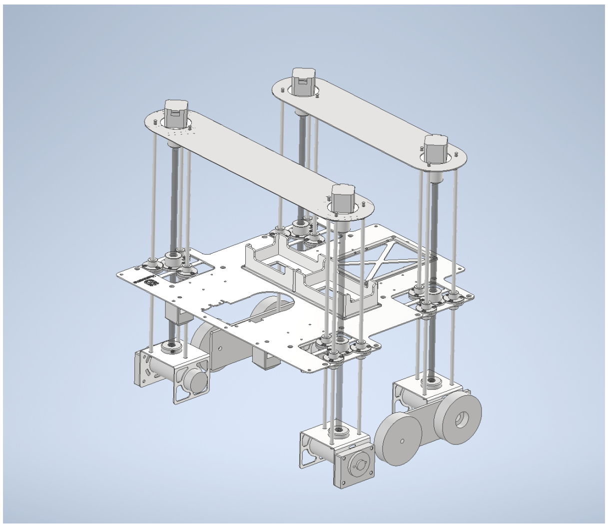


Developing a Robotic Lawn Mower for Climbing

The process of developing a prototype of the mechanism for a climbing lawnmower

Emil Andréasson
Therese Hainer
Oskar Jansson
Simon Lidhage
Emanuel Peterson
Isak Sundvall

Institution of electronics

Chalmers University of Technology

Gothenburg, Sweden 2025
`www.chalmers.se`

Developing a Robotic Lawn Mower for Climbing

Bachelor's Thesis Report

May 13, 2025

Emil Andréasson
Therese Hainer
Oskar Jansson
Simon Lidhage
Emanuel Peterson
Isak Sundvall

CHALMERS

Department of Electrical Engineering
Division of Systems and Control Engineering
Project EENX16-25-13
Chalmers University of Technology
Gothenburg, Sweden 2025

Abstract

This Bachelor's thesis presents the development of a prototype robotic lawn mower capable of climbing vertical obstacles such as curbs and small garden walls. Traditional robotic lawn mowers are limited by their inability to traverse such elevations, requiring manual repositioning. The project addressed this limitation by designing and integrating a height-adjustable wheel system allowing step-by-step elevation of the lawn mower's body. Utilizing components from Husqvarna's 450x and 550 EPOS models, a three-pair wheel configuration was developed where the middle and rear wheels can independently lift themselves and lower via a mechanical elevator system powered by motors. Emphasis was placed on maintaining stability during climbing through center of gravity management and the use of specialized middle wheels. Testing confirmed that the system functioned as intended and was effective in concept. However, manual assistance was occasionally required due to excessive friction in the elevators, which prevented the mower from completing the climbing process independently.

Summary

The Bachelor's thesis project, conducted over four months at Chalmers University of Technology, aimed to extend the functionality of robotic lawn mowers by enabling them to climb vertical obstacles. Current models are unable to handle such challenges, which limits their automation capabilities. The project began by exploring a wide range of climbing concepts, eventually selecting a solution based on height-adjustable wheels. The chosen design consisted of three pairs of wheels, with the middle and rear wheels mounted on elevators. This allowed the mower to raise and lower itself incrementally over obstacles.

The development process included mechanical and electronic design, CAD modeling, material selection, and control system implementation. Critical design decisions focused on stability and structural strength. The prototype was built on a base plate where the elevators, wheels and electrical components were mounted. Some of these components were reused from the existing Husqvarna lawn mowers.

A significant challenge was managing the mower's center of gravity to prevent tipping during elevation. This was addressed by designing a wide middle wheel system for greater contact area. Electronic controls were built using ESP32 microcontrollers and BLDC-motor drivers, with custom software developed for wheel coordination.

Testing confirmed that the system functioned as intended and was effective in concept. However, manual assistance was occasionally required due to excessive friction in the elevators, which prevented the mower from completing the climbing process independently.

Foreword

We want to thank our supervisor Qianlei Jia and our examiner Jonas Fredriksson for all the support with the Bachelor's thesis. We also want to thank Husqvarna who donated the Husqvarna 550 EPOS automower to Chalmers University for students to use for projects. We also express our appreciation to the staff at the CASE lab who have been very helpful with the construction of the prototype. Lastly, we want to thank the library and the department "fackspråket" for all the help with writing the report.

Abbreviations

CAD	Computer-Aided Design
HRP	Husqvarna Research Platform
CASE	Chalmers Autonomous Systems and Electronics
BLDC	Brushless Direct Current Motor
ETA	E-sektionens Teletekniska Avdelning
I/O-pin	Input/Output-pin
PWM	Pulse Width Modulation
ROS	Robot Operating System
SSH	Secure Shell
FEM	Finite Element Method

Contents

Contents

1 Introduction

This chapter presents the context and purpose of the project, along with a short description of the related problem. Establishing this is essential for understanding the purpose and focus of the thesis. The chapter also defines limitations to narrow down the scope of the project, making it more manageable. Ethical considerations will also be taken into account to ensure that the process is responsible and sustainable. Finally, a requirement specification table will be presented to show the objectives of the project.

1.1 Context

Robotic lawn mowers eliminates the need for manual grass cutting. A standard robotic lawn mower can drive, turn, navigate, and cut grass simultaneously. However, there are still functional limitations that could be further explored to develop a more versatile product, particularly the inability to climb over obstacles. By enabling the robot to climb, the operational range can be expanded, reducing the need for manual repositioning or the use of multiple devices for different ground levels.

The primary goal of this Bachelor's thesis is to develop a robotic lawn mower, enabling it to climb vertical obstacles. These obstacles may be curbs, garden walls, or standard steps. To define the scope of the project, limitations will be established regarding the workflow, product development, sustainability, and other relevant factors. Additionally, only a prototype rather than a finalized product will be developed due to constraints such as time and budget.

Features such as terrain recognition using machine learning will not be included, as it would broaden the focus of the project excessively. To gain a deeper understanding of the problem and functionality of robotic lawn mowers, previous research and related work will serve as a foundation for formulating relevant research questions and avoiding previously identified challenges.

This Bachelor's thesis will be conducted at Chalmers University of Technology. The duration of the project is four months. Access to *CASE, Prototyplaboratoriet*, and *Fuse*; three laboratories located at Chalmers, will be available for the use of tools, materials, and production methods such as 3D-printers, laser cutters, water jet cutters, and more.

1.2 Purpose

The purpose of this project is to develop a prototype of a robotic lawn mower by introducing a function that enables it to climb vertical obstacles, allowing it to handle more complex terrain.

1.3 Limitations

The scope of the project will be adjusted to focus on technical development and construction. The aesthetics, user needs, and market appeal aspects will not be prioritized. Instead, the primary focus will be on creating a functioning prototype. Some elements of the product development workflow will still be followed, but modified for more efficiency. The duration of this Bachelor's thesis is four months. Due to this limited time frame, not all potential improvements in robotic lawn mowers can be addressed. These limitations include:

- **Terrain and Weather**
  The project focuses on overcoming vertical obstacles and therefore will not address issues with challenging terrain, such as muddy or slippery ground. Weather conditions are also neglected, as they introduce additional factors that must be considered during design, such as battery life and traction. For this reason, the robot will operate only in dry weather or inside.
- **Sustainability**
  The project will not focus on environmental impact and this will therefore not be considered to a broader extent when designing. Sustainability when developing a products is important, but since this only is a prototype and is not intended for mass production, its environmental impact will be minimal.
- **Budget**
  The budget for this project is limited to 5000 Swedish crowns. This boundary is set by Chalmers: if justified, an application for a bigger budget can be done. However, the goal is for the project to remain within the allocated budget.
- **Prototype**
  The project aims to develop a prototype rather than a market ready product. The prototype will be using components from two automatic Husqvarna lawn mowers, model 450x and model 550 EPOS. The primary objective is to produce a functional prototype. Consequently, a limited effort will be dedicated to the aesthetic design or visual appeal of the product.
- **Functions**
  This project will primarily focus on improving the climbing ability of the robotic lawnmower. Standard functionalities such as grass cutting, forward and backward movement, and turning are assumed to be consistent as those of the Husqvarna robotic lawnmower. As a result, these functions will not be included in the requirement specification table.

1.4 Previous lawn mower projects

Modification of robotic lawn mowers have been done several times in the past by students at Chalmers. In order to learn from their experiences and understand what they would have done differently, previous reports were reviewed. Two key projects were studied, completed in 2023 and 2024.

1.4.1 Autonomous Lawnmower for Line Drawing and Combing of Football Fields

This Bachelor's thesis, completed in 2023, involved modifying a robotic lawnmower to comb grass and paint lines on football fields. The main advantage of this report, and the reason why it is highlighted, is that it contains valuable code that could be useful.

1.4.2 Automatic Goal Line Robot

In 2024 a Bachelor's thesis was created where the main goal was to paint lines on football fields using a lawn mower. Although the focus of that project differs from the current one, there are similarities in the control systems that could be applied for this project, as both projects are based on the same model of robotic lawn mower.

1.5 Ethics

The primary ethical considerations for this research include safety, environmental impact, and responsible development.

The construction and testing of the prototype will be carried out in the assigned lab called CASE to make sure it is in a controlled environment, preventing risks to users and property. The safety of the product could be a concern, as a climbing robotic lawn mower may be dangerous if its blades are operating while it is climbing. This risk should be carefully considered before it is released on the market.

The project involves using parts from an existing robotic lawn mower, which minimizes the waste of the project. However, the use of lithium-ion batteries raises both ecological and ethical concerns. Lithium extraction is often associated with unsafe working conditions and significant environmental degradation, affecting both workers and the surrounding ecosystems [?]. To further reduce the environmental impact, the goal is to be able to restore the robotic lawn mower after the project is complete, so that it can be used for other projects in the future. Therefore, irreversible construction methods, such as the use of strong adhesives that prevent restoration to the original form, will be avoided when possible.

1.6 Requirement Specifications

The requirement specification table serves as a tool to evaluate whether the final product meets its defined expectations; see Table 1. Each category in the table consists of one or two criteria: one representing the minimum requirement and one describing a desirable feature. The requirement must be fulfilled for the product to be considered successful in that category. Although the desirable feature is not mandatory, achieving it is the goal, as it contributes to the development of an optimal solution.

Table 1: Requirement specification

	Sub function	Value	Requirement (R) Desirable feature (DF)	Metod of verifying
1	Climbing height	20 cm	R	Measure maximum climbed height
2		> 30 cm	DF	
3	Time of climb	2 min	R	Measure minimum time when climbed
4		> 1 min	DF	
6	Reuse the original cover		DF	Test if original cover can be fitted
7	Distance from edge to cutting blade	17 cm	DF	Measure distance from edge to cutting blade

Climbing Height
The climbing height requirement is based on the ability to adjust the lead screw screws vertically. This requirement is set at 20 centimeters, which is based on testing of the Husqvarna robotic lawn mower, which could climb 10 centimeters. The requirement is to double the capability of the original designs. The desirable feature is to reach even higher, 30 centimeters or more. It is also a requirement to be able to climb both up and down safely.

Time of Climb
The climbing time requirement is set to two minutes. Considering the target height, this corresponds to a climbing rate of ten centimeters per minute. Although this is relatively slow, the process should not exceed the specified duration. Achieving a faster rate, such as less than one minute per ten centimeter, is considered a desirable feature.

Reuse the Original Cover
An additional desirable feature listed in the requirement specification table is the ability to fit the original cover from Husqvarna onto the prototype. This is beneficial as it enables the reuse of components from the original design in the new construction. However, this is not defined as a requirement, as a new cover could be manufactured if necessary. However, doing so would reduce the overall reuse of materials.

Distance from Edge to Cutting Blade
The distance from the cutting blades to the edge of the original Husqvarna lawn mower is 17 centimeters. This spacing is necessary to prevent the lawn mower from leaving too much grass uncut near obstacles such as walls and other barriers. Having the same distance in the prototype is considered a desirable feature.

1.6.1 Confirming Requirement Specifications

To ensure that the established requirements for the lawn mower are met, each must be verified through targeted testing. One test is assigned to each requirement and desirable feature, as outlined in the requirement specification table.

2 Theoretical Background

This chapter provides the theoretical background for the project. The chapter introduces different manufacturing processes, electronic devices, and other concepts that are important for understanding this report.

2.1 Computer Aided Design

Computer Aided Design (CAD) is a useful tool in fields such as engineering, architecture, and manufacturing. It helps create detailed digital models and technical drawings, which makes it easier for designers to visualize, change, and perfect their projects with great accuracy. This means that the task of creating physical prototypes can often be skipped. CAD covers both 2D drafting and 3D modeling, which allows for thorough testing of structures, components, and materials. Some of the most commonly used software in the industry includes AutoCAD, SolidWorks, and Inventor. This project will use Inventor Autodesk Pro.

2.2 Husqvarna

Husqvarna is a Swedish company with a long history in the manufacturing of gardening products, forest equipment, and lawn mowers. Established back in 1689, Husqvarna has evolved from a weapons manufacturer to being a world leader in motor driven gardening products. Since the 1990s they have been pioneers in robotic lawn mower technology and continue to develop new solutions for effective and automated lawn maintenance. [1]

2.2.1 450x

Husqvarna 450x is an robotic lawnmower using the conventional method with a guide-cable that encloses the working area for the machine, see Figure 1. [2]

Figure 1: Husqvarna 450x
[3]

2.2.2 550 EPOS

Husqvarna 550 EPOS is a robotic lawn mower that uses Husqvarna's own satellite-based navigation system, called Exact Positioning Operating System, (EPOS). What sets it apart from traditional robotic lawnmowers is that EPOS creates virtual borders to define the workspace instead of relying on cables, see Figure 2. [1]

Figure 2: Husqvarna 550 EPOS
[4]

2.2.3 Husqvarna Research Platform

To control 450x and 550 EPOS, Husqvarna is providing research projects with a GitHub repository called *Husqvarna Research Platform* (HRP). It can be used with their lawnmowers that are unlocked for research. The architecture of the lawn mower consists of a CAN-bus network that connects each of the circuit boards of the lawnmower. If HRP is enabled, a Raspberry Pi can be connected to the bus with a CAN-adapter. Researchers then gain access to the lawn mowers CAN-network to read sensors and control motors.

2.2.4 Controller Area Network Bus

Controller Area Network Bus (CAN-bus) is a data-bus mainly used in vehicles to enable multiple control units to communicate. The data-bus consists of two wires, CAN-high and CAN-low that are connected to the control units. Each control unit acts as a node in a network with publishers and subscribers. [5]

2.3 Water Jet Cutting

Water jet cutting is an industrial tool that uses a mixture of sand and water flowing through a high-pressure nozzle to cut materials such as steel and aluminum. The mixture flows through the nozzle and converges on the surface of the material it is supposed to cut, see Figure 3. This leaves every edge at a very small angle where the top part of the material is correct, but the underside somewhat skewed. This problem is magnified by increased material thickness. This must be taken into consideration when working with tolerances.

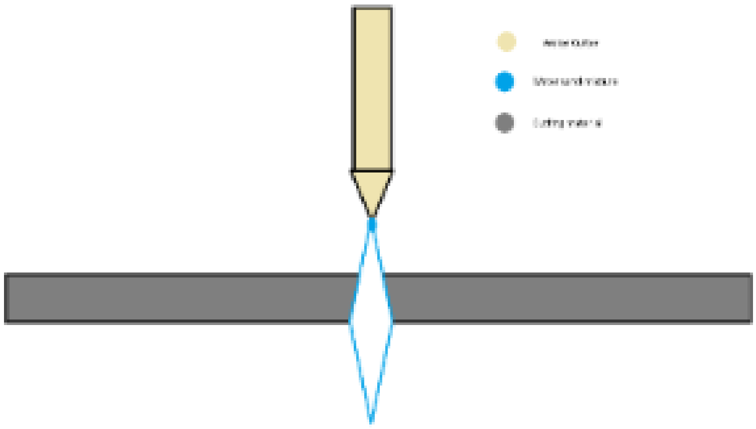


Figure 3: Water Jet Cutter

2.4 Laser Cutting

Laser cutting is a technology that uses a laser to cut materials. It works by directing the laser beam through a series of mirrors and lenses to focus the energy onto a small spot, melting or vaporizing the material. [6]

2.5 Tolerances

Tolerance is the maximum deviation allowed from the intended measurement. This could mean oversizing a bolt hole by three tenths of a millimeter or adjusting for play in the assembly.

2.6 Differential Drive

Differential drive means that the wheels are driven independently, allowing the wheels to rotate at different speeds. This allows for movement forward, backward, and enables steering. See Figure 4 for an example of how the differential drive could be implemented. [7]

2.7 Electronic Components

This subsection describes the electronic components used in the project.

2.7.1 Brush less Direct Current Motors

There are two types of brush less direct current motors (BLDC-motors), the first one (inner Rotor Motor) is where the rotor is located at the center and is surrounded by the stator windings. The second is where the rotor is placed outside, encasing the stator within. The outer casing with permanent magnets rotates around the fixed stator, see Figure 5. Due to that BLDC-motors are in fact brush less, the configuration eliminates

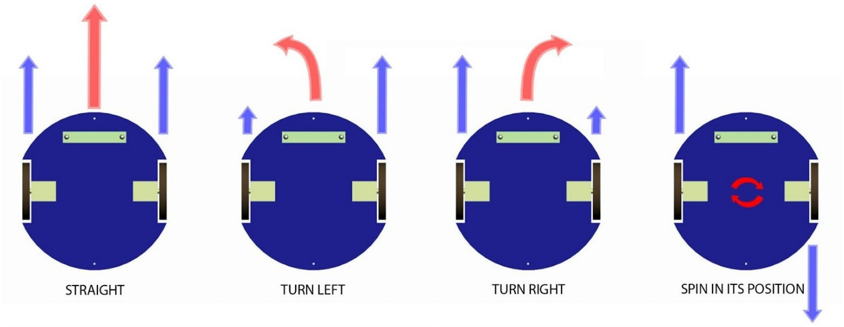


Figure 4: Differential drive
[8]

friction, thereby reducing wear on components such as graphite and rare earth materials, as a result the BLDC-motor operates more efficiently and with a longer lifespan. BLDC-motors are commonly used in automatic lawnmowers because they are reliable and precise. See Figure 6 for the Delta and Y configurations for the BLDC-motor [9].

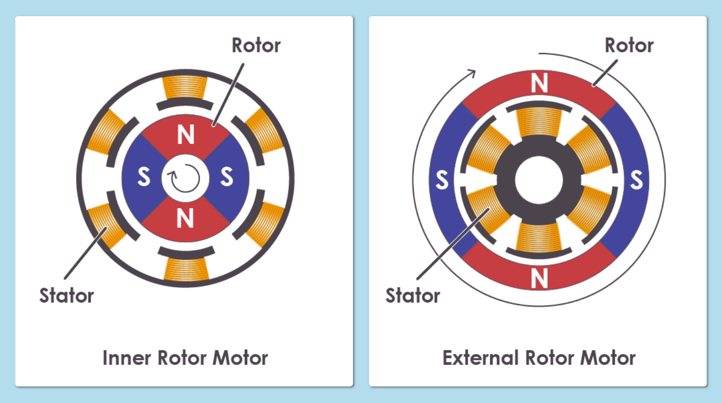


Figure 5: Inner and external rotor
[10]

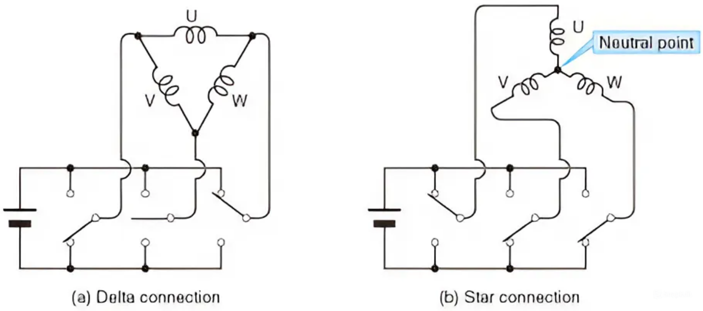


Figure 6: Delta- respective Y-configuration for BLDC-motor
[11]

A BLDC motor can have either a Delta or Y (Star) configuration, each serving different purposes.

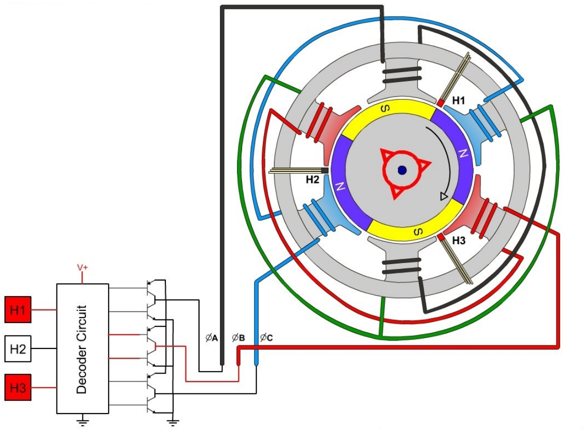
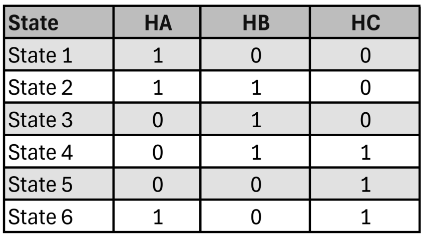


Figure 7: Cross section of a 3-Phase BLDC-motor
[12]

Each BLDC-motor has eight wires of which three is used for the phase and five is used for the hall sensors to encode where the rotor is relative to the stator. More on how this works in chapter 5.

The three Hall sensors in the motor are positioned 120 degrees apart from each other to detect the position of the rotor relative to the stator, see Figure 7. The sensors are arranged in such a way that only one of the three hall sensors changes state at a given moment in time, either from low to high or high to low, at any given time. This encoding scheme is a form of *Gray code* and helps to reduce the risk of readout errors, as there is only one change at a time. This is a very common technology for encoders. The three Hall sensors, H1, H2, and H3 (or HA, HB, HC), produce six unique signal combinations per full electrical revolution, see Figure 8. This provides the BLDC-motor driver with precise information about the rotor's position, and gets encoded by the ZS-X11H driver to then switch two of the correct MOSFETs, (Metal oxide semiconductor field effect transistor).

Some BLDC-motors lack built-in Hall sensors and instead rely on back electromotive force (back-EMF) for position detection. However, this approach requires more complex software algorithms for accurate control, [13].



State	HA	HB	HC
State 1	1	0	0
State 2	1	1	0
State 3	0	1	0
State 4	0	1	1
State 5	0	0	1
State 6	1	0	1

Figure 8: Table for Hallsensor Gray code

The left image in Figure 9 shows the signals for the three motor phases MA, MB, and MC, as well as the outputs from the three Hall sensors HA, HB, and HC, at different rotor positions relative to the stator. The image on the right in Figure 9 illustrates a typical setup for connecting a BLDC-motor to its motor driver.

