creative with the design. Most parts are possible to obtain by buying them off the shelf or using the methods available, but the cover and the sheet metal battery holder needs to be custom-made. If not everything would’ve had to be off the shelves the final design would have most likely have had a similar shape due to the placement requirements of the FarmBot, the wheels and the solar panels, but the vehicle could've had a more appealing design and more practical solutions. For instance, in the beginning it was desired that the herbicide tanks had a modular design so that the farmers couldn’t refill them by themselves and had to buy it from Hormoz Marzbani. This was not developed seeing that the design possibilities were limited and the tanks that were chosen for this vehicle would therefore only work for a prototype. A solution for modular tanks could however have been created for only the CAD-file, just like the cover and the battery holders were, but since the time was limited this was left for future development.

As mentioned in the concept selection of the cover, the two different layers were decided to be different materials so that the design would be more outstanding. One layer was to be made of a slightly shiny material and the other one from a matte material. However, it was very difficult to make this visualization in CAD seeing that the layers were flat and it was problematic to make it look shiny without any curves or edges in the design. The final renders therefore don’t completely justify what the final product would look like in real life. It was also very difficult to try different colors and shades because the renders looked completely different from the CAD models due to the difficulties of setting environments and lights, and it took a very long time to perform renders with the allocated computer. It wasn’t too important to get highly realistic renders for every part since most of them were only small parts and were going to be hidden under the cover, but it was unfortunate that the final render didn’t end up looking exactly like desired.

This was a fairly big project with many parts that needed to be designed and assembled together and the project only stretched over a few months. Decisions therefore had to be made quickly so that the design process could move in a fast pace. Some of the parts alone, for example the camera mounts, could have been developed in the same time frame as the whole project for a more detailed and perhaps better working product. However, since there was a limited amount of time it was decided that fewer concepts were to be generated for each sub problem and some decisions were based on intuition instead of concept screenings. As long as the concepts were functioning well, it was decided that they were good enough for this project. The same goes for the details in CAD and the renders that were made which could've been made more realistic if there was enough time.

When deciding what parts to be ordered there were a few things that had to be kept in mind. First of all they had to fulfill their functions, they had to be as cheap as possible while still being of high quality and they couldn't have a "minimum order" that was well above what was needed to manufacture a prototype. Some of the choices might not be optimal seeing that it was difficult to find something that ticks all of those boxes. Rubber seals, with the correct dimensions, used in the Arduino box could only be found in a package with 300 even though only two were needed. Furthermore, it was difficult to find a box for the board with perfect dimensions so the one that was found is slightly too big for its purpose. It would also have been better if the herbicide tanks were box shaped instead of round so that they could've been placed closer together and not take up as much room as they did. However the chosen ones were much cheaper than the box shaped ones and in that case the price was prioritized over the function.

With a cost of USD 2075.38 for all new parts the design is within the budget of USD 3000. Most of the costs, USD 1543.62, are from parts that were already decided before this phase, such as solar panels, batteries and charge controllers, so there was not too much room to lower these costs except for the extrusion battery holder. With a cost of USD 91.51, excluding the batteries, it is one of the pricier parts for a fairly simple problem. For comparison the cost for the whole frame including connectors is USD 286.24. This is another good reason to switch to the sheet metal battery holder, since it most likely would be cheaper to manufacture. What should be noted about the cost analysis is that every part has had a price per part assigned to it, and that cost has then been multiplied by how many parts that were needed. In reality some parts have to be ordered in bigger quantities than what is needed, which will increase the costs. This is mostly regarding smaller items such as screws and nuts, which won't make a huge impact on the total costs.

When ordering parts online not all dimensions were usually given, which meant that assumptions had to be made. This mainly affects things like sizes and lengths of screws and placement of parts. It will therefore be good to have some extra screws available when manufacturing the prototype to be sure that it will be possible to assemble, and some measurements in the CAD files should only be taken as guidelines. Since t-slot extrusions will be used, it will be very easy to move things around to the perfect positions.

The vehicle is very easy to assemble and assembling the vehicle will mostly consist of attaching parts to the extrusions using screws and t-nuts. Assembly should therefore not take more than a few hours. It has a modular design which means that it will be easy to develop further. If more parts need to be added, they can just be attached straight to the extrusions.

