AUTOPLANT 1

MF2058

RELOADING SEEDLINGS SUBSYSTEM OF AUTOMATED TREE-PLANTING MACHINE

FINAL PROJECT REPORT

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ABSTRACT

The Reloading Seedlings Subsystem of Automated Tree-Planting Machine project was a project founded by Skogforsk and Bracke Forest and performed in collaboration with KTH. It deals with the problem of autonomously supplying a plantation arm with seedlings. The project was carried out by researching, designing and building a prototype that picks five seedlings from their cultivation tray and delivers it to a buffer system which in turn outputs one seedling at a time to a plantation arm. The prototype was successful in operating autonomously with sufficient speed as well as being remotely operated. It was semi-successful in handling seedlings. Failure modes observed in the project were: Picking too many or too few seedlings, crushing the seedlings soil upon delivery to buffer and seedlings are failing to pass through the buffer. Mitigation for these failure modes are further elaborated on and solutions are proposed. Results demonstrated the feasibility of employing an automatic Reloading Seedlings Subsystem.

ACKNOWLEDGEMENT

A special thanks goes to our stakeholders Skogforsk and Bracke Forest for offering the opportunity to work on this project and for the field trip to see the real working environment. We would also like to thank our supervisor Gustav Sten and the members of the expert panel for their inputs to the project as well as Seshagopalan for helping us with parts. Gratitude is also expressed to Schaeffler Sverige AB for sponsoring the project with linear rails.

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1 INTRODUCTION

The Swedish forestry industry is delving into automated solutions for a sustainable regeneration of this vital ecosystem. In this paper a solution contributing to this industry shift is presented. The project background and description are defined, followed by the requirements and delimitations posed on the solution.

1.1 Background

The afforestation and reforestation industry is expected to have an increased interest and dependency on mechanised planting due to factors such as labour shortage [1, 2, 3, 4]. Large scale mechanisation of tree-planting has not been successfully launched despite its good seedling growth compared to manually planted ones [5, 6]. The growing importance of mechanised planting entails promising prospective for automated tree-planting machines due to the increased productivity and good planting results these may yield [7, 8].

Mechanisation, ergo automation, within afforestation and reforestation would replace physically arduous work and require fewer human resources in a declining labour market [1]. Currently, mechanised planting has a reduced appeal due to low profitability for contractors caused by low productivity and cost-efficiency [8, 5, 9]. Identified factors contributing to low productivity in mechanical planting are operator inexperience, low machine utilisation, among others [5]. These may be eliminated or reduced by automating the planting processes to the extent that feasible technological availability allows for. Other factors impacting contractor profitability such as workplace organisation and seedling logistics [5], are outside the scope of this paper.

Presently, there are few automated solutions within the field [7]. In order to attain insight of the requirements for commercially viable automated tree-planting machines, the sought-after qualities and optimisation of mechanised tree-planting machines are taken into account. The desirable features being high quality planting, high productivity, low operating costs, easily serviced, robust and sufficient annual capacity [1, 2]. Contemporary planting machines spend a significant amount of time on manually reloading planting machines with seedlings [8]. Utilising automated seedling feed as a way of reloading the planting machine from cultivation trays is a promising development that may significantly increase productivity by decreasing the machine's idle time [2, 8].

The project described in this paper was sponsored by three entities: the central research body for the Swedish forestry sector Skogforsk, one of the global leaders within forest generation Bracke Forest and one of the world leading high-precision components manufacturer for industrial applications Schaeffler.

1.2 Project Description

In this report, the problem considered was developing a subsystem belonging to an automated tree-planting machine. The function of this subsystem is to grip seedlings from their cultivation trays and hand them over to the plantation manipulator autonomously. Acting as a reloading mechanism giving it its name *Reloading seedlings subsystem*. The receiving plantation subsystem (containing the plantation manipulator) will be delivered by the associate group Autoplant 2. Meaning, the complete planting machine was a collaborative effort given the interactions between the subsystems. The subsystem of this report (the reloading seedlings subsystem) consists of a gantry, gripper and buffer system. A preliminary version of the final product can be seen in Figure 1 where the differentiation of the subsystems are illustrated more clearly. Moreover, a preview of two subsystems of the Autoplant 1 solution can be seen encircled in Figure 1 (the picking and buffer system). These systems are referred to in this paper, thus introduced here for better comprehension.

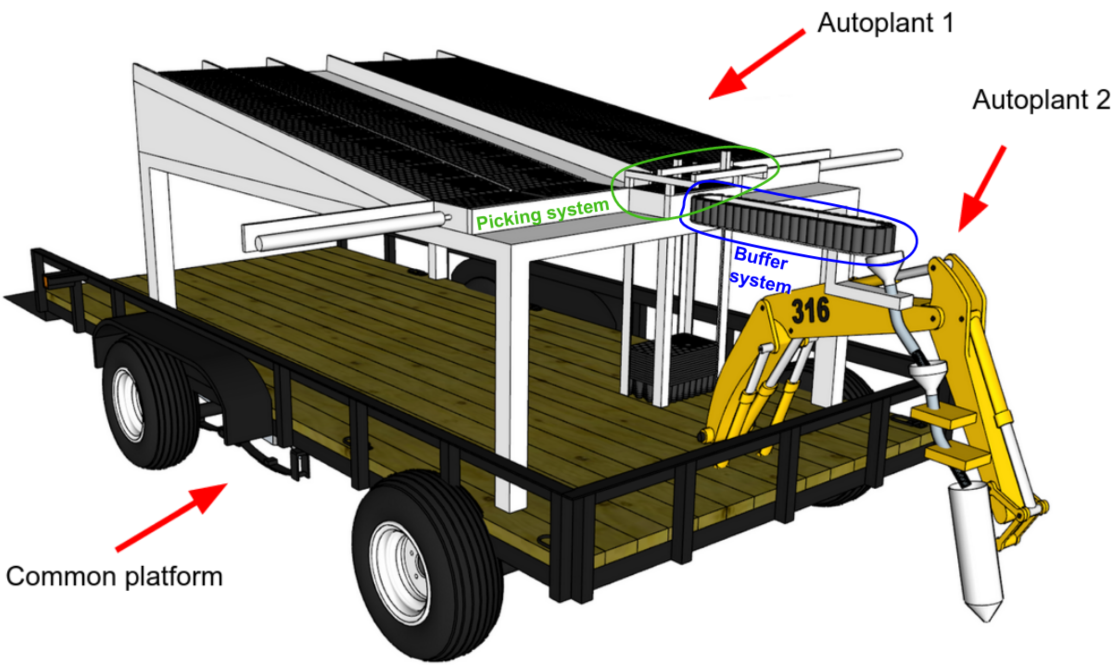


Figure 1: A preliminary illustration of the automatised tree-planting machine containing both subsystems pertaining to Autoplant 1 and 2 indicated by the red arrows. The Autoplant 1 subsystem presented is a preview of a solution provided in Section 3. Autoplant 1's subsubsystems are the picking system (encircled in green) and the buffer system (encircled in blue)

1.2.1 *Definition of parts*

In order to make the following sections understandable, a few parts need to be defined in words, as the following sections repeatedly refers to them.

SEEDLINGS A crucial part to automate all aspects of planting is to safely handle the seedlings so that they do not get damaged. The seedlings used in this project are containerised, which means that they are grown in containers such as tubes. They have a denser root system than bare-root seedlings and therefore are easier to plant.

To preserve the seedling, there are some conditions that must be met. The root system of the seedlings must the protected from outside elements such as the wind and sun. It was therefore recommended that the transportation of the seedling to be done as quickly as possible. This is so that the root system will not dry out. The roots also need access to moisture for the same reason. The seedlings are also sensitive to high temperatures, therefore they need to be contained in a covered and shaded place. They also needs to have good air ventilation. [10, 11]

CULTIVATION TRAY The "cultivation trays" are plastic injection moulded containers that holds the trees from the moment they are seeds, during cultivation and up until the moment they are planted. Their appearance can be seen in Figure 2. The cultivation trays are 352 mm x 216 mm in size and hold 67 trees each. A drawing of the most commonly used cultivation tray, called JackPot can be found in Appendix A.

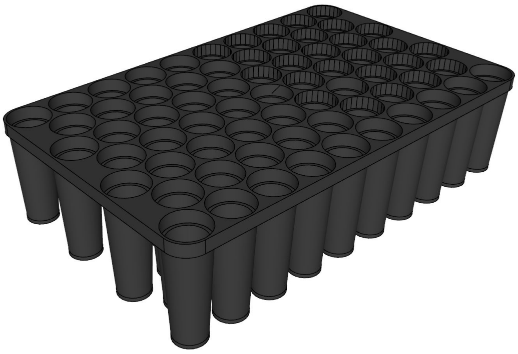


Figure 2: A cultivation tray

RACK The "rack" is a steel frame used to hold and transport several cultivation trays at once in the cultivation factory and during transportation out to the forest. The frame holds 60 cultivation trays, in five rows with twelve cultivation trays in each row, which makes for a grand total of 4020 trees. The dimensions of the rack are 2677 mm x 1820 mm. Figure 3 shows a conceptual picture of a rack with cultivation trays in it. A drawing of the real rack can be found in Appendix B.

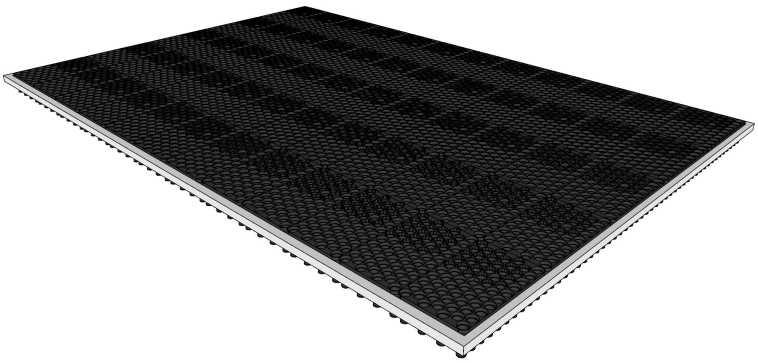


Figure 3: A rack with 60 cultivation trays in it

1.3 Requirements

The requirements for the *Reloading seedlings subsystem* are divided into *Stakeholder requirements* and their corresponding *Technical requirements*. The first set of requirements were communicated by the stakeholders Skogforsk and Bracke Forest, which were interpreted into the technical requirements. These are presented below.

1.3.1 *Stakeholder Requirements*

- Extraction of the seedling from the cultivation tray without damage.
- Transport seedlings safely to the plantation arm subsystem.
- The entire operation should be automated.
- The system should be able to solve disturbances, such as objects becoming lodged, as much as possible.
- Ability to remotely control and overview the process
- Ability to extract and deliver 400 seedlings per hour.
- Operate all year around except for when ground is frozen.

1.3.2 *Technical Requirements*

These technical requirements stated here are system wide, meaning they will be broken down into subsystem specific requirements in Section 5.

- The system should be able to output 400 seedlings per hour.
- The system should be functional in the given environment.
- The system should be autonomous.
- The system should handle seedlings safely.

1.4 Delimitations

The task of producing a fully autonomous system is anything but trivial. In addition to this, both funding and time are limiting factors for the project, therefore some delimitations of the scope is much needed.

ENVIRONMENTAL FACTORS As mentioned, the operational environment of the system was very harsh and feature both high and low temperatures, vibrations and shocks, debris, dirt and dust, and moisture. Both the use of components that satisfy these conditions and the testing of the system were very limited. Components might be too expensive or take too long to order, and testing might be possible, but also time consuming and expensive. Therefore, the environmental factors were considered and discussed in theory and in this report, but the physical prototype were not adapted to these conditions. Instead, the focus of the physical prototype was proof of concept, and that the solution was viable.

INTEGRATION The system of interest is, in theory, a subsystem of a larger system. The integration with the plantation system and the autonomous terrain platform is essential for a fully operational and functional system. However, the possibility to integrate the produced prototype with the other systems was very limited. Because of this, integration was not prioritized throughout this project.

SEEDLING SURVIVAL One of the main goals of the project, and one of the main stakeholder requirements, was the safe handling of seedlings. However, there was no possibility to observe to what extent seedlings were damaged after handling by the system. This would require planting the seedlings and observing how well they manage. This knowledge would be paramount when evaluating a similar system in the future, the goal is, after all, to successfully plant as many of the seedlings as possible. Because of this, the long term health of the seedlings handled by the system could not be discussed within this project. This also limited the possibility to statistically verify successful transports of seedlings.

1.5 Report disposition

The structure of the paper is as follows. Section 2 explores the state of the art within the field and describes the relevant technologies for developing a *Reloading seedlings subsystem*. In Section 3 the methodology employed for procuring said subsystem is presented, followed by Section 4 where the implementation is detailed. The subsequent Sections 5 and 6 describe the test cases used for verifying and validating the technical requirements posed on the system, and the results of these. Finally, in Section 7 and 8 the discussion and conclusions, and future work are presented respectively. As previously stated, the *reloading of seedlings* is a subsystem of the tree planting machine but for the sake of simplicity said subsystem will be referred to as a system. Meaning, the subsystems presented are direct subordinates to the *reloading of seedlings* and not the tree planting machine.

2 STATE OF THE ART

In order to appropriately depict the state of the art of the project, the preceding and current plantation solutions are described followed by relevant theory on a subsystem, hardware, sensor and software level.

2.1 Preceding and Current Planting Machines and Methods

The current planting methods can be divided into two categories: manual and machine planting. Even though there are planting machines most of the planting is still done manually. Some of the methods used for manual planting are planting hoes, planting bars and shovels. These tools are all used to make holes in the ground that the seedlings are placed into. It is done by either digging and removing the earth before placing the plant or by driving the tool blade into the ground and moving it in such a way that creates a hole. There are also tree planting augers that instead drill holes in the ground. While the first three tools use strictly manual labour the auger is electrically powered. There is also the Pottiputki planting tube that creates the hole and plants the seed at the same time. The tube is pushed into the ground which creates a hole and then the seedling slides down the tube into the hole. Most of these tools need good soil conditions which means that first the ground needs to be prepared by machines or other tools. [12, 13, 14]

SILVA NOVA Silva Nova, seen in Figure 4, is a very old machine first produced in 1969 [15] and extensively used in the industry during the 80s and 90s. To this day it is the only machine that has seriously been able to rival manual labour in terms of economical viability. When fully operational it could plant more than 2000 trees per hour. The problem with it was that it required a lot of continuous maintenance and repair in order to keep it operational, so the rate of 2000 trees per hour was not often met in practice, and as the supply of labour increased in Sweden over the years, companies went back to manual labour [16].

Figure 4: The Silva Nova machine [17]

The machine uses two operators, one of whom drives the vehicle and one who supplies seedlings and steers the planting arms. The seedlings reach the planting arms by travelling in a tube from the operators hut out to the arms.

BRACKE P11.A Bracke P11.a is a seedling planting machine that is attached to the arm of an excavator and can be seen in Figure 5. The P11.a makes it possible to conduct the entire rejuvenation process with a single machine. The yellow claw scoops up a patch of soil and the machine then plants the three in the patch. This makes sure that the tree is always planted in fresh nutritious soil.

Figure 5: The Bracke P11.a seedling planting machine [18]

It has a plant storage system that carries 72 to 196 plants depending on configuration, that has to be loaded manually by a worker. Using the P11.a with an excavator, an operator is expected to be able to plant 300 trees per hour. This machine is currently used a lot in industry. It has the advantage of being a reliable machine that a single person can operate while also driving the excavator between planting spots. The disadvantage is that it is slow compared to doing scarification with a disc trencher and planting manually. [16]

MAGMAT MagMat is an extension to the Bracke P11.a for reloading seedlings to increase the speed and capacity (is depicted in Figure 6). It was found that it would increase the reloading speed by a factor of two and productivity by 8-9%. The capacity was increased to 320 seedlings. [19]

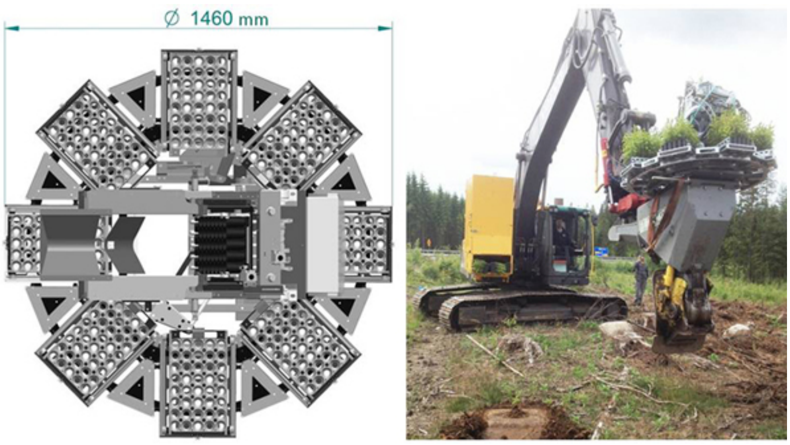


Figure 6: MagMat carousel mounted on the Bracke P11.a [19]

PLANTMA X Plantma X is a new machine currently under testing. It is very similar to the Silva Nova. As of right now, it still takes two people to operate the machine. It can make an attempt to plant a tree every third second with each arm, which makes for about 2400 attempts per hour. The method for transporting the seedling out to the planting arms is different than it was in the Silva Nova. The seedlings are transported on a chain conveyor from the inside of the operators hut out to just above the planting arms. When the seedling reaches the out most position on the chain conveyor, the seedling is dropped. On the planting arm there is a funnel that the seedling falls into, when the planting arm is in its upper position the funnel is located just below the drop zone of the chain conveyor. It is presented in Figure 7.

Figure 7: The Plantma X planting machine [20]

TREE ROVER Tree Rover is a prototype planting robot designed by Nick Birch and Tyler Rhodes from UVic, which can be seen in Figure 8. The machine automatically plants trees in complex terrain without manual operation. It has four wheels, powered by battery and holds the tree planting mechanism which consists of a cultivation tray of 10 tree seedlings. Through the application of compressed air, a hollow spike is dug into the ground which releases the seedlings. After the seeds are in the ground, a mechanical arm taps the earth to secure them and then, with its electric motor, it moves on to the next site. The 10-tree cultivation tray takes approximately 15 minutes to complete [21].

Figure 8: A picture of the prototype planting machine "TreeRover" [21]

RISUTEC APC It becomes clear that most efforts that was identified to mechanise forest plantation have been concerned with the plantation process rather than the transportation or handling of the seedlings. Risutec Ltd designs and manufactures forestry machinery and equipment for more productive silviculture. UPM Risutec APC 1.0 (Automatic Plant Container) one of the silviculture products from Risutec Ltd, completed in summer 2012, was the first automatic seedling feeder in the forest industry. APC 1.0 has a series of pneumatically operated parallel gripper mounted on a custom assembly which grabs the seedlings from the cultivation tray and transports it to the buffer system. The unique and simple parallel gripper mechanism has two flat parallel L-shaped plates which grab the seedlings just above the roots, the area with the biggest cross-sectional area. Thus creating a plane contact which ensures a good grip of the seedlings. It can be observed from the Figure 9 that the gripping plates are twisted outwards to ensure the seedling is not missed even if its slightly eccentric. [22]

Figure 9: Risutec APC 1.0 gripper [22]

In Summer 2014, Risutec Ltd came up with a another automatic planting solution similar to the APC 1.0, but more efficient and lighter than its predecessor. This machine is hydraulic controlled and has a series of parallel grippers. The APC 2.0 grips the seedling at two points of contact instead of one, as shown in Figure 10. The gripping mechanism has four circular rods two at the bottom, and rest two at the top. The rods translate with respect to each other such that the centre to centre distance between them increases and decreases while opening and closing. Either of the rods from top and bottom have rubber padding which ensures, undamaged gripping and transport of seedlings. [22]

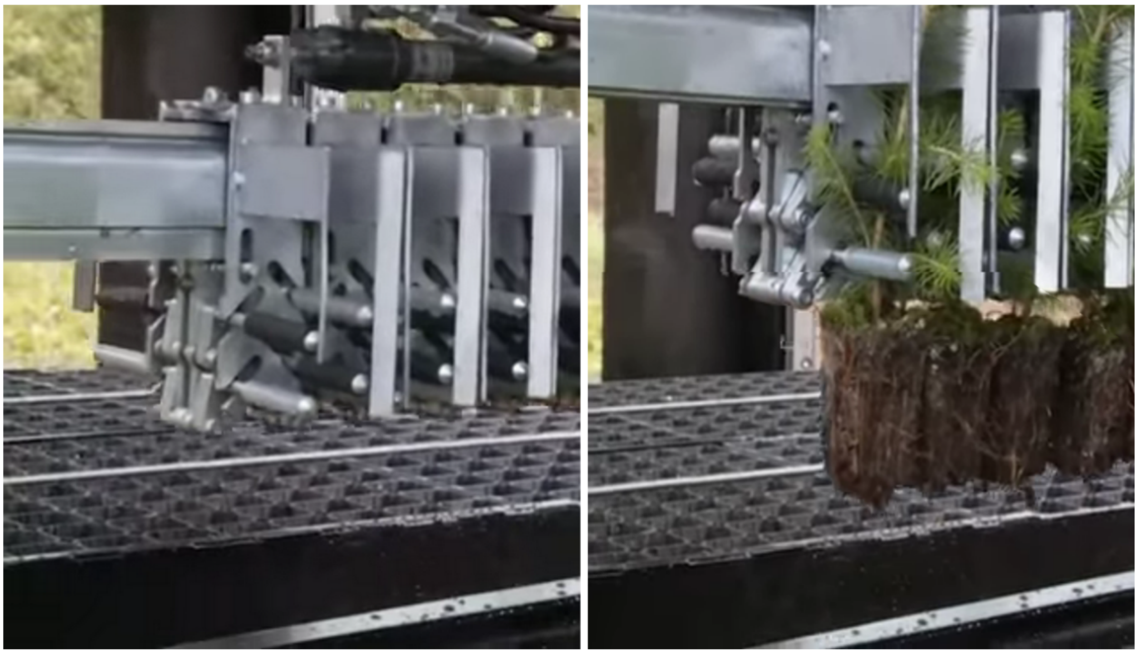


Figure 10: Risutec APC 2.1 gripper [22]

2.2 Gripper

Planted seedlings are delicate in nature, thus the gripper handling said seedlings are required to be robust to withstand the harsh operating environment but also pliable enough to not damage the seedling.