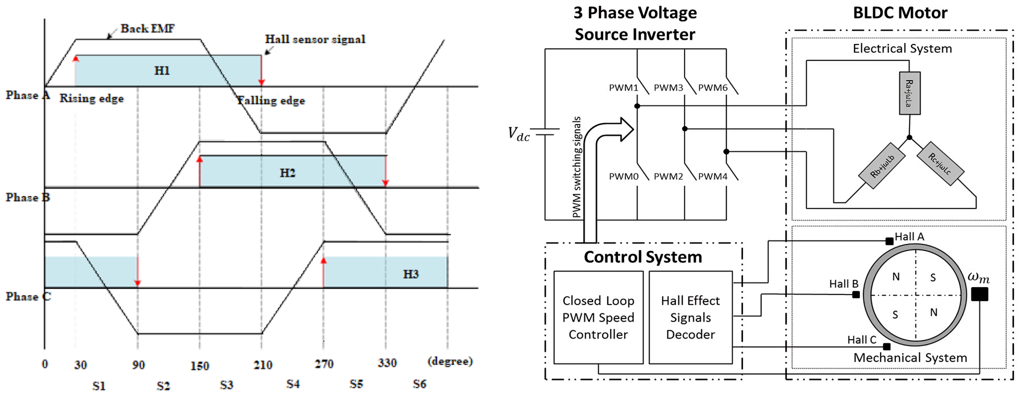


Figure 9: Phase diagram for BLDC-motor and typical connection [14][15]

2.7.2 BLDC-Motor Drivers

A BLDC motor driver is an electronic device that manages the power, speed, and direction of a BLDC- motor. It determines the rotor's position using sensor-based or sensor-less techniques. It is commonly used in projects requiring high efficiency and precise speed control. To drive the BLDC-motors, the BLDC-motor driver ZS-X11H is used to control each motor, see Figure 10. [16] [17]

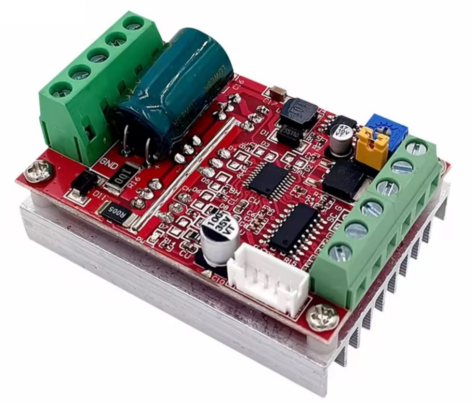


Figure 10: ZS-X11H BLDC-motor driver [18]

2.7.3 Stepper Motors

A stepper motor is a brush less DC electric motor that rotates in a series of small and discrete angular steps, see Figure 11. Stepper motors can be set to any given step position without needing a position sensor for feedback. The step position can be increased or decreased to create continuous rotation, or the motor can maintain its position at one given step. In this project a bipolar NEMA 17 stepper motor is used, it is commonly found in 3D-printers. Figure 12 shows the inside of the motor. It has a permanently magnetized rotor surrounded by coils in the stator. It is driven by four wires, two pairs of wires used to excite each of the two poles, respectively.[20]

Figure 11: NEMA 17 stepper motor
[21]

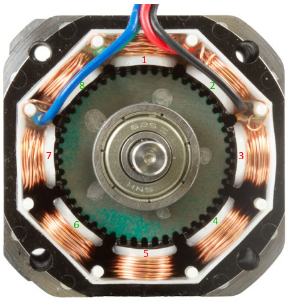


Figure 12: The inside of a NEMA 17 stepper motor
[22]

2.7.4 Stepper Motor Drivers

A stepper motor driver is used between a microcontroller and a motor to deliver the current sufficient to drive it, see Figure 13. The stepper driver that will be used for the stepper motors is A4988. Each stepper driver needs two signals, step and direction. [23]

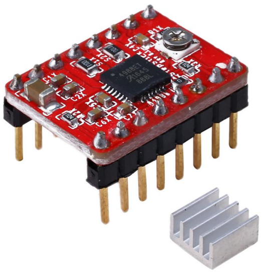


Figure 13: A4988 stepper motor driver

2.7.5 ESP32

The ESP32 is a powerful microcontroller that is used to control motors and sensors. To perform specific tasks based on signals from the input pins, the microcontroller must be programmed to be able to manage its various functions. The code is written in C++ programming language. Green circles are IO-pins that are safe to connect, and red ones are not safe to connect, see Figure 14. [24]

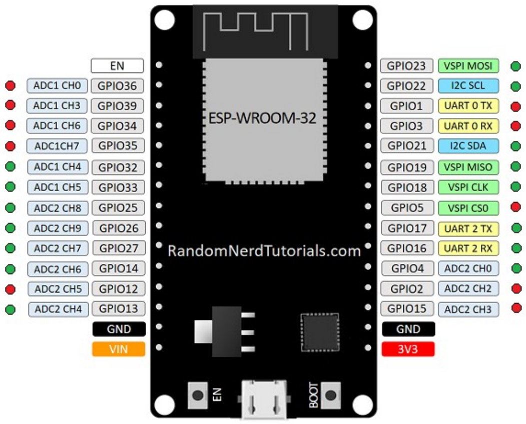


Figure 14: ESP32 with 30 pins

2.7.6 Buck Converter

A buck converter is a DC-to-DC converter that decreases voltage while increasing current from its input to its output, see Figure 15 for an example. They are useful for tasks such as converting the supply voltage to lower voltages. [25]

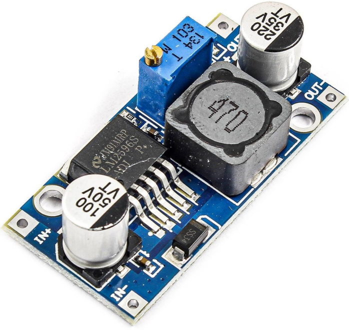


Figure 15: Buck Converter LM2596

2.7.7 Relay

A relay is an electrically operated switch. A solenoid operated by a low-power signal can control a higher-power circuit. The relays used are Double Pole Double Throw (DPDT), see Figure 16. Each of the four relays can alternate the middle contact between being connected to the left or right terminal. [26]

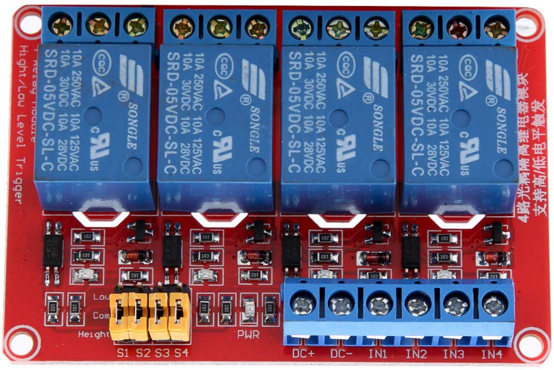


Figure 16: Four Channel relay

2.7.8 Pulse with Modulation

The ESP32 and many other microcontrollers are using a technique to control the power of a load by rapidly switching a signal on and off, called Pulse Width Modulation (PWM). By varying the pulse width (duty cycle), the average power delivered to the load is adjusted. The duty cycle can be calculated by dividing the time that the signal is high by the period, see Figure 17.

$$Dutycycle = Time\_on/Period$$

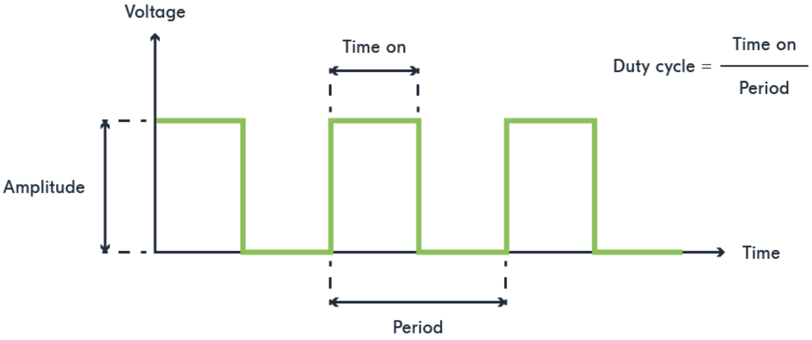


Figure 17: PWM

3 Idea Generation and Selection of Concept

This chapter describes the process of developing ideas that led to the final concept. A structured approach was used to guide the generation and evaluation of different solutions to the problem. The process began with brainstorming and sketching, which produced a variety of potential approaches. To determine which of these ideas was the most appropriate, the list was gradually narrowed down based on the project's defined criteria and practical considerations. Once a single concept remained, the idea generation phase was considered complete and the final solution was chosen.

3.1 Brainstorming

To explore a range of possible concepts, a brainstorming session was conducted as the initial method of idea generation. Brainstorming is an effective tool to produce potential solutions without limiting creativity. The focus is not necessarily on feasibility or practicality, but rather on encouraging diverse ways of thinking about a problem and exploring all approaches. In this case, a session that lasted 3 minute was done, during which all group members independently wrote down ideas on how to solve the problem. This process resulted in a total of 20 different concepts for the climbing problem, see Table 2.

Table 2: The 20 solutions after the brainstorming session

Triple wheels	Hot air balloon	Big wheels with spikes	Winch from a tree
Double wheels	Helicopter	ramp	elevator
Support poles	Hydraulic cannon	Height adjustable platform	Drawbridge
Rubber tracks	Height adjustable wheels	Worm	Grappling hook
Spider	Claw/arm	Big tractor tires	Articulated steering

3.2 Elimination of Solutions

At this stage, none of the concepts generated during the brainstorming session had been discarded. However, not all ideas were suitable for the project or technically feasible. Since the brainstorming phase allowed for unrestricted creativity, several unrealistic proposals, such as the *hot air balloon* and the *winch from a tree*, were removed early in the evaluation process. To further narrow down the list, each concept was evaluated on the basis of three main criteria: relevance to the project, technical feasibility, and alignment with the project's requirements. This initial filtering significantly reduced the number of candidate solutions.

To refine the selection even further, a group vote was conducted in which each team member chose the solution they believed best addressed the problem., see Table 3. The table includes four main concepts that were considered the most promising for solving the problem, along with two partial solutions that could potentially be integrated with any of the four to enhance the final design. Sketches were developed, and further discussions followed to determine the most viable option. Ultimately, a final concept was selected that formed the basis for the project.

Table 3: 4 main solutions with 2 partial solutions

Main solutions:	**Partial solutions:**
Multiple wheels	Articulated steering
Rubber tracks	Claw/arm
Big wheels	
Height adjustable wheels	

Main Solutions:

- **Multiple wheels:** This solution is based on a wheel composed of two or three smaller wheels; see Figure 18. This concept allows the wheel to drive against obstacles and overcome them by rotating around its center axis, thus changing which of the smaller wheels come into contact with the ground. This mechanism provides a relatively straightforward and potentially effective approach to navigating obstacles of moderate height.

Figure 18: Multiple wheels
[27]

- **Rubber Tracks:** Using rubber tracks would significantly increase the traction of the lawn mower on the ground and, if properly designed, could allow it to climb steep or even vertical obstacles. A key requirement for this solution is that the lawn mower must be able to initiate a lifting motion. This could potentially be achieved by incorporating one of the partial solutions, such as a claw or arm, to begin the lifting phase, see Figure 19.

Figure 19: Rubber tracks
[28]

- **Big Wheels:** Larger wheels present a possible solution for overcoming taller vertical obstacles. By increasing the diameter of the wheel, the lawn mower gains additional ground clearance and leverage, which in turn improves its ability to climb. The added leverage also improves traction, making it easier for the mower to scale higher obstacles in the right conditions.

- **Height Adjustable Wheels:** This concept involves equipping the wheels with an elevating mechanism, allowing them to be raised or lowered independently. By coordinating the movement of different pairs of wheels in a specific sequence, the lawn mower could climb vertical obstacles through a step-like motion. For this approach to work effectively, the system must include at least three or more pairs of wheels, as maintaining balance requires a minimum of two pairs to remain in contact with the ground at all times.

Partial Solutions:

- **Articulated Steering:** A partial solution to the problem could involve articulated steering, see Figure 20. This concept can be combined with the main solutions discussed above to form a more comprehensive and effective solution. The advantage of articulated steering is that it provides the lawn mower with greater flexibility, allowing for more advanced movements. This makes it easier to control the mower and integrate additional functions.

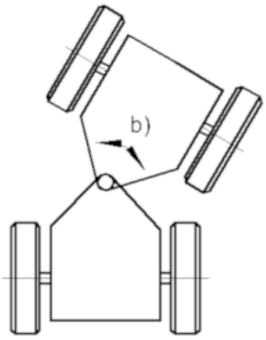


Figure 20: Articulated steering

- **Claw/Arm:** Another partial solution involves integrating a claw, arm, or similar extension that could provide more leverage for pulling or pushing. The benefits of having such an extension are significant and versatile in various scenarios. For example, a claw could grab something and pull the lawn mower both forward and upward. Another example is to use an arm to push against the ground and, therefore, to raise itself.

3.3 Discussion of Concepts

From the main and partial solutions, several design concepts were developed to address the problem.

Big Wheels:
Using large wheels on a lawn mower can help it overcome obstacles. However, this design is less effective for cutting grass. Larger wheels raise the lawn mower's body higher off the ground, increasing the distance between the blades and the grass. To maintain effective cutting, the blades would need to be lowered, which could be considered dangerous due to increased exposure to the blade. Additionally, the effectiveness of this solution is

limited as the size of the wheel directly affects the maximum climbable height, meaning that achieving significant elevation would require impractically large wheels.

Multiple Wheels with Tracks:
Another proposed solution involves the use of multiple wheels in combination with a rubber track. By mounting a smaller wheel alongside a larger one at the rear of the lawn mower, see Figure 21, and connecting them to a rubber track, the track functions as a hook-like mechanism to assist the mower climb over obstacles. Although this configuration may improve climbing ability, it presents several notable limitations. For example, the mower would have to reverse onto obstacles, and there is no effective means of descending. Furthermore, the design lacks adaptability to varying obstacle heights, as this would depend on the fixed dimensions of the wheels, thus reducing its overall flexibility.

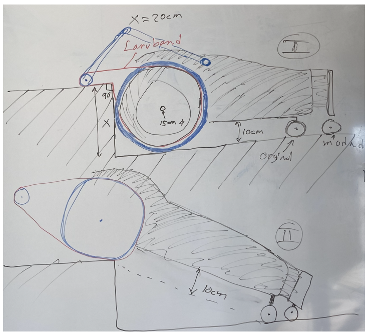


Figure 21: Combination of wheel and tracks

Height Adjustable Wheels:
The solution involving height-adjustable wheels is more complex, but offers significantly greater flexibility. It enables the lawn mower to navigate obstacles of varying heights without the constraints associated with fixed wheel sizes. This design also allows for ascent and descent, improving overall maneuverability, see Figure 22 and 23. However, maintaining balance during the climbing process can be challenging, particularly if the mower becomes unstable. For the system to operate effectively, it must be capable of independently raising and lowering each wheel as required.

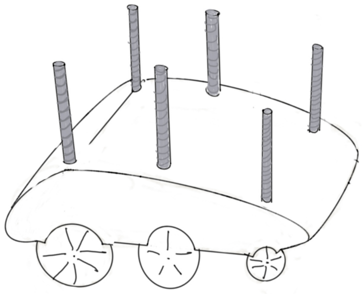


Figure 22: Height Adjustable Wheels 1

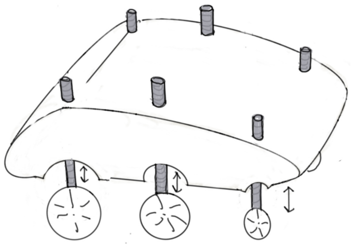


Figure 23: Height Adjustable Wheels 2

Drop-Down Bridge:
This solution is based on a partial concept that involves a mechanical claw or arm. The proposed idea is to mount a foldable bridge on top of the lawn mower. Upon encountering an obstacle, the bridge would be deployed by unfolding downward in front of the mower, forming a ramp from the top of the obstacle to the ground where the mower is currently positioned, see Figure 24 and 25. The lawn mower could then climb the bridge, cross the obstacle, and retract the bridge back to its top. This approach also enables the mower to descend from elevated surfaces. However, to reach higher elevations, the mower must be able to climb steep inclines, as the bridge cannot be excessively long due to spatial and weight limitations. To address this, the wheels may need to be fitted with rubber tracks to provide increased traction on steep surfaces.

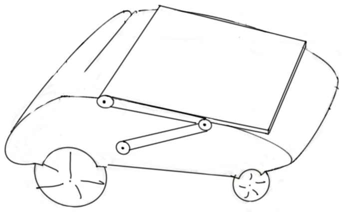


Figure 24: Drop-Down Bridge 1

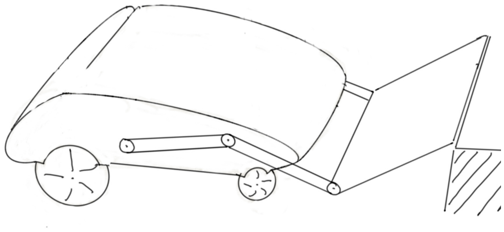


Figure 25: Drop-Down Bridge 2

3.4 Final Concept

The final concept was decided to be the *height adjustable wheels* because it was the most versatile solution. Several of the alternatives previously discussed were constrained by factors such as wheel size or excessive spatial requirements, which introduced additional complications. In contrast, the main limitations of the chosen concept are the maximum climbable height, determined by the length of the vertical posts supporting the adjustable wheels, and the challenge of maintaining balance. Since the posts extend vertically without increasing the width of the system, the design remains compact and well suited to navigate varied terrain while still allowing the mower to overcome a variety of obstacle heights. However, stability remains a critical concern, as it is closely related to the mower's center of gravity and must be addressed in the design process.

This design introduces a re-engineered wheel system for the robotic lawn mower, enabling independent vertical movement of each wheel. Unlike other concepts, this solution functions as a standalone system and does not rely on a combination with partial mechanisms. By concentrating on a single well-defined operation, the problem becomes more tractable. In this context, *raising the wheels* refers to adjusting the vertical position of the mower's body relative to the wheels. Each wheel can be independently extended or retracted, allowing the mower to incrementally raise itself and traverse obstacles by adjusting its pair of wheels to align with the next level of ground.

3.5 Operational Flow

The operating flow sequence for how the lawn mower climbs can be divided into four steps, providing a clear understanding of the process.

Step 1 involves navigating and positioning the lawn mower directly in front of the obstacle. Accurate alignment is necessary to ensure a stable and successful ascent. When in position, the lawn mower raises its base plate until it reaches the correct height to overcome the obstacle, see Figure 26.

(a) Accurate alignment

(b) Raised base plate

Figure 26: Step 1

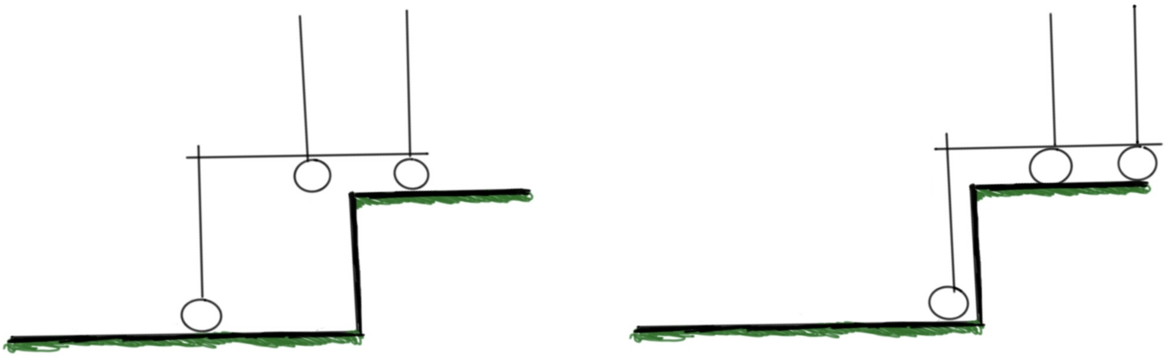
In Step 2 the lawn mower raises its front wheels and then drives forward with the help of the middle and rear wheels, until the front wheels are in contact with the elevated surface, see Figure 27.

(a) Raised front wheels

(b) Front wheels on next ground level

Figure 27: Step 2

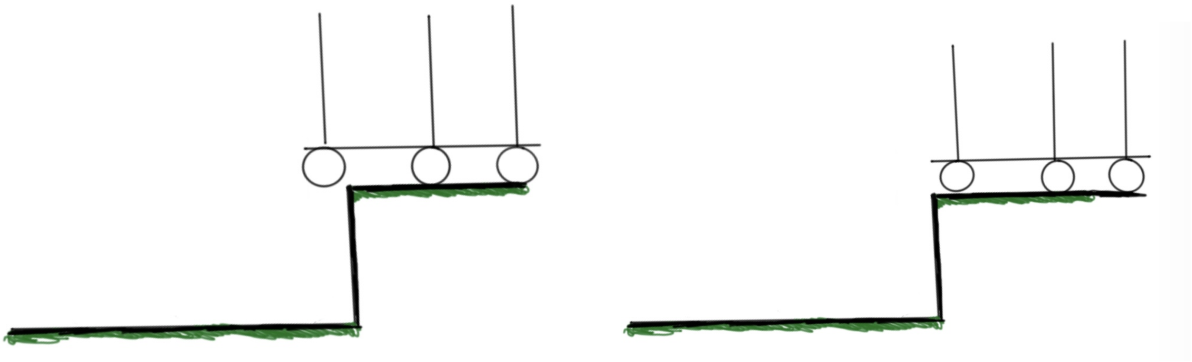
Step 3 consists of raising the middle wheels and driving forward using the rear and front wheels until the middle wheels also reach the next surface level. At this stage, the lawn mower has the front and middle wheel pairs on the elevated surface, while the rear wheels remain at the original ground level, see Figure 28.



(a) Raised middle wheels (b) Middle and front wheels on new level

Figure 28: Step 3

Step 4 involves raising the rear wheels. Once elevated, the lawn mower advances forward using the middle pair of wheels to connect the rear pair of wheels to the elevated surface level, see Figure 29.



(a) Raised rear wheels (b) Lawn mower on the new ground level

Figure 29: Step 4

4 Mechanical Design and Development Process

This chapter outlines the design and development of the climbing robotic lawn mower prototype. It details the design considerations, modifications, and integrations of key components such as the base plate, wheel system, and elevators.

4.1 Product Description

The climbing robotic lawn mower was made up of several main components that together enable movement and climbing. For clarification during the design phase, the system was divided into four main components; the base plate which provides structural support and a place for all the other components to attach, formation of wheels, elevating mechanism responsible for adjusting the lawn mower's height during the climbs, and center of gravity which was critical for stability and balance. By doing this division, it allowed iterative improvements for each part.

4.2 Base Plate

The base plate serves as the structural foundation of the lawn mower, holding all its components together. When designing it, the goal was to ensure efficiency and flexibility, specifically to support the climbing mechanism.

To make climbing possible, a third pair of wheels was added. This ensures that at least two pairs of wheels remain in contact with the ground at all times, maintaining stability while one pair is elevated. As a result, the dimensions of the base plate, particularly its length and width, had to be adjusted. Initially, reusing the base plate from the 550 EPOS model was considered an option. However, due to its limited size and suitability for only two pairs of wheels, it was incompatible with the new design.

Although the third wheel pair improves climbing stability, it also increases the length and overall size of the mower; see Figure 30 for an example sketch. This extension can be a problem when it comes to maneuvering in small spaces, for example, around trees.

The placement of the cutting blade was another consideration in the base plate design. The cutting blade has a radius of approximately 110 millimeters from the lawn mower's center and had to be positioned to avoid interference with the wheels, motors, and other components. Additionally, there was a desirable feature from the requirement specification table to maintain a similar distance from the front of the lawn mower to the outer diameter of the cutting blade as in the 550 EPOS model, measured to 170 millimeters. This appears to be a standard among Husqvarna's robotic lawn mowers. This requirement also contributed to an increase in the length of the lawn mower, as the blades occupy a considerable amount of space.