The downside of the design is that some of the parts are not very easily accessible and if something needs to be changed it will be a bit of struggle since most of the parts need to be accessed from underneath. Since this is only a prototype this is not something that has been prioritized seeing how these parts most likely won't have to be accessed that often. For future development this should be taken into consideration, a possible solution could be to design the solar panel attachments so that they can be opened from the top so that the parts can be accessed from the top.

10.2 Conclusion

The final product that has been developed in this master thesis is considered to meet the goals of the project. The goal was to make it lightweight to minimize soil compaction, cost efficient compared to the competitors, and appealing to attract investors so that it can be further developed. With those requirements met the next stage is to present the design to farmers and investors and to make a prototype. The supervisor, Hormoz Marzbani, was very pleased with the final product because of the low manufacturing costs, the design, the low weigh, and because it can do everything it needs to. Seeing that the weight of the vehicle was highly prioritized there is a possibility that it is a bit unstable. If the prototype test proves to be unstable some modifications might be needed, otherwise the design process can continue. If the product is successfully launched it could help optimizing crop yield, simplify farmers everyday job as well as helping to combat herbicide resistant weeds which is the ultimate goal of the project.

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_10307_10131_10132_10133,searchweb201603_45,ppcSwitch_7&algo_expid=94336f7a-f262-4f11-beb9-4c67b6869ac6-1&algo_pvid=94336f7a-f262-4f11-beb9-4c67b6869ac6&priceBeautifyAB=0

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Appendix A Work distribution and Time plan

This section shows the Gantt- scheme and the work distribution.

A1. Work distribution

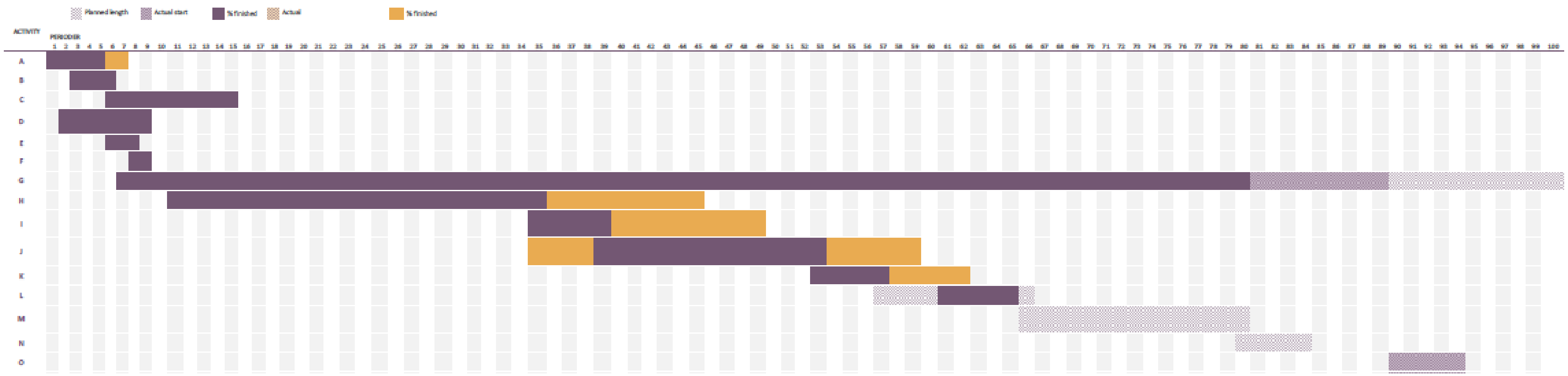
During this project the work distribution was divided equally in the team. Both students were working throughout the process and made all the decisions and activities together.

A2. Project plan and outcome

The Gantt-scheme can be seen below (shown in two tables for enhanced readability). Purple color represents planned start and length whereas orange color represents actual start and length. Since there was no time to do the prototype, this is shown in a light purple color, and since there wasn't any need for further development this is also shown in light purple. The presentation is still to be done and is shown in a darker shade of purple.