To protect the plant during the grabbing process, the gripping force of the gripper need to be controlled. There are two methods to limit the gripper from being too rough, which is control method and hardware method, respectively. The control method considers installing force sensors on the gripper to detect grasping situation. Possible ideas include installing force sensors on the forepart to measure feedback force, or use proximity sensors to confirm the location of the seedlings and perceive if gripping was successful. The disadvantage of control method comes to more of a coding task. High accuracy result are needed in the project, quality sensors are thus required for the system. Considering that the planting machine will work in a harsh environment, the sensors would in reality need to be shielded to avoid malfunction.

Another way to reduce damage via the structural design of the gripper. The simplest way is to add silicone or sponge protective cover on gripper fingers, which could effectively act as a damper.

Vital to the system functionality is some sort of solution that can actually lift and hold on to the plant during transportation. As mentioned, the careful handling of the trees is crucial and the main focus from the stakeholder perspective. According to the stakeholders, the seedlings are removed from their containers before plantation manually today. It was stated in the initial task description that a gripper was to be included in the final system, and after communicating with the stakeholders, it became clear that a gripper was a requested solution. Initially there were discussions regarding other solutions such as biodegradable baskets, but these have since been discarded in favour of a gripper. It is assumed here, as this is the indications given by the stakeholders, that the seedlings are to be gripped by the stem.

FORCES NEEDED TO EXTRACT PLANTS FROM CULTIVATION TRAY According to a study the maximum force needed to extract a pine seedling from a jackpot tray is approximately 17 N when the seedling is watered and the soil is wet. The study was performed on different kinds of trees and cultivation trays including the trees and tray used in this project. During the study, a machine to detect the forces needed to extract the seedlings from their cultivation trays was built and tested. In the results, it is also shown that the force is different if the seedling soil is wet or dry as well as if the seedling is removed slowly or quickly. The study shows that it takes more force to extract a seedling when the soil is wet and when the seedling is extracted quickly rather than slowly. Since the seedlings need moisture and are required to be watered this is the values that was most interesting for this project. [23]

2.2.1 Gripping mechanisms

A gripping device is essentially a mechanism that translates an input force produced by an actuator into a gripping motion [24]. It is common that gripping devices are randomly designed by trial processes, it is important to produce multiple concepts and evaluate these in a systematic manner [24]. Grippers are generally specialised devices, designed to handle a specific part or product, or a few similar ones [24], which will also be the case in the solution. Roughly, grippers can be categorised into the following groups [24];

- Mechanical finger type grippers
- Vacuum and magnetic type grippers
- Universal grippers

Universal grippers are used to handle objects of differing sizes and shapes [24], which is not applicable to this problem. This could indicate that a universal gripper would be too complex without any added benefits of this complexity for the problem at hand. Magnetic grippers use electromagnets to lift objects, and vacuum grippers use suction [24], because of the lack of magnetism in a plant a magnetic gripper is not very useful. Furthermore, because of the lack of appropriate surfaces on a plant to attach suction cups, this is likely not an appropriate solution either. Therefore, by elimination, the solution would probably benefit best from a mechanical finger type gripper out of the four categories identified.

As mentioned, a gripper is essentially a device that translates an input actuation force into a gripping motion. For the mechanical finger type grippers, the available actuation force providers are [24];

- Motors (electric)
- Pneumatic devices
- Hydraulic devices

In an article [25] published by engineering.com, where the author has spoken to experts from automation suppliers Festo and SMC, pros and cons of the three different types of actuators are listed. A hydraulic actuator is said to provide extremely high forces, but the compromise is its high price tag and possible leakages, maintenance and regular checks. A pneumatic actuator is said to be simple, inexpensive and fast, but the movement is less controllable and they require maintenance and replacement. Lastly, electric actuators are said to be very fast and highly accurate and controllable, but they are more expensive and more complicated to install. It seems that, considering the low weight of a plant, a hydraulic actuator would be unnecessary. The decision between pneumatic and electric actuators could come down to accuracy versus price.

Actuators provide the force, but some sort of mechanism has to transform this force into a gripping movement. The available mechanism for mechanical type grippers are [24];

1. Linkage type
2. Gear-and-rack type
3. Cam type
4. Screw type
5. Rope-and-pulley type
6. Miscellaneous

Additionally, for mechanical type gripping devices, springs are commonly used to guarantee automatic release action [24].

2.2.2 Gripper Design

The mechanical finger type grippers enable three types of gripping movements, a "beak", a "bite" and a parallel movement [24]. The most common type is the parallel gripper, which is also typically the most accurate gripper [26]. Grasping, holding on to the work piece, can be done through two principles [27];

- Force closure - the work piece is grasped by the use of friction between the piece and the gripper fingers.
- Form closure - the work piece is grasped by fixing its position using the form of the gripper fingers.

Given that the diameters of the seedlings vary, a form closure gripping may not be as appropriate as a force closure gripping.

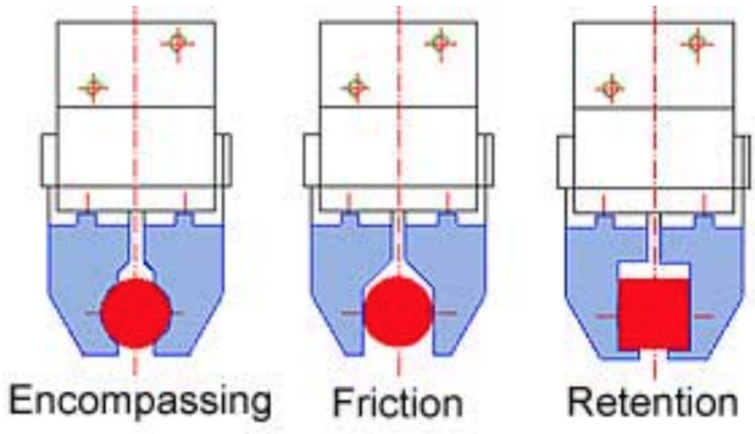


Figure 11: Examples of form and force closure [26]

Figure 11 exemplifies force closure (friction) and two types of form closure (retention and encompassing). Form closure is preferable because it is more stable and reduces the necessary force used to grasp the piece, however, the additional jaw travel required needs to be considered [26]. When work pieces are fragile, as in this case, a solution could be to line the contact surfaces of the fingers with a resilient material which will allow for impact distribution [26].

Other design considerations that could be important is the number of fingers. 2-jaw grippers are most common, but additional jaws provide more points of contact with the piece and more accurate centering [26]. Furthermore, a gripper could be designed as external or internal, meaning that gripping is done by enclosing or pushing [26], which is illustrated in Figure 12. For the problem at hand, an internal gripper is likely not a viable solution since a plant provides no apparent appropriate grasping points.

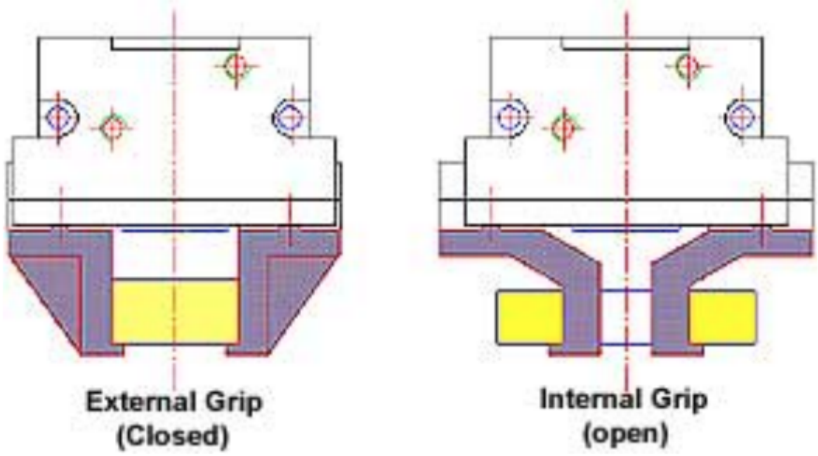


Figure 12: Internal and external grasping [26]

In the listed existing solutions in Section 2.1 above, parallel grippers are used. The Risutec APC 2.1 gripper utilise two pairs of grippers, which should provide a more stable grasp. It can also be concluded that Risutec has opted for a force closure and fitted the fingers with a material to help the grasping.

2.2.3 *The gripping process*

The gripping process could, despite the teams best efforts, fail. Therefore it could be important to discuss unforeseen issues and how these should be handled, as it could affect the demands put on the gripper. If the system attempts to grip a plant, failure could happen on different stages;

- The gripper does not successfully grip the plant and the plant is left in its initial position in the cultivation tray.
- The gripper drops the plant during transportation to the buffer and plantation system.

As part of the solution to identify these failures, the gripper could be equipped with sensors, which might in turn affect the gripper design or possible movement and range. Additionally, if it is concluded that dropped plants needs to be retrieved, this could demand a more complex range of freedom of the gripper as the plant stem could be horizontal as opposed to vertical.

2.3 Hardware

Viable options for the final solution in terms of hardware are presented.

2.3.1 *Mechanical components*

In this section, mechanical design components that could be of importance for the system of interest are presented.

SPRINGS Springs are resilient elements that experience appreciable deflection without permanent deformation. Unlike most machine elements, springs exhibit large and visible deflections under applied loads. They usually have predefined linear or nonlinear relationships between applied loads and associated deflections. Therefore, springs are used to introduce controllable flexibility by deflection under applied loads. Depending on the loads they carry, springs can be classified as:

- Extension springs - designed to carry tensile force and to store energy.
- Compression springs
- Torsion springs - used to exert rotational moment, or torque.
- Bending springs

Helical coil springs are probably the most widely used springs, these take both extension, compression and torsional loads, the only difference is the configuration of the ends of the spring. The defining characteristic of a spring is its rate. The spring rate is the ratio of change in load to the corresponding change in deflection. For an extension or compression spring, the applied load refers to tension or compression and deflection is extension or contraction. For a torsion spring, the applied load is torque and deflection is angular deflection. For linear springs, the rate represent the relationship between the applied load and the deflection [28].

COUPLINGS Apart from the primary function of connecting shafts to transmit power and torque, couplings can compensate for misalignments between the coupled shafts. Some couplings can also absorb shock and vibration, or act as a safety device to prevent overload on a machine. Mechanical couplings are typically divided into two broad categories: rigid couplings and flexible couplings. Table 1 present a selection of couplings that might be of interest with regards to the system of interest, along with their applications and characteristics [28].

Table 1: Types of couplings

Type of coupling	Applications	Category
Flanged couplings	Simple structure, low cost. Suitable for heavy-duty, slow speed, stable load applications.	Rigid
Sleeve couplings	Simple structure, small radial dimension. Suitable for light duty applications.	Rigid
Ribbed couplings	Convenient for assembly and disassembly. Suitable for small to medium torque, slow speed and stable load transmission, such as in vertical pumps, agitators, and many other types of applications.	Rigid
Oldham coupling	Simple and compact structure, small radial size, low costs. Suitable for slow to medium speed, high torque drives.	Flexible
Slider block coupling	Simple and compact structure, small radial size, low costs. Suitable for low to medium power, high-speed applications.	Flexible
Resilient couplings with spider	Simple structure, convenient for maintenance, reliable. Suitable for strong vibration occasions, small to medium power transmission; operating temperature limited to −35°C–+80 °C.	Flexible
Tyre Couplings	Simple structure, excellent misalignment compensation and vibration dampening capability, yet require ample radial space. Suitable for frequent start/stop cycles, reversing torque loads, heavy shock, vibration applications.	Flexible

BEARINGS Bearings are standardized machine elements widely used in various machines. They support rotating shafts while permitting relative motion between two elements. Rolling bearings have pins or balls that facilitate the sliding motion, and sliding bearings are instead characterized by direct sliding of a journal on a bearing. Rolling bearings have low starting and good operating friction, and are ideal for applications with high starting loads, such as in vehicles, trains, aeroplanes and mobile equipment in general. Sliding bearings are better suited to high speed and heavy load applications. They can also realize high precision position and quiet operation. Compared with sliding bearings, rolling bearings require minimum lubrication and less axial space. They have high efficiency and reliability, and minimum maintenance requirements. [28]

2.3.2 *Motors*

There are several options when deciding what kind of motor to use, all with different advantages and disadvantages. The picking mechanism is thought to move the same way as a Cartesian 3D printer as seen in Figure 13.

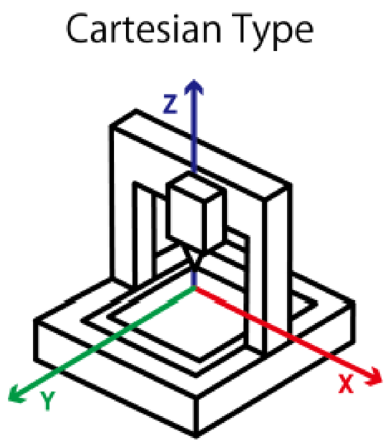


Figure 13: Cartesian type 3D printer [29]

DC MOTORS On advantage of using DC motors is the ease of controlling the speed and direction. Because DC motors features a high ratio of torque to inertia, it can quickly respond to changes in the control signal. They can be controlled to zero motion and instantly accelerate in the opposite direction without the need for complex power-switching circuits [30].

If an encoder is attached to the shaft of the motor, the position can be measured which makes it a closed-loop system.

SERVO MOTORS Servo motors are not a specific class of motor, the term refers to a motor suitable for use in a closed-loop system. It consists of a motor coupled to a sensor for position feedback. It also requires a controller, often a dedicated module designed specifically for servo motors [31].

STEPPER MOTORS Stepper motors come in a wide variety of sizes and specifications. They are often used when precise positioning and control are of importance. A stepper motor is a DC motor that moves in discrete steps. One rotation is divided into a fixed number of steps. Precise control can be achieved with the help of a stepper motor driver [32].

A stepper motor driver sends pulses to perform steps. The rotational velocity of the motor is determined by the pulse frequency sent to the driver [33], which can be generated by a microcontroller.

There are multiple stepper motor drivers out on the market, with varying power and microstepping capabilities. Microstepping divides each step into even smaller steps, this allows for smoother rotations to the cost of torque. The drivers usually only need two signals from a microcontroller to operate, a direction and a pulse signal. The direction is chosen by setting a logical one or zero to the direction pin. This makes stepper motors easy to control.

BRUSHLESS DC ELECTRIC MOTOR Brushless DC electric motors(BLDC) are DC powered synchronous motors with electronic commutation. The motors come in single-,2- or 3-phase configurations, where the last is the most common [34]. These phases are driven by AC current generated by an inverter or switching power supply.

The electric commutation improves the efficiency over regular DC motors and makes them more durable due to no brushes that can wear out. The enhanced efficiency makes it possible to have a smaller size with the same power output compared to a regular DC motor [35].

Downside of an BLDC is the increased complexity and with that higher cost. The electrical commutation comes with a need for a controller that can provide current at correct timing and amount to control the speed.

ELECTRONIC SPEED CONTROL Electronic Speed Control(ESC) are required to be able to control the speed of an BLDC motor. These controller creates the AC power for each phase of the motor. To do this at the correct timing the back EMF from the windings can be used to detect the motors rotation. Other methods such as hall effect sensors or encoders can also be used [35][34].

One popular ESC is the open source project VESC initiated by a Swedish engineer named Benjamin Veeder [36]. This initiative have led to more reasonable prizing of these units. Many ESCs based on VESC can also control the position of the motor with the use of an feedback source like an encoder.

There is another open source initiative named ODrive [37]. This controller handles the electrical commutation but also have dedicated hardware for encoder inputs and built in controller loop for position control. This initiative have strong focus on offering a complete servo controller at a low-cost. This controller has the advantage over VESC that they offer an official complete APIs for both python and C, for controlling the motor and set various parameters.

LIMIT SWITCHES Mechanical switches suffers the issue of debouncing. Debouncing occurs when the switch latches up and down when released due to the spring action of the switch. This creates more then one triggered signals, which is problematic. There are two common solutions to this, one is the use of a low pass filter and the other is to use software.

2.3.3 Power Transmission

A mechanical drive, sometimes called a power transmission, is usually used to transmit power and motion from one rotational element to another [28]. The application requires transmission systems that are well thought out and balanced. On one hand, the application will run in a pretty harsh environment, in warm and cold weather, in dirt and moisture and since it is to be mounted on a mobile vehicle travelling in rough terrain, receive shocks and vibrations. On the other, the application requires quite complex mechanics, with many degrees of freedom, something that requires moving parts to be nested on top of each other. Systems like these, 3D printers, CNC machines, Laser cutters and pick and place machines are usually stationary and placed indoors, protected from the outside temperature variations and the shock and vibrations that come from being placed on a moving vehicle.

BELT Belt-driven actuators are common in CNC-machines and 3D printers. They are quieter than other transmission systems and lack the need for lubrication. There exist belts that have teeth on the inside surface, which is called positive belt drive. This reduces the chance of slipping, which increases accuracy.

The disadvantage of belt-drives is that they must be properly tensioned to function and they are affected by heat.

In harsh environments, belt-driven actuators have the advantage that they are unaffected by liquid contamination such as water or oil [38]. Most belt-driven actuators can be sealed to avoid the ingress of contamination. One potential problem with using belt-driven linear actuators in this application is that they usually are accompanied by some sort of linear bearing, to limit the lateral movement along the direction of the belt. Since these linear bearings have a high precision they are more sensitive. They have usually not gone through surface treatment that protects them from corrosion and they could jam if too much dirt enters the bearings.

CHAIN The chain drive is durable and strong since it is made out of metal. This enables it to transmit more power than belts. Chains are dependable and easy to repair. If it breaks, it does not snap as a belt-driven system does [39]. There are no slippage occurring during chain-drive and it is not as sensitive to heat.

The disadvantage of chain-drives is that they require lubrication to run smoothly. Some alternatives runs without lubrication, but they are more expensive.

LEAD SCREW Lead screws are used for transmitting force and/or positioning by converting rotary to translational motion. The most popular lead screws are the Acme and stub-Acme threads e.g. symmetric trapezoidal threads. Lead screws can have one or multiple starts, increasing the number of starts increases the lead thus increasing the translational velocity of the nut for a given fixed angular velocity of the screw. The pros of using lead screws include:

- Quiet operation.
- Small moving mass and small packaging.
- Availability of high helix angles resulting in very fast leads.
- Availability of very fine threads for high resolution applications.
- Possibility of self-locking to prevent the drive from being back-drivable, thus eliminating the need for a separate brake system.
- Low average particulate generation over the life of the system.
- Elimination of the need for periodic lubrication with the use of self-lubricating polymer nuts.
- Possibility to work in washed-down environments.
- Compact size, which make it especially suitable for space-limited mechanical structure.

Cons of using lead screws include friction-induced vibrations and backlash. Another disadvantage is that screw threads have higher friction than other types of linkages, which leads to lower efficiency. When applying lead screws, energy losses and wear should be considered. When choosing a lead screw it is important to consider the Critical speed, which is the rotational speed that matches the screw's natural frequency, thus causing excessive vibration/resonance. The objective behind the lead screw design therefore should be to keep the max travel speed of the screw less than the critical speed [40], [41].

BALL SCREW In many applications the ball screw serves both as a power and position transmission element [42]. They have very hight efficiency, around 90 percent as opposed to lead screws which have an efficiency of around 30 percent or less [43]. In [44], it is claimed that ball screws are noted for efficiently moving high loads with outstanding accuracy. Further, ball screw are described to consist of a threaded shaft and a nut, and either one can act as the traversing component. Ball screws work in a similar fashion to ball bearings, where hardened steel balls move along an inclined-hardened inner and outer race. Because ball screws often work in environments exposed to dirt and debris, manufacturers should take precautions to keep out contaminants and prevent premature failure. The backlash effect of ball screws can be minimized by pre-loading the transducer (the nut). Pre-loaded ball screws are therefore reliable when it comes to repeatability [42]. However, the rolling elements of ball screws can quickly be destroyed by contamination or shock loads [43].