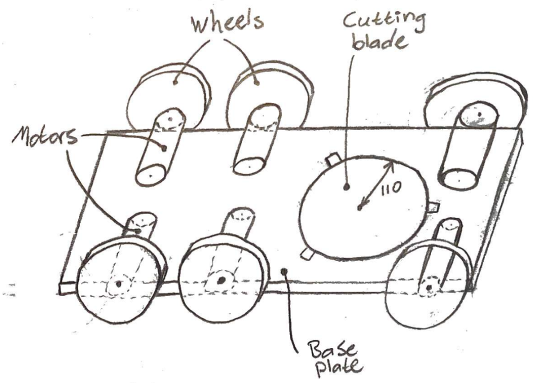


Figure 30: Long base plate

One proposed solution to reduce the overall length of the base plate was to stagger the wheel pairs rather than align them in a straight line, see Figure 31 for a sketch. By widening the middle section of the base plate and positioning the middle wheels farther from the centerline, the wheels can partially overlap at the front and rear wheels. This layout creates a more compact design as the middle and rear wheels can be closer to each other along the x-axis. Additionally, the base plate length can be further reduced by placing the cutting blades centrally. This design shifts the lawn mower from a long and narrow configuration to a shorter but wider one.

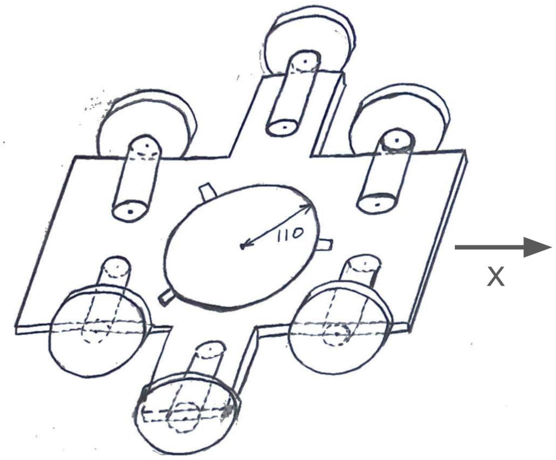


Figure 31: Shorter but wider base plate

The next iteration of the base plate involved adding dimensions and ensuring that all components could be placed without interfering with each other. The priority was to fit the motors, cutting blade, battery, and wheels on the base plate, as these are the largest components. At this stage, the lawn mower's form was mostly defined, still incomplete but sufficient for preliminary estimations and layout planning. For example, the exact placement of the screws and mounting holes had not yet been finalized. Figure 32 shows a sketch of this base plate iteration, including the motors, wheels, and cutting blade. The sketch is not scaled, but the annotated dimensions accurately reflect this design stage.

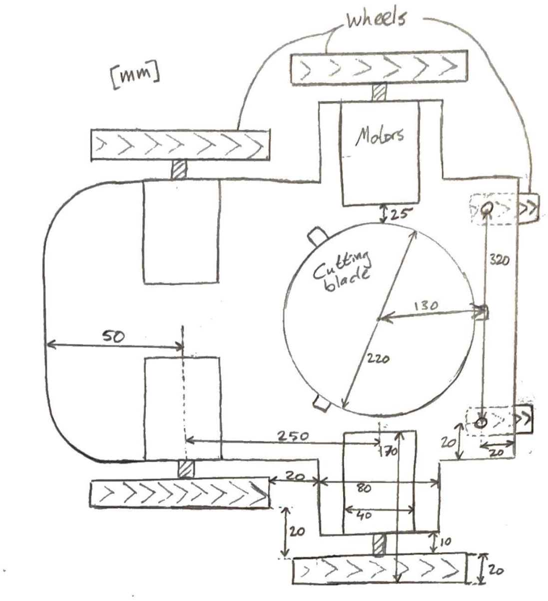


Figure 32: Sketch of the base plate with dimensions

4.2.1 Final Design of the Base Plate

Once the dimensions and positions of the major components were finalized, a complete base plate design could be created. This version includes all necessary details, such as mounting locations for components and screw holes for attachment. To reduce overall weight of the base plate, material cutouts were added in the design, see Figure 33. These cutouts were strategically placed in areas with excess material, avoiding weakening the structure and ensuring that the base plate maintains its mechanical integrity.

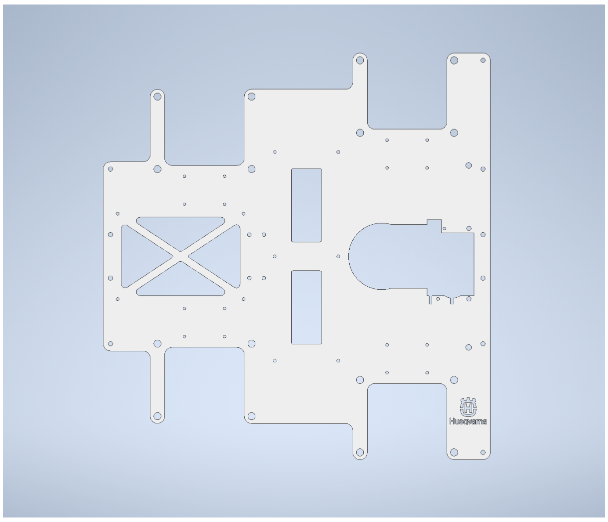


Figure 33: Final base plate drawing

4.2.2 Choice of Material

Various materials for the base plate were considered, including steel, aluminum, wood, and acrylic glass. As the primary goal was to create a functional prototype, the material did not need to match the one for the commercial product. The estimated total weight of the lawn mower was between 10 and 20 kilograms, so the base plate material needed sufficient strength to support this load. The material also needed to be stiff to minimize flexing.

The weight of the material itself was another important factor, as the motors needed to lift the entire lawn mower without an excessive load. Time and cost were additional considerations, ruling out materials such as carbon fiber, titanium, and molded plastics. 3D-printed plastic could also be considered, but would not be strong enough to support the full load and could potentially crack. The base plate had to be manufactured using the tools available at Chalmers, either at CASE or Prototyplaboratoriet. Prototyplaboratoriet is equipped with a water jet cutting machine suitable for precise metal processing, but achieving similar precision with wood would be difficult. Since the base plate required many holes and complex geometries, making it from wood with hand tools was seen as impractical. Wood was therefore excluded as a material option. Metals were more preferable because of their compatibility with water jet cutting.

If using a metal as the material for the base plate, it had to be determined which one out of steel or aluminum would be the most suitable, since those were the options to choose between in the laboratories. Aluminum has a lower strength than steel, but has a lower density. However, for this project it was important to ensure mechanical stability, since the lawn mower will carry a lot of load. Therefore, to reduce the risk of structural failure, it was decided to choose the strongest one rather than the lightest one. A 2 millimeter thick steel sheet was selected as the best material for the base plate *if* using a metal. The steel was cut to the right shape with a water jet cutter and painted to prevent rust to achieve a better finish.

Acrylic glass was also considered as another material for the base plate. It is relatively lightweight and could be cut quickly and accurately using a laser cutter, but it is not as strong or stiff as steel. A second base plate was manufactured from a 6 millimeter thick acrylic glass as an alternative to the steel version. This decision was made due to concerns that the steel plate might be too heavy for the motors responsible for elevating the lawn mower. However, at this stage, the total weight of the prototype and the motors' lifting capacities were still uncertain. To reduce the risk of overloading the system, the acrylic base plate was seen as a good lightweight alternative. However, there were concerns about whether it could support the lawn mower's total weight without breaking. To prevent this, additional mounted holes were included to allow later installation of small steel brackets for extra stability if needed. The steel base plate remained a backup option in case the acrylic version proved insufficient. Since it was unclear which solution would perform better, having both as an option was considered a practical approach during development.

During testing, when the lawn mower was tested by driving it, noticeable wobbling occurred as in the acrylic version of the base plate, which created movement in components that was not desired. Although this did not significantly affect the performance, it introduced a large risk of breaking. With the steel base plate, this was not an issue since the it had much more structural stability. Considering the benefits of reduced load on the motors by using the acrylic plate, it still remained a good option if the steel plate would be to heavy. But if the steel plate does not give any issues on the motor, that one is the most suitable one to choose.

4.2.3 Number of Elevators Required

A design decision was made to use only two pairs of elevators instead of three, which would leave one pair of wheels without elevators on them. With this setup, the front wheels are mounted directly to the base plate without any lifting mechanism. This reduces mechanical complexity, material usage, cost, and weight.

However, this configuration introduces a specific operational constraint. During climbing, the lawn mower must move forward when climbing up and backward when descending. This is because the front wheels must be the ones that make contact with the elevated surface first when climbing up, or be the last to leave when climbing down due to keeping the balance and always having at least two pairs of wheels in the ground at the same time. This does impose a limitation on how the lawn mower can operate during climbing. However, it is unlikely to cause significant issues in practice, as lawn mowers often follow a planned route.

4.3 Wheels

The next iteration of the base plate focused on optimizing the wheel size and shape. By using different wheel diameters, they can have unique properties and, therefore, can be used in different ways. In the first iteration the wheels all had the same dimension, 250 millimeters, since it was a good starting point. However, this was changed multiple times throughout the development process to improve the overall performance and functionality of the lawn mower.

4.3.1 Choice of Front Wheels

One modification was to replace the front wheel with the original front wheels of the Husqvarna 550 EPOS lawn mower, which have a diameter of 100 millimeters, see Figure 34. These wheels were selected because they are designed to rotate 360 degrees, providing a simple and effective solution for steering. Using fixed, non-rotating wheels at the front would have required implementing a differential drive system, where the lawn mower turns by varying the speeds of the wheels. Although this approach was technically feasible, it was unnecessarily complex for this application. The original Husqvarna wheels addressed the steering challenge more efficiently. Their smaller diameter also helped reduce the overall length of the lawn mower, which is advantageous in tight or obstacle-dense environments.

4.3.2 Number of Motors

One important consideration during the design process was determining which pair of wheels should be motorized. Initially, the concept involved powering all six wheels, but further analysis showed that this was unnecessary. The chosen climbing mechanism requires that only one pair of wheels be lifted at a time, which means that at least two

Figure 34: Original Husqvarna front wheel

pairs remain in contact with the ground for stability. This constraint can be leveraged to simplify the design by ensuring that two of the three pairs of wheels are always in contact with the ground, only those two need to be motorized. Regardless of which pair is elevated, on pair of powered wheels will always remain in contact with the surface, allowing the mower to retain its mobility. This means that any two of the three pairs of wheels, front, middle, or rear, can be driven and the optimal configuration can be determined through future testing. Reducing the number of motorized wheels simplifies design, reduces cost, reduces total weight, and saves space.

The next iteration of the wheel design combines the two previous modifications; enabling the front wheel to rotate freely and reducing the number of pairs of powered wheels from three to two. These two features complement each other well, as the original front wheels of the Husqvarna lawn mower cannot be motor driven due to their design. Therefore, it was decided that the back and middle wheels would be powered while the front wheel would remain passive.

During normal operation, such as cutting grass, the lawn mower must be able to steer. The design includes three pairs of wheels,the front pair of which is capable of rotating freely. The remaining two pairs are fixed and cannot steer, which complicates turning and introduces the need for a differential drive system. This presents a challenge when the four wheels are in contact with the ground; all must be precisely coordinated to turn to avoid slippage. Although this issue could be addressed through complex control algorithms, a simpler mechanical solution was chosen. If only one of the non-steerable wheel pairs is in contact with the ground at a time, the turning problem is effectively eliminated. The wheels can then rotate without causing friction or drag. To implement this, one of the non-steerable wheel pairs can be lifted off the ground using the existing elevator mechanism. This approach simplifies steering and improves maneuverability. An additional benefit is that reducing ground contact during turns helps minimize lawn damage.

After this decision, it was necessary to determine whether the middle or back wheels should be lifted. The decision was made to lift the middle wheels, as this would have less impact on the mower's stability compared to lifting the rear wheels. Additionally, lifting the middle wheels is feasible because the lawn mower's is still powered using the back wheels. If propulsion were only delivered from the middle wheels, it would not function effectively. By lifting the middle wheels, the mower's operation becomes more similar to the original Husqvarna model, which features large rear wheels and rotating front wheels.

4.3.3 Choice of Back Wheels

The back wheels have previously been stated to 250 millimeters in diameter. This is beneficial because it is the same size as the Husqvarna stock wheels. In this project it is useful to reuse as much components as possible because it gives more time to focus on the main goal of the project; creating a climbing lawn mower. A smaller back wheel could result in the creation of a shorter lawn mower, which is advantageous because it then becomes more nimble and easier to maneuver in tight places. This is however not the main focus of this project and therefore the original back wheel was used.

The middle wheels were redesigned because they would give better stability for the lawn mower. This is more explained in the next chapter, where the problem and eventually the solution is described.

4.4 Center of Gravity Management

To ensure that the lawn mower remains stable and well balanced during the climbing procedure, the center of gravity must be managed. If the center of gravity shifts too far in any direction, the robot risks tipping over. In the case of the Husqvarna 550 Epos, the center of gravity is positioned towards the rear due to the heavy batteries and larger wheels. However, this design cannot be replicated in the new solution, particularly with the addition of an extra wheel pair, which would make the robot even more rear-heavy.

The concept behind adding a third pair of wheels is that not all wheels will be in contact with the ground at the same time during climbing, enabling the robot to elevate. First, the base plate is elevated using the back and middle pairs of wheels, both of which are designed to raise and lower themselves to reach the next level. The robot then drives forward until the first pair of wheels reaches the new ground level. The middle pair is then raised, allowing the robot to continue moving forward with the back wheels still in contact with the ground, until the middle wheels also reach the new ground level. Finally, the same procedure is repeated for the back pair. If the center of gravity is not properly adjusted, this system will be unstable or may fail entirely, as the rear of the lawn mower will hang off the edge for a while during this procedure. Several solutions have been proposed to address this problem.

The problem lies in the need for the lawn mower to remain stable while lifting each pair of wheels, with only two pairs in contact with the ground at the same time. The middle pair can be lifted without risking instability. The back pair must also be lifted while maintaining stability. This means that the center of mass must be directly over a single stable point, the midpoint of the middle wheels, where they make contact with the ground, see Figure 35 for a visual explanation. Note that the provided sketch does not depict the correct wheel placements or dimensions but rather serves to clarify the center of mass problem. The location in which the center of mass must be positioned is very small, and this challenge must be addressed through careful design. Several potential solutions to this problem have been explored.

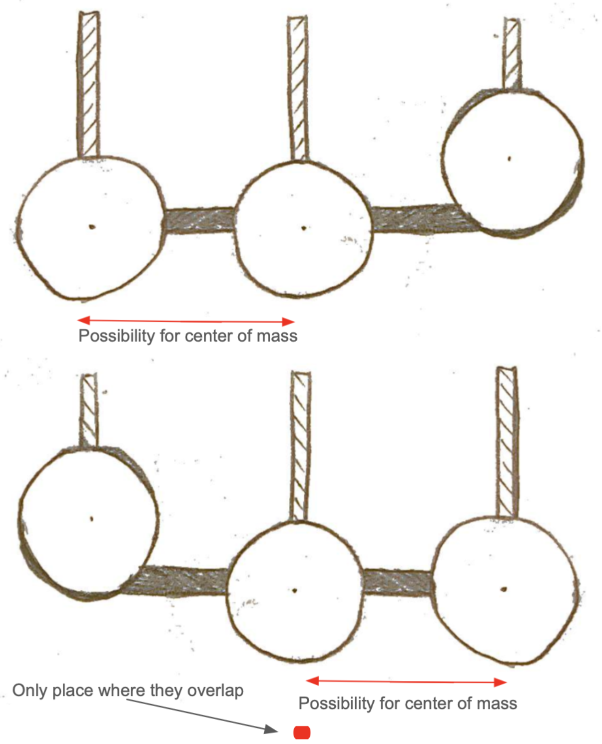


Figure 35: Center of mass problem

4.4.1 Moving the Center of Mass

The first concept for managing the center of gravity involved implementing a regulation system by mounting the main mass, such as the battery, on a movable rail. This system would allow the mass to shift forward and backward during climbing, thereby maintaining balance. However, this approach would require a lot of space within the lawn mower and add extra weight since it would require an additional motor. Given that many components already occupy space on the base plate, assigning room to a large moving mass proved to be a challenge.

An alternative idea was to use a liquid mass that could be pumped between compartments within the mower. This solution would offer more flexibility in positioning the center of gravity. However, it would also introduce added complexity; requiring a pump, sealed tubing, and the weight of the liquid itself. Although technically feasible, this approach was considered too time-consuming to implement, especially since other complex elements are already present in the design. As a result, it was deemed impractical to pursue these ideas further.

4.4.2 Larger Contact Area

A more practical solution was to extend the surface area of the middle wheels. Using oval or triangular wheels with a larger contact area, the design introduces a greater margin of error for the center of mass during climbing. This concept can be further enhanced by integrating tracks into the wheels, increasing the surface connection with the ground, see Figure 36.

As a result, the robot does not balance at a single point but instead distributes its weight over a larger area, improving stability during the climbing process. Importantly, the middle wheel pair is only used while climbing; the tracks do not touch the ground during regular operation and, therefore, do not damage the grass.

This solution proved to be both effective and simple. It does not require additional electronics or complex manufacturing and adds minimal extra weight. For all these reasons, this concept was selected for further development to optimize climbing performance.

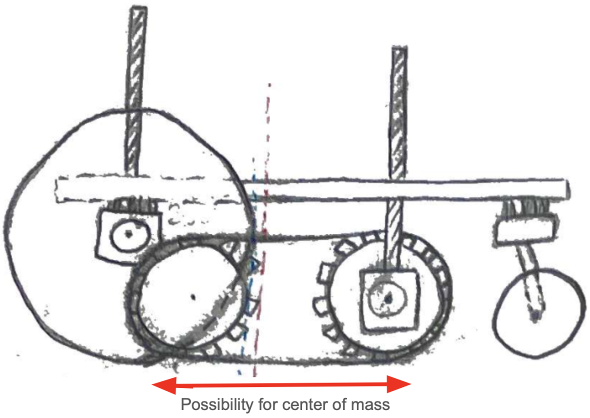


Figure 36: Tracks on middle wheel

The next iteration focused on implementing an oval-shaped or triangular wheel configuration. Although both options could function effectively, a design using three wheels would unnecessarily increase the system's complexity and weight. Instead, a simpler solution was considered sufficient, using two wheels connected by a rubber track. The track would provide additional traction for the middle wheels, improving performance on uneven terrain.

However, since the goal of this project is to develop a working prototype for a controlled laboratory environment, maximizing traction is not a priority. Therefore, high-performance rubber tracks were not manufactured or included in this prototype. Despite this, the lawn mower can still climb obstacles without them, although its performance and reliability would be improved with their use in future iterations.

Without rubber tracks, only one of the two middle wheels, the front one, is powered by a motor, as shown in Figure 36. This is sufficient as the front portion of the middle wheel is the first to contact the ledge during climbing. This allows the mower to start lifting itself as soon as the powered wheel engages with the obstacle.

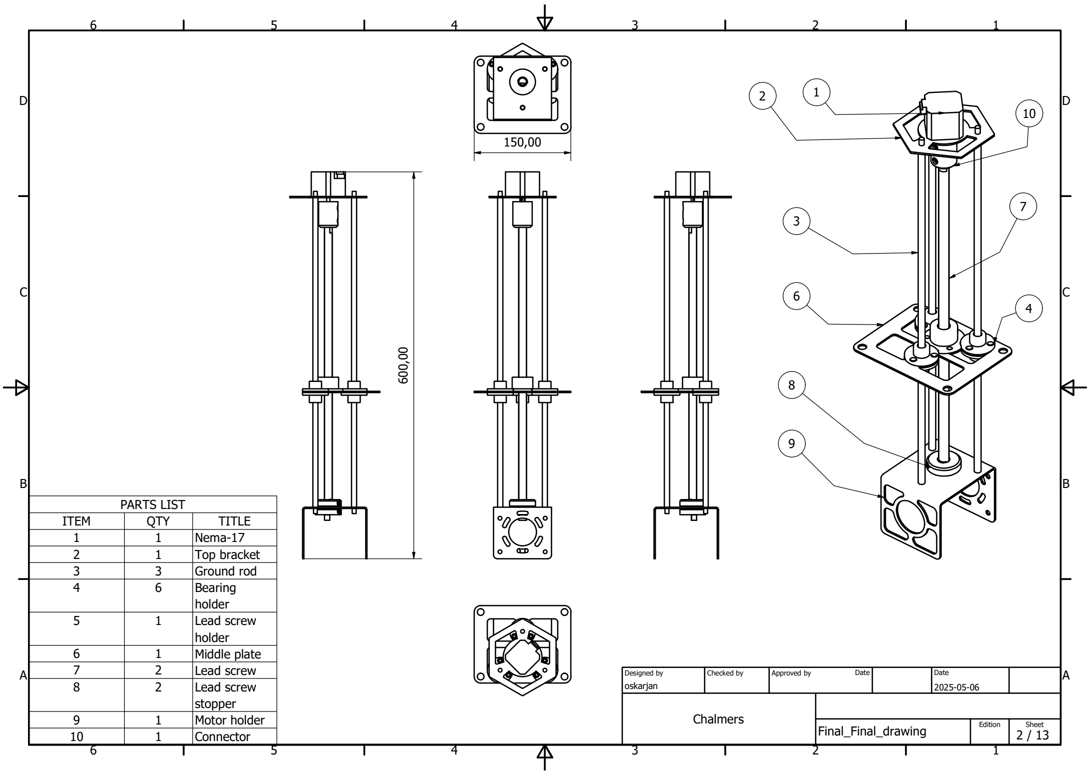
The both middle wheels were designed with a radius of 100 millimeters and be 25 millimeters wide. The wheel connected to the motor had two spikes on the back side because the motor had two holes in its axle where these could be inserted, which would transfer the rotating force without using a press fitting. A small distance of 2 millimeters was also introduced so the wheel would not interfere with the rest of the design on the motor and creating unwanted friction. The wheel would be secured on the motor via a nut.

The other middle wheel was place on a connecting plate, described more in the section *Attachments*. This wheel was placed 150 millimeters away from the center of the other first middle wheel. The wheel would be secured to the plate by a screw and a nut.

4.5 Elevators

The wheel elevator adjusts the height of the lawn mower, allowing it to climb, as described in Section 3.5. Figure 37 shows that the elevator consists of three metal plates, rods with linear bearings, a lead screw and nut, a stepper motor and a wheel motor, which is the final design. The bottom plate holds the wheel motor, the middle plate houses three linear bearings, the lead screw nut, and the top plate mounts the stepper motor. A coupling connects the lead screw to the stepper motor, allowing them to rotate together. Two stoppers at the bottom of the lead screw lock it to the bottom plate.

The elevator operates by rotating the lead screw using a stepper motor. The lead screw is threaded through a nut that is fixed to the middle plate. As the screw rotates, the threads cause the nut and the middle plate to move vertically, either upward or downward depending on the direction of rotation. The lead screw is connected to the bottom plate through stoppers, so the movement of the middle plate is transferred to the bottom plate. This causes the entire wheel assembly to be raised or lowered.



PARTS LIST

ITEM	QTY	TITLE
1	1	Nema-17
2	1	Top bracket
3	3	Ground rod
4	6	Bearing holder
5	1	Lead screw holder
6	1	Middle plate
7	2	Lead screw
8	2	Lead screw stopper
9	1	Motor holder
10	1	Connector

Figure 37: Elevator drawing

The design and development of the elevator system followed an iterative process. Multiple design alternatives were explored and tested to assess their performance. During this process, several previously unanticipated failure modes emerged. These issues were systematically resolved through continuous refinement and improvement of the design in successive iterations.