Gantt

ACTIVITY	PLANNED START	PLANNED LENGTH	ACTUAL START	ACTUAL LENGTH	FINNISHED
A. Gathering of General Information	1	5	1	7	100%
B. Process Planning	3	4	3	4	100%
C. Research	6	10	6	10	100%
D. Identifying and Ranking of Customer Needs	2	8	2	8	100%
E. Benchmarking	6	3	6	3	100%
F. Establish Product Specifications	8	2	8	2	100%
G. Writing of the Report	7	94	7	83	90%
H. Concept Generation	11	25	11	35	100%
I. Concept Evaluation and First Selection	35	5	35	15	100%
J. Combination and Visualization of Concepts	39	15	35	25	100%
K. Final Concept Selection	53	5	53	10	100%
L. Concept Testing	57	10	61	5	100%
M. Further Concept Development and Improvements	66	15	0	0	0%
N. Prototying	80	5	0	0	0%
O. Prepring of Presentation	90	5	90	5	0%



Planned length
Actual start
% finished
Actual
% finished
ACTIVITY
PERIODER
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O

Appendix B. Bill of Material

B1. Bill of material for the entire vehicle

Seen below is the bill of material for the entire vehicle as well as the weight and cost for the parts and the total weight and cost.

Part	Amount	Weight (g)	Cost (USD)
Front Camera			
Front Camera	1	20.0	0.00
3D Printed Parts	3	56.0	0.00
M4x12	6	12.0	0.77
M4 Nut	4	2.0	0.2
T Slot Nut M4	2	2.0	0.20
M4x12 Knob	1	3.0	2.20
Total		*95.0*	*3.37*
Middle Camera			
Middle Camera	1	20.0	0.00
3D Printed Parts	4	65.0	0.00
M4x12	8	8.0	1.03
M4 Nut	4	2.0	0.20
T Slot Nut M4	4	4.0	0.40
M4x12 Knob	2	3.0	2.20
Total		*102.0*	*3.83*

Herbicide Tanks			
Herbicide Tanks	4	3200.0	98.00
M6x25	16	107.2	3.46
T Slot Nut M6	4	24.0	1.49
Tubes 6.5m	4	1040.0	25.74
Total		*4371.2*	*128.69*
Joystick			
Joystick	1	700.0	0.00
3D Printed Parts	1	130.0	0.00
M6x14	4	22.0	0.86
T Slot Nut M6	4	6.0	0.37
M4x14	2	4.2	0.26
Total		*860.0*	*1.49*
Board			
Nvidia Jetson TX2 Development Kit	1	1540.0	0.00
3D Printed Parts	1	44.0	0.00
Waterproof Box	1	400.0	5.00
Waterproof Ethernet Cable Gland	1	30.0	3.00
Waterproof Cable Gland	5	20.0	0.58
M6x14	4	22.0	0.86
M4x14	4	8.4	0.52
M4x18	2	5.0	0.26
M6 Nut	4	6.0	0.37

M4 Nut	6	3.0	0.3
Total		*2078.4*	*10.89*
Solar Panels			
327W SunPower E20 Solar Panel	1	37 200.0	1050.00
M6x14	8	44.0	1.73
M6 Nut	8	12.0	0.74
Total		*37 256.0*	*1052.47*
Charge Controller			
Charge Controller	1	300.0	79.98
M4x12	8	16.0	1.03
M4 Nut	8	4.0	0.40
Total		*302.0*	*81.41*
Battery			
Battery	4	23 040.0	413.64
3D Printed Parts	4	8.0	0.00
Extrusion 180	8	2707.2	8.12
Extrusion 280	8	4211.2	12.63
Extrusion 185	4	1391.2	4.17
Connector 90 Degree	4	292.0	15.44
T Type Connector	8	560.0	22.84
Rubber Strap	2	188.0	2.40
M4x12	4	8.0	0.52
T Slot Nut M4	4	2.0	0.20

M6x12	32	163.2	6.9
T Slot Nut M6	32	48.0	7.42
L Type 90 Degree Connector with Screw	24	1200.0	10.87
Total		*33 818.8*	505.15
Arduino			
Arduino Mega 2560	1	37.0	0.00
3D Printed Parts	2	176.0	0.00
Rubber Seals 4mm	2	1.3	0.05
M4x14	4	8.4	0.52
M2x25	4	16.0	0.52
M2x12	4	14.0	0.52
M2 Nut	8	3.2	0.03
T Slot Nut M2	4	2.0	0.2
Total		*257.9*	*1.84*
Wheels			
Front Wheel 13x5.00-6	2	5800.0	14.00
Back Wheel 10” Caster Wheel	2	7200.0	12.00
3D Printed Parts	4		0.00
M6x18	16	97.6	2.76
M10x14	8	159.2	2.88
M10 Nut	8	92.8	3.56
M6 Nut	16	24.0	1.48
Total		*13 373.6*	*36.68*