LINEAR RAILS Linear guides are one of the most basic guides of linear motion systems. The usual components include a carriage or slide that moves over a rail or guide and motion occurs along one axis. The reasons for using linear rails are numerous, but their most obvious benefits over other types of guides are load bearing capacity, travel accuracy, and rigidity. The other important design factors is that these systems can experience considerable friction when in motion.

V-GROOVE WHEELS AND RAILS V-Groove wheels and rails are an appealing option in harsh environments. The 90° edge guide wheel design creates a velocity gradient due to the range of contact diameters of the wheel. With the inner diameter traveling at a lower velocity than the outer, debris is naturally drawn outward. This velocity gradient causes a constant sweeping action, thus cleaning debris from the track [45].

2.4 Sensors

In order to successfully automate the reloading seedlings task, the use of appropriate sensors are important, these are presented below.

2.4.1 *Sensors for Transmission feedback*

HALL EFFECT SENSOR A Hall effect sensor measures the magnitude of a magnetic field. It outputs a voltage that is proportional to the magnetic field strength through it. The working principle of a hall effect sensor is demonstrated in Figure 14.

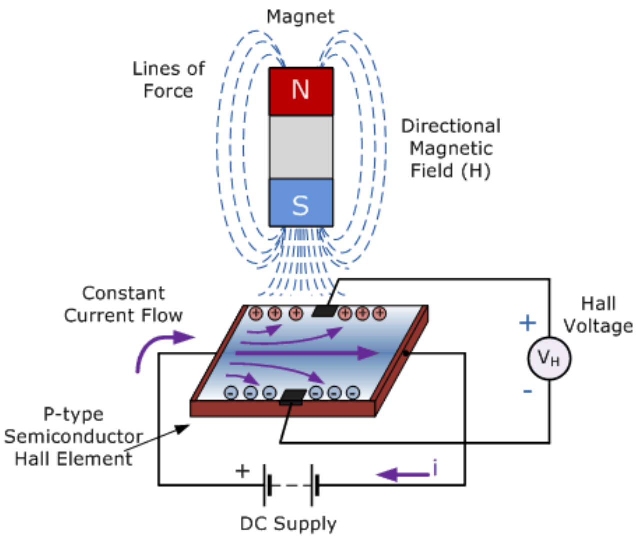
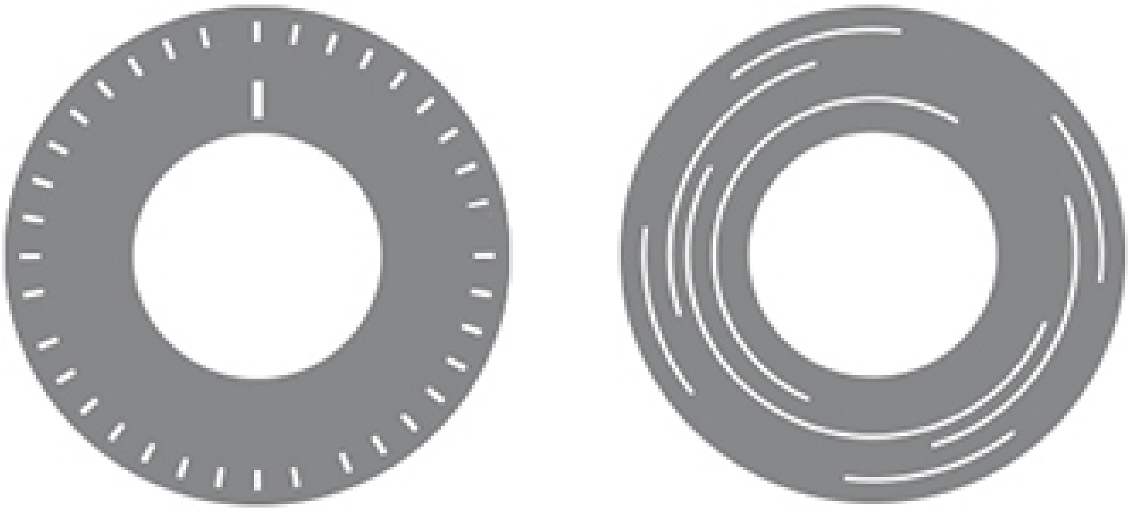


Figure 14: Hall effect sensor [46]

The voltage variation can be detected with a micro controller. The sensor with threshold detection makes it suitable to use as a switch. The advantage of using this in a harsh environment is that they are not affected by dust and humidity, which would likely be very useful characteristics in a forest setting. Furthermore, it does not rely on contact as a mechanical switch which reduces the wear over time.

ENCODERS An encoder is a device that provides feedback, it translates mechanical motion to an electrical signal. The signal can then be processed to determine position, speed, count, or direction [47]. Encoders can be divided into two subgroups, absolute and incremental encoders.



(a) Incremental encoder (b) Absolute encoder

Figure 15: Encoder types [48]

Incremental encoders provide a signal when something has changed. It does not specify the actual position, only that it has changed. Incremental encoders are simple and consist of only a few components, which makes them very cheap. [49] Absolute encoders have unique markings as shown in Figure 15b. All the positions have a unique code, it outputs a word of bits. If the power is lost (or at startup), this code will indicate the encoder position [48]. Robustness is more important for the solution than keeping the price down, which might indicate that an absolute encoder would be more relevant.

MAGNETIC ENCODERS A magnetic encoder consist of a sensor and a magnetic disc with poles around its circumference. The sensor detect the change of the magnetic field.

OPTICAL ENCODERS Optical encoders has a light emitter and detector. The source and detector is mounted as shown in Figure 16. The disc has opaque and transparent segments, the light gets interrupted as the shaft rotates.

To determine direction, the light beam can be split into two parallel beams resulting in two phases. The relative phase between the two determines the direction [50]. Since the environment is rough and dirty, and the machine might be used in both daylight and the dark, optical encoders might not be the best available approach to transmission sensing.

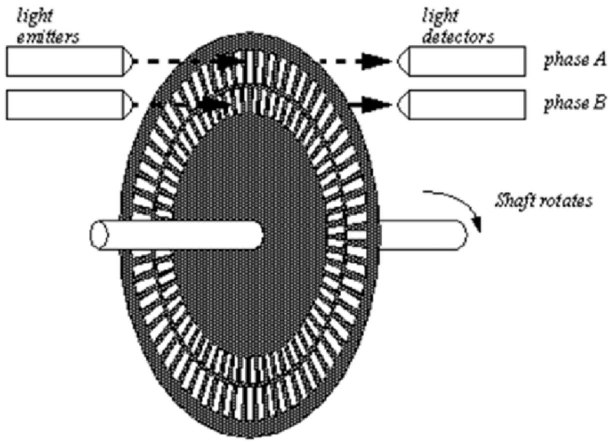


Figure 16: Optical incremental encoder [51]

2.4.2 Proximity Sensors

Proximity sensors will have multiple applications within the system. For example to detect if a seedling is gripped properly, or to detect weather a seedling is present in a specified location. The selection of sensors must consider the size, since seedlings are small and come closely stacked in the trays. Multiple types of sensors such as Capacitive, IR sensors, and Ultrasonic sensors were tested for plant detection, and are presented in this section.

CAPACITIVE PROXIMITY SENSOR Capacitive proximity sensors are non-contact devices that can detect the presence or absence of virtually any object regardless of material. They utilize the electrical property of capacitance and the change of capacitance based on a change in the electrical field around the active face of the sensor. The change in capacitance created by a moving plant can be regarded as relatively small. This makes it difficult to notice the capacitance change and thus difficult to detect if slippage has occurred during the extraction of the seedling. Therefore, making it possibly unsuitable for detecting extraction slippage.

IR PROXIMITY SENSOR IR, in short for infrared, detects the presence of an object by emitting a beam of infrared light. It works similarly to ultrasonic sensors, though instead of using sonic waves, IR is transmitted. It consist of an IR LED that emits, and a light detector for detection of reflection. It has an in-built signal processing circuit that determines an optical spot on the Position Sensitive Device (PSD).

The biggest drawback of this type of sensor was it requires line of sight between transmitter and receiver for detection. Since the sensor was designed to be placed inside the cups, it was be exposed to direct dirt particles and granuels which could obstruct the line of sight of the sensor and therefore make it useless. Because of these reasons, the IR sensors could not be used.

ULTRASONIC PROXIMITY SENSOR An ultrasonic sensor is an instrument that measures the distance to an object using ultrasonic sound waves. It uses a transducer to send and receive ultrasonic pulses that relay back information about an object's proximity. By calculating the travel time and the speed of sound, the distance can be calculated. They sense most materials (metal, wood, plastic, glass, liquid, etc.) and are unaffected by color, transparency, shininess, or lighting conditions.

2.4.3 Force Sensors

The successful gripping and extraction of seedlings from their respective cultivation trays may be verified using sensors. A viable option for this application could be force sensors. Force sensors are used to detect the forces generated by or applied onto a manipulator end effector. It can be used to control the force generated by robot manipulators, and it is effective in laborious work as well as restrictive and coordinated work. In this project, using pressure sensors is a prospective solution to control the gripping of the seedlings in a precise manner.

The ideal implementation of a pressure sensor in a robot is a stress detector applied on to the contact surface of the gripper. The most commonly used sensing element is a piezoresistive strain gauge as seen in Figure 17. The sensor data of the strain variations may be used to calculate the pressure applied on the gripping contact area to ensure the adequate amount of normal force is being applied for a successful extraction.

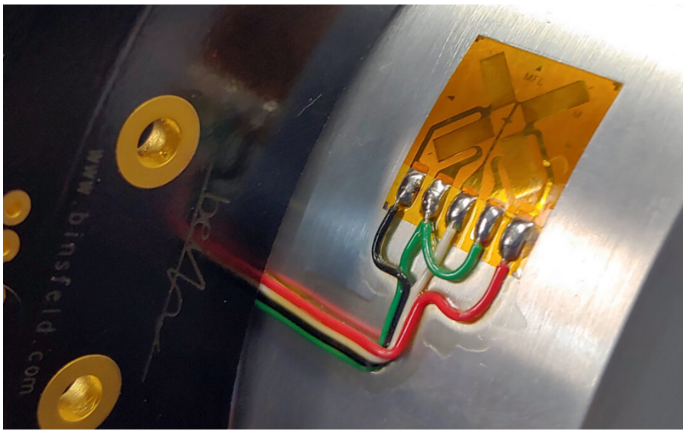


Figure 17: Application of a strain gauge [52]

The sensing part of the strain gauge consists of the bending of folded cantilever beams. The beams are actually resistance elements, which is the sensitive part of the strain gauge that measures the strain of the component. The overall width of the sensor is relatively thin which is an advantage if placed on the seedling gripping contact area. The sensor is small in size and light in weight. It also has good insulation properties, moisture resistance and heat resistance, which are important characteristics for outdoor tasks. Moreover, the strain gauge has high resolution which is able to measure relatively small strains with error generally less than 1 percent. Moreover, a fact making this sensor an attractive option is that mostly strain gauges are inexpensive and vary in its geometric arrangement, which is suitable to be used in large quantities.

Applying infrared proximity sensor could help the control system perceive if the gripper extracted the seedlings successfully. It may also be conductive for confirming that the cultivation trays are in the right location.

2.5 Software

Relevant theory and descriptions for the software related development of the *Reloading Seedlings* system is presented.

2.5.1 *Message Queuing Telemetry Transport*

Message Queuing Telemetry Transport (MQTT) is a lightweight protocol with publish-subscribe topology. It can be used with any network protocol that is ordered, lossless and bi-directional and most often TCP/IP is used [53]. It is designed to be lightweight for restricted network bandwidth. This is good when considering the real world scenario where the machine would only have a mobile network or satellite internet connection depending on the coverage of the mobile network.

Sending and receiving messages over these topics is handled by a so called broker, which can be seen as a server. All clients then connects to this broker to exchange these messages. There are several broker one can use, one of which is Mosquitto [54]. This broker is open source and provides library for several programming languages.

2.5.2 *Control Systems*

The extent of automation within the tree-planting industry has been, at best, semi-automated. The reloading of cultivation trays has at the time of this paper never been fully automated, human interference has always been needed. This leaves little precedence as to which control systems and appropriate sensors best emulate the manual labour and tasks performed when reloading said trays. In this section, various control systems potentially applicable to the solution of the research problem are described.

Given the demanding environment the automated planting machine would have to operate under, the control system of the manipulator may need to account for the vibrations endured to ensure the appropriate identification and handling of the seedling. A system accounting for vibrations for a three degrees of freedom flexible robot is presented in a paper by Feliu et al. [55]. The control system is composed of two nested multi variable control loops. An inner loop and an outer loop: The inner loop is the motors position control system, the outer loop is the position control of the tip of the robot. By utilizing these nested loops vibration cancelling is achieved, where the vibration is caused by the robot manipulator's structural flexibility during movement. This scheme achieved successful trajectory tracking even with a variable payload. Flexible manipulators are not popular for terrestrial operations and perhaps not suitable when transversing rough terrain, the aspect of vibration control may still hold relevance even for even for structures that are not flexible. The control system showed stability and robustness in simulations whilst having uncertain motor parameters without saturating the actuators. It is based on simple linear controllers that can be tuned easily and produces good trajectory accuracy. [55]

The fragility of the seedlings have been stated before due to the importance of handling them safely. One way of ensuring this is through the implementation of force control in the gripper. This can be obtained with force sensing resistance which are robust (including vibration insensitive) [56]. Data feedback from such a sensor alongside PID control can enable safe grasping of object by empirically obtaining the control gains [57].

The control system for a cartesian robot may also be equipped with a nine points calibration method using machine vision. Said method provides good accuracy and efficiency for handling and high precision requirements. [58]

2.5.3 Single Board Computers

A Single-Board Computer (SBC) is a complete computer built on a single circuit board, with microprocessors, memory, input/output (I/O) and other features required of a functional computer. Unlike a desktop personal computer, SBCs often do not rely on expansion slots for peripheral functions or expansion. It reduces a system's overall cost, by reducing the number of circuit boards required, and by eliminating connectors and bus driver circuits that would otherwise be used. By putting all the functions on one board, a smaller overall system can be obtained. [59]

2.5.4 Microcontrollers

Microcontroller Unit (MCU) boards differ from SBC's in various attributes, some of the attributes are the processing power, operating system capabilities and I/O interfaces. The effective use of an Arduino could be used as a slave to the master SBC. It could be used in scenarios where a SBC is difficult to reach, or some section of the machine needs an isolation. The communication between them can be through SPI or I^2C as it is commonly supported by both the boards. One common MCU is Arduino, which is an open-source software and hardware company that produces MCU boards with the same name.

3 METHODOLOGY

The methodology that was carried out to achieve the final prototype of the *Reloading Seedlings* system is described in this section.

3.1 Project Management

To manage the work several project management tools were used. Internal communication in the team took place in a Slack Workspace which was created for the project. In Slack, several channels were created with different purposes, for example discussing design issues and posting meeting notes. Trello was used to organize the work during sprints. During the project several sprints took place, mainly during integration and during report writing. Weekly meetings were held where every teammate filled the rest of the team in on what they had been doing the last week and what they planned to do next. During these meetings, designs and upcoming deadlines were also discussed. Meeting notes were taken and posted in Slack.

RISK ASSESSMENT In order to maintain a good workflow throughout the autumn when realising the seedling reloading subsystem, a risk assessment was made for conflict prevention. This can be seen in Table 2.

Table 2: Risk assessment for the project during the fall

SELECTION OF DESIGN CONCEPT NOT FEASIBLE FOR LARGE SCALE PRODUCTION	Establish twice a month updates to stakeholders to inform of component selections and design concept being followed to avoid unfeasible creations.
INACCURATE PRIORITIES	Implement the use of status-reports to confirm project is on the right track with supervisor. Set up meeting or send status report to stakeholders for confirmation.
PROJECT TEAM MISUNDERSTAND SCOPE	Verify with the supervisor and stakeholders early in the project that the defined scope is realistic and correct.
UNREALISTIC DEADLINES	Once a week, each member must participate in checking and marking progress or completion of tasks.
PROJECT MEMBER DOES NOT WORK ON THE PROJECT	Regular status updates about progress on tasks. Each subgroup should be held responsible for the assigned tasks. Continuously updating the created Gantt chart and having weekly meetings where the subgroup's work is presented to the entire group will keep track of everybody's contribution. The individual contributions in the report(s) will be documented to ensure distributed workload.
NOT FINDING TIMES TO WORK AND/OR MEET UP	Schedule meetings in advance and whoever cancels a meeting has to propose a new meeting time within half a week. Alternatively, propose a task to do in compensation.
ORDERED PARTS DELAYED OR CANCELED	When ordering parts there is always the risk of delays or sometimes not receiving the items at all. Place orders well in advance and before ordering check the current stock to avoid delays.

3.2 Project Organization

A requirement for the course was that every person in the team would be knowledgeable and have worked with all parts of the system, including mechanical-, electrical- and software design. In order for this to work efficiently the system was split into three different subsystems. The Gripper, the Buffer and the Gantry, each of which contain mechanical, electrical and software parts. The team was split into three subgroups, each having the responsibility of a single subsystem, although the responsibility was split the team has worked together and helped each other over the boundaries of the subsystems, having weekly meetings to discuss the different parts of the system so that everyone is always knowledgeable of all parts of the system.

During the literature study and state of the art, the team listed some major topics related to the project. These topics were further sorted depending on the co-relations between them and then summed up, leaving the team with three major sections containing multiple topics to be researched on. Each member chose one of the sections based on self interests and worked in sub teams of three.

3.3 Budgeting and Costs

All part costs were recorded in a Google docs spreadsheet for easy access by all group members. The cost for water jet and machine workshop labour was estimated to be 400 SEK and 500 SEK per hour respectively. The final cost for the complete machine can be seen in Appendix M.

3.4 Mechanical Design

For Mechanical design, the CAD (Computer Aided Design)-tool Onshape was used. The choice of using Onshape even though most of the team was familiar with the CAD-tool Solid Edge prior to the course is motivated by the significant ease of collaboration that Onshape provides. Onshape works in the web browser and stores everything in the cloud, allowing for several people to work in the same project and even the same file at the same time with ease. This was deemed a large advantage for this type of project as there is a need to sync files often.

Larger structures of the system were designed with aluminium profiles and accessories like T-nuts and angle brackets. This allowed for quick assembly and expansion as the slots in the aluminium profiles can easily be used to adjust the positioning of different parts by sliding them in as well as ease of adding new parts by connecting them to the slots.

For smaller structures, an iterative prototype design approach was used. 3D printed PLA and laser cut acrylic were used in the first iterations of the designs. For prototype parts where the geometry allowed it, laser cutting was preferred over 3D printing as the manufacturing process is much faster and less error prone. Most of the final parts were water jet and made in aluminium or steel. When designing with manufacturing process in mind, it is also smart to prototype in acrylic as very little changes are required when moving to aluminium. Designing for 3D printing is very different and more changes are required when changing a design from a 3D printed one to a water jet one. Parts that required complex geometry are 3D printed even in the final design.

3.5 Electrical Design

For electrical design a combination of computer software was used. Falstad [60], which is an online circuit simulator suited for simpler systems, was used to test out the circuits. For the schematics and PCB board layout Eagle CAD 9.6.2 was used. The Printed Circuit Board (PCB)'s were then milled from double sided copper board and components were manually soldered. As this was a manual process, human errors can always occur and the milling machine is not always as precise as one might expect. Therefore the boards were always thoroughly inspected at every step in the process for shorts to ground and that all components had intended connections with the help of a multi-meter set to continuity mode. For a good topology layout the PCBs were placed in close proximity to the system they were intended to control or supply with the desired electrical signals. Cabling to these subsystem were manage from one central electrical cabinet.

3.6 Software Design

Software design was intended to be as modular as possible with focus on useful APIs from every subsystem. The code was written in a way where each major function could be tested on its own without the actual hardware.

Git and Github were used to collaborate on software design. An organization was set up on Github where three teams were created, Gripper, Gantry and Buffer. Each team was given a repository with the same name. Each team had direct write access to their repository and read access to the other repositories. If a person from one team added code to a repository of another team, a pull request had to be made and a person from that team had to approve the changes before they were pulled into the repository. Gitkraken, a Graphical User Interface for git was used to manage the activity on Github.

3.7 Simulation

Simulations were done in several different ways, simple kinematics simulations were done in Onshape, to make sure that assemblies moved in the way they were intended. Electrical circuit simulations were done in Falstad [60]. More complex simulations of mechatronical system dynamics were conducted in Simulink/Simscape. Software simulations were done by conducting unit tests.

4 IMPLEMENTATION

This section encompasses the various design proposals that were considered for the final solution. These are described and the chosen solution justified. The simulations performed are included and a system overview of the solution is provided. Additionally, for better insight a more detailed description of the final design on a mechanical, electrical and software level are depicted.

4.1 Design Proposals and Evaluation

During the spring term several different concept designs were made. This section describes these design proposals. Three mechanical designs are conveyed for the overall system and for the gripper subsystem. Furthermore, an overview of the control architecture and hardware choices are described. Section 4.2 describes the final design, if not interested in the different early design concepts, one can skip to said section.

4.1.1 Overall system

In the following paragraphs, four different concepts design, describing the overall system are presented.