4.5.1 First Concept

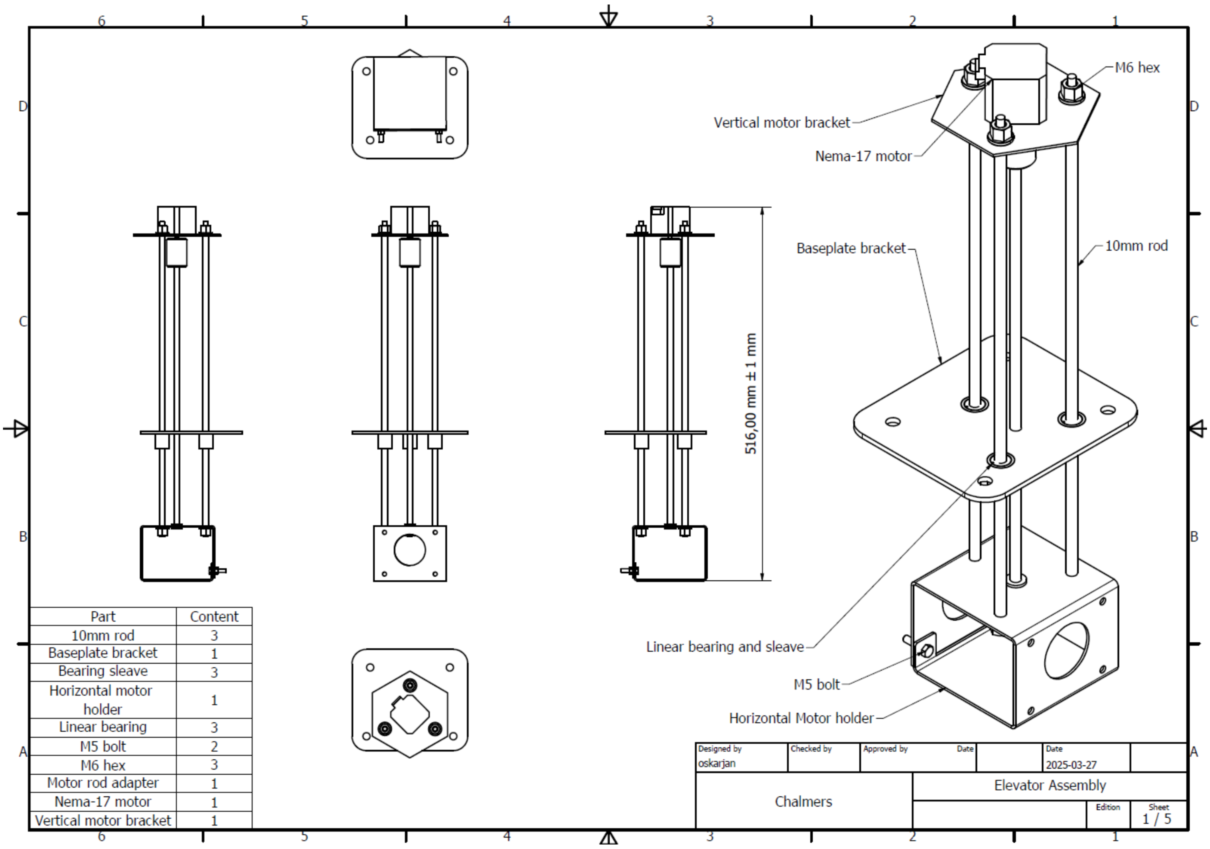
The initial concept featured four rods connecting the plates, drawing inspiration from the vertical motion mechanisms of 3D-printers, which often use lead screws. Alternative approaches, such as hydraulic systems or scissor lifts, were considered but ultimately dismissed due to cost constraints and complexity. A preliminary prototype was constructed using leftover materials to serve as a proof of concept, see Figure 38. This prototype is constructed from three steel plates, four 2 mm metal rods, an M10 threaded rod, and a M10 nut. The top and bottom plates are connected by the 2 mm rods, which are welded in place and serve as guides for the sliding motion of the middle plate. The M10 nut is welded to the underside of the middle plate, and the M10 threaded rod passes through it. This prototype functions the same way as the final iteration but does not include the lead screw stops, meaning it is only capable of lifting the robot and not lowering it in a controlled manner. This was tested using a electrical screwdriver to rotate the threaded rod.

Figure 38: Proof of concept

This prototype presented several significant challenges in both fabrication and design. The first issue was to ensure that all steel rods remained parallel to each other. If not aligned, it could cause excessive vibrations when the elevator reaches its top or bottom positions. This led to the decision to rule out fabrication methods that generate heat, such as welding, as the heat could slightly deform the small metal components. Another problem encountered was friction between the rods and the middle plate, which hindered smooth movement. The final issue involved the pitch of the M10 screw, which increased the travel time. Although this was anticipated during the design phase, the screw was included in the prototype because it was unnecessary to order new parts at the this stage.

4.5.2 Second Iteration

The second prototype focused on the first ones flaws but encountered a lot of unforeseen problems, see Figure 39. It was first modeled in CAD, where motors, bearings, and screws were measured and positioned. The initial design closely resembled the final one but contained some flaws that made it impossible to build.



Part	Content
10mm rod	3
Baseplate bracket	1
Bearing sleave	3
Horizontal motor holder	1
Linear bearing	3
M5 bolt	2
M6 hex	3
Motor rod adapter	1
Nema-17 motor	1
Vertical motor bracket	1

Figure 39: First design of the second iteration

The design process for the second iteration began by replacing the four connecting rods with three thicker ground rods, dimensioned to fit linear bearings. This change was made to reduce the friction between the middle plate and the rods seen in the prototype. Since the elevator system consists of numerous moving parts, friction would accumulate and place unnecessary strain on the stepper motor. Therefore, reducing friction at all possible points was a priority. Additional modifications included replacing the M10 screw with a 12 mm lead screw with a pitch of 3 mm, increasing the number of rotations required for vertical travel. The material thickness was increased from 1 millimeter steel to 2 millimeter and the electric screwdriver used in the first prototype was replaced with a Nema-17 stepper motor with 0.52 Nm torque. From equation 1 the configuration results in an axial force of approximately 86.7 N when using the 12 millimeter lead screw. With four elevators in the mower, this amounts to a total vertical force of 35.8 kg, which considered to be sufficient for the design.

$$\frac{Torque_{Nema-17}}{Radius_{Leadscrew}} * elevators = \frac{0.52}{0.06} * 4 \approx 86.7N \tag{1}$$

The first issue from the prototype was the friction between the plates. The plan was to press-fit the linear bearings into the 2 millimeter steel middle plate with a small bushing. This approach proved impractical as the thin material would not be able to handle horizontal forces. To address this, the bearings were replaced with flanged versions, see Figure 40.

Figure 40: Bearing with flange

However, due to the high cost of flanged bearings, purchasing them would have exceeded the budget by several thousand Swedish crowns. As a cost-effective alternative, 3D-printing linear bearings and using Airsoft bullets was considered, as they have relatively low tolerances, about ±0.01 millimeters, and are quite durable. See Figure 41 for an illustration of this design. The bearing was composed of three parts: two lids and a central cylinder that contained the Airsoft pellets. The central cylinder is shown in the figure.

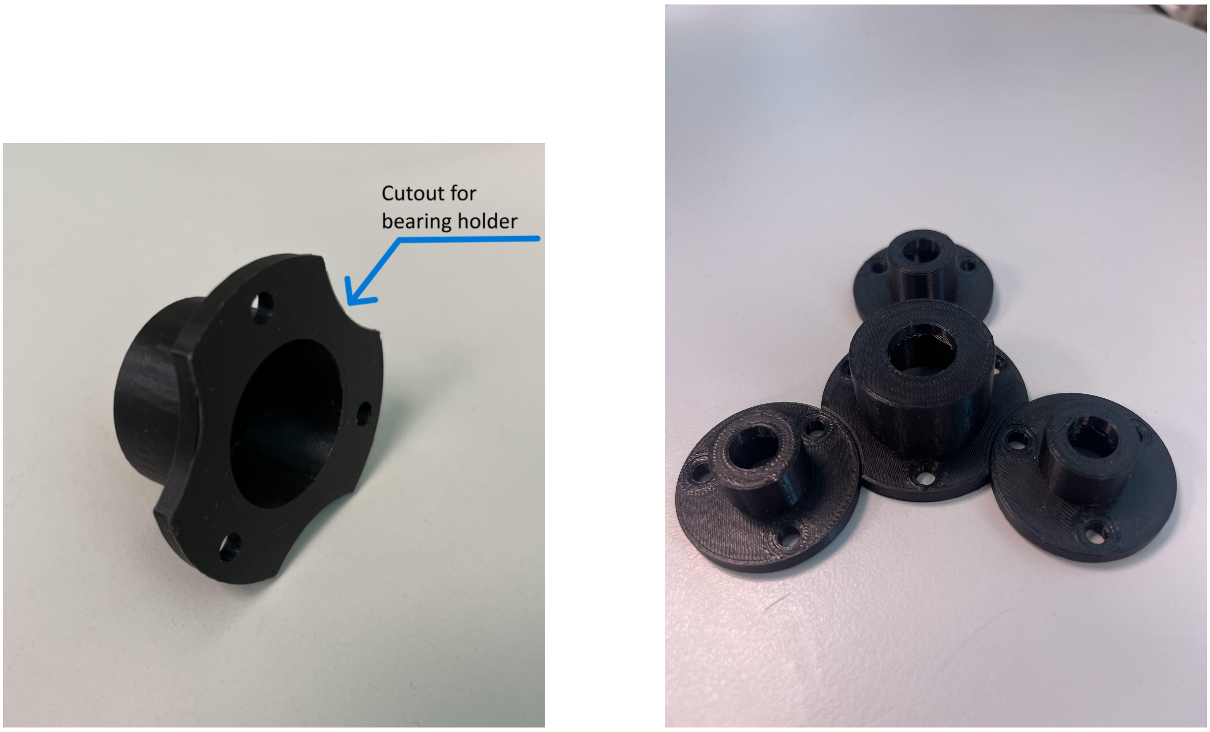
Figure 41: Printed bearing

Following re-budgeting and design revisions, the 3D-printed bearing was quickly discarded. The new mower design only needed four elevators instead of six and therefore buying cheap bearings without a flange became a viable option. The new solution utilized relatively low-cost bearings, with custom 3D-printed holders designed to be screwed into the plate, see Figure 42.

Figure 42: Printed bearing holder with flange

This design introduced certain challenges when integrating 3D-printed components with water-cut metal parts. Due to the angled nature of the water-cut edges, the printed parts could only be inserted from one direction. To address this, small tolerance rings were initially printed for testing, ultimately determining that a 0.2 millimeter reduction in size was required for a proper fit. Although this solution remained imperfect, with minor flaws left unresolved, they were sufficiently negligible and did not cause significant operational problems. One such flaw was that if one of the mounting screws was tightened more than the other two, the bearing could tilt, resulting in vibrations during the vertical movement of the plate.

A similar budget constraint occurred with the lead screw, where a flanged version proved too expensive. As an alternative, a custom 3D-printed holder was created, see Figure 43a. The primary challenge was to accommodate the lead screw holder along with the bearing mounts, which initially interfered with each other. This issue was resolved by adding cutouts to the lead screw holder, allowing it to fit around the bearing mounts, see Figure 43b.



(a) Lead screw holder

(b) Mounts together

Figure 43: How lead screw and bearing mounts fit in the assembly

The design of the three plates required precision, and this process began with the redesign of the motor holder, as shown in Figure 39. During the design phase, it was not considered that performing a 360-degree bend in metal is not feasible. As a result, the design was revised to a two-part assembly, held together with bolts, see figure 44. Upon initial assembly, it became evident that the holder was unnecessarily heavy and overly complex. Consequently, the bottom bracket was removed, simplifying the design to a single-piece component.

Figure 44: Two parted motor holder

The middle plate was redesigned to accommodate three bearings, a lead screw, and four mounting holes for the base plate, see Figure 45 This modification was completed before the final design of the holders, so their screw holes are not present. However, the holders can still be fitted in the test assembly later, but not with screws. The top bracket got redone to fit the stepper motor, see Figure 46.

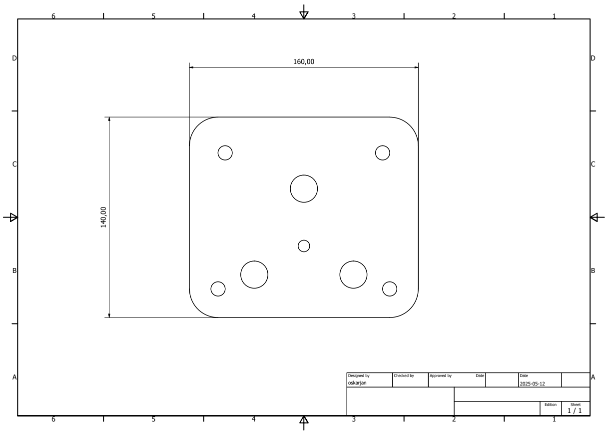


Figure 45: First iteration middle bracket

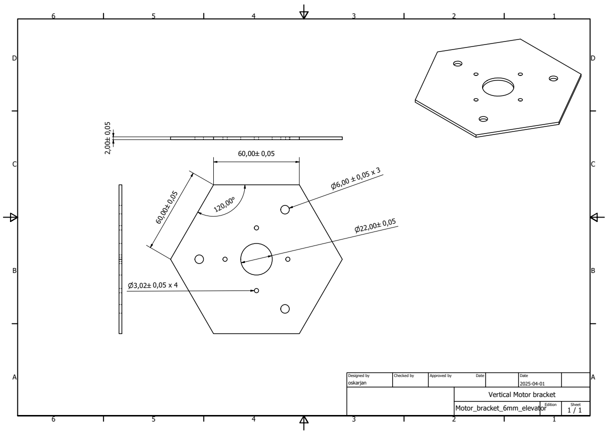


Figure 46: First iteration top bracket

With the three plates finalized and functioning as intended, the next step involved preparing the 8 millimeter ground rods. Each rod was cut to a length of 500 millimeters and then machined to create a 10 millimeter M6 thread at both ends. Ideally, this process would have produced three identical rods. However, due to the hardness of the material and the time-consuming nature of the cutting and lathing process, especially considering that 12 ends had to be machined, a length tolerance of approximately ±1 millimeter was observed, see Figure 47.

Figure 47: 8 millimeter rods lathed with M6 thread

As a result, the top plate sat at a slight angle, causing misalignment between the stepper motor and the lead screw. To compensate for the length discrepancy, washers were added to offset the shorter rods, see Figure 48. Although most of the 8 millimeters rods were within acceptable tolerances, the shortest one ideally should have been remade. However, no additional ground rods were purchased to account for potential errors. The rods were supplied in bundles of three lengths of one meter, and two packs were just sufficient for the project. To remain within budget, no extras were purchased.

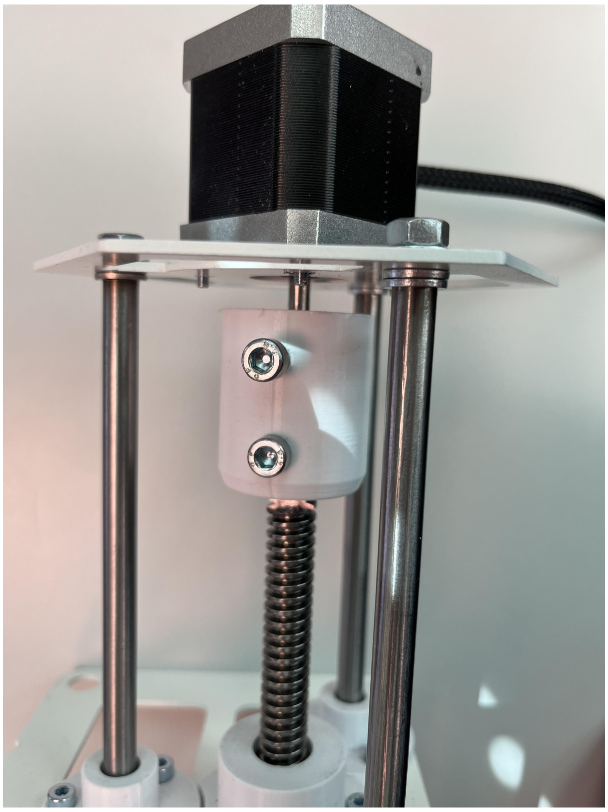


Figure 48: Extra washer on the final iteration

The rods could be fitted to the plates and the bearings with holders could be tested, see Figure 49. Although the elevators were not functional yet, the assembly somewhat showed proof of concept and what needed to be adjusted for the next iteration. It soon became apparent that the overall weight of the build was excessive, though this was improved in later iterations. Additionally, the water-cut metal began to rust within a few days, and some clearance issues were identified.

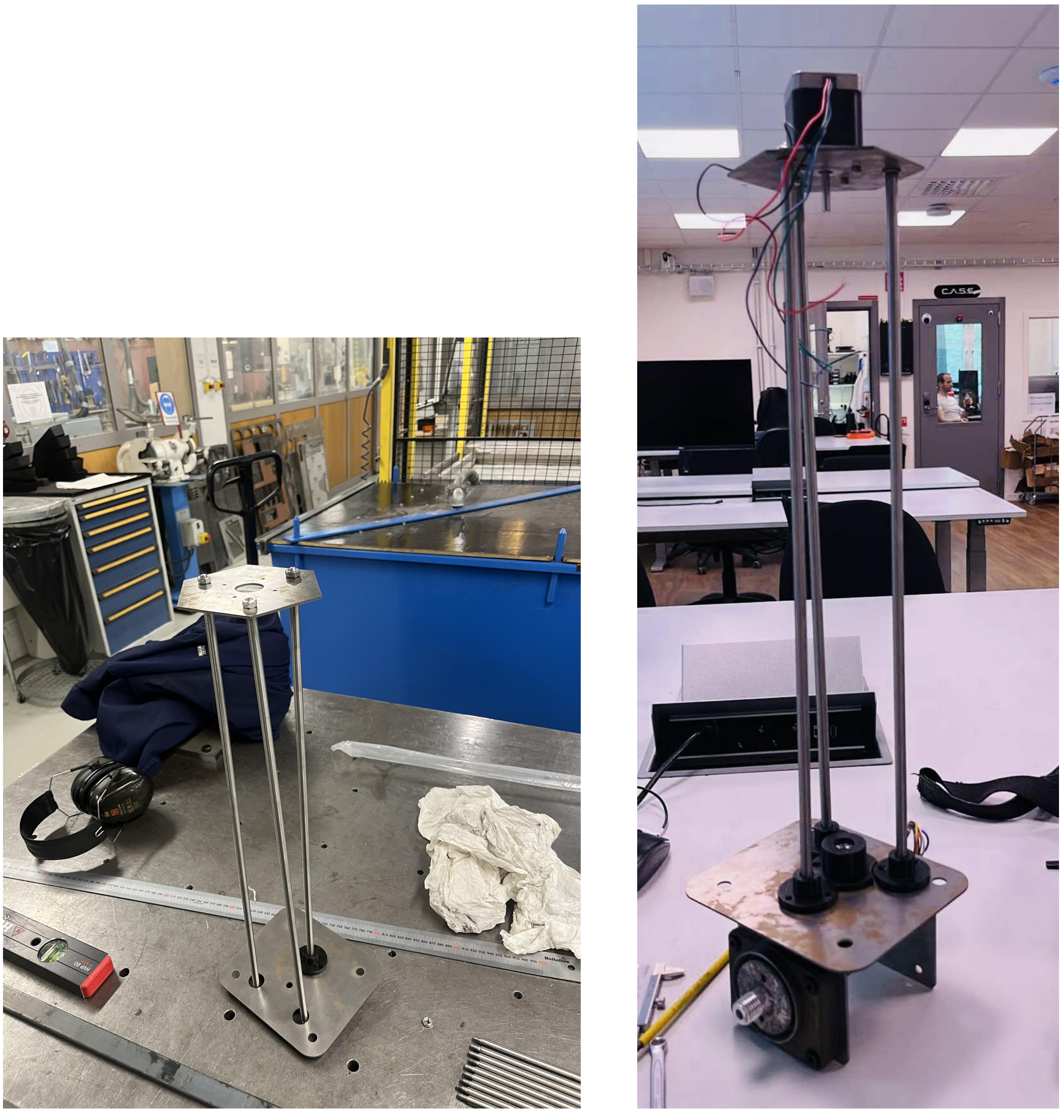


Figure 49: Testing different stages of the elevator assembly process

During the second iteration, the general outline of the final solution began to emerge. However, by the end of this phase, the connection between the lead screw and the stepper motor had not yet been implemented, nor had the later designated component been designated as the lead-rod stop screw.

4.5.3 Final Iteration

As in the the previous phase, the final iteration focused on addressing unresolved issues and refining the design based on identified shortcomings. The resulting configuration is presented in Figure 50 and previously in Figure 37.

Figure 50: Final iteration

In this iteration, all previous design efforts were integrated into a cohesive solution. The development of both the lead-rod stop screw and the connection between the stepper motor and the lead screw was initiated. To enable the mounting of components on the lead screw, D-shaped axles were milled onto both ends, see Figure 51.

Figure 51: D-axle milling

The connector is now able to securely grip the milled D-axles, see Figure 52 It is designed as a diameter converter that features two D-axle locking mechanisms. One end contains a 12 millimeters diameter opening to accommodate the lead screw, while the other end has a 5 millimeters opening to fit the stepper motor shaft.

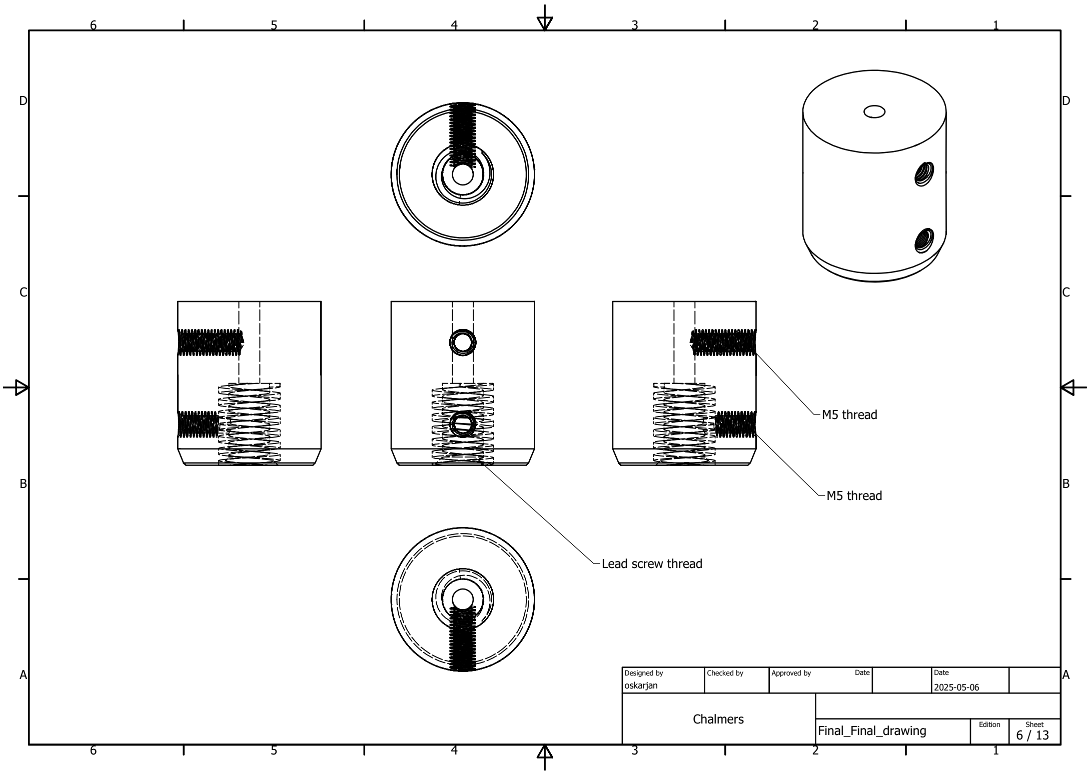


Figure 52: Stepper-motor lead connector

One of the primary challenges with this design was ensuring that the M5 threads were strong enough to securely lock the axles in place. To address this, various thread tests were performed using different materials and dimensions, see Figure 53. The final solution involved printing the component with PETG, a more ductile material compared to, for example, PLA, and reducing the tolerances. This combination allowed the threads to engage more effectively with the bolts, resulting in a strong and reliable connection.