Motor			
Motor	2	6000.0	0.00
3D Printed Parts	2	454.0	0.00
M12x200	2	361.6	0.00
M12x65	2	135.0	0.00
M12 Nut	10	173.0	0.00
Total		*7124.2*	*0.00*
Frame			
Extrusion 1630	2	6128.8	18.39
Extrusion 1500	6	1699.2	50.98
Extrusion 689 70 Degrees	4	5203.3	15.61
Extrusion 233	4	1752.2	5.26
Extrusion 2012	2	7565.1	22.70
Extrusion 314.9	2	1184.0	3.55
Extrusion 280	10	5264.0	15.79
Extrusion 300	2	1128.0	3.38
Big 90 Degree Connector	8	640.0	13.53
Small 90 Degree Connector	12	720.0	30.00
L-Type 90 Degree Connector with Screw	56	2800.0	25.37
3D Printed Parts	18	1444.0	0.00
M6x12	192	979.2	42.70
T Slot Nut M6	192	300.0	38.98
Total		*36 808.8*	*286.24*

FarmBot			
FarmBot	1	25000.0	0.00
3D Printed Parts	2	54.0	0.00
Total		*25 054.0*	*0.00*
Total		**154 377.7**	***2075.38***

B2. Bill of material for the FarmBot

Seen below is the bill of material for the FarmBot.

Part	**Amount**
Extrusions	
2040 V Slot Aluminium Extrusion 1500 mm	2
2060 V Slot Aluminium Extrusion 500 mm	2
2060 V Slot Aluminium Extrusion 1500 mm	1
2020 V Slot Aluminium Extrusion 1000 mm	1
Plates and Brackets	
Track End Plates	4
Gantry Wheel Plates	2
Cross Slide Plate	1
Z-Axis Motor Mount	1
Long Cable Carrier Mount	1
Peripheral Mount	2
Belt Clips	6

Z-Axis Hardstops	2
Drivetrain	
V-Wheels	30
X-Axis GT2 Timing Belt	2
Y-Axis GT2 Timing Belt	1
20 Tooth GT2 Pulleys	3
5mm to 8mm Flex Coupling	1
8mm ACME Leadscrew	1
Leadscrew Block	1
Electronics and Wiring	
Electronics Box	1
Power Supply	1
Power Supply Cable	1
Raspberry Pi 3	1
MicroSD Card	1
Pi Adapter Board	1
Push Buttons	5
LED Indicators	4
Farmduino	1
Stepper Drivers	5
Raspberry Pi Power Cable	1
Farmduino Data Cable	1
USB Adapter Cable	1
Jumper Wires	12
NEMA 17 Stepper Motors with Rotary Encoders	4
Motor Cables	4
Encoder Cables	4
X- and Y-Axis Cable Carrier	2

Z-Axis Cable Carriers	1
Universal Tool Mount Cable	1
Solenoid Valve	1
Vacuum Pump	1
Vacuum Pump Cable	1
Solenoid Valve Cable	1
Peripheral Leads	2
Borescope Camera	1
Jumper Links	4
LED Strip	1
UTM PCB	1

Plastic Parts	
Horizontal Cable Carrier Support	13
Vertical Cable Carrier Support	4
Cable Carrier Spacer Block	1
Cable Guide	2
Horizontal Motor Housing	3
Vertical Motor Housing	1
Vacuum Pump Housing	1
Cable Carrier	120

Fastener and Hardware	
M2.5x4 Screw	8
M2.5x6 M/F Standoff	4
M2.5x16 M/F Standoff	4
M3x6 Screw	10
M3x12 Screw	40
M3 Lockouts	20
M5x10 Screw	175

M5x16 Screw	40
M5x30 Screw	45
M5 Lockout	70
M5 Washer	100
M5x6 Spacer	30
M5x6 Eccentric Spacer	15
M5 Tee Nuts	175
Dowel Pins	6
Miscellaneous	
15x5x5 Ring Magnets	21
60 mm Zip Ties	50
100 mm Zip Ties	25
200 mm Zip Ties	10

Appendix C. Links

In this section the links for the parts that are to be ordered are presented.