LARGE PICKING SYSTEM AND BUFFER SYSTEM One design proposal is to keep the cultivation trays in the racks that they come in and have a large picking system that would be able to grab any of the trees. It would consist of three linear actuators, one in each direction, like a 3D printer, and on the out most part there is a parallel gripper. The linear actuators can be driven by either belt or chain. The proposed system can be seen in Figure 18.

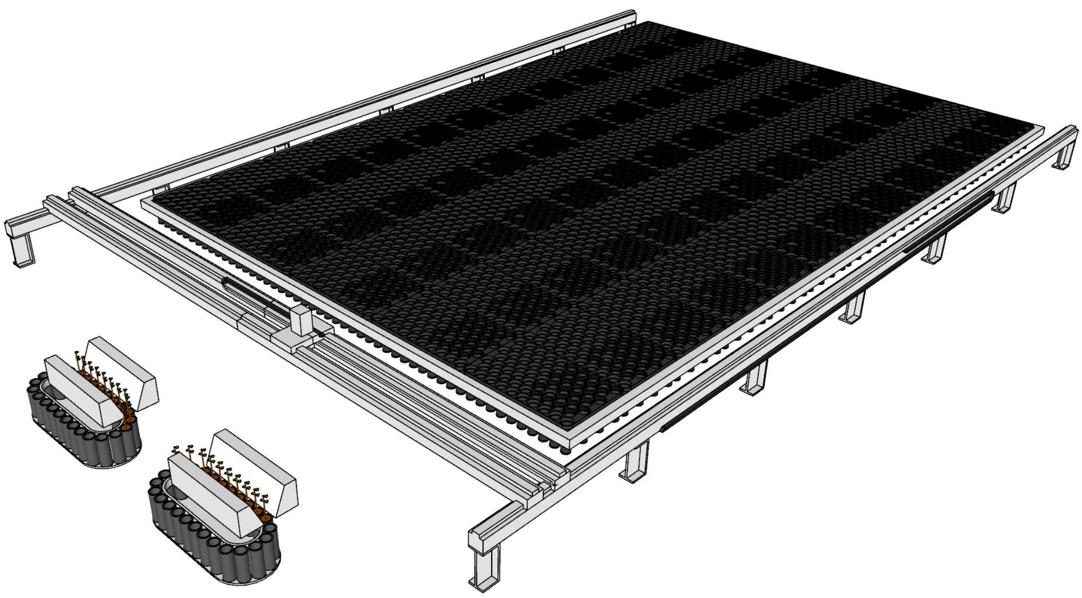


Figure 18: The proposed large picking system

This system would grab one or several plants each time and transfer them to a buffer system. The buffer system could be a carousel-like chain conveyor like the one in the Plantma X. The proposed buffer system can be seen in Figure 19. The angled walls are there to steer the plant into the cups in case of a positional or angular misalignment.

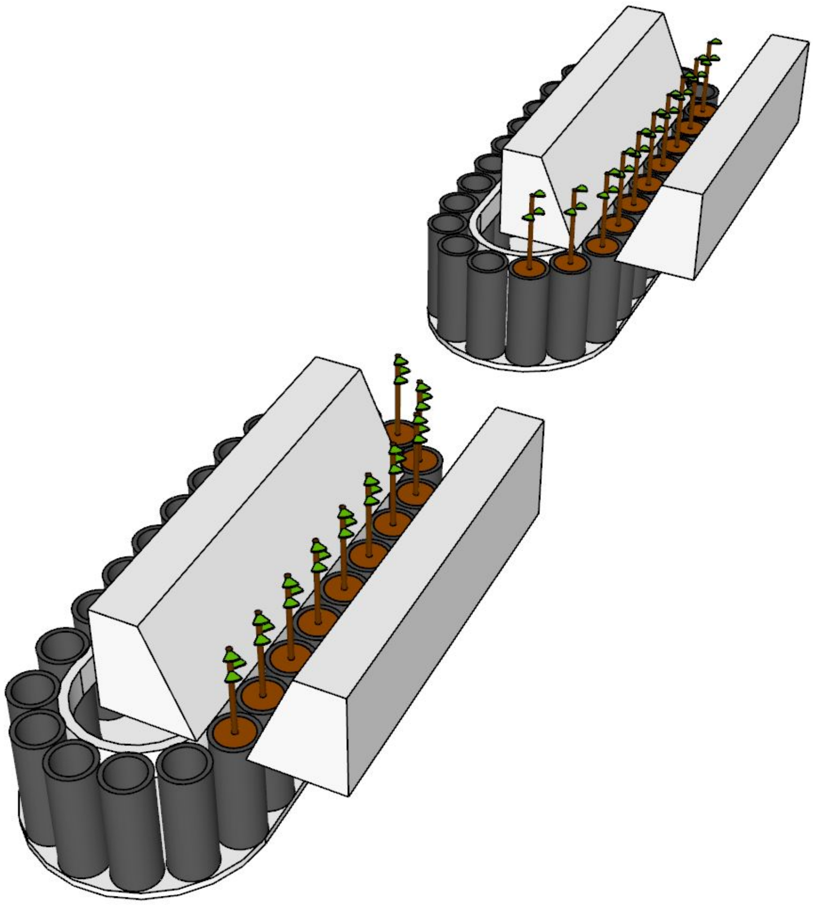


Figure 19: The proposed buffer system

The advantage of this system is that the loading of the cultivation trays onto the machine could be handled very fast as the entire rack could be placed on the machine by an operator with a forklift. It also has fairly few moving parts. Grabbing several plants at once adds complexity to the system, however if the system grabs only one plant each time, it could have significant problems in fulfilling the speed requirements since the weight of the system itself will be quite high due to its size and the travel distances can be quite long, especially when grabbing the plants on the opposing side of the rack.

LARGE MULTI-PLANT PICKING SYSTEM AND BUFFER SYSTEM A variation of the Large picking system and buffer system is to have the gripper be a multi-plant gripper. Allowing for the gripper to pick several plants at once. This brings an overall speed upgrade to the system and makes for a better utilization of the buffer system as the buffer system can be refilled with several plants every time and then output one plant at a time. Having a buffer system with only a single plant gripper would limit the output speed to the speed of the large picking system. Further, a single plant gripper system would only see the benefit of a buffer system if the use case would be to plant intermittently so that there would be a time slot when no trees are planted and the buffer system could be refilled. The downside of a multi-plant gripper is that it is a more complex system.

SMALL PICKING SYSTEM AND CULTIVATION TRAY CONVEYOR SYSTEM One design proposal is to use the same type of chain conveyors used in the Plantma X to deliver the trees to the planting arms and simply replace the operator that fills the cups of the conveyor with trees. The replacement would be a Picking system in the form of a three dimensional linear actuator system, like a 3D printer, with a parallel gripper attached to the end effector. In this design proposal the picking systems reach would only span one single cultivation tray in order to cope with speed requirements.

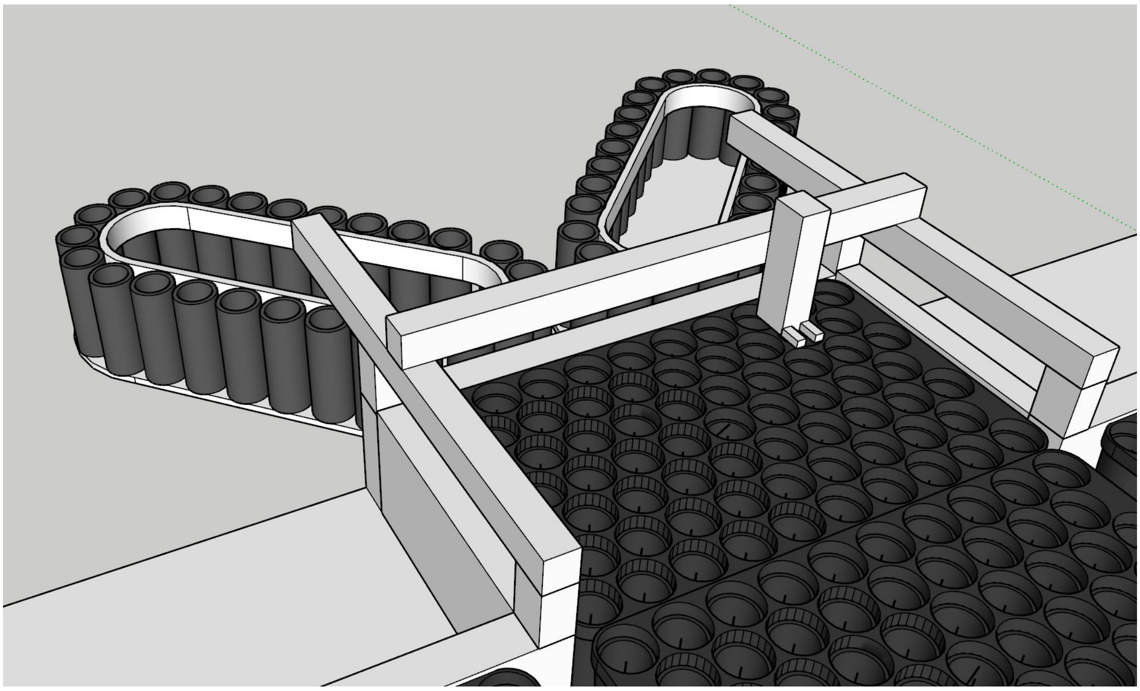


Figure 20: The proposed small Picking system engaging with one tree cultivation tray

The system would grab one plant from a cultivation tray at a time, by the base of the tree stem and place it into one of the cups of the carousel-like chain conveyor. When the cultivation tray is empty of trees, it will be removed from the picking zone by a trap door opening or similar. When the trap door opens, the cultivation tray can fall down and stack on each other or fall down on a return conveyor. This design proposal also includes a conveyor system that handles the cultivation trays and pushes a new cultivation tray into the picking zone, it can be seen in Figure 21.

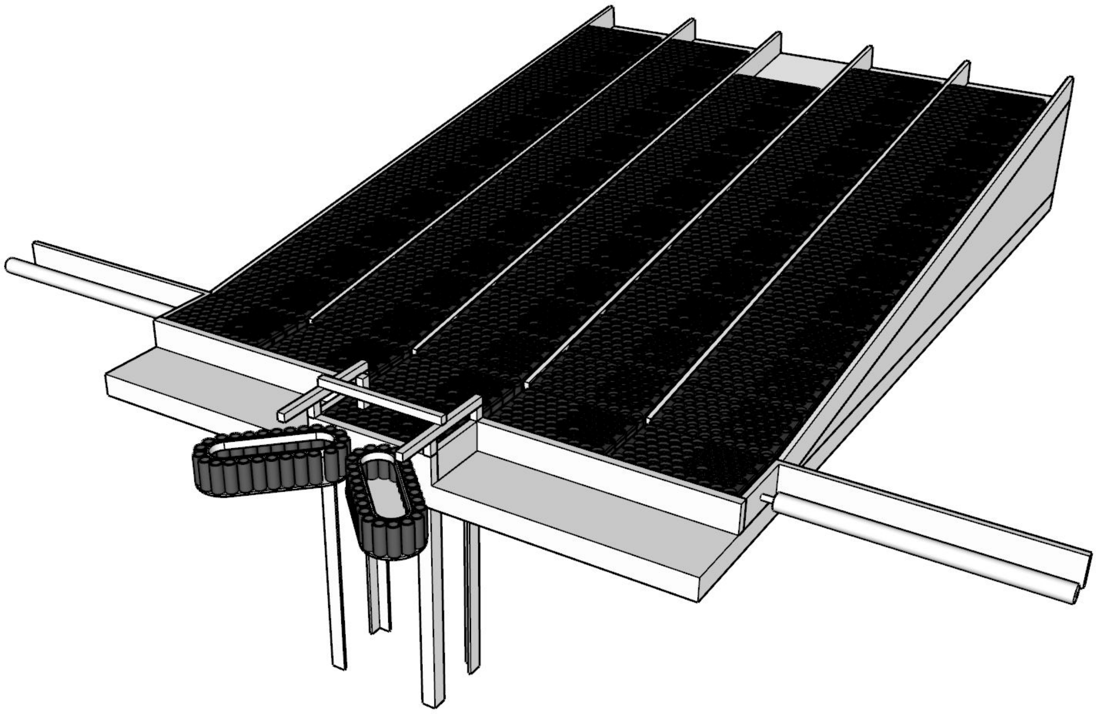


Figure 21: The proposed conveyor system that transports a cultivation tray of trees onto the picking station

This system could be built in many ways, with roller conveyors, chain conveyors, pushers and so forth. The system in the pictures uses tilted, non driven roller conveyors, where the cultivation trays are propelled down towards the picking zone by gravity together with two pushers that handle the rows of cultivation trays that are not directly aligned with the picking zone. In Figure 22, one of the actuators pushing on a cultivation tray can be seen, as well as the cultivation trays of the center row all having been dropped down into a stack beneath the picking zone.

Figure 22: The proposed small 3D linear system engaging with one tree cultivation tray

This design proposal does not use the racks that the cultivation trays come in. This adds some manual labour. Instead of simply putting the entire rack on top to the machine with a forklift, an operator would have to transport each cultivation tray from the rack onto the machine. However, since the cultivation trays are light, the task not performed that often, and won't take very long each time, this is not considered a problem. The benefits of this design is that it allows for a fast picking system as a larger one might have problems coping with the speed requirements. Removing the rack can also be seen as a benefit as the location of a cultivation tray from within a rack could be hard to pinpoint, due both to deliberate clearance and the wide tolerance span that large welded structures often have.

Another solution for how to manage the cultivation trays that are not directly in the path of the picking system would be to have the picking system move instead of the trays. When one full row of cultivation trays has been emptied of plants the picking system would move one step so that it is in line with a new fully loaded row of trays. This can be managed by having the picking system on some sort of frame so that it could move left and right. For this to work the buffer systems would either need to move with the picking system or the buffer system could span the whole length that the picking system can move so that it can be stationary. Figure 23 shows such a system with a stationary buffer system. The rows of cultivation trays that are not currently handled can be held in position by a spring loaded stopper that is pushed away by the picking system when it switches to that position. Using this method makes it easier to have a simple gravity propelled return conveyor tilted the opposite direction beneath the picking system since it can drop trays at different positions.

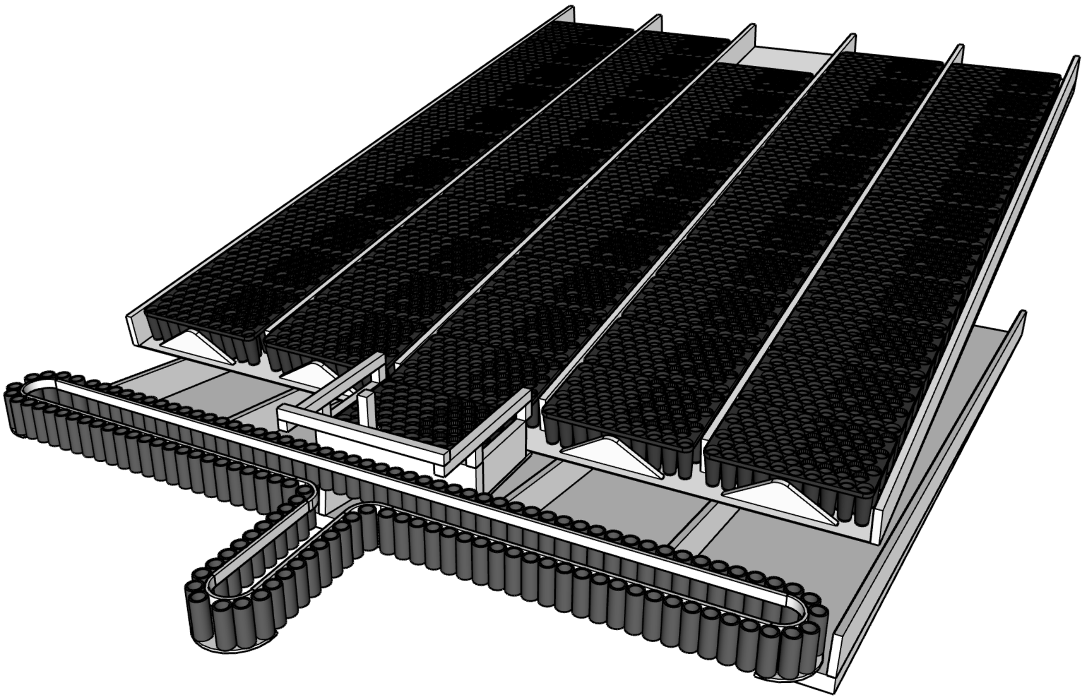


Figure 23: An alternative concept with a conveyor system and a mobile picking system

CULTIVATION TRAY GRIPPER AND PLANT GRIPPER A design proposal is to use a two gripper system, each gripper based on the Figure 13, the "3D printer" linear actuator system setup. Each gripper would be moved in X,Y,Z direction by linear actuators. For the cultivation tray gripper to lift up the cultivation tray, some alternative proposed solutions exist. Modifying the cultivation tray to have loops that can be hooked into, a clamping system that grabs hold on the cultivation tray edge frame or electromagnets that can lift the frame. An overview of the proposed design can be seen in Figure 24.

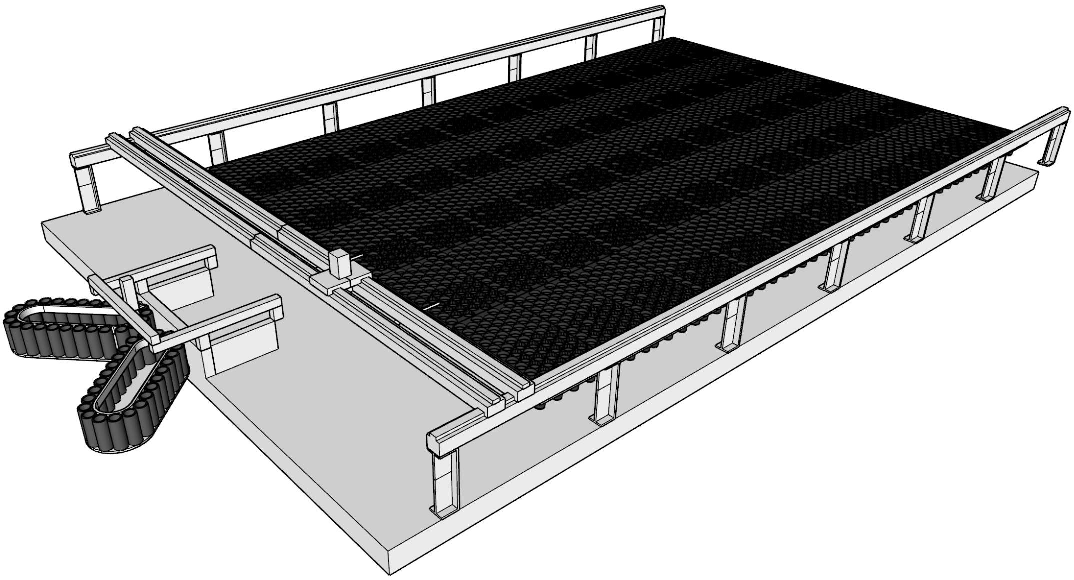


Figure 24: The proposed double gripper system

The system will start with all cultivation trays in the frame, and no cultivation tray in the area for the small gripper. When the system start, the large gripper will pick up a cultivation tray, as can be seen in Figure 25, and deposit it in the designed holder. From here the small gripper can pick up one, or several, plants and drop the plant into the conveyor system, Figure 26. Which transports the plant to the plantation device. When the cultivation tray is emptied, the large gripper picks it up and puts it back in the now empty spot in the cultivation tray where it stood originally, before picking up another cultivation tray and delivering it to the small gripper. The advantage with this delivery system is that compared to other concepts it requires less added structures to the frame. But a disadvantage is that there can be down time in the picking/planting while the cultivation tray are being replaced.