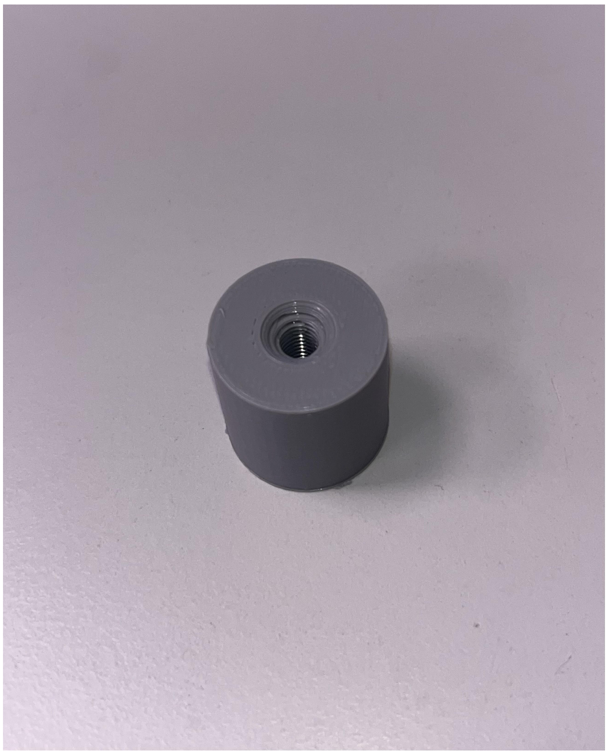


Figure 53: M5 thread test

The last component to be designed was the lead-rod stop screw, as shown in Figure 54. This part connects the motor holder to the lead screw, allowing for vertical movement. It was designed as a lead screw nut, which is secured to the D-axle using an M5 bolt to lock it in place.

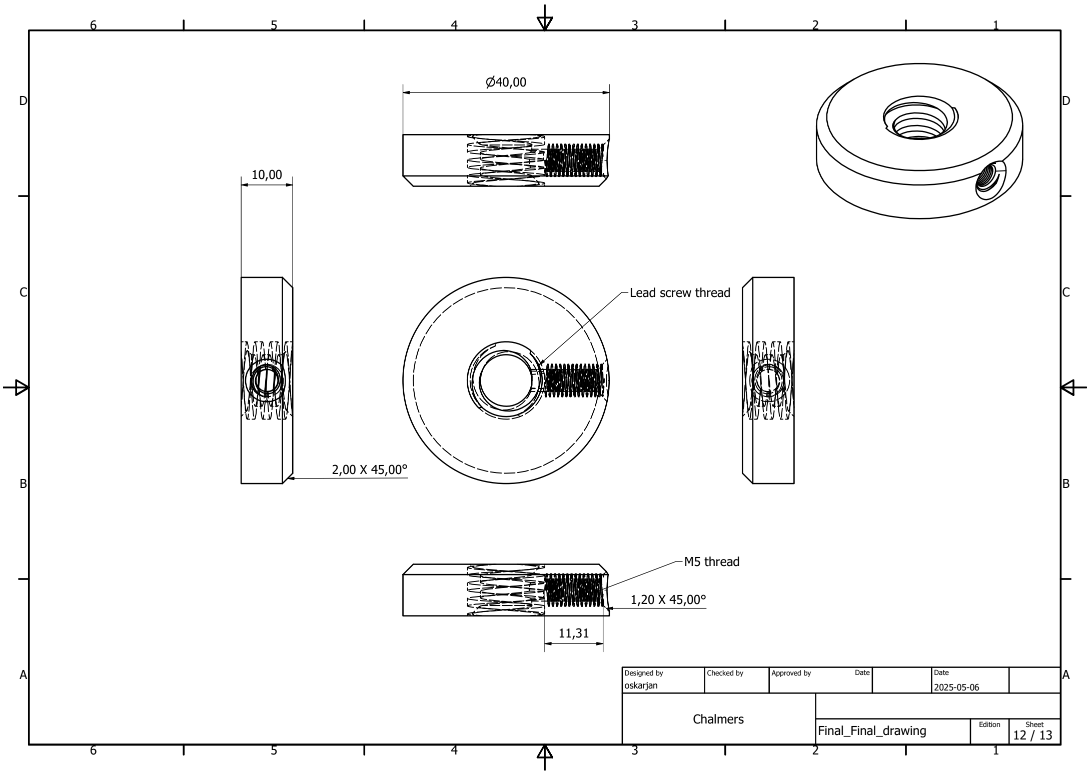


Figure 54: Lead screw stopper

When the all the new parts were done, the old parts could be focused on. The modifications focused on reducing the weight of the three plates, which were altered by adding holes to achieve this goal. This approach was based on trial and error; however, in hindsight, a more effective method for maximizing weight savings would have been to employ an ISO grid pattern, where each node is connected by a bolt hole. This design is commonly used in space applications, as shown in Figure 55, and could be optimized through the simulation of the Finite Element Method (FEM). Another possibility would have been to use CAD-AI to generate the most efficient pattern. However, this approach was not prioritized due to time constraints. It could be considered for a final production model, such as a lawn mower, but the machining process would likely make it prohibitively expensive.

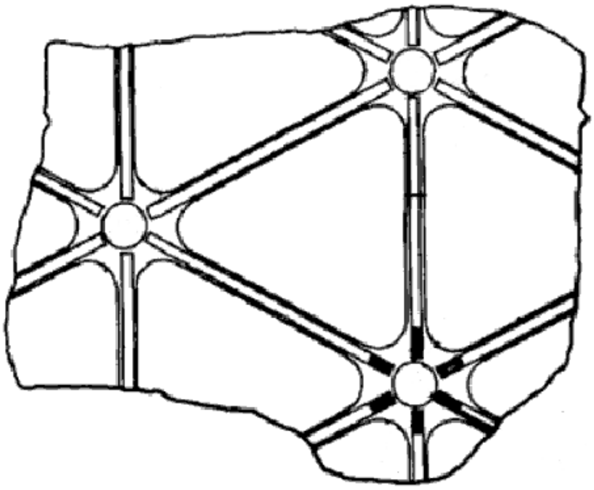
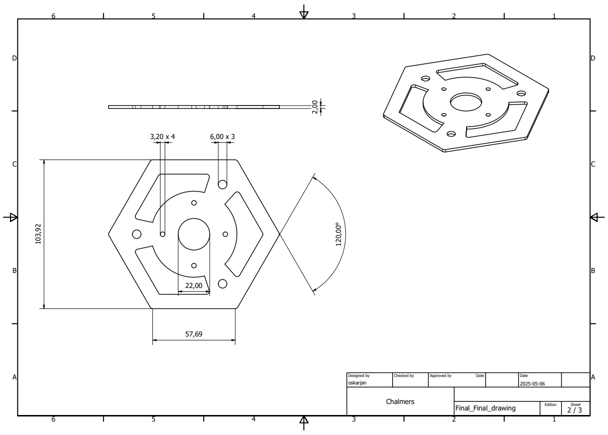
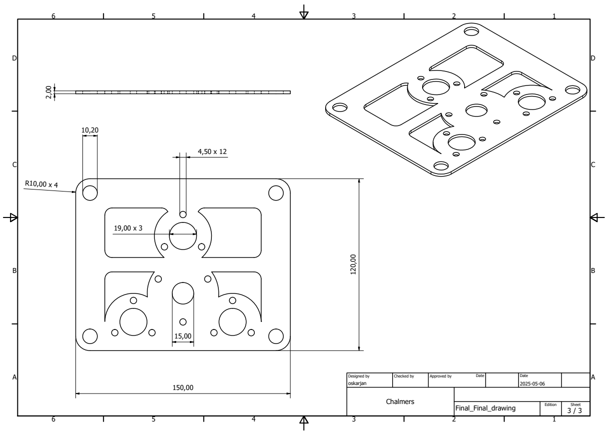


Figure 55: ISO-grid

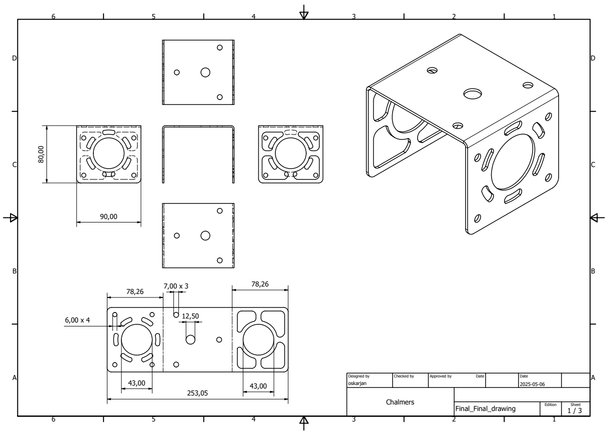
The final design of the plates is shown in Figure 56. Functionally, it remains largely the same as in the second iteration, with the primary improvement being a reduction in weight. The only notable functional change is that the motor holder was slightly taller to accommodate the lead screw stopper.



(a) Top plate



(b) Middle plate



(c) Motor holder

Figure 56: Final design of the three 2 mm metal plates

The plates were then painted as seen in Figure 57.

Figure 57: Painting plates

When all the parts were dry the elevators could be assembled. The assembly process requires a special order to keep the three ground rods parallel to each other. This is done by assembling everything but not tightening the six M6 bolts to the ground rods. Then lowering the middle plate (Figure 56b) to the bottom and tightening the three M6 bolts on the motor holder (Figure 56c) and the raising it to the top and tightening the three bolts on the top bracket (Figure 56a). This is because the mounting holes for the ground rods are a bit larger allowing them to be adjusted. When assembling the elevator it is easy to build in stresses in the lead rod creating pressure on the lead screw stopper. This was solved by adjusting the connector and lead screw stop so they let go of the downwards pressure. Otherwise there is no other thing to keep in mind when assembling.

4.6 Attachments

To assemble the components necessary for the lawn mower to function, a few additional parts were required. These parts were; a breadboard holder, front wheel holders, battery holder, holder for the grass cutter and also the connecting plate between the both middle wheels.

4.6.1 Breadboard Holder

The breadboards responsible for controlling the wheels needed to be placed on the base plate and a holder was therefore created. This part consists of a frame to hold the breadboards in place and holes in the corners so it could be screwed to the base plate. See Figure 58 for a drawing on this part.

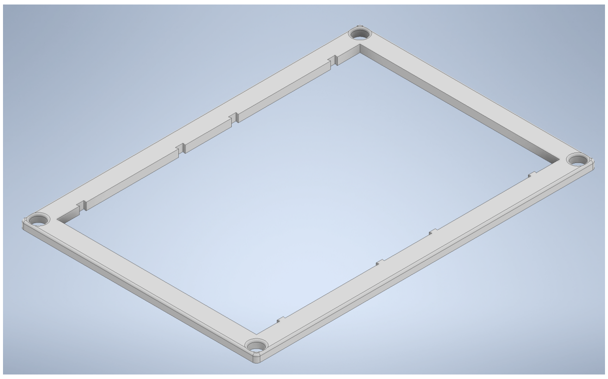


Figure 58: Breadboard holder

4.6.2 Front Wheel Holders

The front wheels had to be fitted on the prototype and they needed a support system. The front wheels had only an axle as its mounting system so a converter had to be produced so it could be mounted on the base plate. The part consists of a hole where the front wheel axle could be inserted and another hole a, small distance higher, so a screw could be inserted in both the base plate and the new part. This created a distance from the wheel and the base plate which is necessary because the lawn mower must be level compared to the back wheels which are larger. This part was 3D-printed, see Figure 59 for a drawing.

4.6.3 Battery Holder

The batteries from the original Husqvarna lawn mower was also used in the prototype. These needed a holder so they could be secured on the lawn mower and not have the risk of falling off. See Figure 60 for a drawing of the holders. This part was 3D-printed.

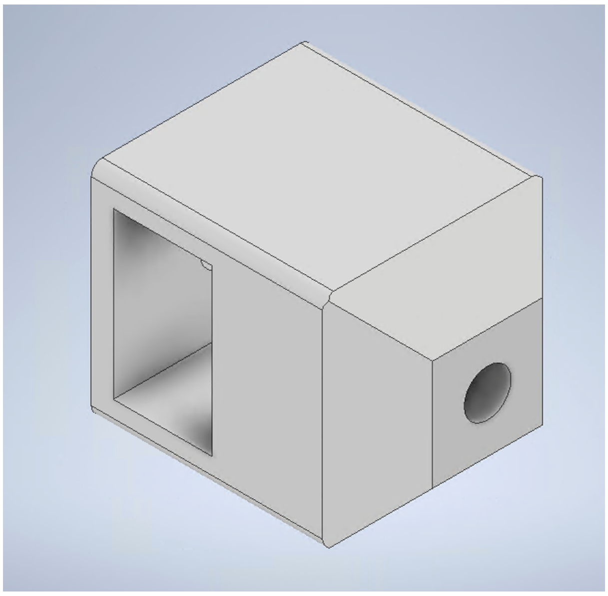


Figure 59: Front wheel holder

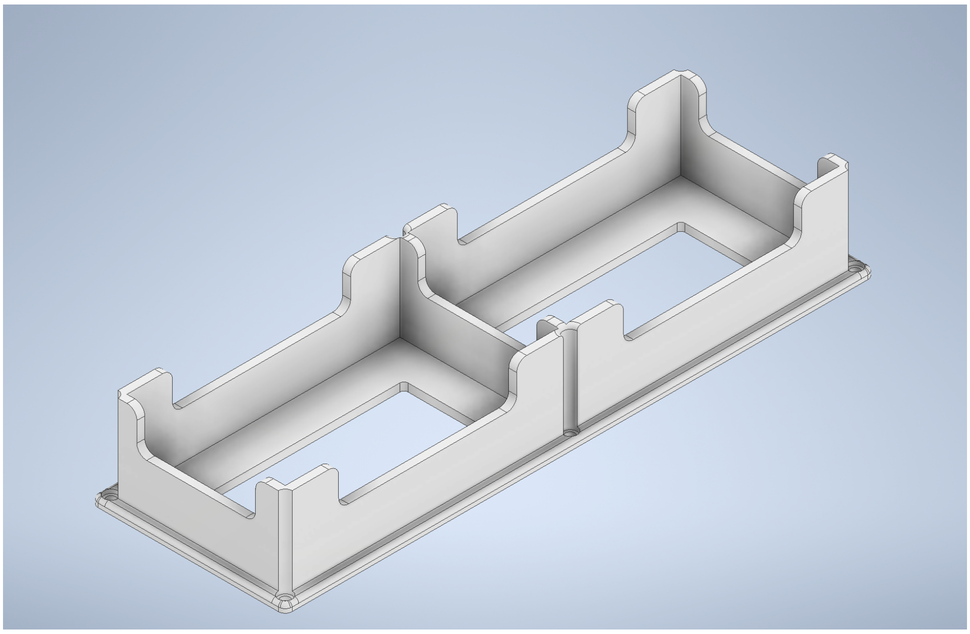


Figure 60: Battery holder

4.6.4 Holder for Grass Cutter

The cutting blade and its components were reused from the original Husqvarna lawn mower. This decision was made because the blade functions effectively and does not impact the climbing mechanism. However ,it had to be mounted on the new base plate, so a support bracket was designed in CAD. The design was based on the original Husqvarna configuration to ensure compatibility, but with minor modifications. The bracket was then 3D-printed. However, some dimensions were slightly off, so a second version had to be printed. The final version is shown in Figure 61.

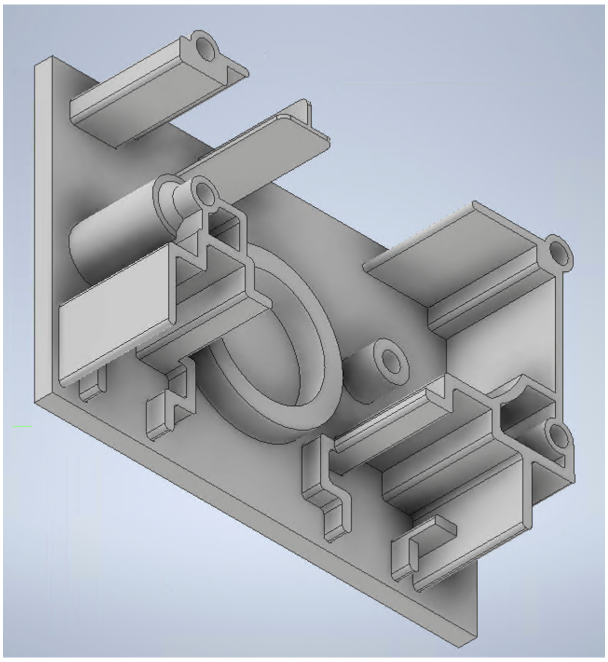


Figure 61: Holder for grass cutter

4.6.5 Connecting Plate

The connecting plate is used to hold the middle wheels and separating them by a certain distance. The optimal distance from both wheels was decided to be 150 millimeters, center to center. This was because it would give the largest possible range where the center of mass could be without interfering with the back wheel. The plate consists of an acrylic glass sheet which have 4 holes so it could be screwed in place on the motor as seen in Figure 62.

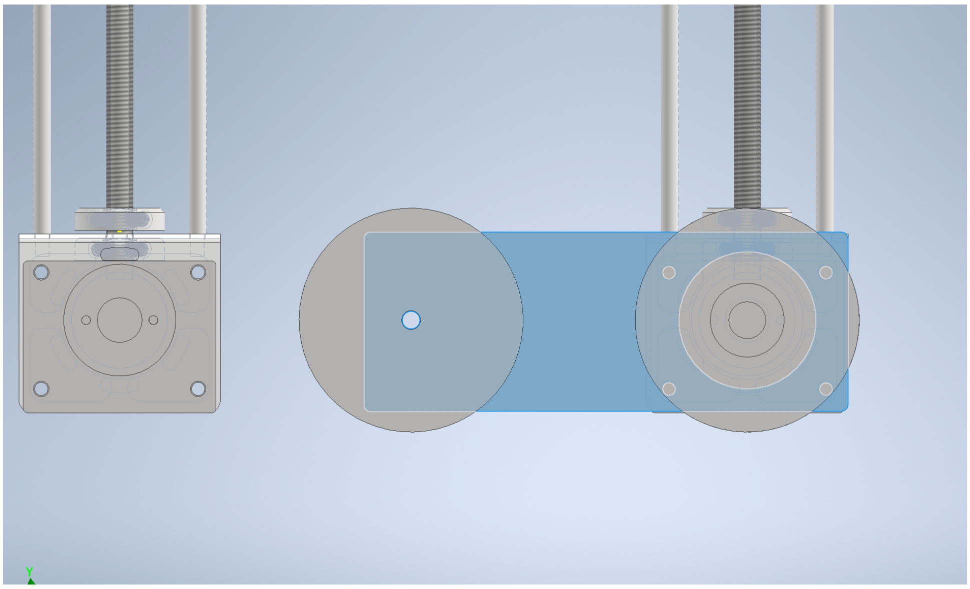


Figure 62: Connecting plate marked in blue

4.7 Final Product

The final product is similar to the final concept, but with the front wheels mounted to the base plate, as mentioned above, instead of using elevators on all the wheels. The whole CAD assembly with the base plate, elevators, motors, and middle wheels can be seen in Figure 63.

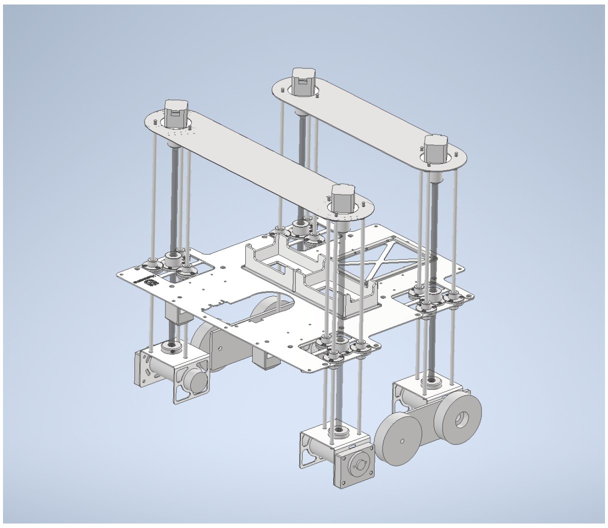


Figure 63: Final Assembly

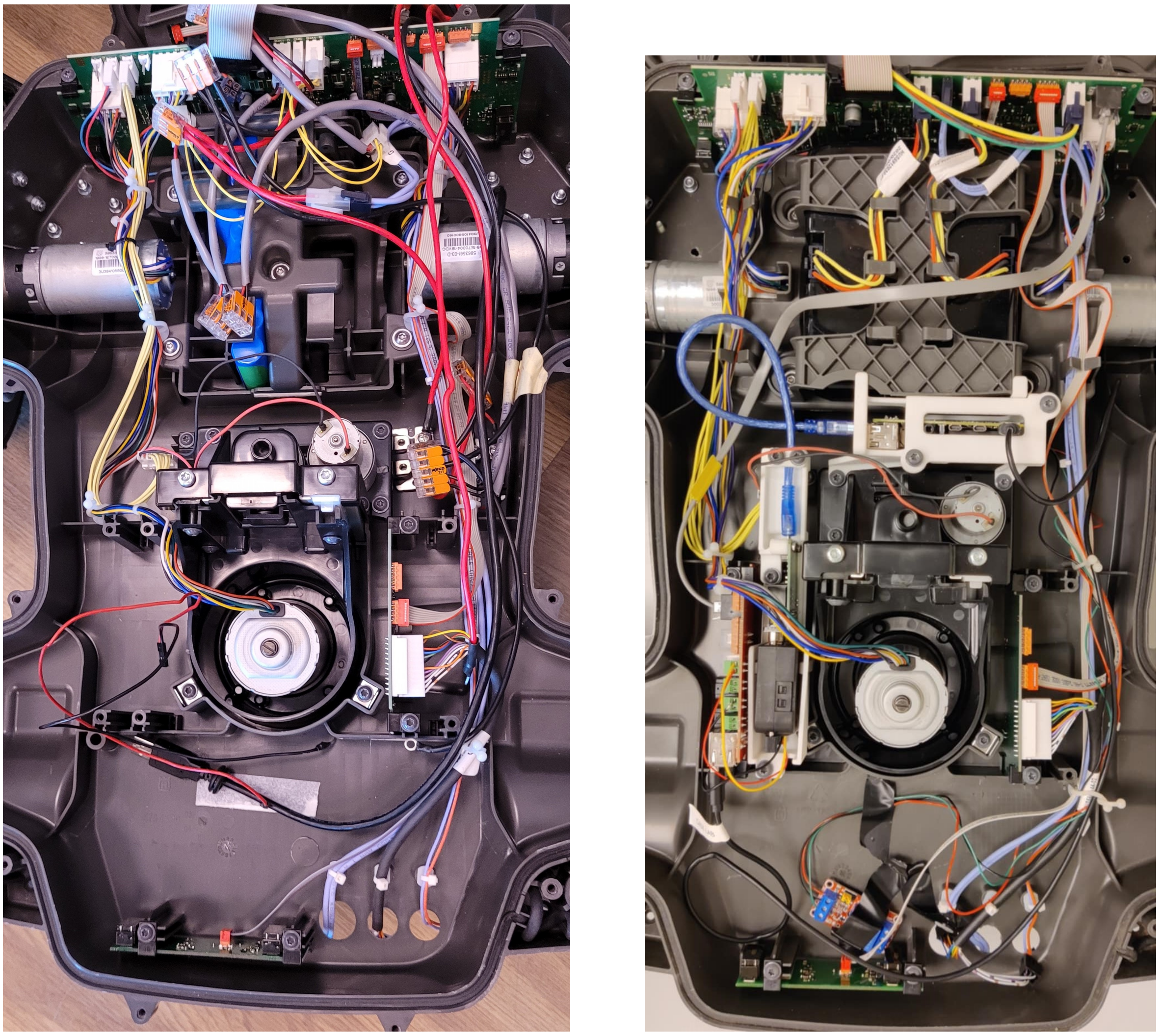
5 Electronic control system development

This section describes the progress of developing the electronic system to manually control the lawn mower.