Extrusions and connectors

Extrusions MJ-8-4040D
https://www.alibaba.com/product-detail/aluminum-extrusion-profiles_947387300.html?s=p

Big 90 Degree Connector
https://www.aliexpress.com/item/4080-corner-fitting-angle-aluminum-40-x-80-connector-bracket-fastener-match-use-4040-industrial-aluminum/32461843303.html?spm=2114.search0104.3.133.787556ealX1Zl1&ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_10547_319_317_10548_10696_5728811_10084_10083_10618_10307_10131_10132_10133_5733211_328_5733311_10059_10884_5733411_10887_100031_321_322_10103_5733611_5733111_5733511,searchweb201603_55,ppcSwitch_0&algo_expid=af8a7403-3955-45c9-be27-70e7a4ae56fd-19&algo_pvid=af8a7403-3955-45c9-be27-70e7a4ae56fd

Small 90 Degree Connector
https://www.ebay.com.au/itm/8-Set-of-Corner-Fittings-4040-Aluminium-Extrusion-T-Slot-Profile/283024316472?epid=1687902663&hash=item41e5905838:g:M7sAAOSwGzlTwK2C:rk:37:pf:0

L-Type 90 Degree Connector with Screw
https://www.aliexpress.com/item/10PCS-L-Shape-90-Degree-Corner-Connectors-Joint-Interior-Brackets-T-Slot-Aluminum-Profile-Accessory-for/32385144478.html?spm=2114.search0104.3.59.796f2d057lrKu9&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=f4f0f35e-217b-4881-abd9-cf29c070529e-8&algo_pvid=f4f0f35e-217b-4881-abd9-cf29c070529e&transAbTest=ae803_4

Flat Connector 90 Degree
https://www.aliexpress.com/item/Hot-Sale6063-T6-Joint-Board-Plate-Corner-Angle-Bracket-Connection-Joint-Strip-for-Aluminum-Profile-2020/32847685479.html?spm=2114.search0104.3.312.2abd440ettyh3U&ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_317_10696_450_10084_10083_10618_452_535_534_533_10307_532_10131_10132_10133_204_10059_10884_323_10887_1000

31_320_321_322_10103_448_449,searchweb201603_55,ppcSwitch_0&algo_expid=b8816770-d2f2-4dfa-ac08-570c5b2541ee-46&algo_pvid=b8816770-d2f2-4dfa-ac08-570c5b2541ee

T-Type Connector
https://www.aliexpress.com/item/10PCS-European-Standard-Carbon-Steel-T-Type-Connection-Plate-for-3030-Aluminium-Extrusion-Profile/32887779048.html?spm=2114.search0104.3.245.56547273zk5LN5&ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_317_10696_450_10084_10083_10618_452_535_534_533_10307_532_10131_10132_10133_204_10059_10884_323_10887_100031_320_321_322_10103_448_449,searchweb201603_55,ppcSwitch_0&algo_expid=4aed50bd-b448-48f5-b21e-69d6da21cbf5-36&algo_pvid=4aed50bd-b448-48f5-b21e-69d6da21cbf5

Hardware

Herbicide Tanks
https://www.alibaba.com/product-detail/Customized-10L-Flexible-PVC-Water-box_60447909189.html?spm=a2700.details.maylikehoz.7.66354eedcwjYOR

Tubes
https://www.alibaba.com/product-detail/Clear-chemical-resistant-water-dispenser-silicone_60322049181.html?spm=a2700.7724838.2017115.232.7c4911399lh0t9

NVIDIA Jetson TX2 Developer Kit
https://store.nvidia.com/store;jsessionid=D3A509B049E8D1DDCBB94DC58F0D8D97?Action=DisplayPage&Locale=en_US&SiteID=nvidia&id=QuickBuyCartPage

Waterproof Box
https://www.alibaba.com/product-detail/280-280-130mm-Low-Price-IP65_60790473014.html?s=p

Waterproof Ethernet Cable Gland
https://www.alibaba.com/product-detail/IP67-RJ45-Pass-Feed-Through-Cable_60773685244.html?spm=a2700.7724838.2017115.119.143b4db4XzvTuH

Waterproof Cable Gland
https://www.aliexpress.com/item/High-Quality-IP68-PG7-3-6-5MM-Waterproof-Nylon-Cable-Gland-No-Waterproof-Gasket-Plastic-Cable/1985680407.html?spm=2114.search0104.3.23.3d725afdeAfy7W&ws_ab_test=searchweb0_0,searchweb201602_4_10065_10068_10130_318_10547_319_5727315_10548_10696_10084_10083_10618_452_10307_532_10131_10132_10133_5727215_204_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=7b2344b2-39bb-40d0-ac65-f01238b5c06a-3&algo_pvid=7b2344b2-39bb-40d0-ac65-f01238b5c06a&priceBeautifyAB=0