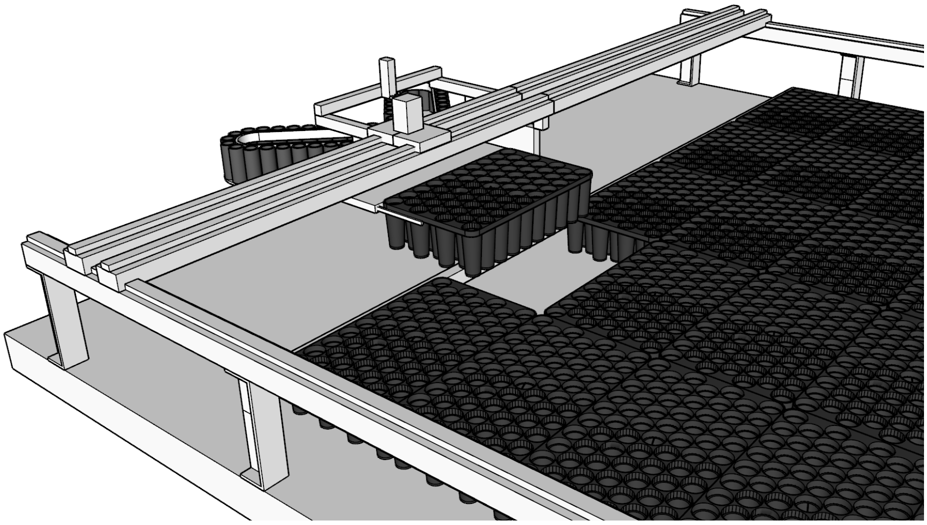


Figure 25: A cultivation tray being carried in a gripper

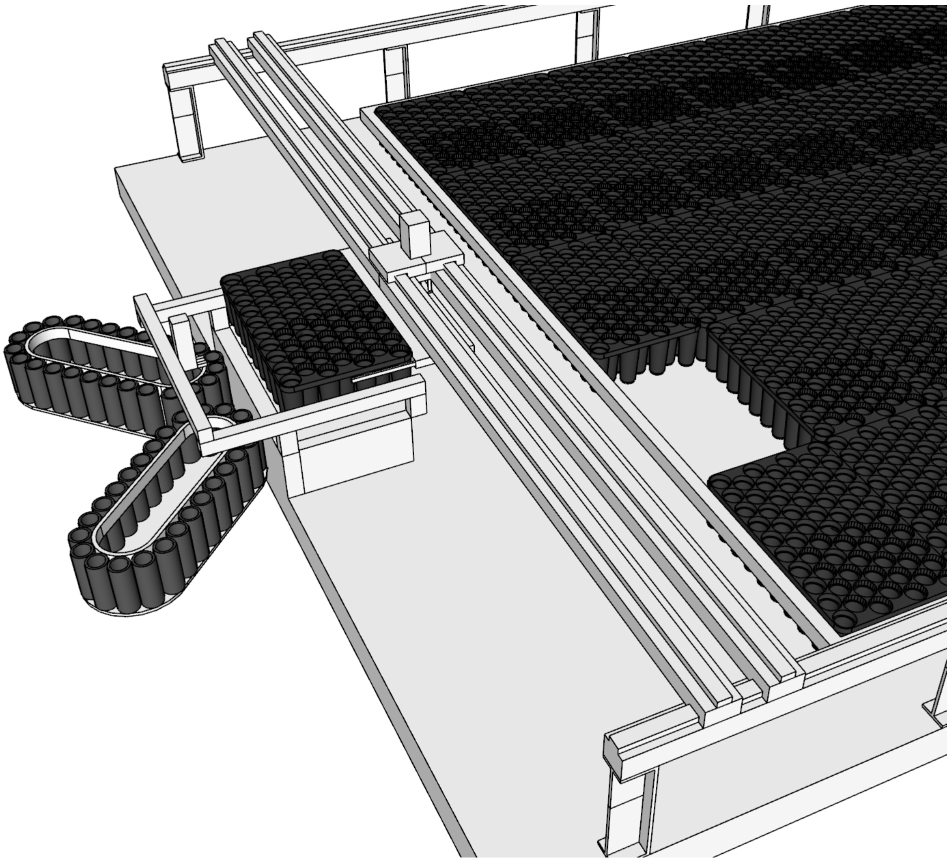


Figure 26: A picture of the cultivation tray in the area for the small gripper

EVALUATION To make a design choice, the different concepts were discussed and compared on several metrics. In Table 3 the result of these metrics can be seen.

Table 3: Evaluation between concept designs

Metrics	**Large picking system and buffer system**	**Large multi-plant picking system and buffer system**	**Small picking system and cultivation tray conveyor system**	**Cultivation tray gripper and plant gripper**
Complexity	Low	Medium	Medium	High
Speed	Medium	High	High	High
Level of Autonomy	Full	Full	Semi	Full
Items of complexity	Plant gripper	Multi-Plant gripper	Plant gripper, Conveyor	Plant gripper, Tray gripper

Due to the limited time and resources, keeping the complexity of the system low was of great importance. The "Cultivation tray gripper and plant gripper" option is particularly complex as it required two different grippers and two different gantry systems. It also required one extra degree of freedom on the tray gripper in order to rotate it 180 degrees. For this reason it was ruled out.
As mentioned earlier, the cultivation trays are stored in steel racks when they are brought to the machine. All systems except for the "Small picking system and cultivation tray conveyor system" allows for these steel racks to be placed directly on to the machine without any manual handling of individual cultivation trays. The complexity of the system also lie in the large conveyor system. A complex system that is also large is a disadvantage as it will cost more time and money to iterate on the design. The combination of the complexity lying in the large structure and the fact that it could only be semi automated was the reason this system was ruled out.
In the end the choice stood between the two Large picking systems. The question boiled down to having either a single plant gripper or a multi-plant gripper. In the end a multi-plant gripper was chosen, to cope with the speed requirements of the system and to efficiently utilize the buffer system.

4.1.2 Gripper subsystem

For the mechanical design of the gripper three different concepts were created and evaluated. The different concepts were all inspired by the Risutec APC machine where a vertical motion from the actuator enables horizontal displacement of the gripper fingers. To simplify the design in an effort of avoiding control complexity it was also decided for the multiple grippers to have a common actuator. To achieve this the five individual grippers were mounted onto the same plate that is displaced vertically by the actuator with the help of a lead screw.

PROPOSAL 1 In this proposal, a gripper controlled by slide rail was proposed. As shown in Figure 27, the gripper fingers can move horizontally in two paralleled guide rails while their position is determined by the actuation boards. There are five actuation boards fixed on a beam side-by-side, each board can fix the position of two groups of fingers. A motor is fixed on the main frame of the gripper with a threaded shaft going through the beam. When the gripper receives the 'start' instruction, the motor rotation will be converted to the vertical motion of the actuation boards. When the actuation boards go down, the slots on the boards force the fingers to move closer to do the clamping job.

One of the advantages of this proposal is its assemble-friendly design. All the parts of the gripper is modularized making it easy to assemble and replace. The overall structure is rather compact and light. The modular design also makes the model more adjustable. For example, if the number of grippers needed to change to meet different requirements or varying the distance between each gripper for cultivation trays of varying dimensions, then only the beam and mount or several pieces of the actuation board would need to be replaced. However, this design makes the gripper totally exposed to air. Considering its working environment, dust and other debris may go into the rail and make the fingers get lodged. Also, dissimilar from the CAD model, the cross slides and rails on the real product may also cause lodging problems.

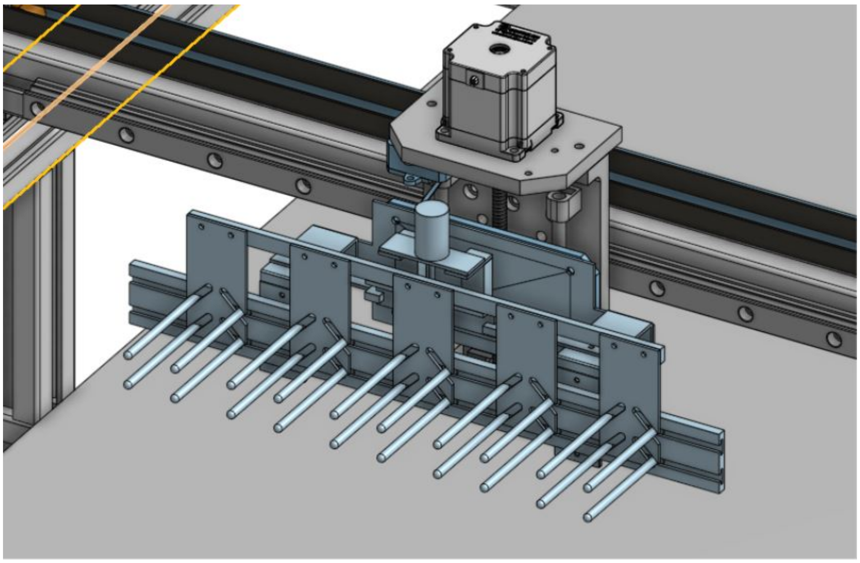


Figure 27: Proposal 1 - Slide rail drived gripper

PROPOSAL 2 In proposal 2, a gripper implementing link mechanism was designed. As shown in Figure 28, the motor drives an actuation plate that is displaced vertically. The gripper fingers are connected to the linkage mechanism which in turn are mounted onto the actuation plate. Similar to proposal 1, this design also uses a lead screw to transmit the motor rotation for the displacement. When the actuation plate moves downwards, each set of two fingers move closer until gripping the seedlings. Linear shaft bushings are located on both side of the gripper to limit its motion path.

Most of the parts in proposal 2 are standard cuboids and cylinders. Less complex structure (e.g. metal sheets) leads to an alleviated transition into prototyping. The linear bushings and the linkage mechanism with revolute pairs ensure motion smoothness. The only short coming is that this proposal is the heaviest one among the three proposal with maximum size. In order to hold this gripper, the power of the motor need to be considered carefully. Although the shell encompassing the subsystem gives good protection from the environment, it also makes the overall assembling more difficult.

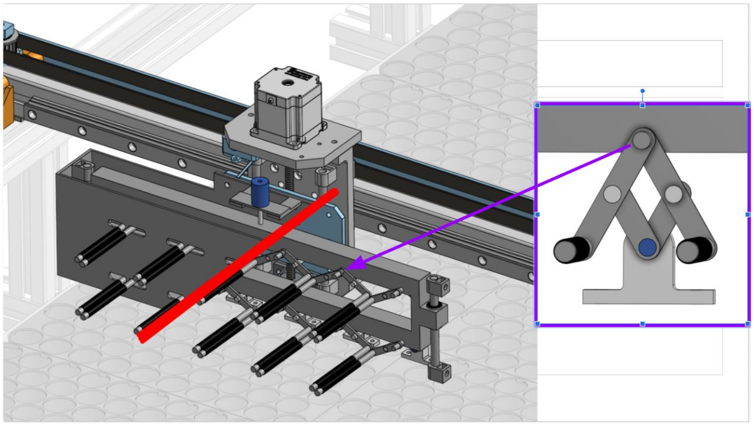


Figure 28: Proposal 2 - Linkage drived gripper

PROPOSAL 3 The third concept proposal utilised a curved rail for the transition from vertical to horizontal movement. As before all the grippers are connected with a beam that is moved up and down by the actuator with the help of a lead screw. The gripping fingers are connected to the actuation beam through a rail. When the beam moves up and down the fingers will slide on the rail pulling and pushing the fingers to open and close. The curved rail is meant to give a smoother motion to the gripping mechanism. The main issues with this design is that it is fairy complex and the small dimensions that are needed for the gripper pose a problem.

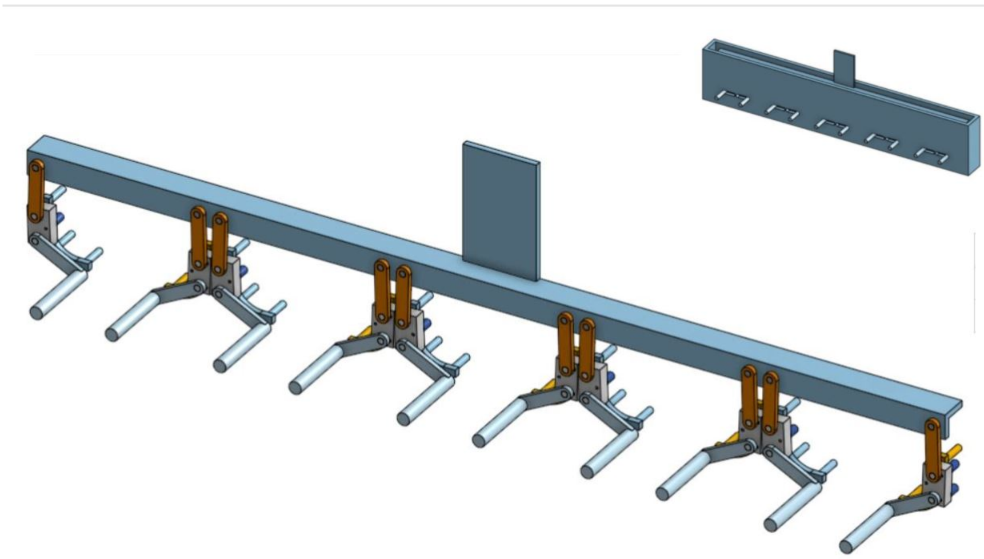


Figure 29: Proposal 3 - Curved rail gripper

EVALUATION In order to decide on a concept, a weighted design evaluation was executed represented in Table 4. All the concepts were evaluated based on the characteristics that were deemed the most important for this project. Each characteristic was weighted on a scale of one to three, with three signifying most important. The proposals were also assessed on a scale of one to three with three being the best in terms of the listed characteristics. The total score of each proposal was calculated by summation of the characteristic score times the weight assigned to the respective characteristics. This gave the result that the most optimal proposal was Proposal 2, the linkage driven gripper.

Table 4: Evaluation of gripper design proposals considering weighted desirable characteristics

Characteristics	Weight of the characteristic	Proposal 1	Proposal 2	Proposal 3
Design complexity	2	2	3	1
Weight (kg)	1	2	1	3
Stability	3	2	3	2
Debris insensitive	2	1	3	3
Compactness	2	3	3	2
Displacement smoothness	3	1	3	3
TOTAL		23	37	30

4.1.3 *Buffer subsystem*

The buffer was originally conceptualized as a rotating system, but during the initial phase of the fall term, the system was further evaluated. Two concepts were explored; a rotating system and a linear system. These are illustrated in Figure 30. The purpose of these concepts was to explore the most appropriate work flow with regards to the system, and not so much about mechanical design.

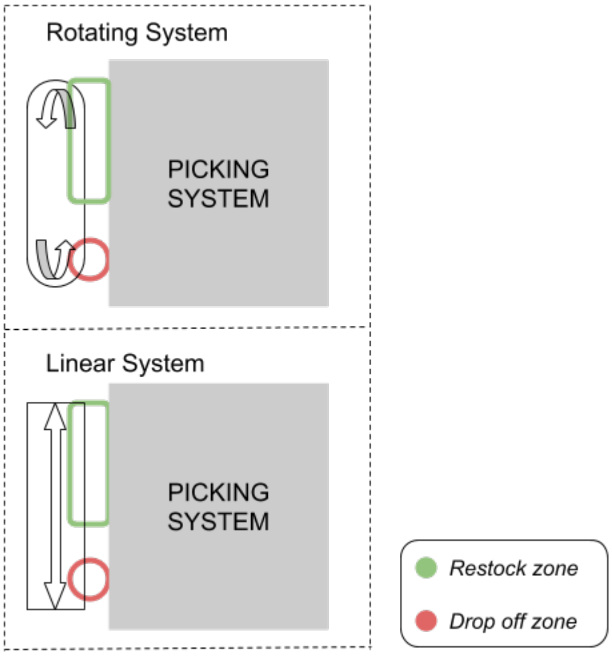


Figure 30: Buffer concepts

The evaluation criterion used, their weight (importance), and the score of each concept can be seen in Table 5. The linear approach seemed better suited for the task, and so the rotating system was discarded in favor of a linear one.

Table 5: Evaluation of Buffer System concepts.

Criteria	Weight	Linear	Score	Rotating	Score
Speed	2	5	10	3	6
Complexity	1	5	5	1	1
Reliability	4	5	20	3	12
Safe handling of seedlings	5	5	25	5	25
Robustness to environment	3	3	9	3	9
Score			**69**		**53**

When the linear concept had been chosen, the functions of the system were further defined:

- The buffer shall have a defined interface with the other subsystems; a restock zone where it can receive seedlings from the picking system, and a drop off zone where it can hand over seedlings to the plantation system.
- The buffer shall have a linear movement.
- The buffer shall be able to receive, carry and hand over seedlings in a safe manner.
- The buffer shall be able to detect and solve lodged seedlings and other operational disturbances.
- The buffer system shall be operational in the defined harsh environment.
- The buffer shall meet the requirements regarding speed and output a seedling every nine seconds.

The work flow of the system was also defined, and a solution with two separate buffers were presented. The idea was that while one buffer is dropping off seedlings to the plantation system, the other receives seedlings from the transportation system, and then they switch. This would result in a continuous flow of seedlings to the plantation system, but also make the system redundant to failures. If only one buffer is operational, the restock zone could be expanded to two zones, this would enable one buffer to be corresponding to two buffers in terms of speed. Hence, the linear buffer system is modular, and could be even further extended if need be. Because of this, a singular buffer will be further discussed as to not confuse anything. The following sections present the seedling carrying solution, the tray and cups, and the linear movement solution.

4.2 System Overview

This section describes the overall final design and how it operates. The final chosen design is based mostly on the Large Picking System and Buffer System, described in Section 4.1.1, but changed in some ways. The first noticeable change is that the final design is smaller, with place for only two by two cultivation trays instead of five by twelve, focusing on proof of concept. In Section 5 it is discussed whether the results are transferable to a larger system. Another difference compared to the original concept design is that a multi-gripper, that grips five plants at a time instead of just one was used. This was chosen in order to be able to meet the speed requirements.

As previously mentioned, the machine consists of three different subsystems, the Gripper and the Buffer, circled in Figure 31 and the Gantry, which is everything else in Figure 31.

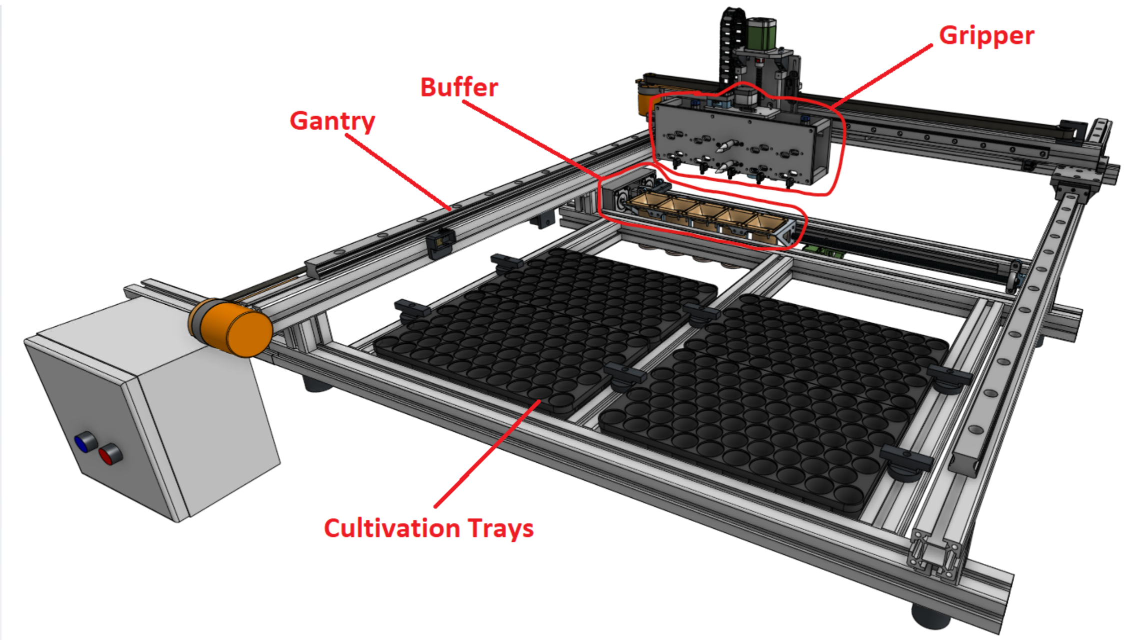


Figure 31: System overview, showing integration of the different subsystems

The process the machine works in will now be described. Something to have in mind when reading the following section is that the Z-axis, the part that moves the gripper vertically, can not travel above the plants. This is an intentional delimitation. If the Z-axis was to be able to travel above the plants, it would need to be much higher and have a longer stroke. This would make the machine less robust in the terrain its intended to be used in, where there will be plenty of shocks and vibrations. The result of this is that the gripper has to travel around the plants.

PROCESS DESCRIPTION The gripper picks five plants at a time. There is nine or ten plants in each row of the cultivation tray JackPot, the drawing for which can be seen in Appendix A, alternating between ten and nine every other row. In Figure 32a the gripper can be seen in position to grab the first five plants.

The gripper then grips the plants and the Z-axis then moves upwards with the plants in the gripper. This can be seen i Figure 32b and Figure 32c.

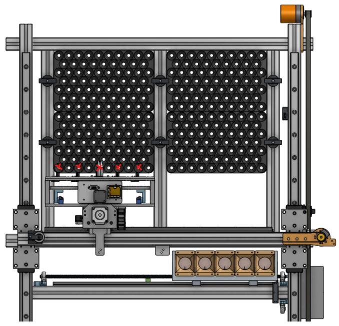
After the plants are picked the gripper moves straight backwards to the beginning of the column and then a little more, this is crucial as a diagonal movement would cause the gripper and Z-axis to crash into the plants and destroy them. After it has moved backwards it may move sideways to align with the Buffer restock position. This can be seen in Figure 32d. This free space between the cultivation trays and the Buffer system is called the safe zone, because the gripper can never damage any plants moving in this space. Note that this particular sequence is different depending on which column of cultivation trees the system is picking from and in which position the Buffer is about to restock from, this will explained a little clearer further down in this section.

It waits in this position until the Buffer signals that it is ready to receive new plants. When that happens it moves over the Buffer and holds the plants above the Buffer. This can be seen in Figure 32e and 32f.