5.1 Using the Original Control System

Initially the plan was to modify an existing Husqvarna Automower. The project started by reading the report of last year's lawn mower project where a Husqvarna 450x and a Husqvarna 550 EPOS were used.

The lawn mower first received was the 450x. When opening this lawn mower it was found that it lacked some of its components, it had fore example only one battery and lacked some electronic, see Figure 64 (a). In a meeting with a researcher from last years lawn mower project, he described that they mainly had been working with the 550 EPOS model. After acquiring the 550 EPOS and looking inside, it was clearly that this had more complete internals, see Figure 64 (b). One crucial difference was that 450x had no Raspberry Pi that could communicate with the CAN-bus.



(a) 450x

(b) 550 EPOS

Figure 64: The electronics inside the lawn mowers

5.1.1 Control With Phone Application

The Husqvarna lawn mowers can be controlled using the "Automower" smartphone application, which allows users to schedule automatic mowing and manually steer the mower using a virtual joystick. While this feature was tested and found to be functional, it exhibited a lot of input lag. Since the code is not open source, it had limited integration with custom hardware features, such as adding the lifting mechanism, making it unsuitable for the needs of this project.

5.1.2 Control with HRP

To enable external control of the lawn mower, the GitHub repository from last year's project was used, which was based on the Husqvarna Research Platform (HRP) system. Visual Studio Code, with the "Remote Development" extension, was set up to establish an SSH connection to the computer shell of the Raspberry Pi. After unlocking the lawn mower, a script could be executed to launch a ROS node. The goal was to develop a script called "keyboard_remote_drive", allowing manual control of the lawn mower via a computer keyboard. This would replicate the joystick functionality from the phone application, but with reduced delay. This code is also open for modification so that control of the lifting mechanism could be added.

However, after repeated testing the script was never successfully started. The process was cumbersome, involving multiple steps just to get it started, and frequent disconnections. Overall, the ROS-based structure proved unnecessarily complex for this application.

The lawn mower was initially accessed via the smartphone application using Bluetooth. A computer could then connect to the onboard Raspberry Pi over a local Wi-Fi network, using a secure Shell (SSH) connection. However, this wireless setup was not efficient because it often disconnected if left inactive. Although a wireless solution would have been ideal, a simpler and more stable alternative to control the lawn would be to use direct wired connections for control.

The system interface was based on Robot Operating System (ROS2). It features an architecture with nodes where components act as Publisher and/or Subscriber. Each node then has subjects and topics that it publishes or listens to. For larger projects, ROS can be helpful. However, for this application it mainly added complexity since only basic functionality was required for driving the motors, and not all the sensor data that for example the previous years project used for their GPS functionality.

5.2 Developing a new Control System

The original electronics from the lawn mower were removed, as they introduced unnecessary and limited flexibility for the objective of this project. Tools such as the phone application, SSH access, and ROS were great resources for a large-scale system, but in this case they mainly acted as an obstruction for the development and workflow. The mower was disassembled, and only the essential parts were obtained. Specifically, the motors for the wheels and the assembly for rotating the cutting blade.

The new method to control the lawn mower was created using two ESP32 microcontrollers. One transmitter used as a remote controller to manually operate the lawn mower with user input, and one as a receiver onboard the lawn mower connected to the motor drivers.

5.2.1 Transmitter ESP

The transmitter needs to capture user input and the initial plan was to use a joystick. The inspiration came from a video-game controller. So joystick testing was started; a picture of the model can be seen in figure 65. It features two potentiometers that detect the angle of the joystick on the x- and y-axes. These are intended to be connected to the analog input on the ESP32. During testing, a problem was observed regarding that the joystick only produced accurate reading near its center position. When moved further in any direction, the output jumped to the minimum or maximum value respectively.

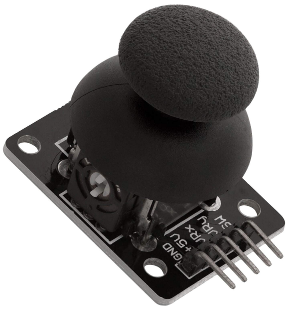


Figure 65: Joystick

A simple test with a setup was assembled to measure the output voltage in relation to the joystick's angle, allowing for direct comparison, see Figure 66 and 67. It uses a protractor aligned with the joystick axis, a voltage source and a multimeter measuring voltage. Voltage was measured for a few angles, but the measuring was terminated early after high levels of mechanical flex was observed on the linkage between the stick and potentiometer.

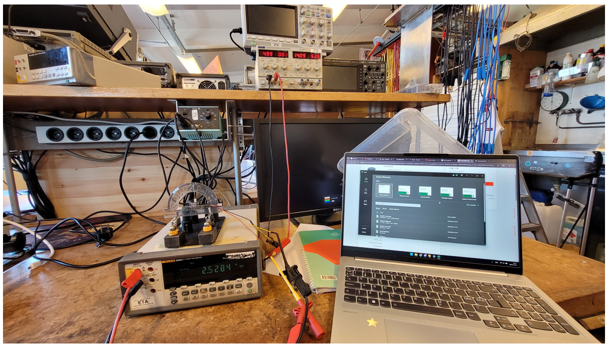


Figure 66: Measuring rig

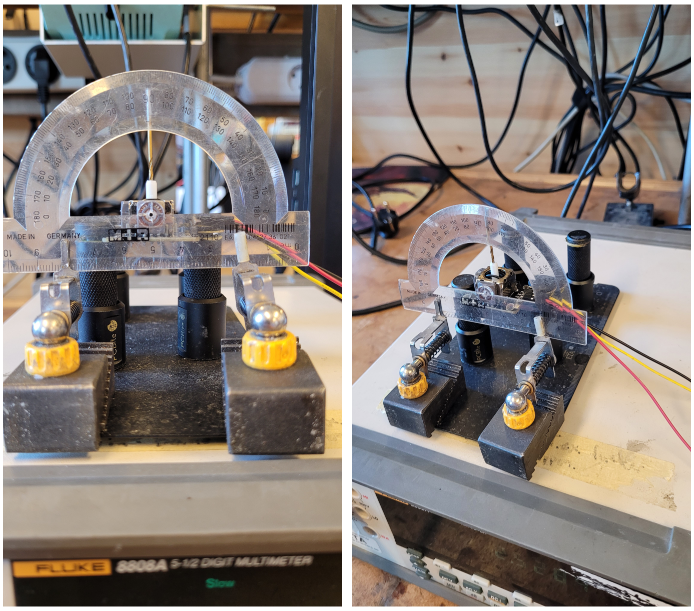


Figure 67: Measuring device

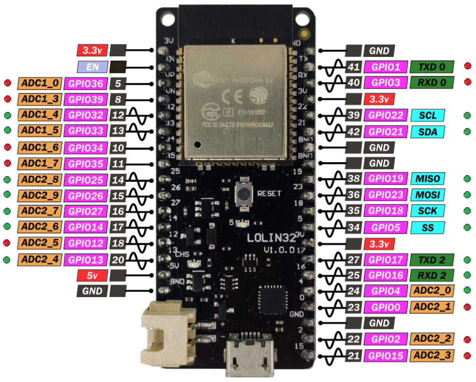


Figure 68: ESP32-LOLIN32 pinout
[38]

Due to poor performance of the joy stick, a custom controller was developed using a perfboard, where eight buttons were mounted, four buttons to control the movement of the lawn mower with BLDC-motors, and four to control the stepper motors, were two buttons controlled the two front elevators up and down, and the last two buttons controlled the back elevators up and down. An ESP32-LOLIN32 module was mounted on the perfboard and configured as the transmitter, communicating with the receiver module ESP32-Devkit using the ESP-NOW [36] protocol, see Figures 68 and 69. See Appendix A.1 for the transmitter code.

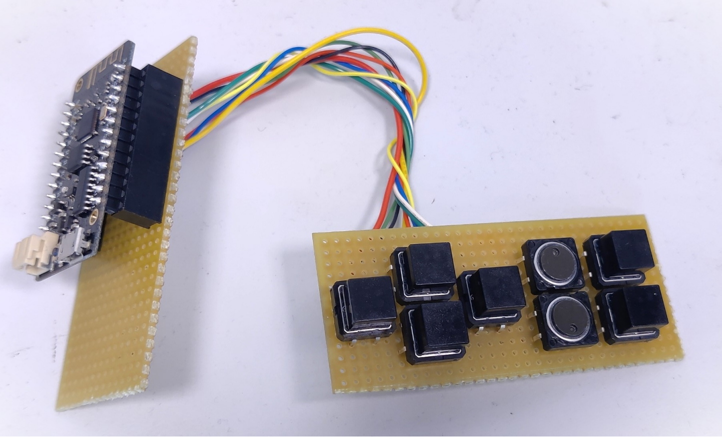


Figure 69: The transmitter

5.2.2 Receiver ESP

The receiver ESP:s job was to handle the control of all the motors. In this project, the receiver ESP was ESP32-DevKit. See Figure 70 for the pin out for the ESP32 used in the receiver part. See Appendix A.2 for the receiver code.

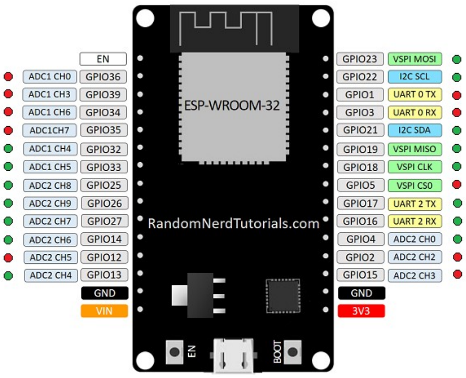


Figure 70: ESP32-DOIT-DEVKIT-V1 Pin out
[37]

5.2.3 Investigation of BLDC-Motors

An investigation was initiated to determine which type of motor was used in the original lawn mower, see Figure 73 and 74. With additional research and valuable assistance from the Electronics Division of the Chalmers Student Union *ETA*, which provided helpful throughout the project, it was determined that the motors were BLDC motors, Brushless Direct Current motors. Closer inspection revealed that each motor had eight wires: three thicker phase wires labeled MA, MB, and MC, and five thinner wires. Among the thicker wires, three were identified as Hall sensor signal wires: HA, HB, and HC, while the remaining two provided power to the Hall sensors: +5V and GND. When the motor was known, they were tested with this configuration, see Figure 72.

Since Husqvarna's proprietary BLDC-motors are being used, see figure 71, obtaining detailed specifications has proven difficult, as the company does not publish an open datasheet for the internal winding configuration. However, the available sources indicate that these motors are most likely three-phase motors with a Y configuration (or Star configuration). This setup is commonly used because it provides lower peak power and rotational speed but delivers higher torque at the same supply voltage compared to a Delta configuration; see figure 6. [11] [32]

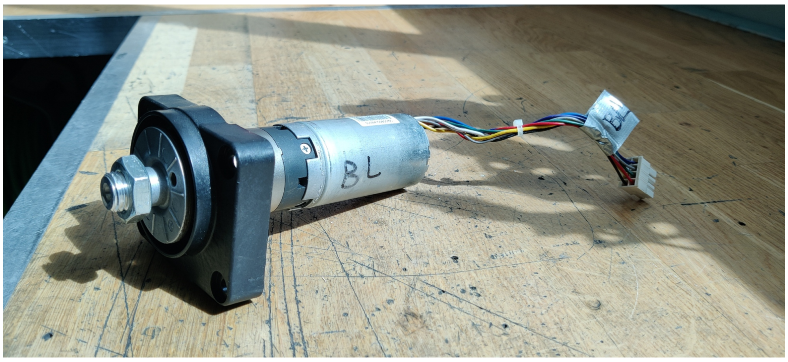


Figure 71: Original Husqvarna BLDC-motor

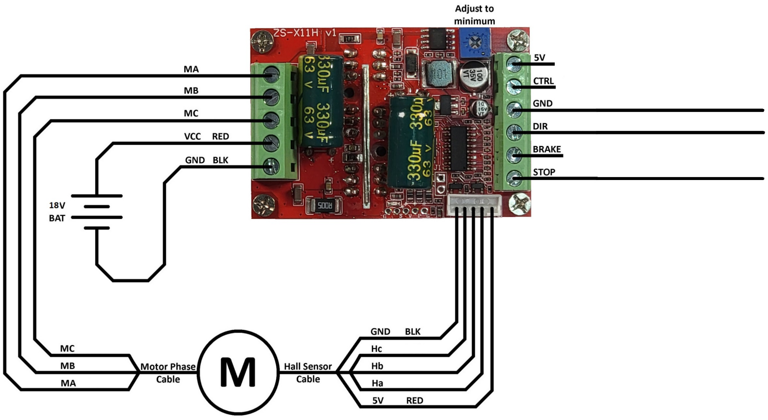


Figure 72: ZS-X11H setup with a BLDC-motor
[17]

Four BLDC-motors was harvested from the two Husqvarna lawn mowers. They were of same model. To ensure clarity throughout the documentation, the following acronyms will be used to refer to the four BLDC motors: **BL** - **B**ack **L**eft, **BR** - **B**ack **R**ight, **FL** - **F**ront **L**eft, and **FR** - **F**ront **R**ight. These designations will be consistently applied in all subsequent diagrams and descriptions.

A key challenge when working with BLDC-motors is correctly identifying their wiring configuration. Each motor includes three phase wires and three Hall sensor signal wires, resulting in a total of six possible combinations for the phase connections and another six combinations for the Hall sensor connections. Of these six combinations, only two result in proper operation, one enabling clockwise direction and the other counterclockwise. The remaining four phase configurations cause the motor to vibrate erratically when supplied with power and speed signal.

The BLDC motor was successfully brought into rotation after the correct connection of the phase wires (MA, MB, MC) and Hall sensor wires (HA, HB, HC). However, motor speed could not be controlled, despite attempts using both the built-in potentiometer on the motor driver and a PWM signal sent from the ESP32 to the BLDC-motor driver's P input (Speed input) ZS-X11H.

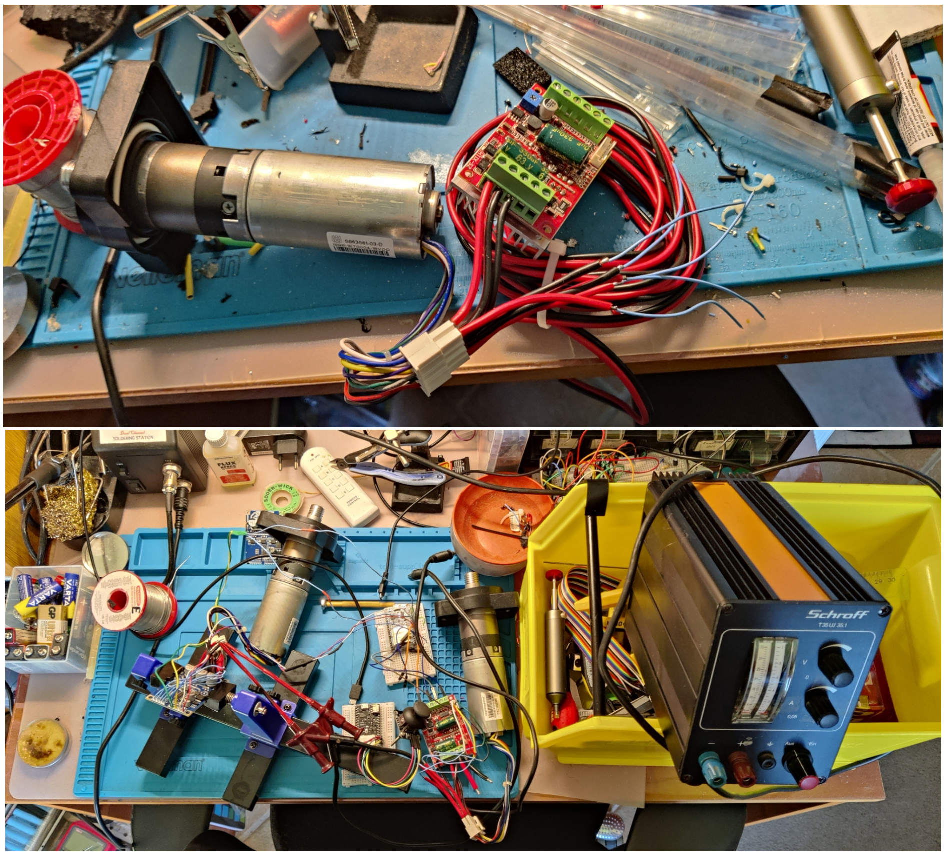


Figure 73: Early testing of the Husqvarna BLDC-motor at home

The issue was traced to a missing connection to the BLDC motor driver's STOP-signal, which functions as an enable input for the motor driver and is active low. The signal had been connected only to GND and rather than to the microcontroller. To resolve this, a function was implemented to enable the motors via software control.

Notably, the STOP-pin required configuration as `INPUT` using `pinMode(enableMotors_pin, INPUT)`, even though it functioned as an output. The reason for this behavior remains unclear, but the configuration was effective in practice.

```
    pinMode(enableMotors_pin, INPUT);
```

To prevent the motor from entering sleep mode, a function was implemented to periodically wake it every three seconds. This was achieved by first calling disableMotors(), followed by enableMotors() with awakeMotors().

The functions responsible for activating and deactivating the BLDC motor driver's are presented below:

```
void enableMotors()
{
  pinMode(enableMotors_pin, INPUT);
  delayMicroseconds(10);
}
void disableMotors()
{
  pinMode(enableMotors_pin, OUTPUT);
  digitalWrite(enableMotors_pin, LOW);
```

```
  delayMicroseconds(1);
}
```

```
void awakeMotors()
{
  if(millis() > previousTime + 3000)
  {
    disableMotors();
    previousTime = millis();
  }
  else
    enableMotors();
}
```

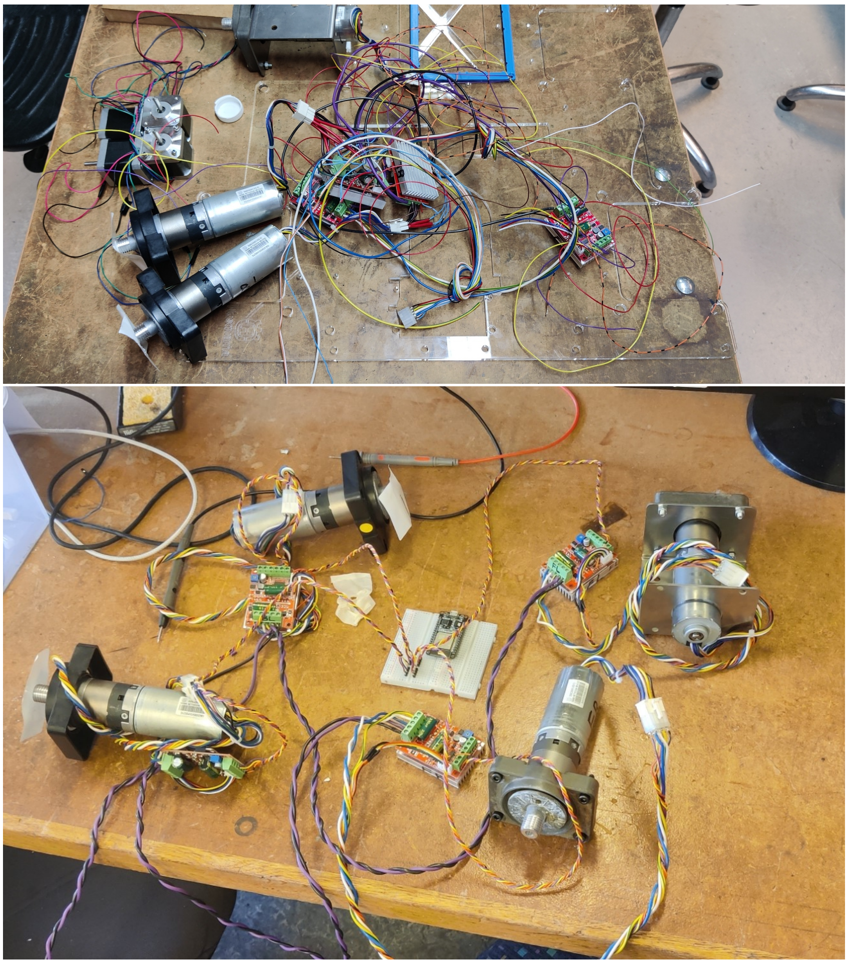


Figure 74: Later testing with all four Husqvarna BLDC-motors

5.2.4 Testing of Diffrent BLDC-Motor Drivers

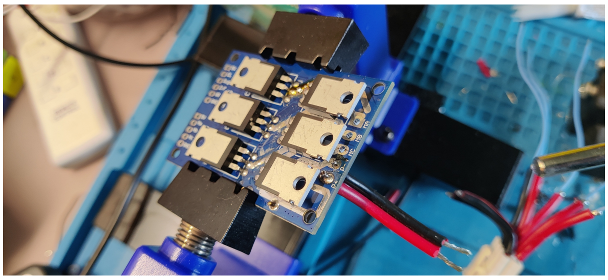


Figure 75: BLDC-motor driver of low quality

The blue BLDC-motor driver was a cheap low quality driver that was first experimented on, see Figure 75. One of the main challenges was determining which BLDC-motor driver to use, given the limited budget. An initial attempt was made to use a more affordable option found on Amazon. However, these proved to be of poor quality, with solder bridges causing unintended short circuits. Additionally, the board became noticeably hot when power was supplied. These drivers were ultimately non-functional.

As a result, the decision was made to use the red motor drivers known as ZS-X11H, which had been successfully utilized in a previous project by a member and were known to operate as intended, despite being slightly more expensive.

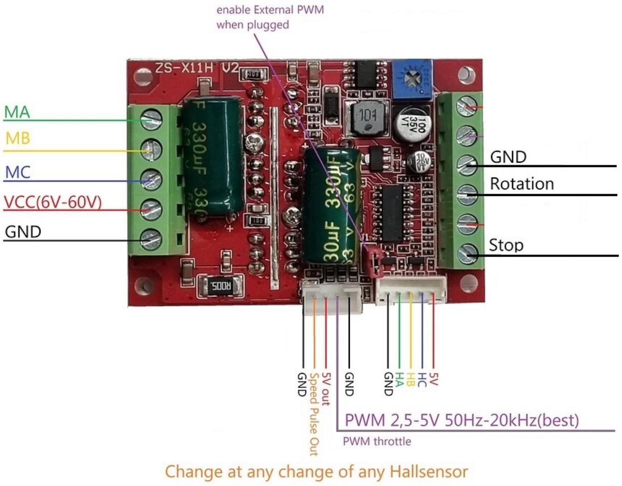


Figure 76: ZS-X11H BLDC-motor driver Pin out
[33]

This BLDC-motor driver was reliable, compared to the blue driver, see Figure 76. In the ZS-X11H pin configuration, there are 3 control signals. DIR (Rotation), Stop (enable motor driver), and PWM throtle (Speed input). These go to the ESP32-Devkit main controller. The other connections MA, MB, MC, VCC, GND, 5V, GND, HA, HB, HC and 5V are connected to one of the BLDC-motors. In our project there was 4 BLDC-motor drivers, one for each BLDC-motor.