Arduino Mega 2560
https://store.arduino.cc/usa/arduino-mega-2560-rev3

Rubber Seals
https://www.aliexpress.com/item/400pcs-4mm-Inner-Diameter-Black-White-Dual-Side-Open-Hole-Plug-Cable-Wiring-Rubber-Protector-Ring/32791908807.html?spm=2114.search0104.3.2.f2412c141LLCKp&ws_ab_test=searchweb0_0,s

earchweb201602_4_10065_10068_10130_318_10547_319_5727315_10548_10696_10084_10083_10618_452_10307_532_10131_10132_10133_5727215_204_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=715105df-1a21-4a83-a41b-3b8424f091e1-0&algo_pvid=715105df-1a21-4a83-a41b-3b8424f091e1&priceBeautifyAB=0

Battery
https://www.ebay.com.au/itm/New-12V-20AH-AGM-SLA-Deep-Cycle-Battery-for-Golf-Cart-Buggy-Wheel-Chair-Scooter/132365211421?epid=14007288879&hash=item1ed194d71d%3Ag%3Ahc0AAOSw-EJZ5CZo&boolp=1&action=BESTOFFER

Rubber Straps
https://www.alibaba.com/product-detail/Good-quality-tie-down-for-trucks_60743897356.html?spm=a2700.7724838.2017115.381.9f067082FLO6Li

Charge Controllers
https://www.ebay.com.au/i/253363062776?chn=ps

327W SunPower E20 Solar Panels
https://www.solaronline.com.au/327w-sunpower-e20-solar-panel.html

Front Wheel
https://www.alibaba.com/product-detail/Heavy-Duty-13-Inch-Tractor-Tyres_60749662038.html?spm=a2700.7724838.2017115.184.75993d0fS1E8m6

Back Wheel
https://www.alibaba.com/product-detail/10-Inch-Shock-Absorber-Pneumatic-Rubber_60089679705.html?spm=a2700.7724838.2017115.213.e90759abHngDXX

FarmBot
https://farm.bot/products/farmbot-genesis-v1-4

Screws and Nuts

M2x12
https://www.aliexpress.com/item/50-pc-lot-Metric-thread-M1-6-M2-M2-5-M3-L-3-4-5/32804364826.html?spm=2114.search0104.3.8.72ec3331j4zOOr&ws_ab_test=searchweb0_0,searchweb201602_4_10065_10068_10130_318_10547_319_5727315_10548_10696_10084_10083_10618_452_10307_532_10131_10132_10133_5727215_204_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=130a7432-2f14-4ca5-a432-01104f89b5a0-1&algo_pvid=130a7432-2f14-4ca5-a432-01104f89b5a0&priceBeautifyAB=0

M2x25
https://www.aliexpress.com/item/50-pc-lot-Metric-thread-M1-6-M2-M2-5-M3-L-3-4-5/32804364826.html?spm=2114.search0104.3.8.72ec3331j4zOOr&ws_ab_test=searchweb0_0,searchweb201602_4_10065_10068_10130_318_10547_319_5727315_10548_10696_10084_10083_10618_452_10307_532_10131_10132_10133_5727215_204_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=130a7432-2f14-4ca5-a432-01104f89b5a0-1&algo_pvid=130a7432-2f14-4ca5-a432-01104f89b5a0&priceBeautifyAB=0

M2 Nut

https://www.aliexpress.com/item/QINTIDES-M2-5-M14-Hexagon-thin-nuts-304-stainless-steel-hexagonal-thin-nut-Flat-nut-and/32859374883.html?ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_10696_10084_10083_10618_452_10307_532_5727311_10131_10132_10133_204_5727211_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=1a938148-4059-4ee6-8fbe-075437b0e046-1&algo_pvid=1a938148-4059-4ee6-8fbe-075437b0e046&priceBeautifyAB=0