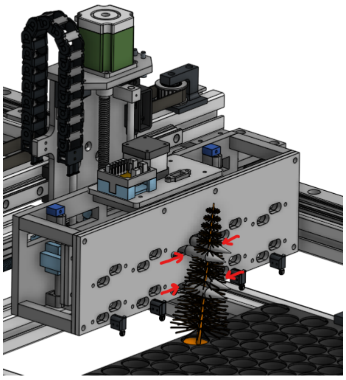
The Z-axis then moves down so that the plants are lowered down into the Buffer cups, see Figure 32g.

The gripper then releases its gripping fingers and the gripper moves backwards. The root of the plant is inside the Buffer cup. When the gripper moves backwards the cup holds the root in place, this makes sure that the plant is not stuck to gripper finger and makes for a very robust delivery to the Buffer system. This can be seen in Figure 32h.

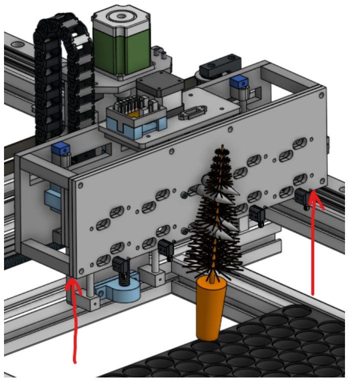
The gripper then moves sideways to not collide with the plants that are now in the Buffer system. Then it moves into position to grip the next five plants, see Figure 32i. After this the circle is complete and the machine continues in the same manner. The machine is intended to finish one column of cultivation trays at a time. It will take some time longer to pick from the rows that are furthest from the Buffer, the idea is that if the Buffer is ready to receive plants very fast, faster than can be picked from the furthest rows, the machine will choose to pick from another column instead, which still has plants close to the Buffer system. This is more important for a full scaled version. This will be discussed further in Section 5 and 7.



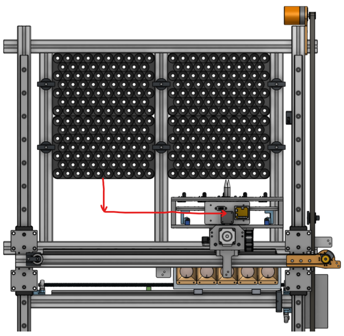
(a) Gripper positioned over first 5 plant



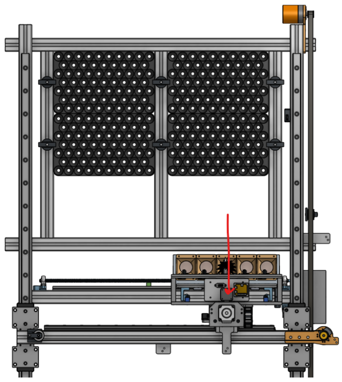
(b) Gripper closes, only one of five grippers is showed for clarification



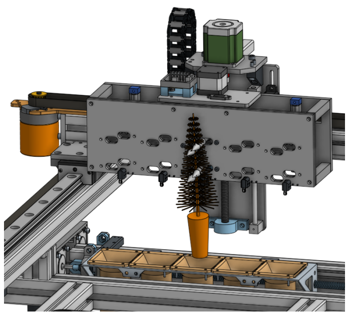
(c) Z-axis raises and plant is lifted out of cultivation tray



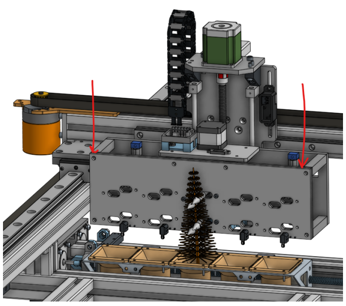
(d) Gripper moves backwards so its clear of the trays and then sideways to the position of the buffer



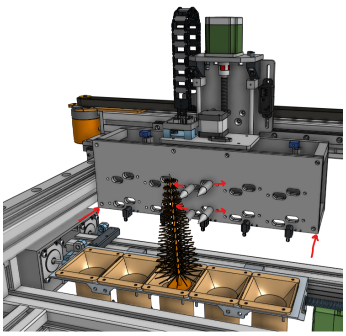
(e) Gripper waits until it receives a message from the buffer saying its ready to receive, then moves to above the buffer



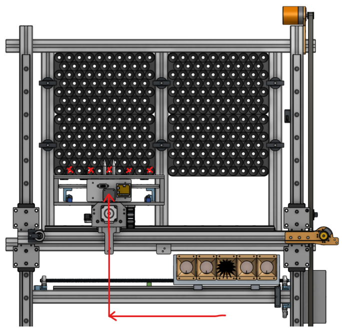
(f) Gripper with plant above buffer



(g) Z-axis moves down so plants go in the buffer cups



(h) Gripper opens up and moves the gripper backwards. The buffer prevents the plant from sticking to the gripper by enclosing its roots

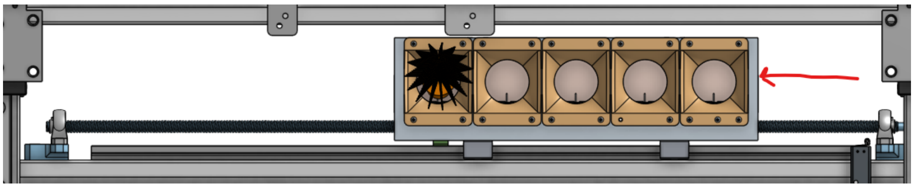


(i) The gripper then moves sideways to not collide with the plants in the buffer

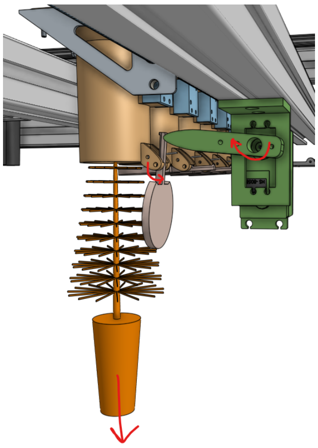
Figure 32: Process description of the system

The Buffer system was also changed from how it was initially conceptualized. Instead of a loop, a reciprocating linear motion is used.

After the plants have been left in the Buffer system, the Buffer tray moves sideways, see Figure 33a. In the middle of the Buffer system there is a cup opening mechanism. A motor turns a lever which opens the spring loaded latch on the underside of the cup. The plant then falls down. This is the interface provided to AutoPlant 2, the project that deals with the plantation arm. The plantation arm is to come here and catch the falling plant. The Buffer system continues like this until all plants have been dropped. When its finished with the five plants, the Buffer tray will be located at the opposite side. This is the other Buffer restock zone. The gripper will come and drop off plants here and then the Buffer system will perform the same routine, dropping plants to the plantation arm, but moving in the opposite direction.



(a) Buffer from above



(b) Buffer cup opening mechanism

Figure 33: Buffer system in action

The process is further described in the flowchart in Figure 34.

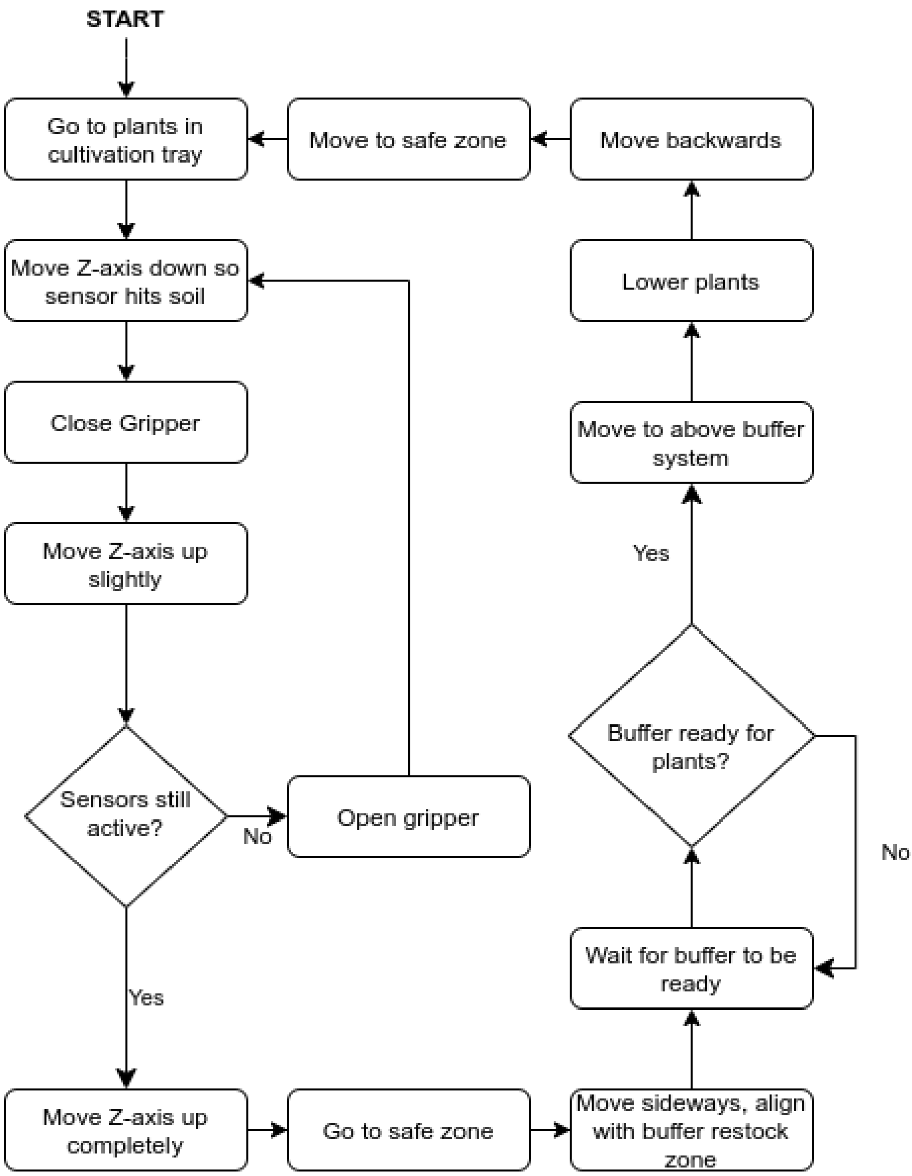


Figure 34: A flowchart of the systems operational process

4.3 Mechanical design

This section describes the mechanical design implemented in the different subsystems of the machine.

4.3.1 Gantry

The Gantry is a cartesian style machine, much like a 3D printer or a CNC milling machine, it consists of three axes, X, Y and Z, their orientation can be seen in Figure 35.

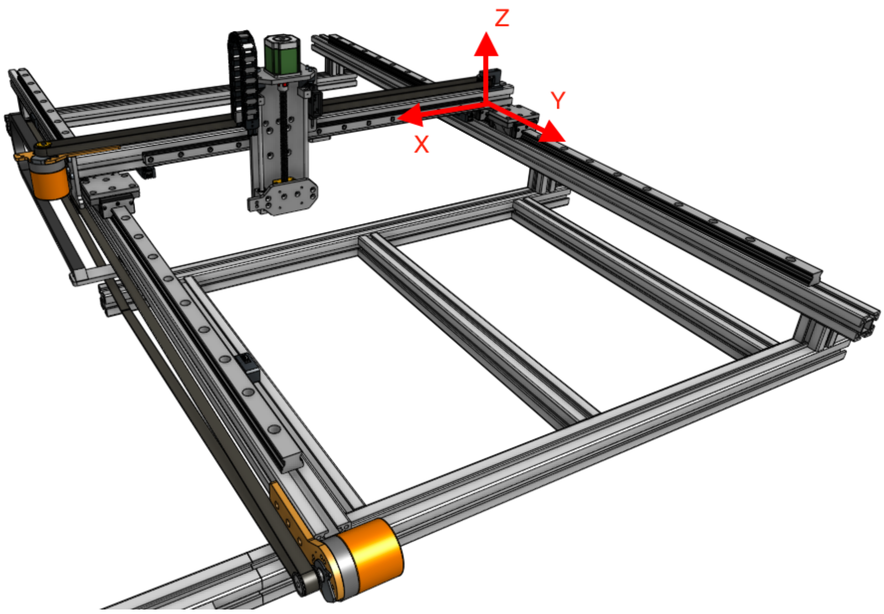


Figure 35: A picture of the Gantry showing its coordinate system

X- AND Y-AXES The X- and Y-axes were designed in a similar fashion. They are belt driven. Belt was chosen as the transmission method over ball or lead-screw for several reasons: The travel distances are quite long, ball or lead screws are typically only supported in the ends, this can cause problems if chocks and vibrations are present as the screw would be long compared to its diameter and would be flexible. The application does not require the gantry to be as precise as a CNC machine, the self-locking attribute of a screw is not needed, in fact it would do more damage than good as chocks and vibrations might eventually damage the stiff screw. Instead disturbances are taken care of by the much more dampening alternative of a belt with positional feedback. Screws are also typically geared down quite substantially, with a pitch typically of a few millimeters, more suitable for exact positioning and high torque. With a belt and the size of the belt pulley chosen, the travel length per revolution is about 75 millimeters, allowing for high speeds and sufficient torque and accuracy.

Linear guide rails were chosen for their smooth motion, wide availability and ease of mounting on aluminium profiles. The pair of large linear guide rails on the Y-axis were sponsored by Scheaffler and are made out of steel. The linear guide rail on the X-axis was bought from Rollco and is a special kind, made completely out of aluminium except for the surface where the ball bearings roll, which is made in a thin sheet of stainless steel. The choice of aluminium on the X-axis was made to minimize the weight, as it is a moving part, bringing down the inertia of the system and thereby making the machine capable of going faster and consume less energy.

The Y-axis is only driven with a belt on one of its side, making one side the master and the other the slave. Early in the design phase it was discussed whether this would be a problem or not. The problem could have been that if the X-axis was not stiff enough and the mass on the slave side of the Y-axis had too much inertia or friction, the slave side would wobble and the machine would not be very robust. This was prepared for by ordering a long shaft, an extra belt and an extra belt pulley. Had the X-axis not been stiff enough, the shaft could have been connected to the other side of the Y-axis motor and the belt could have been put on the other side as well, to pull equally on both sides. However after some testing it was clear that the system was sufficiently stiff for it not to be needed. However this might be the way to go if the machine is expanded in scale for more cultivation trays.

The encoders of the motors were built into the motor brackets. There is a reason they are mounted in this way which will be explained below.

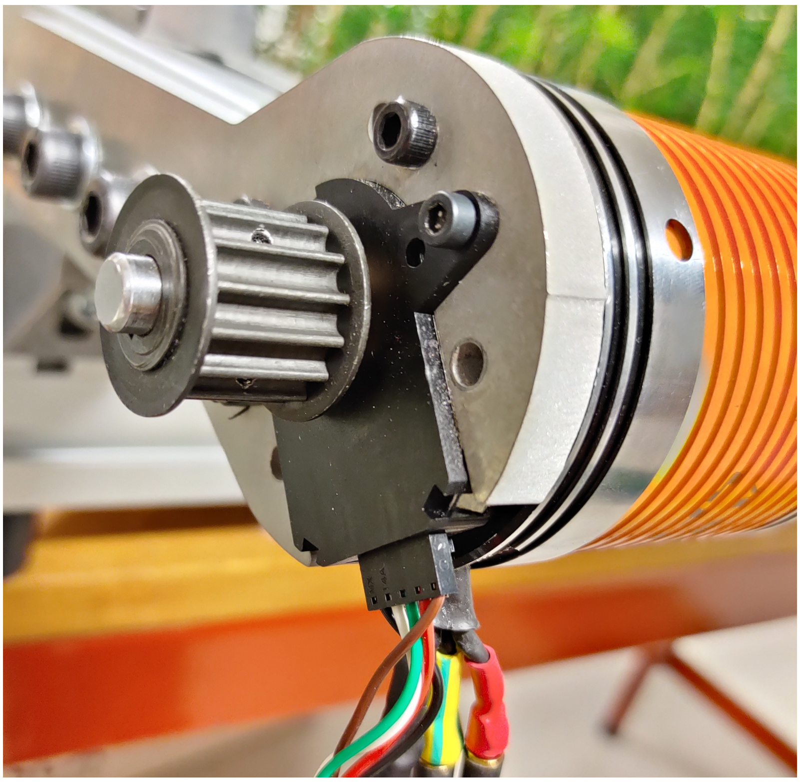


Figure 36: Encoder mounted on motor bracket

This was done in a particular way to deal with some issues that arose earlier. The encoder consists of four parts, which can be seen in Figure 37. Part 1 is the bracket that attaches to encoder to the motor bracket, the one in the picture is slightly different from the one used in the project. When part 2 and 3 are pressed together, and when they mesh together, their conical shape makes them pinch down on the motor shaft. Part 3 has teeth on its perimeter, these teeth mesh with the teeth in part 4, where the actual encoder is. So part 2 and 3 should be rigidly attached to the shaft. The problem that arose was that the conical connection released itself after some time, which caused the encoder to slip from the motor shaft and not actually measure the angle of the shaft. This mechanical problem induced software errors that were very confusing, but that stopped occurring after the mechanical problem was taken care of. The way the encoder is mounted allows for the pulley to press down on the conical connection, hindering it from detaching.

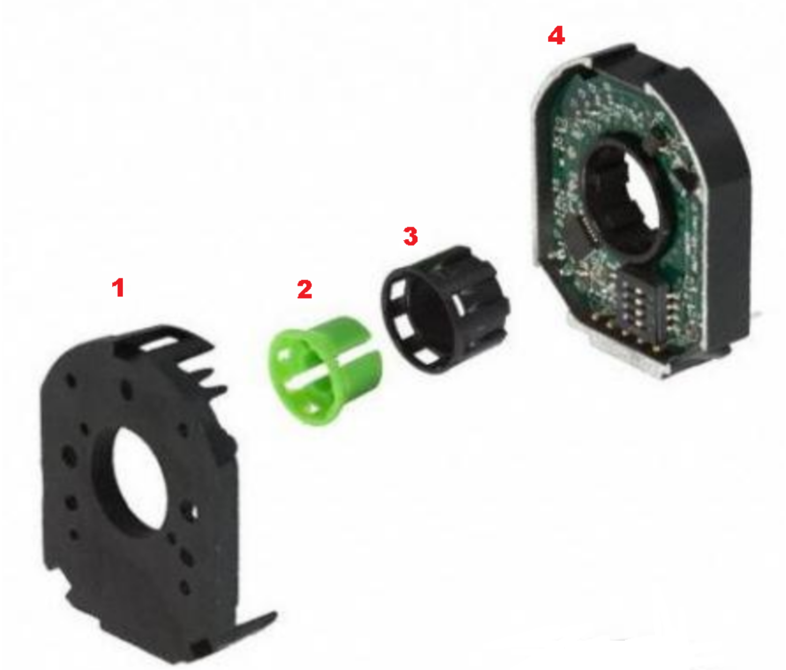


Figure 37: Encoder parts

The Z-axis is located on top of the X-axis, it is constructed in aluminum which makes it lightweight. Just as the X-axis, the goal was to minimize the inertia to enable the machine to move faster.

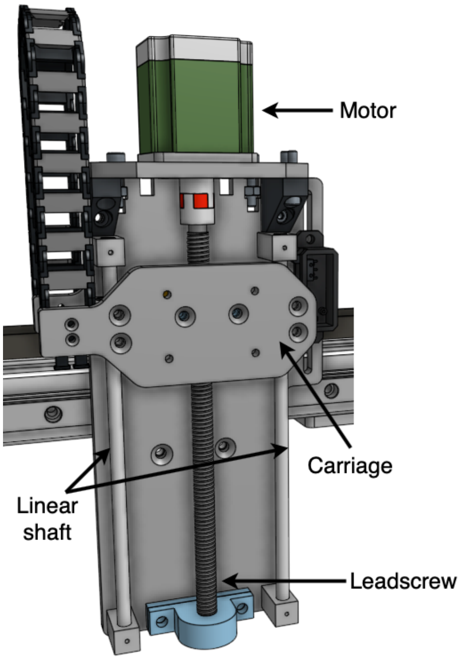


Figure 38: Z-axis CAD model

The leadscrew is coupled to a stepper motor as shown in Figure 38. The leadscrew translates rotary motion obtained by the motor, to linear motion. The advantage of using a leadscrew in combination with a stepper motor is the high precision. The leadscrew used in the Z-axis had a lead of 6 mm per revolution and 200 steps/rev, the theoretical resolution is calculated as

$$\text{mm per step} = \frac{6\ \text{mm}}{200\ \text{step}} = 0.03\ \text{mm/step}.$$

It enables exact positioning as well as increases the torque as described in Section 4.3.1.

The carriage should only translate up and down. To reduce the degrees of freedom down to one. Two linear shafts are connected to the base plate. The carriage is connected to these shafts via two linear bearings. This restricts the motion of the carriage and only enables it to move up and down. The linear shafts take up the radial forces while the lead screw takes up the axial forces.

To limit the range of motion there is a limit switch attached at the top. The microcontroller reads the state of the switch, when it is pressed the motor is stopped to prevent it from moving too far.