5.2.5 Stepper Motors

The motor that was used was Nema 17 stepper motor, see Figure 77 Initially, the DRV8825 stepper motor driver was used, but it proved unreliable. The motor exhibited erratic behavior and frequent stalling. Considerable time was spent troubleshooting the stepper motors, and in hindsight, using geared DC motors would have been a better choice due to their lower complexity and higher torque output compared to small stepper motors.

Hardware and software issues were encountered. The exact cause remains unclear. The software initially relied on a library called “AccelStepper,” which appeared to be incompatible with the stepper motors in use. As a result, the A4988 stepper motor driver was tested instead of the DRV8825, and a custom control script was developed to manage motor operation.

One possible explanation for the stuttering and weak motor performance is that the current limit potentiometer on the driver may have been set too low. Another likely cause could be incorrect wiring of the stepper motor coils.

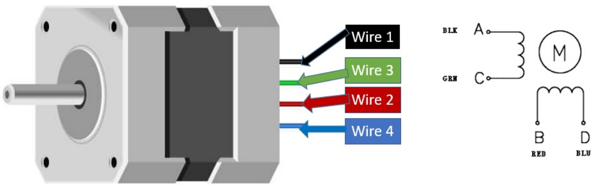


Figure 77: Nema 17 stepper motor coil configuration
[34]

5.2.6 Stepper Motors Drivers

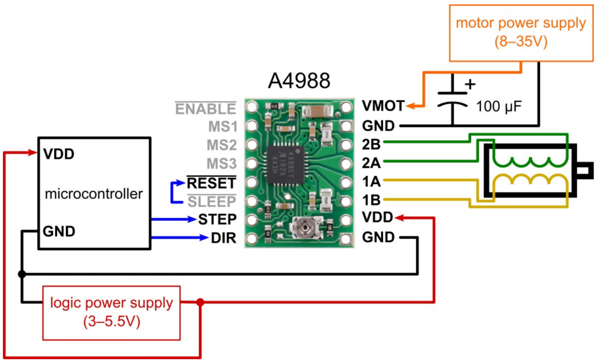
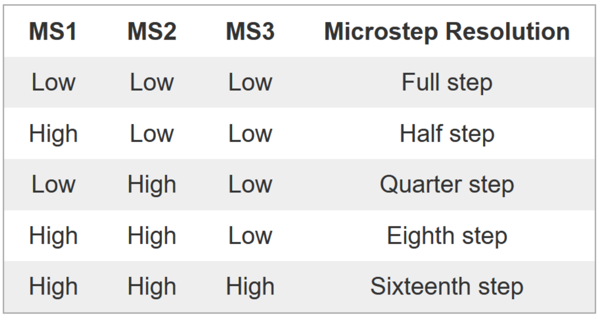


Figure 78: Wiring diagram for the stepper motor with Stepper driver
[35]

The stepper motor driver was hocked up as Figure 78. The enable pin is active low and tied to the ESP pin 33, to be able to disable the stepper motors when not in use to save power. The MS1, MS2, and MS3 are micro-stepping pins, see figure 79, they are used to take steps that are less than 1.8 degress which is called a microstep. A full step is 1.8 degrees, which means that a full rotation has 200 steps.



MS1	MS2	MS3	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	Quarter step
High	High	Low	Eighth step
High	High	High	Sixteenth step

Figure 79: Micro stepping for the A4988 [35]

5.2.7 Schematic of the Receiver Circuit

The schematic shown in Figure 80 and are also on GitHub.

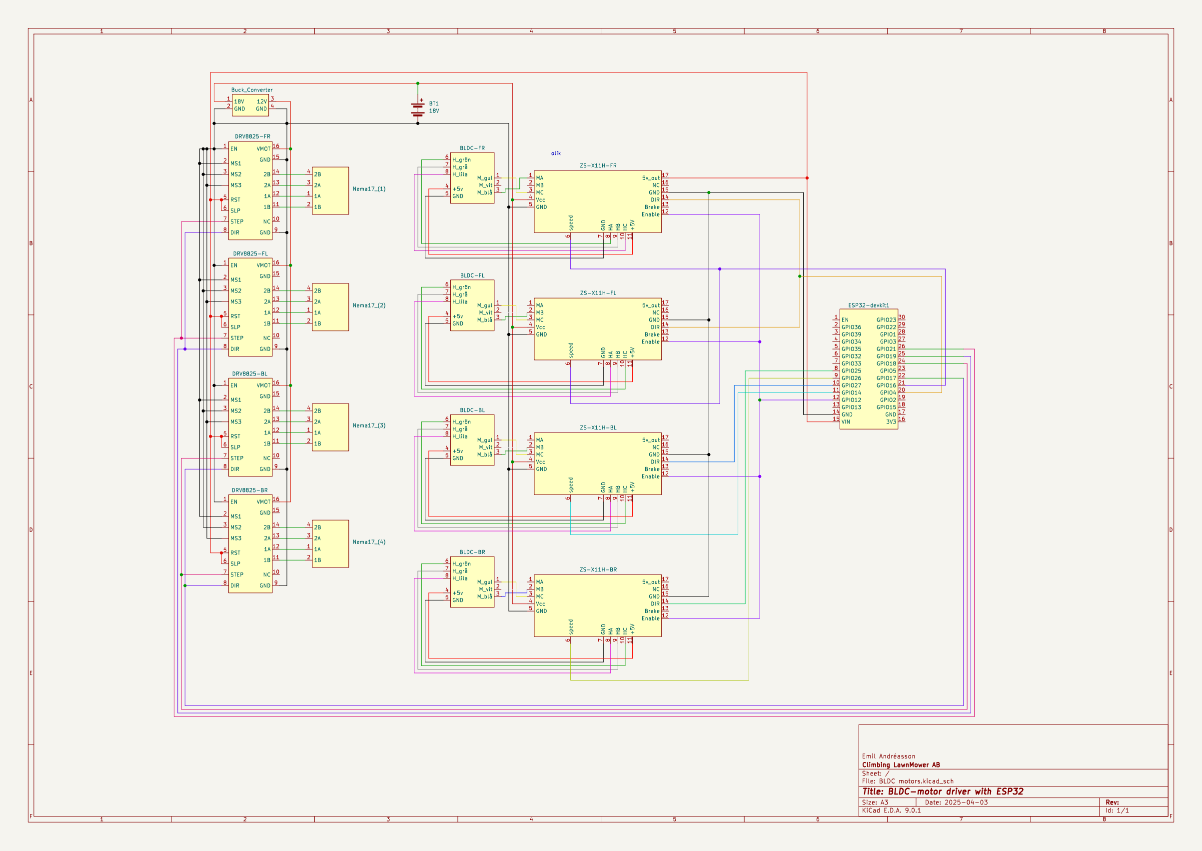


Figure 80: Schematic for the BLDC- and Stepper-motors together with ESP32 (receiver)

5.2.8 Battery

The original lawn mower had two of these black batteries as seen in Figure 81, each is 18V. However, investigations were conducted to determine how the batteries were connected to the original circuit board of the lawn mower. The two yellow wires are unknown for their purpose, it could be for the battery management system (BMS) or something else. The batteries were never parallel connected due to the risk of failure.

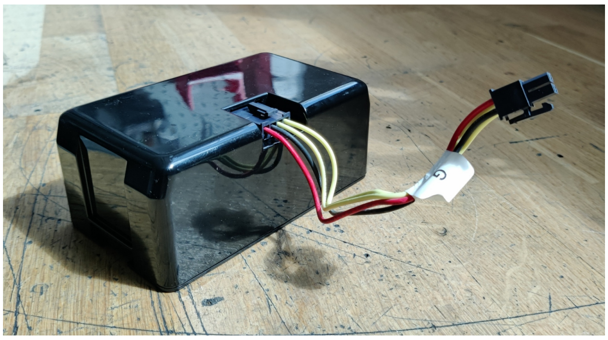


Figure 81: Original Husqvarna Battery

5.2.9 Abandoning the Stepper Motors

Controlling the stepper motors has taken a lot of time and generated poor results. They do not have the torque needed to turn the lead screws and are also very slow. Therefore it was decided to change to a gear reduced DC-motor. The decision was made during one of the last days of the project. The DC-motor has a lot higher torque, higher speed and is much simpler to control, it just needs to have a voltage applied to run. To run the motor, each motor will now be connected to one relay on each wire.

The work involved troubleshooting the stepper motors. Various microstepping settings were tested at higher frequencies, but these did not work as expected. The supply voltage was increased to 16 V and the current limit was set up to 2.5 A. However, the A4988 driver consistently drew only around 1 A, which was significantly below the 2.3 A required by the stepper motors. The original plan was to use the DRV8825 drivers, but they did not work.

5.2.10 Gear Reduced DC-Motor

When the stepper motor lacked the torque needed to turn the lead screw another motor was needed. Larger stepper motors could be used instead, but it had been realized that stepper motors were not really necessary. They are meant for applications needing accuracy, but case mainly just need sufficient torque. Therefore regular DC-motors could just be used instead. The motor would then need a reduction-gear since the rpm-range is too high by default. There was little time left until deadline so ordering motors was not an option. At the CASE-lab in the motor drawer there were relatively large dc-motors with a planetary gearbox at the end, see figure 82. When gripping the shaft by hand, one could feel that this motor had significantly more torque. This variant had a unloaded speed of 1154 rpm. It was less complex to control since it just need applied voltage. In its most rudimentary form this can be achieved with one relay on each wire to control it in both directions.

Figure 82: DC-motor with planetary gearbox

6 Testing

This chapter includes the tests and how they should be executed.

6.1 Testing of Original Robotic Lawn Mower

Before dismantling the robot, a test was performed on it to establish a baseline of its capabilities. First, the robot was driven head on to a small step to see if it could climb over it. The step height was then incrementally increased to find the robot's limit. The tests were carried out inside on a stone floor, and for the steps a variety of planks were used. Once the limit for the robot was identified, the robot was rotated 180 degrees and the test was repeated in reverse. This is interesting to look into since the robot has different sizes on the front and back wheels. Reversing to the step was seen to be easier; therefore, it was concluded that larger wheels also meant being able to conquer larger steps. The same procedure was followed with reversing as with accelerating, gradually increasing the step height to assess the robot's capabilities in different directions.

6.2 Testing of Prototype

The different tests for the lawn mower are as follows according to the requirement specification table.

- **Measure maximum climbed height**
  This experiment was conducted by placing a rectangular object with a 90-degree angle in front of the lawn mower. The object needed to be firm and have a minimum length of 50 centimeters and width of 40 centimeters, because this is the size of the lawnmower. The height of the obstacle was increased incrementally by placing additional smaller rectangular blocks under the main rectangle between each test. This was done until the maximum height was reached and the lawn mower could not conquer the obstacle anymore. It was important that the different rectangular blocks stayed in place and did not move relative to each other or the floor in any direction, due to the fact that this can impact the maximum climbing height. When having this defined obstacle the lawn mower would each time be placed in front of it and then start the the whole climbing sequence.
- **Measure minimum time when climbed**
  To measure the time of climbing the same obstacle was used as described above when testing maximum climbing height. When measuring the time the maximum height possible was used to get the maximum minimum time. The time was captured using a standard mobile phone with a timing function. The time started when the lawn mower was placed in front of the obstacle completely inset, the default mode when cutting grass, and stopped when the lawn mower once again was inset, but now on top of the obstacle. This is regarded as the full climbing time.
- **Testing so the lawn mower does not fall over**
  It is a constraint for the project that the lawn mower will operate only in a controlled laboratory environment and not outside. This reduces a lot of uncertain variables such as wind, slipperiness of the grass and small unevenness in the ground. Due to these limitations of the project, it was easier to test the stability of the lawn mower.

This test is based on the same obstacle as described above in the other tests and if the lawn mower could climb over the obstacle it is regarded in different heights without falling it was

- **Measure distance from edge to cutting blade**
  The distance from the front edge of the Husqvarna lawn mower to the cutting blade was measured to be 17 centimeters. According to the requirement specification table, this was classified as a desirable feature. The intention was to maintain the same cutting area without reducing it. However, even if this measurement had changed, the lawn mower would still have functioned properly, which is why it was not set as a strict requirement.
- **Drivability**
  To test the drivability of the lawn mower the lawn mower should be able to drive forward, backward, turn right, and turn left. The back wheels must complete this or else the lawn mower would not be approved in the driving criteria. The middle wheels must also be able to drive forward and backwards, but they do not need differential drive because it is not necessary in the climbing procedure.

7 Results

The functionality of the prototype was evaluated through testing, see chapter 6 for the different tests and how they were conducted. These results will be discussed in the discussion.

7.1 Maximum Climbing Height

The different elevators worked independently and could both ascend and descend. Sometimes they got stuck, but with some manual input they could restart. The lawn mower could perform the climbing sequence, although it needed some manual assistance during the initial phase of the climb. It needed a lift assistance of approximately 50 newtons upwards to relive some pressure on the motors. Due to the fact that the lawn mower did not complete a full climb on its own, this criteria was seen as a fail. This, moreover, lead to the fact that maximum climbing height was not tested since it did not complete a full climb. The height tested was 30 centimeters, which it could do with some manual input. The height did not impact if the lawn mower could climb or not, it would have needed a lift assistance if climbing any height. See Figure 83.

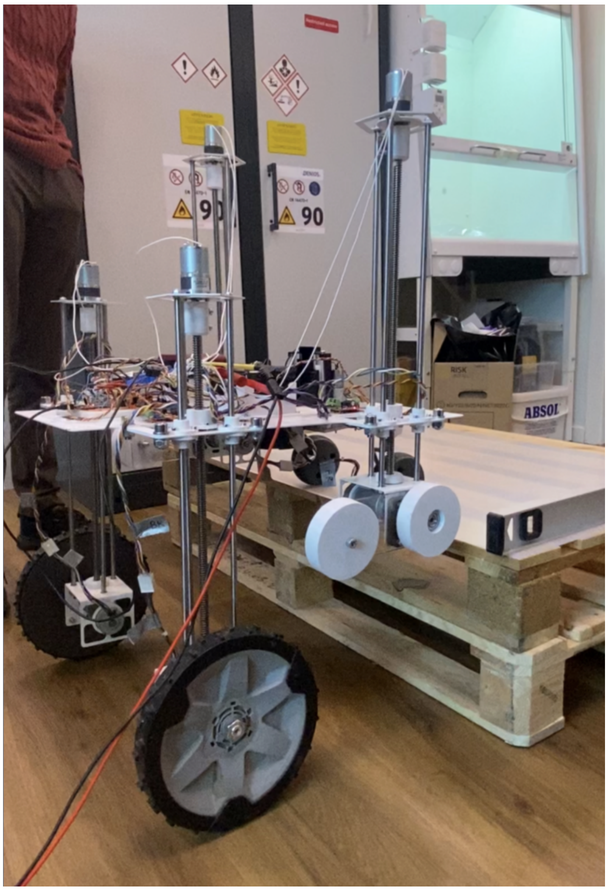


Figure 83: A stage of the climbing procedure

7.2 Climbing Time

Due to the fact that the lawn mower could not complete a full climb on its own this test was regarded as a failure. The climbing time was not relevant when manual input was used.

7.3 Management of Center of Gravity

The center of gravity was tested and the lawn mower could lift each pair of wheel without falling. This criteria was therefore succeeded, but when measuring the margin for the center of gravity when it was climbing it was not sufficient enough because it did not have a safety margin, see Figure 84.

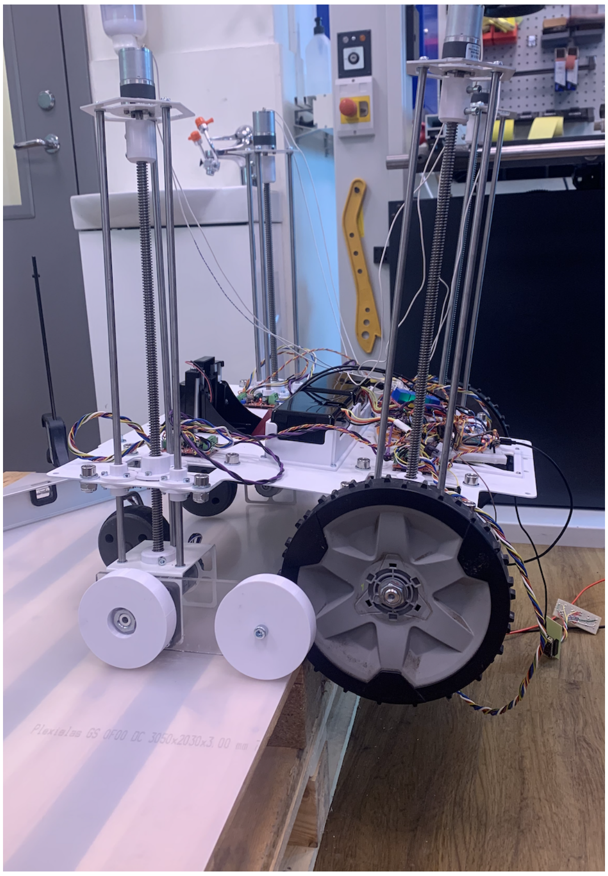


Figure 84: Center of gravity margin when climbing

7.4 Distance from Edge to Cutting Blade

After assembling all components and taking measurements, it was confirmed that the distance remains 17 centimeters. Therefore the desirable feature has been successfully achieved.

7.5 Drivability

It was observed that the lawn mower could drive forward, backward, and turn both ways using the back wheels. It could also align itself against the rectangular obstacle, which is necessary. The middle wheels worked as well and could drive both forward and backward. The drivability was therefore seen as a success.

8 Discussion

This chapter is about the discussion of the report, where the results are combined with information from the rest of the document. This part shows what could have been done differently and what aspects to fucus on if further developing the lawn mower.

8.1 Motor Discussion

The NEMA-17 stepper motors had been chosen as motors for the elevators. They have high precision when operating, which is necessary because the elevators needs to be elevated the same distance at the same time. Calculations made been made which stated that they should be able to lift the lawn mower. When testing the NEMA-17 motors they could although not produce the required output of power and was not able to lift the lawn mower. This is thought to be because the used motor driver was not the right one. It could not provide enough amperage for the motor to function properly. However, it could also stem from different settings in the code but is not certain.

Further development of the control system could be done. This entails mainly the controlling of the BLDC motors so the mower autonomously slow down when approaching a climb. To regulate the speed a PID controller could be used alongside two sensors measuring distance and alignment. To regulate the speed, the motors rotational speed needs to be measured. This could be done by reading the S-pin (Speed pulse out) on the BLDC motor driver ZS X11H.

8.2 Battery Safety

To be able to safely use the batteries a Battery Management System (BMS) should be used. That ensures that the batteries operate in safe conditions to prevent damage of the batteries. It manages so the voltage is in a safe range and that the current does not exceed the safety limit currents. Multiple cells in multiple battery-packs also need the be kept balanced. This should be done in the future if continuing the work on this prototype.

8.3 Autonomous Driving

Another thing that can be further developed is implementing machine learning with terrain recognition to enable the lawn mower to work on its own, without manual steering. Now, the prototype is not autonomous, which can not be the case if creating a market ready product. The climbing procedure must also be autonomous and all steps must be programmed in a way that the lawn mower could climb on its own. Having a system that recognizes which obstacles to climb and which not to climbed could be implemented in the future using machine learning.

8.4 Improvements on the Elevators

The biggest problem with the elevators was friction. This came from different sources, but mainly between the motor holder (bottom plate holding the wheel) and the lead screw stopper rubbing when the motor turned the lead screw. This is because the lead screw stopper pushes or pulls on the motor holder when the elevator lowers or raises itself. This is a quite difficult problem since it requires a solution that reduces friction and can handle force. Unfolding this complications it was thought to be solved using a bearing that can take vertical force when positioned in the horizontal position. Tho this friction is not that large, you could still turn it by hand, but still large enough for the motor turning the lead screw to stop. However, since its statical friction is larger the kinetic, just applying moderate amount of force to start the turning movement could be enough to keep it moving. Therefore it was reasoned that the best solution would have been to combine lowering friction with a stronger motor. To test this theory out the first take was to replace the Nema-17 motor with a DC motor. Therefore the top plates were re-drilled, see Figure 85. This was done by first measuring the DC motors bolt pattern and then 3D-printing a drill guide that mounted into the Nema-17 motor holes.

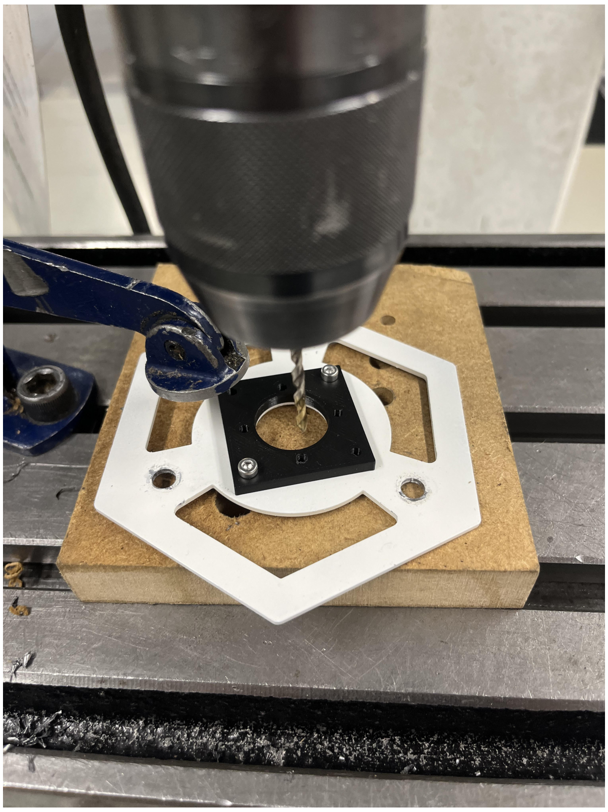


Figure 85: Re-drilling top plate

After testing the DC motors were still not powerfull enough. Therefore the next step was to reduce the gear ratio on them. This decision was prompted by the discovery of a planetary gearbox model designed for a Nema-23, as shown in Figure 86. The intention was to modify the model to fit the DC motor. However, difficulties encountered during the 3D printing process caused significant delays, and as a result, the modified gearbox could not be completed in time for inclusion in this report.

Figure 86: Nema-23 planetary gearbox

The elevators suffered from more complications when testing. If the base plate was not level when operating, if raising only 2 elevators tilting the robot, it would cause the elevators to bind up. This is because they were not designed to take a large amount of horizontal force.

Keeping everything square and parallel was another challenge. This worked when testing the elevators separately, one by one at a slow speed, but caused problems when putting everything together. Since time was short, this was solved by leaving the lead screw and bearing holders loose so they could adjust. The problem could also stem from the lead screw stopper not having the right weight distribution causing a vibration when turning fast.

In conclusion, the elevators final iteration should not have been its last. The design was a solution that fit with the budget of the project and complexity of the time frame. There are better designs that are more appropriate for this type of solution, like hydraulics or pneumatics, but would probably encounter other problems. As stated in the results, the lawn mower was unable to complete the climb independently. However, with external assistance, it was able to climb, demonstrating that the concept is viable. While this may not be the ideal outcome, it nonetheless proves the potential of the approach. With further development of the elevator mechanisms described here, the prototype could potentially achieve autonomous climbing in the future.

8.5 Center of Gravity

The center of gravity was, as seen in the results, located at a place in the lawn mower so it could balance on the middle wheels. However, there was almost no room for error and the lawn mower was not stable enough. This must be solved if continuing the work on the lawn mower to be able to guarantee a reliable product. One solution is to re-balance the lawn mower by changing the layout of the component and placement of the wheels. Another option is to extend the length of the base plate so the connecting plate for the middle wheels, made of acrylic glass in this prototype, also can be extended. If it where to be extended the middle wheels could have a greater range to ensure that the center of gravity would be between the both wheels.