M4x12

https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M4x14

https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M4x18

https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M4 Nut

https://www.aliexpress.com/item/QINTIDES-M2-5-M14-Hexagon-thin-nuts-304-stainless-steel-hexagonal-thin-nut-Flat-nut-and/32859374883.html?ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_10696_10084_10083_10618_452_10307_532_5727311_10131_10132_10133_204_5727211_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=1a938148-4059-4ee6-8fbe-075437b0e046-1&algo_pvid=1a938148-4059-4ee6-8fbe-075437b0e046&priceBeautifyAB=0

T Slot Nut M4

https://www.aliexpress.com/item/50Pcs-M3-M4-M5-M6-M8-For-20-30-40-Series-Slot-T-nut-Sliding-T/32916197165.html?spm=2114.search0104.3.7.42b67627KcgV6D&ws_ab_test=searchweb0_0,sea

rchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715-5731415,searchweb201603_55,ppcSwitch_0&algo_expid=f7dd4d4d-8e0a-4c6d-82ed-96ce3be33d83-1&algo_pvid=f7dd4d4d-8e0a-4c6d-82ed-96ce3be33d83&transAbTest=ae803_4

M4x12 Knob
https://www.aliexpress.com/item/5pcs-M4-plastic-head-knob-screws-hand-twist-screw-T-type-rotating-bolts-tighten-rotary-bolt/32884545605.html?ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_10696_10084_10083_10618_452_10307_532_5727311_10131_10132_10133_204_5727211_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=8a0a2918-9685-48dc-afe5-e9429101bcdc-35&algo_pvid=8a0a2918-9685-48dc-afe5-e9429101bcdc&priceBeautifyAB=0

M6x12
https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M6x14
https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M6x18
https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M6x25
https://www.aliexpress.com/item/AXK-20Pcs-M4-M5-M6-ISO7380-Stainless-Steel-304-A2-Round-Head-Screws-Mushroom-Hexagon-hex/32869977872.html?spm=2114.search0104.3.167.47c128ffRA59nW&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715,searchweb

201603_55,ppcSwitch_0&algo_expid=20c70bd7-34c3-4942-86cb-468d08c191af-23&algo_pvid=20c70bd7-34c3-4942-86cb-468d08c191af&transAbTest=ae803_4

M6 Nut

https://www.aliexpress.com/item/QINTIDES-M2-5-M14-Hexagon-thin-nuts-304-stainless-steel-hexagonal-thin-nut-Flat-nut-and/32859374883.html?ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_10696_10084_10083_10618_452_10307_532_5727311_10131_10132_10133_204_5727211_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=1a938148-4059-4ee6-8fbe-075437b0e046-1&algo_pvid=1a938148-4059-4ee6-8fbe-075437b0e046&priceBeautifyAB=0

T Slot Nut M6

https://www.aliexpress.com/item/50Pcs-M3-M4-M5-M6-M8-For-20-30-40-Series-Slot-T-nut-Sliding-T/32916197165.html?spm=2114.search0104.3.7.42b67627KcgV6D&ws_ab_test=searchweb0_0,searchweb201602_2_10065_10068_10130_5731315_318_10547_319_10548_317_5728815_10696_10084_10083_10618_452_10307_532_5731115_5731415_10131_10132_5731215_10133_5731615_204_328_10059_10884_5731515_323_10887_100031_320_321_322_10103_5731715-5731415,searchweb201603_55,ppcSwitch_0&algo_expid=f7dd4d4d-8e0a-4c6d-82ed-96ce3be33d83-1&algo_pvid=f7dd4d4d-8e0a-4c6d-82ed-96ce3be33d83&transAbTest=ae803_4

M10x14

https://www.alibaba.com/product-detail/iso-m3x8-m4-m6-m10-titanium_60729252440.html?spm=a2700.7724838.2017115.11.520c53d8ApAGB0&s=p

M10 Nut

https://www.aliexpress.com/item/QINTIDES-M2-5-M14-Hexagon-thin-nuts-304-stainless-steel-hexagonal-thin-nut-Flat-nut-and/32859374883.html?ws_ab_test=searchweb0_0,searchweb201602_1_10065_10068_10130_318_10547_319_10548_10696_10084_10083_10618_452_10307_532_5727311_10131_10132_10133_204_5727211_10059_10884_10887_100031_320_10103,searchweb201603_60,ppcSwitch_0&algo_expid=1a938148-4059-4ee6-8fbe-075437b0e046-1&algo_pvid=1a938148-4059-4ee6-8fbe-075437b0e046&priceBeautifyAB=0