4.3.2 Gripper

The final design of the gripper is an improved version of proposal 2. The basic working principle is to use the vertical movement of an actuation plate to drive the fingers to move horizontally. As shown in Figure 39, a framework-like shell defines the working space of the gripper. The back plate is a board with threaded holes, which is used to mount the gripper on the gantry system's Z-axis. The motor used for driving the actuation plate is mounted on the top of the frame. The motor shaft is connected with a lead screw via a coupling, enabling the transmission of motor torque into linear displacement. The lead screw goes through a nut mounted on the back of the actuation plate. On both sides of the actuation plate, linear shafts and assorted linear bushing is assembled on the back face to prevent the actuation plate from deviating from the intended degree of freedom due to vibrations and shocks. Each gripper finger is installed on a standard Scott Russell linkage mechanism. The fixed point of the linkage is mounted on the front plate of the gripper shell. The fixed point may also be called the driving point which in turn displaces the driven point. The gripper finger is fastened on the driven point in order to displace horizontally, as seen in Figure 40a. When the actuation plate descends, the symmetrically placed fingers move towards each other until they grip the seedlings with enough contact force to ensure a steady grip during the cultivation tray extraction. The finger tips are designed in a conical shape. Implementing the conical shape prevented the fingers from pushing the flexible seedlings away during the gripping sequence. This way the fingers are elongated without having gripping contact area that reaches the seedlings on the next row whilst still sliding in between seedlings without pushing them back and away from the gripping contact area of the fingers. There are two pairs of fingers arranged in two rows for each single gripper. The lower row was to ensure a grip near the base of the stem of the seedling and the upper row for maintaining the seedling somewhat straight. The importance of maintaining the seedling straight was for increasing the likelihood of successful insertion of the seedlings into the buffer system. It should be noted that that every pair of fingers row-wise had a height difference of 8.5 mm. This allowed for a slightly skewed grip of the seedlings for a more gentle grip. The plants used were fairly flexible and able to bend when a force was applied to them.

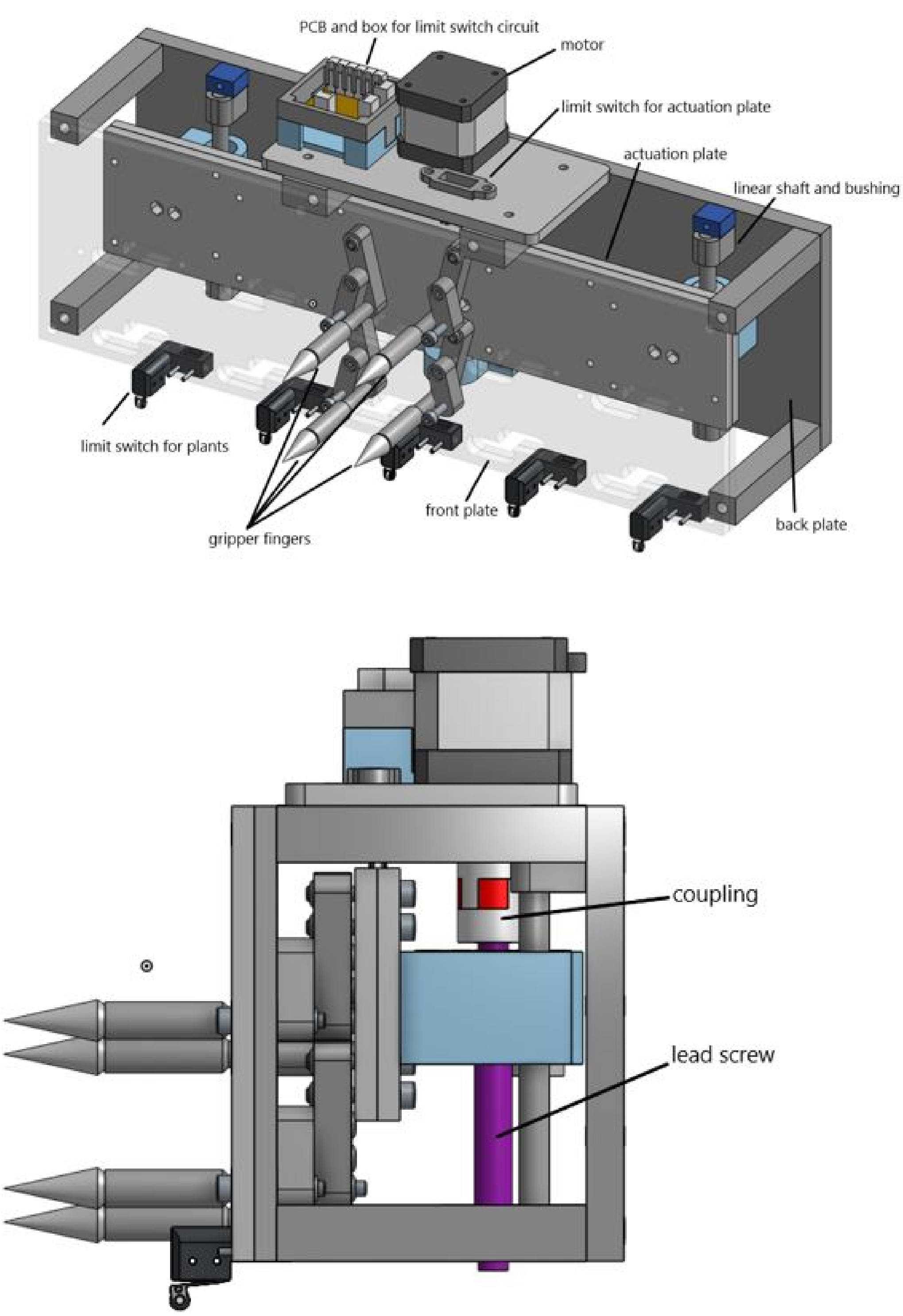
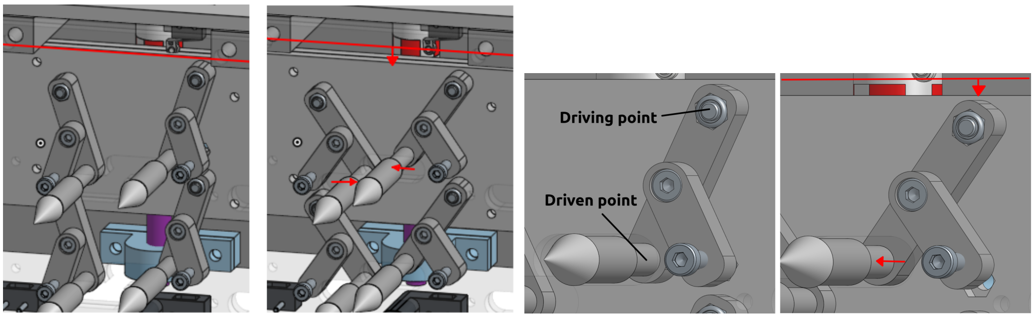


Figure 39: The finished CAD model of the multi-gripper, only one single gripper out of the five is depicted



(a) Vertical displacement of actuation plate and horizontal displacement of fingers indicated with red arrows

(b) Driving point and driven point of the linkage mechanism indicated in black. The displacements of these are indicated in red arrows

Figure 40: Depiction of how the Gripper systems vertical displacement enables horizontal displacement

As mentioned previously, the choice of a large picking system which needed longer time for transmission resulted in the need of a multi-gripper with five sets of fingers (each set consisting of two pairs of fingers arranged along two rows) was used to meet the speed requirement stated in Section 1.3. The distance between each seedling gripper was 70.2 mm corresponding to the distance between alternating cells in the cultivation tray. There are nine or ten seedlings placed in each row in the cultivation tray, meaning attaining gripping completion for each row requires two cycles. Considering the speed requirement of the Autoplant 1 system of extracting and delivering at least 400 plants per hour translates to one plant every nine seconds. With the multi-gripper, five plants can be delivered each time. In this way the deliver period can be extended to 45 seconds, which provided increased opportunity for improving gripping accuracy and reduce omissions.

FREE BODY DIAGRAM ANALYSIS In this project the Scott Russell mechanism is applied to the gripper fingers. The Scott Russell straight-line mechanism is a linkage mechanism used to perform a straight-line gripping motion. As shown in Figure 41, when point B moves horizontally, point A moves along an exact straight line in a standard Scott Russell straight-line mechanism. The problem of this mechanism is the location of the pivot which is in the way of both point A and B [61]. When implementing this linkage the pivot might stop the gripping motion. Therefore, every bar and mounting point of the linkage was set in different layers to avoid collision or lodging of the links.

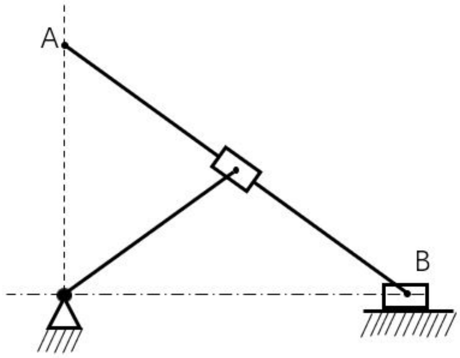


Figure 41: Standard Scott Russell straight-line mechanism

Figure 42 shows the front view of a single finger. The free body diagram of links ABD and BC is also illustrated in the image. Point D represents the position of center point of the gripper finger. Point A is fixed on the actuation plate, which moves vertically with the plate. Point C is a pivot fixed on the front plate of the gripper shell. When point A moves downward with the actuation plate along the AC line direction, point D moves in towards point C and the angle α increases. The goal is to check if the gripping force is appropriate for the requirement when the gripper is closed.

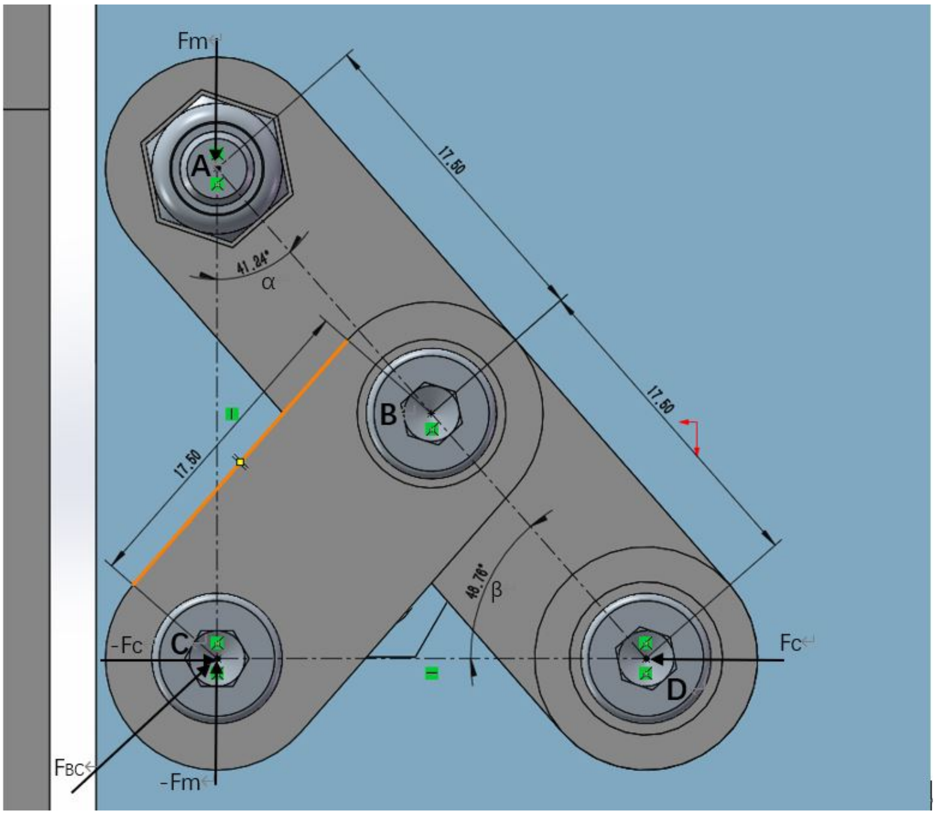


Figure 42: Force body diagram of links

As shown in the free body diagram, link BC is a two-force link. The force at point C is same as point B but in opposite direction parallel to line BC. Although the bars of the linkage are not on the same plane, the moment present in the normal direction is ignored in order to simplify the computation. The driving force F_m created by the motor is along line AC which is vertically downward. All calculations are made when the gripper is at the closed position. In Figure 42 the gripper is at the near closed position. The relationship between driving force F_m and gripping force F_c can be derived. In this way the gripping force can be checked conveniently once the motor output is known. The assumption is that the maximum gripping force occurs when the fingers (point D) move away from point C to grip the seedling. The following equations shows the calculation process:

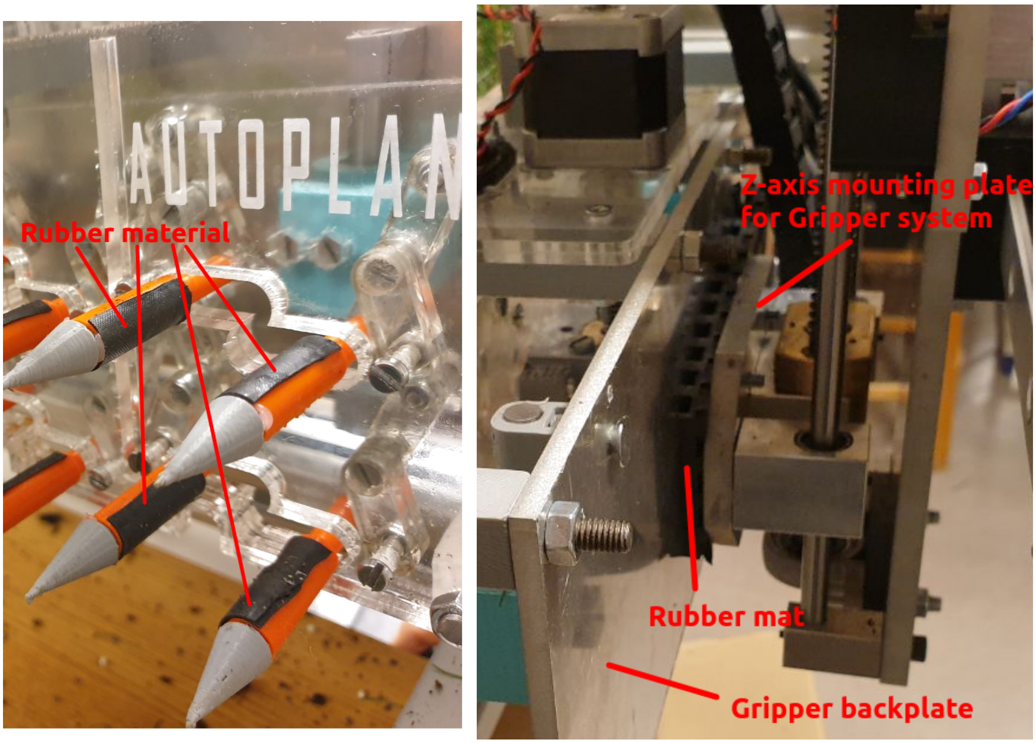
$$F_m = 2\pi\eta T/NL, \text{ Actuation plate force along AC, provided by motor}$$
$$\eta = 0.9, \text{ Transmission efficiency of lead screw}$$
$$T = 0.39 \text{ Nm}, \text{ Holding torque of stepper motor 103H5208-5210}$$
$$L = 2 \text{ mm}, \text{ The lead of the lead screw}$$
$$N = 20, \text{ Number of fingers}$$
$$\alpha = \cos^{-1}(AC/35), \text{ Angle } \alpha$$
$$F_{BCx} = -F_c, \ F_{BCx} \text{ is component of } F_{BC} \text{ in X direction}$$
$$F_{BCy} = -F_m, \ F_{BCy} \text{ is component of } F_{BC} \text{ in Y direction}$$
$$F_m \cdot 17.5 \cdot \sin\alpha = F_c \cdot 17.5 \cdot \cos\alpha, \text{ Moment equilibrium equation at point B}$$
$$F_c = F_m \cdot \frac{\sin\alpha}{\cos\alpha} = F_m \cdot \tan\alpha, \text{ Gripping force normal to line AC}$$
$$F_{BC} = F_m \cdot \cos\alpha, \text{ Force along link BC}$$

Through the calculations above, a counter-intuitive result is that the gripping force only depends on motor output and angle α. When motor power is stable, the increase of α yields the increase of the gripping force. In the existing gripper model, the angle α can reach over 41 degrees, which results in a force $F_c \approx 0.87F_m$. The stepper motor and lead screw chosen and used in the gripper result in a maximum force of 48 N.

PROTOTYPE The prototypes for the gripper mechanism was created in an iterative process. The first two prototypes were made with a single gripper (containing only two pairs of fingers, arranged in two rows) to simplify and test out the concept before making the whole mechanism. The main focus for the first prototype was to develop the mechanical design so that it could be made with the available tools, such as 3D printing and laser cutting.

The second iteration of the gripper prototype was a refinement of the first. It also incorporated the other elements of the design such as the electrical components, actuator, lead screw etc. For this prototype the electrical circuit and code was also developed so that the prototype could be tested. It was also designed with the rest of the system in mind, such as how it would be mounted on to the Gantry system and how the control system for the gripper would look like.

The third prototype was of the whole five gripper system. It incorporated all five grippers with the sensory limit switches and other electrical components which will be described in more detail in subsequent sections. The five-gripper prototype was iterated two times. The second time the gripper was improved with better tolerances and improved links and fingers with rubber material on the gripping contact area in order to improve the gripping capability and stability as seen in Figure 43a. When the gripper was mounted on to the gantry a rubber mat was also placed in-between the gripper back plate and the gantry, illustrated in Figure 43b, in order to isolate the gripper subsystem from any system vibrations.



(a) The gripping fingers of the Gripper subsystem were coated with rubber material on the gripping contact area

(b) A rubber mat was placed in-between the Gripper subsystem and the Gantry's Z-axis for vibration dampening and isolation

Figure 43: Improvements provided in the final iteration of the multi-gripper

4.3.3 Buffer

The job of the so called buffer system is to handle the transfer of the seedlings between the seedling transportation system and the planting system. The buffer system can receive multiple seedlings, and output them one at a time to the plantation system. As described, this will ensure a continuous output of seedlings. When designing the buffer system, a main concern was to keep it as close to a full scale prototype as possible. This would ensure that the system needed minimal changes in an actual implementation and that all vital functions were considered during the design process. As described, a rotational buffer system was discarded in favor of a linear system. This section will present how the linear actuation and the containers for seedling transportation were implemented.

LINEAR ACTUATION There are various alternatives for linear drives, but the one chosen for the buffer system was a lead screw. Although this decision was a bit contradictory with the other drive choices, it was backed by several reasons. Lead screws can be designed to achieve high speeds, they are self locking, offer precise positioning, are compact in size and are functional in harsh environments.

After the lead screw drive was selected as the primary buffer drive mechanism, mechanical design calculations were performed to select the right lead screw diameter and pitch. The calculation were referred from Appendix F, and the parameters of the selected lead screw along with resulting critical speed and required torque are available in Table 6.

Table 6: Buffer system lead screw parameters and resulting critical speed

Parameter	Value
Screw length	800 mm
Pitch	6 mm
Support factor	1.88
Screw diameter	8.5 mm
Linear force	28 N
Critical speed	2496 rpm
Torque required	0.133 Nm

To drive the lead screw a stepper was selected. These were readily available in school, and offered self locking, accurate and easy positioning.

The design of the buffer system was made in such a way that the lead screw only takes up the motion related torque forces and not the vertical loading. Linear rails where chosen to support these forces for smooth motion. The choice landed on "drylin® W single rail WSQ" from Igus.de because they offered a drylin based bearing technology which gives the balanced friction on the rails, no lubrication needed and the plastic liners in the carriages dampen the friction. They are also extremely quite as compared to other rail systems. The rail is made out of anodized aluminium which offers less wear resistance and is light in weight. These rails have equidistant holes for mounting which makes them easy to mount on the aluminium profile based frame. The carriages are directly bolted to the tray.

Initially the plan was to use a single linear rail instead of two since the forces were thought to be small, and therefore one rail would be sufficient to support them. But when the rails were actually implemented and tested, the overhang of the trays caused the lead screw to bend while in motion which is undesirable. The design was changed to support the tray on both ends with a parallel linear rail configuration. This design worked well, and gave the benefit of the lead screw only bearing the torque forces. The loading forces could be completely supported by the two linear rails.

SEEDLING CONTAINERS(CUPS) To successfully transport the seedlings, the Buffer system require some sort of seedling containers. The design of a container is limited by the distance between seedlings when they are dropped of by the gripper. Further, the container has to be large enough so that seedlings do not get stuck. Because of these constraints, the design process was pretty straight forward. The presented solution consists of a tray that can hold a number of cups in which the seedlings can travel. This solution is also modular, and could be extended or reduced if need be. The idea of the design concept was to drop the seedlings in a predefined position to the plantation system. In order to manage this, the seedling containers of the Buffers must open. The first consideration made was weather a passive or active opening mechanism would be most beneficial. A passive mechanism would minimize the complexity of the system, but also limit the controlability of the opening of the containers. Because of this, an active opening mechanism was proposed. The second consideration made was weather a single opening system for all containers was better, or if each container should have its own actuator. Again, a compromise between controlability and complexity had to be made. Since the functionality and design of the two options would be similar, and the complexity largely depends on the number of units to control, the decision landed on a single actuator.