The test showed that the lawn mower's center of gravity was positioned at the very limit of what was allowed for successful climbing. This was seen as an issue, as this offers minimal tolerance on the overall stability. To ensure safe operation at all times, the design must be adjusted to allow a greater margin for balance while climbing. Several ways to approach this could be taken to address. One solution is to extend the base plate, which would provide more flexibility in positioning components and shift the center of gravity forward. Alternatively, using smaller rear wheels could allow the middle wheels to be extended further back, offering better rear support. Another approach would be to change the way of solving this completely, by for example implement a regulation system that redistributes weight during operation to maintain balance.

The base plate was seen to experience a lot of flexing, both during operation and when stationary, due to the weight of the attached components (LÄGG IN BILD?). The issue was most apparent with the acrylic glass base plate, due to its lower stiffness, but some degree of flexing was also observed in the metal version, though to a lesser extent. From this, the elevator system, which is highly sensitive to incorrect alignment, was affected. Even the slightest variation in vertical alignment caused by the base plate flexing led to operational issues and reduced performance. To avoid this, the design should be improved to obtain greater structural stability. This could, for example, involve additional support to minimize deformation and the resulting strain, or changing the layout completely.

8.6 Leveling the Base Plate

To further make the system work better, it would be a beneficial idea to implement some sort of regulation system on the motors. The base plate must be level, otherwise the elevators will revive a lot of unwanted stresses. A regulation system could be implemented so they can improve the motors precision in keeping the base plate straight at all time. Currently, the system does not have anything measuring the angle of the base plate, and when one elevator is just a tiny bit off, the whole system has a harder time being able to lift the plate since there are a lot of friction and traction added because it is not kept straight.

8.7 Method for Lifting the Lawn Mower

The chosen elevator mechanism for the prototype is not space-efficient, as the vertical elevators extend directly upward from the lawn mower's body. This results in a bulky design that could be considered impractical. Furthermore, without a protective top cover, the exposed elevator posts may create a safety concern due to their height positioning.

The main point of this prototype is to show that a climbing lawn mower is possible and that it is possible to achieve this by lifting the wheels in a specific order. Using elevators based on leads screws is although not the only possible solution for lifting and lowering the wheels. Other methods could be used, for example hydraulics or scissor lifts. Hydraulics is an effective solution because it can handle high pressures and heavy weights without problems. Using hydraulic cylinders to lift the wheels, instead of screwing them, the lawn mower could be smaller in size and also be more reliable. The problem with hydraulics is that it is complicated to work with and it is crucial to have everything sealed to avoid leaks, which leads to power losses. Another option would be to replace the current elevators with a scissor lifts. This method would result in a compact and low-height lawn mower when the climbing is not needed, combined with the ability to climb high obstacles when necessary. This solution was not chosen in this project because it includes a lot of moving parts, which have the risk of creating a lot of unwanted friction. As an improvement point, the next generation of this lawn mower prototype could implement one of these systems as a new system for raising and lowering the wheels.

8.8 Climbing Limitations

The current lawn mower will only be able to climb certain obstacles, with certain characteristics. One such limitation is that the obstacle must be perfectly vertical, it must have a at least a 90° angle to the lawn. This is because the wheels in this prototype are quite close to each other, because the lawn mower would otherwise be too long. This does however also limits the length each wheel can travel without having the next wheel interfering with the obstacle. For example, the front wheels must be placed on the ledge before the middle wheels can be lifted from the ground. If the obstacle has a slope, the middle wheels will interfere with the obstacle before the front wheels can be placed on top of the obstacle. The result of this is that the lawn mower will not be able to climb the obstacle. Figure 87 shows three different obstacles, where the first obstacle cannot be climbed because it does not fulfill the requirement of having an angle of 90° or more. The other two obstacles meet this requirement and can therefore be climbed.

Figure 87: Climbing direction

This is a limitation of this prototype in this project, but if further developed, this could be a point of improvement. It could be solved in some different ways; lengthen the distance between the wheels or alternatively use the BLDC motors to hold the lawn mower in an incline position or something else. Having a lawn mower that could climb both vertical obstacles and steep slopes would be beneficial and something that could be developed in the future.

8.9 Climbing Stairs

Currently, the prototype can only climb one step at a time, requiring the landing to be larger than the size of the lawn mower's body. An interesting thing to solve would be to create a product that can climb stairs, and therefore be able to climb several obstacles at one time since it's whole body does not have to pause and recharge on a ledge. This creates a product that does not need to rest before climbing the next step and would widen the usage a lot. One way to start implementing this would be to add elevators on the front wheels, so they also can raise and lower themselves.

8.10 Reducing the Size of the Lawn Mower

The lawn mower prototype is rather large, a smaller would be beneficial because it would be easier to maneuver in tight places. This could be achieved in some different ways, for example by changing the layout of the base plate. The current base plate has a width extension so the cutting blade can fit in the middle. The motors responsible for driving the middle wheels is placed next to the cutting blade and this creates a wide base plate. By eliminating the motors in the middle the base plate can be significantly less wide. The problem with removing them is that the lawn mower needs two pairs of drivable wheels, as described in the section with the choice of wheels. The current state is that the back and middle wheels are powered by motors, but not the front ones. By changing this so the back and front wheels are driven, and not the middle wheels, the lawn mower can be smaller. The front wheels can although not be powered in their current state because they have the original rotating front wheels from Husqvarna and they can not be powered. If they were changed to another type of wheel and also changed the steering from pivoting front wheels steering to a 4 wheel differential drive, this concept would be possible. The steering could be completed by coding a 4 wheel differential drive. The result of this is that this new lawn mower would fulfill the same goal and be equal to the prototype developed in this project, but it would be a smaller size more compact. This concept was not possible to be explored further in this project, but could be achieved if having more time.

8.11 Implementing the Cutting Device

The crass cutter of the lawn mower have not been installed properly during this project. The reason behind this is that the main goal for the project was to develop a prototype for the climbing aspect. The cutting part could be included, however, it was not necessary because the prototype would only be tested in a laboratory environment with climbing in mind and not the aspect of cutting of grass. A system was designed on how the grass cutting equipment from the original Husqvarna lawn mower could be transferred to the prototype, but only parts from the cutting device was moved. This did although show that it is possible to integrate the cutting device on the prototype and if further developed it could be transferred completely and made working there.

9 Conclusion

This Bachelor's thesis describes the feasibility of creating a prototype of a robotic lawn mower that can overcome vertical obstacles through the method of having a height adjustable wheel system. With focus on mechanics and electronics, a solution was developed. When testing the lawn mower it could not complete a climb fully on its own. Although, with some external assistance the lawn mower could complete the climbing procedure, which does prove that the concept is possible in theory. If applying the changes described in the discussion and further developing the lawn mower, it will be able to climb.

The challenges that were met during the project included managing the center of gravity, working towards structural stability and developing the elevator mechanism. Advance features such as obstacle detection and self driving were excluded in the project to have a more manageable scope, but the discussion provides a foundation for further development on how this could be implemented.

References

[1] *Husqvarna* https://www.husqvarna.com/se/robotgrasklippare/

[2] *Maskinklippet* https://www.maskinklippet.se/tradgard/robotgrasklippare-och-tillbehor/robotgrasklippare/husqvarna-am450x-seno-dk-fi-robotic-lawn-mower

[3] *Husqvarna 450x picture* https://www.husqvarna.com/se/robotgrasklippare/automower-450x-nera/

[4] *Husqvarna 550 EPOS picture* https://www.husqvarna.com/se/robotgrasklippare/automower-550epos/

[5] *CAN* https://sv.wikipedia.org/wiki/Controller_Area_Network

[6] *Laser cutting https://www.twi-global.com/technical-knowledge/faqs/what-is-laser-cutting*

[7] *Differential Drive,* https://www.cs.columbia.edu/~allen/F17/NOTES/icckinematics.pdf

[8] *Differential drive picture* https://www.researchgate.net/figure/Differential-drive-robot-motions-Ottoviani-2020_fig2_351141316

[9] *BLDC* https://www.mantech.co.za/Technical/Attachments/BLDCM-22.pdf

[10] *BLDC picture* https://www.ablic.com/en/semicon/applications/bldc-motor/what-bldc-motor/

[11] *y and d configuration bldc* https://www.nidec.com/en/technology/motor/basic/00021/#:~:text=The%20connection%20type%20to%20be,unless%20special%20motors%20are%20used

[12] *cross section of 3-phase BLDC-motor* https://skill-lync.com/student-projects/week-7-challenge-dc-motor-control-135

[13] *Hall Sensor vs. Sensorless BLDC Drivers* https://mechtex.com/blog/hall-sensor-vs-sensorless-bldc-drivers

[14] *BLDC connector picture* https://www.researchgate.net/figure/Control-signal-and-back-EMF-electromotive-force-of-brushless-direct-current-BLDC_
fig3_339360562

[15] *BLDC connector picture* https://www.semanticscholar.org/paper/Performance-analysis-of-conventional-and-digital-of-Azarudeen-Mary/7bd94c5520ea87952b7bafdfd4fe865389715cea

[16] *BLDC motor driver - ZS-X11H* https://forum.arduino.cc/t/zs-x11h-bldc-motor-driver-arduino-gnd-connection/1097421

[17] *ZS-X11H* https://mad-ee.com/easy-inexpensive-hoverboard-motor-controller/

[18] *motor driver* https://electropeak.com/zs-x11h-dc-brushless-motor-drive-module-400w-9

[19] *ZS-X11H picture* https://electropeak.com/zs-x11h-dc-brushless-motor-drive-module-400

[20] *Stepper motor Nema 17* https://components101.com/motors/nema17-stepper-motor

[21] *Stepper motor Nema 17 picture* https://alexnld.com/product/nema-17-stepper-motor-42mm-1-68a-for-cnc-router/

[22] *NEMA 17 stepper motor picture inside* https://core-electronics.com.au/stepper-motor-bipolar-200-steps-rev-20-30mm-3-9v-0-6-a-phase.html

[23] *Stepper Motor Driver A4988* https://cdn.prod.website-files.com/5bea6b103705ec65e37d13f6/62d960c546c36f966163f16a_A4988.pdf

[24] *ESP32* https://www.electronicwings.com/esp32/introduction-to-esp32?utm_source

[25] *Buck converter LM2596* https://www.ti.com/product/LM2596?utm_source=google&utm_medium=cpc&utm_campaign=app-null-null-GPN_EN-cpc-pf-google-eu_en_cons&utm_content=LM2596&ds_k=LM2596&DCM=yes&gad_source=1&gclid=Cj0KCQjwna6_BhCbARIsALId2Z04Is3rW644V8Pu9p-WUFx5Ze5GvhxgaAPfEv878RDEJoaB8V479ocaAiKcEALw_wcB&gclsrc=aw.ds

[26] *Relay* https://www.amazon.se/-/en/Relay-Module-Channel-Optocoupler-Trigger/dp/B07QLY4Y4M

[27] *Multiple wheels* https://www.360castorsandwheels.com/shop/stairclimber-wheels/

[28] *Rubber tracks* https://trackspadsandbuckets.com/our-products/general-information

[29] *ISO-grid* https://en.wikipedia.org/wiki/Isogrid

[30] *Bearing with flange* https://www.euro-bearings.com/lmem.html

[31] *espadc* https://randomnerdtutorials.com/esp32-adc-analog-read-arduino-ide/

[32] *bldc discussion* https://discuss.ardupilot.org/t/selecting-and-configuring-brushless-motors-and-escs-for-use-on-mowers/127638

[33] *ZS-X11H pinout* https://forum.arduino.cc/t/zs-x11h-control-exact-rpm-with-pwm-using
1062746

[34] *control nema 17 with A4988* https://diyprojectslabs.com/control-stepper-motor-with-esp8266-a4988/

[35] *A4988 micro stepping* https://www.pololu.com/product/1182

[36] *ESP-NOW* https://randomnerdtutorials.com/esp-now-esp32-arduino-ide/

[37] *ESP32 30 pin pinout* https://mischianti.org/esp32-wemos-lolin32-high-resolution-pinout-and-specs/

[38] *ESP32 LOLIN32 pinout* https://mischianti.org/esp32-wemos-lolin32-high-resolution-pinout-and-specs/

[39] *github*, https://github.com/lil-dawg/Climbing-Lawnmower/tree/main

[40] *PCF8591* %https://el-supply.dk/shop/85-andre-integrerede-kredse/60266-pcf8591t2-isup2c-8bit-adc-4ch--dac-sol16/?srsltid=AfmBOorPksWaAVRJVyyKAd0gF6ki2EoCQRqvLp1pV-g3qRX6Y7rmIaDv7Qk&gQT=2

A Appendix

The complete code are available on GitHub.

A.1 Transmitter code

```
#include <Arduino.h>
#include <esp_now.h>
#include <WiFi.h>

#define upPin 25
#define downPin 23
#define leftPin 22
#define rightPin 14

#define pistonF_Up_Pin 27
#define pistonF_Down_Pin 26
#define pistonB_Up_Pin 17
#define pistonB_Down_Pin 16

uint8_t broadcastAddress[] = {0x24, 0xDC, 0xC3, 0x9F, 0xE1, 0xA0};
typedef struct struct_message {
  //Movment
  bool up;
  bool down;
  bool left;
  bool right;
  //Pistons
  bool pistonF_Up;
  bool pistonF_Down;
  bool pistonB_Up;
  bool pistonB_Down;
} struct_message;
struct_message transmitterData;
esp_now_peer_info_t peerInfo;
void OnDataSent(const uint8_t *mac_addr, esp_now_send_status_t status) {}

void setup() {
  Serial.begin(115200);
  WiFi.mode(WIFI_STA);

  //Movment
  pinMode(upPin, INPUT_PULLDOWN);
  pinMode(downPin, INPUT_PULLDOWN);
  pinMode(leftPin, INPUT_PULLDOWN);
  pinMode(rightPin, INPUT_PULLDOWN);
  //Pistons
  pinMode(pistonF_Up_Pin, INPUT_PULLDOWN);
  pinMode(pistonF_Down_Pin, INPUT_PULLDOWN);
  pinMode(pistonB_Up_Pin, INPUT_PULLDOWN);
  pinMode(pistonB_Down_Pin, INPUT_PULLDOWN);

  if (esp_now_init() != ESP_OK) {return;}
  esp_now_register_send_cb(OnDataSent);
  memcpy(peerInfo.peer_addr, broadcastAddress, 6);
  peerInfo.channel = 0;
  peerInfo.encrypt = false;
  if (esp_now_add_peer(&peerInfo) != ESP_OK){return;}
}

void loop() {
  transmitterData.up = digitalRead(upPin);
  transmitterData.down = digitalRead(downPin);
  transmitterData.left = digitalRead(leftPin);
  transmitterData.right = digitalRead(rightPin);

  transmitterData.pistonF_Up = digitalRead(pistonF_Up_Pin);
  transmitterData.pistonF_Down = digitalRead(pistonF_Down_Pin);
  transmitterData.pistonB_Up = digitalRead(pistonB_Up_Pin);
  transmitterData.pistonB_Down = digitalRead(pistonB_Down_Pin);
```

```
  //Movement
  Serial.print("Up: ");
  Serial.print(transmitterData.up);
  Serial.print(", Down: ");
  Serial.print(transmitterData.down);
  Serial.print(", Left: ");
  Serial.print(transmitterData.left);
  Serial.print(", Right: ");
  Serial.print(transmitterData.right);
  //Pistons
  Serial.print(", PistonF_Up: ");
  Serial.print(transmitterData.pistonF_Up);
  Serial.print(", PistonF_Down: ");
  Serial.print(transmitterData.pistonF_Down);
  Serial.print(", PistonB_Up: ");
  Serial.print(transmitterData.pistonB_Up);
  Serial.print(", PistonB_Down: ");
  Serial.println(transmitterData.pistonB_Down);

  esp_err_t result = esp_now_send(broadcastAddress, (uint8_t *) &transmitterData,
      sizeof(transmitterData));
  delay(10);
}
```

A.2 Receiver - Steering the elevators with DC-Motors

```
#include <Arduino.h>
#include "I2Cdev.h"
#include "Wire.h"
#include "PID_v1.h"
#include <esp_now.h>
#include <WiFi.h>

#define enableSerialprint

typedef struct struct_message {
  //Movment
  bool up;
  bool down;
  bool left;
  bool right;
  //Pistons
  bool pistonF_Up;
  bool pistonF_Down;
  bool pistonB_Up;
  bool pistonB_Down;
} struct_message;
struct_message buttons;

//Piston DC motor
  //PistonF
  #define cwDcFPin 19
  #define ccwDcFPin 18
  //PistonB
  #define cwDcBPin 32
  #define ccwDcBPin 13

//BLDC-motors
  //Enable all BLDC-motors
  #define enableMotors_pin 12

  //BL Motor
  #define directionMotor1_pin 27
  #define speedMotor1_pin 14

  //BR Motor
  #define directionMotor2_pin 25
  #define speedMotor2_pin 26

  //FL and FR Motor
  #define directionMotor3and4_pin 4
  #define speedMotor3and4_pin 16

  #define enableStepperMotor_pin 33

void awakeMotors();
void disableMotors();
void enableMotors();
void OnDataRecv(const uint8_t * mac, const uint8_t *incomingData, int len);

bool DirectionBR;
bool DirectionBL;
bool DirectionFLandFR;
float SpeedBR = 0.0;
float SpeedBL = 0.0;
float SpeedFLandFR = 0.0;

float maxSpeed = 255.0;  //av 255

long previousTime = 0;

void OnDataRecv(const uint8_t * mac, const uint8_t *incomingData, int len) {
  memcpy(&buttons, incomingData, sizeof(buttons));
}

void setup()
{
```

```
  WiFi.mode(WIFI_STA);
  if (esp_now_init() != ESP_OK) {return;}
  esp_now_register_recv_cb(OnDataRecv);

  pinMode(enableMotors_pin   , OUTPUT);
  pinMode(directionMotor1_pin, OUTPUT);
  pinMode(directionMotor2_pin, OUTPUT);
  pinMode(directionMotor3and4_pin, OUTPUT);

  pinMode(speedMotor1_pin, OUTPUT);
  pinMode(speedMotor2_pin, OUTPUT);
  pinMode(speedMotor3and4_pin, OUTPUT);
  pinMode(speedMotor3and4_pin, OUTPUT);

  pinMode(enableStepperMotor_pin, OUTPUT);

  pinMode(cwDcFPin, OUTPUT);
  pinMode(ccwDcFPin, OUTPUT);
  pinMode(cwDcBPin, OUTPUT);
  pinMode(ccwDcBPin, OUTPUT);

  // join I2C bus (I2Cdev library doesn't do this automatically)
  #if I2CDEV_IMPLEMENTATION == I2CDEV_ARDUINO_WIRE
    Wire.begin();
    Wire.setClock(400000); // 400kHz I2C clock.
  #elif I2CDEV_IMPLEMENTATION == I2CDEV_BUILTIN_FASTWIRE
    Fastwire::setup(400, true);
  #endif

  Serial.begin(115200); //Serial communication
}

void loop()
{
  //Movment - BLDC-motors ------------------------------------------------------------------------------
  if(buttons.up)
  {
    Serial.print("Up, ");
    SpeedBL = 0.5*255;
    SpeedBR = 0.5*255;
    DirectionBL = false;
    DirectionBR = true;

    SpeedFLandFR = 0.5*255;
    DirectionFLandFR = true;
  }
  else if(buttons.down)
  {
    Serial.print("Down, ");
    SpeedBL = 0.5*255;
    SpeedBR = 0.5*255;
    DirectionBL = true;
    DirectionBR = false;

    SpeedFLandFR = 0.5*255;
    DirectionFLandFR = false;
  }
  else if(buttons.left)
  {
    Serial.print("Left, ");
    SpeedBL = 0.5*255;
    SpeedBR = 0.5*255;
    DirectionBL = false;
    DirectionBR = false;

    SpeedFLandFR = 0.0*255;
    DirectionFLandFR = true;
  }
  else if(buttons.right)
  {
    Serial.println("Right, ");
    SpeedBL = 0.5*255;
```

```
    SpeedBR = 0.5*255;
    DirectionBL = true;
    DirectionBR = true;

    SpeedFLandFR = 0.0*255;
    DirectionFLandFR = true;
  }
  else
  {
    Serial.print("Idle, ");
    SpeedBL = 0.0*255;
    SpeedBR = 0.0*255;
    DirectionBL = false;
    DirectionBR = true;

    SpeedFLandFR = 0.0*255;
    DirectionFLandFR = true;
  }

  awakeMotors(); //to make sure the drivers arn't going to sleep mode

  if (SpeedBR >= maxSpeed)
    SpeedBR = maxSpeed;

  if (SpeedBL >= maxSpeed)
    SpeedBL = maxSpeed;

//Elevators DC-motors -----------------------------------------------------------------
    //PistonF
      //PistonF_Down
      if (buttons.pistonF_Down) {
        digitalWrite(cwDcFPin, LOW);
        digitalWrite(ccwDcFPin, HIGH);
      }
      //PistonF_Up
      else if (buttons.pistonF_Up) {
        digitalWrite(cwDcFPin, HIGH);
        digitalWrite(ccwDcFPin, LOW);
      }
    //PistonB
      //PistonB_Down
      if(buttons.pistonB_Down)
      {
        digitalWrite(cwDcBPin, LOW);
        digitalWrite(ccwDcBPin, HIGH);
      }
      //PistonB_Up
      else if(buttons.pistonB_Up)
      {
        digitalWrite(cwDcBPin, HIGH);
        digitalWrite(ccwDcBPin, LOW);
      }
    //Idle
      if(!(buttons.pistonB_Up || buttons.pistonB_Down ||  buttons.pistonF_Up || buttons.pistonF_Down))
      {
        digitalWrite(cwDcFPin, LOW);
        digitalWrite(cwDcBPin, LOW);
        digitalWrite(ccwDcFPin, LOW);
        digitalWrite(ccwDcBPin, LOW);
      }

  analogWrite(speedMotor1_pin, SpeedBL);
  analogWrite(speedMotor2_pin, SpeedBR);
  analogWrite(speedMotor3and4_pin, SpeedFLandFR);

  digitalWrite(directionMotor1_pin, DirectionBR);
  digitalWrite(directionMotor2_pin, DirectionBL);
  digitalWrite(directionMotor3and4_pin, DirectionFLandFR);

  #if (defined enableSerialprint)
    Serial.print("Up: ");
    Serial.print(buttons.up);
```

```
    Serial.print(", Down: ");
    Serial.print(buttons.down);
    Serial.print(", Left: ");
    Serial.print(buttons.left);
    Serial.print(", Right: ");
    Serial.print(buttons.right);
    Serial.print(", PistonF_Down: ");
    Serial.print(buttons.pistonF_Down);
    Serial.print(", PistonF_Up: ");
    Serial.print(buttons.pistonF_Up);
    Serial.print(", PistonB_Down: ");
    Serial.print(buttons.pistonB_Down);
    Serial.print(", PistonB_Up: ");
    Serial.println(buttons.pistonB_Up);
  #endif
}

void awakeMotors()
{
  if(millis() > previousTime + 3000)
  {
    disableMotors();
    previousTime = millis();
  }
  else
    enableMotors();
}

void enableMotors()
{
  pinMode(enableMotors_pin, INPUT);
  delayMicroseconds(10);
}

void disableMotors()
{
  pinMode(enableMotors_pin, OUTPUT);
  digitalWrite(enableMotors_pin, LOW);
  delayMicroseconds(1);
}
```

INSTITUTION OF ELECTRONICS
Chalmers University of Technology
Gothenburg, Sweden 2025
www.chalmers.se