Two functions are needed:

1. The containers must stay closed until they are supposed to open.
2. The containers need to be designed so that an actuated force can open them.

The chosen solution to these issues is a lid with a torsion spring that can ensure that the container is continuously closed. To open the container a lever driven by some actuator can be used, see Figure 46a. The spring must be able to hold the lid closed even with a seedling is inside the container, and the spring and lever will effect the force needed from an actuator to open the lid. Additionally, the container and lid must be designed to fit an appropriate torsion spring and enable opening by the lever. The spring must withstand a seedling traveling inside the container, but more importantly withstand a seedling being dropped in the container. The force required to withstand such a drop was found to be 2.4 N, based on the approximate weight of the seedlings and drop height. Based on this force, a spring could be selected. Other requirements was that the operational angle of the spring was at least 180°, and that it had the smallest possible diameter as to avoid very large movements and keep the design compact, as well as the spring being a standard configuration and easily available and cheap. The torsional spring constant of the selected spring was $0.7\ \mathrm{Nmm}/^{\circ}$. The appropriate preloading angle of the torsional spring was found through testing, described in Section 5.3. The force needed by an actuator to open the lid depends on the springs torsional force and length of the lever. Since the spring travels to 180° when in open lid position, the required torque will be:

$$\text{Spring Torque} = 180 \cdot 0.7 = 126 \text{ Nmm or } 0.126 \text{ Nm}.$$

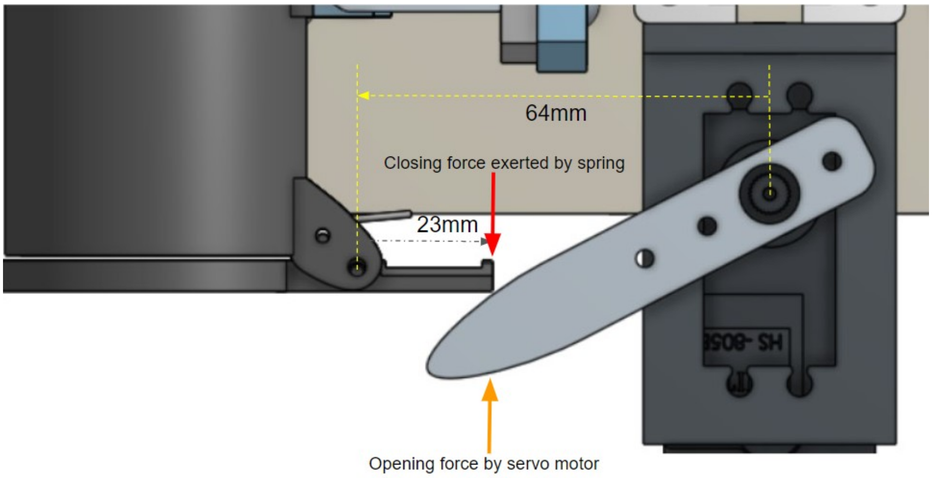


Figure 44: Force diagram lever

The spring will exert 0.126 Nm of max torque onto the lid when in open lid position. As shown in Figure 44, the lid lever is 23 mm, therefore the downward force exerted by the spring on the lid lever will be:

$$\frac{0.126}{0.023} = 5.47 \text{ N}$$

To open the lid the actuator must exert an upward force greater than 5.47 N.

Therefore the torque required by the actuator can be calculated as:

$$T = F \cdot d,$$

where T is the Actuator torque. F the force required and d the net effective distance. With numerical values inserted resulted in

$$5.47 \cdot (0.064 - 0.023) = 0.2247 \text{ Nm}.$$

The servo motor should have a torque rating of at least the actuator torque. An available servo motor, the Turnigy TS910, which has 0.258 Nm of torque, fulfilled this requirement and was selected for the application. This servo motor is powered by 5 VDC supply and is directly controlled using PWM signal such that 90° corresponds to 50% PWM and 180° to 100%. This PWM signal is mapped in the Arduino code to get the desired opening and closing angles on the servo motor. The lever attached to the motor is a 3D printed part, but can be manufactured in metal if required.

4.4 Electrical design

The core electrical components can be seen in Figure 45. All of the system components that required power was supplied from four 12 V lead acid batteries configured as 2S2P (two batteries in series and two in parallel) and hence delivered 24 V. Both the ODrive and the stepper motors were connected to the batteries.

A Raspberry Pi 4 (4GB RAM edition) was chosen as it is a small, low cost single-board computer. The computer is able to run Linux based operating systems. This offers flexibility in terms of software one can run over an MCU. The Raspberry Pi 4 features multiple USB-ports as well as two micro-HDMI ports.

The Raspberry Pi needs 5 V to operate, to achieve this, the voltage is reduced down to 5 V through a voltage regulator. The 5 V regulator was designed to be compact so that it would fit in the electronic cabinet. The circuit board can be found in Appendix I.

The Raspberry Pi ran the main program. It controlled the BLDC motors through an ODrive motor controller and communicated with two Arduinos, which were responsible for controlling the stepper motors.

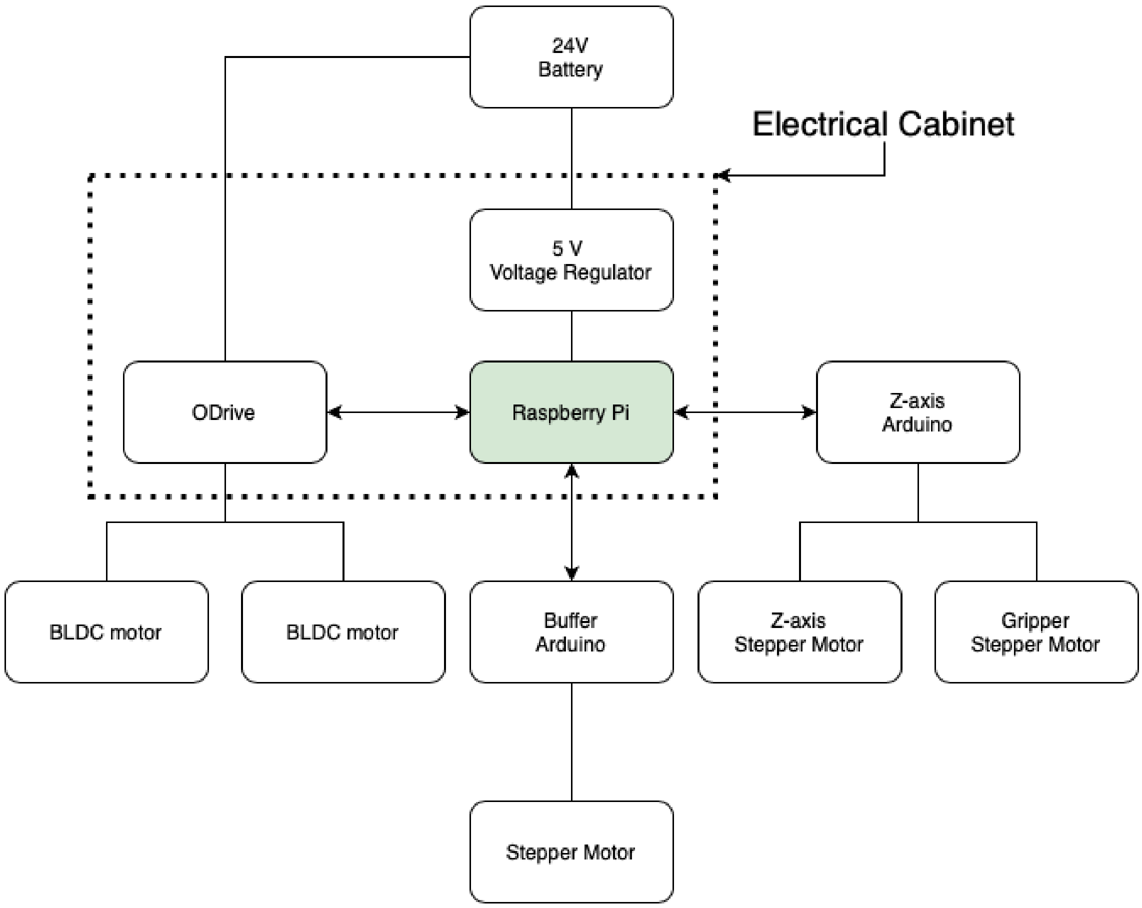
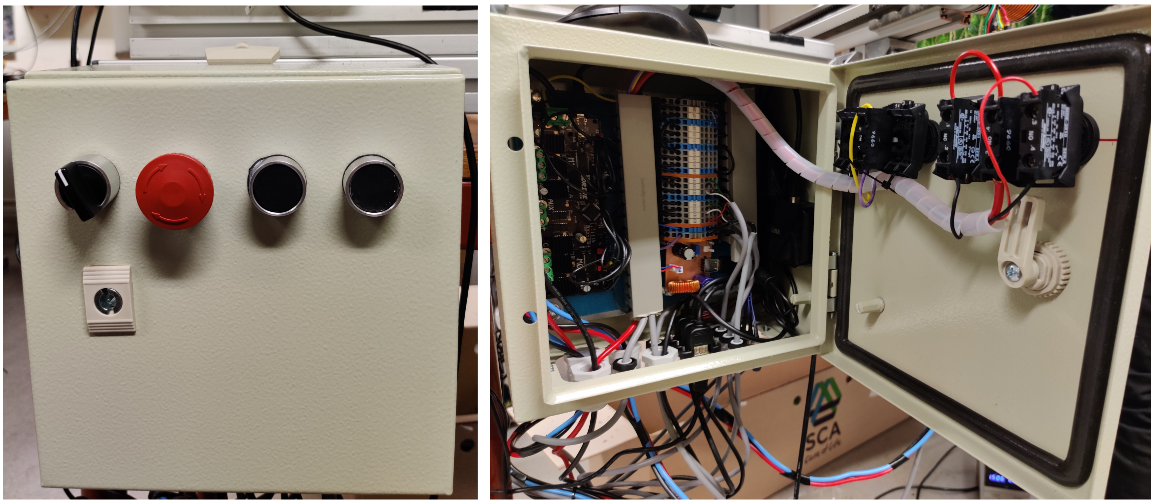


Figure 45: Electrical Architecture

ELECTRICAL CABINET To keep most of the electronics and power distribution in one place an electrical cabinet of model RS PRO Steel Wall Box(H250 mm × W250 mm × D150 mm) was used, see Figure 46. This cabinet has an IP66 rating, which means that it can withstand dust and rain [62]. Too keep the cabling tidy punch-down blocks were used for organising the various electrical connections, see Figure 46a.



(a) Outside of the electrical cabinet

(b) Inside

Figure 46: The electrical cabinet

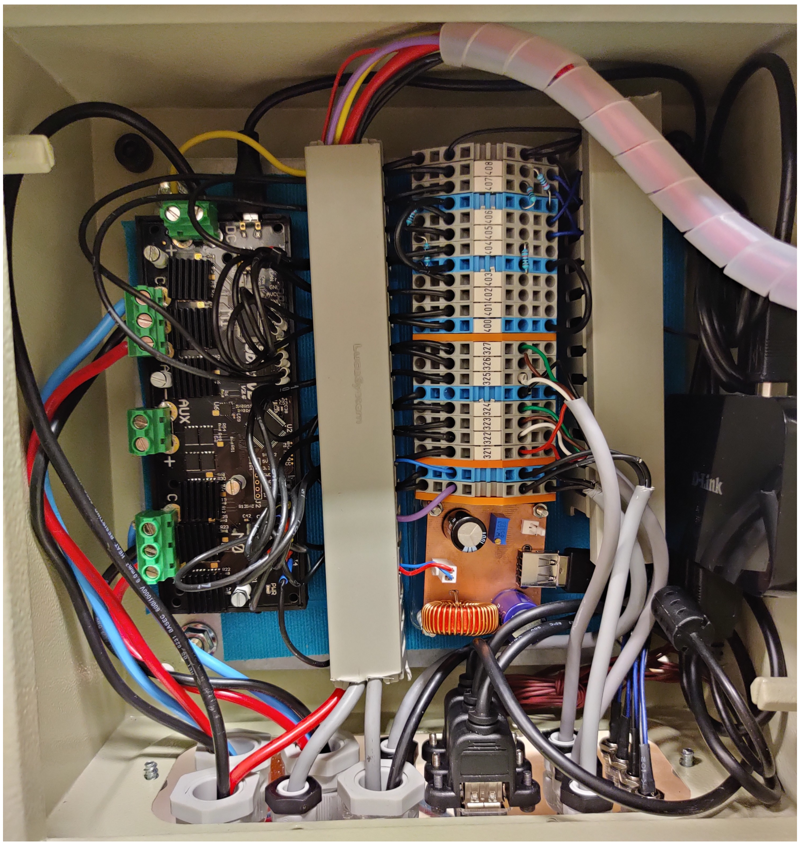


Figure 47: Closeup view of the inside

On the front door one on/off switch, one emergency switch and two buttons were placed. One of the buttons was to reset the power for the ODrive motor driver and the other one was a spare button with no function for the time being.

Since the machine is fast moving and strong there is a risk if injury if one is not careful. The machine might also malfunction in one way or another and being able to quickly cut the power is of high importance. To do this one can use the emergency switch on the door of the electrical cabinet, but there is also a movable emergency switch, see Figure 48. This can be moved around the machine to have it easily accessible at anytime.

Figure 48: Movable emergency switch

Cable glands and panel mounted sockets were used to have the cabling secured into the cabinet. For the end stops 3-pole M8 connectors were used and shielded M12 5-pole were used for the encoders. For the Arduinos, panel mounted USB ports were used and connected to a USB hub which had a single connection to the Raspberry Pi. The Raspberry Pi got power from one of the panel mounted USB ports, which was connected internally to a 5 V regulator of own design.

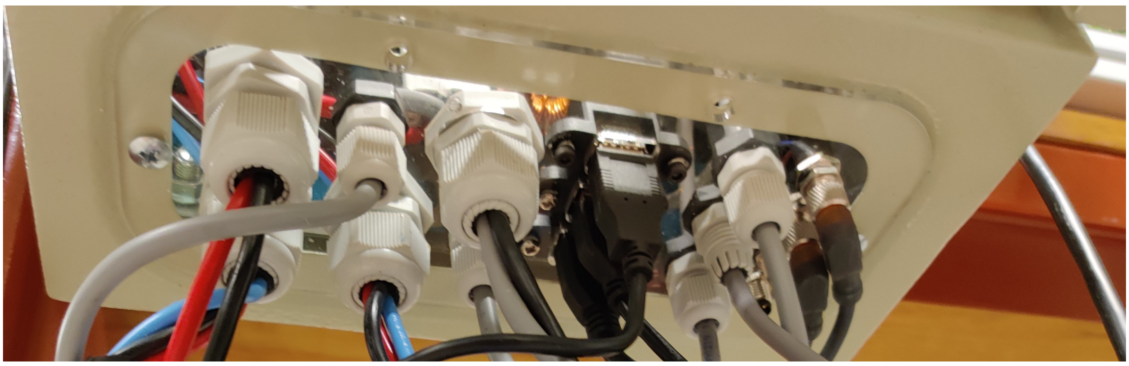


Figure 49: Cable interface on the electrical cabinet

4.4.1 *Gantry*

For the X- and Y-axes the motors used was two Turnigy D5035-125KV BLDC motors, coupled with two ATM102 encoders, see Appendix C and E respectively. These were obtained from the SAAB project of last year. The motors had more power than needed but since they were free of charge and available from the start of the project and it was deemed unnecessary to purchase smaller motors. The use of servo motors were considered early on, but so was stepper motors for the X- and Y-axes. Servo motors were always the wanted type, since they offer high speed and reliability for positioning due to the use of feedback from encoders. This is perfect for a non sturdy environment. The encoders were kept since they are recommended by the maker of oDrive.

The motor driver used was an ODrive V3.6 56V version [37], see Figure 50 and was provided from the aforementioned project of last year. This driver has the capability to drive two BLDC motor and has input for two encoders. This was perfect for the X- and Y-axes motion of the gantry.

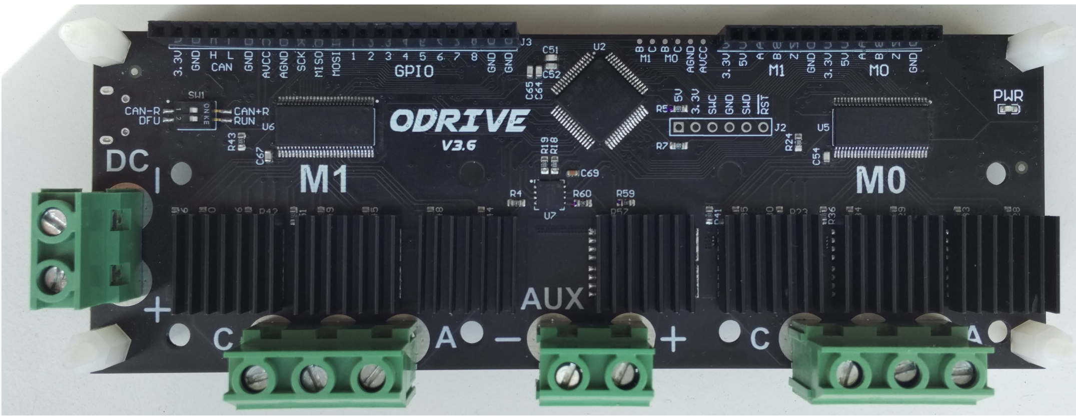
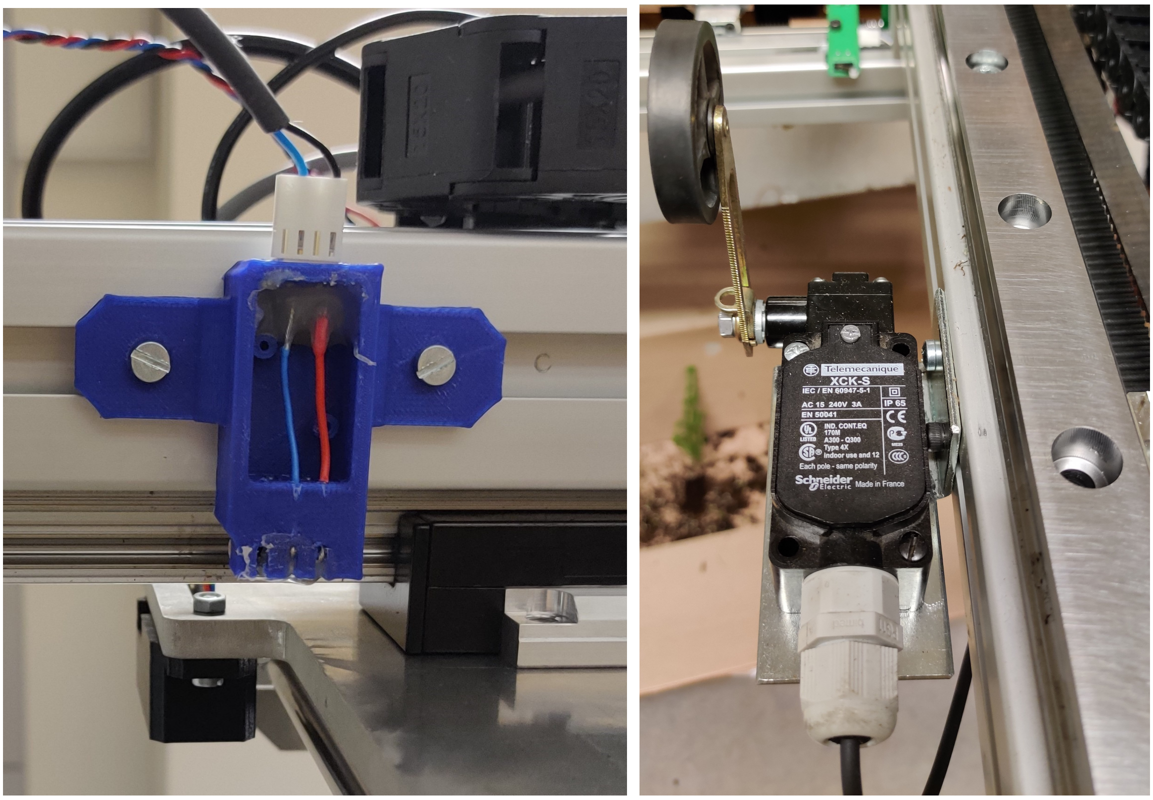


Figure 50: oDrive V3.6

When testing the system unwanted behaviour occurred due to electrical noise from the encoder, resulting in the Z(index) pulse being inverted at random. This was fixed with a 47 nF capacitor between Z- and ground pin. The most likely factor for this was the fact that the encoder cables was placed in close proximity to the motor cables in the same cable chain. To further prevent noise shielded cables was ordered and to be used. But they unfortunately did not arrive until after the project.

The ODrive can have a break resistor connected at the AUX port to dissipate the back EMF energy when the motors are breaking. This is mainly used with power supply since the back EMF will charge the output capacitors off the power supply quickly if they are not very large. This will make the voltage of the capacitor increase to the point were the power supply's overvoltage protection trips. In this project batteries were used, which can handle the regenerative energy from the motors and hence no brake resistor was used.

The ODrive also provides 8 General Purpose Input Output (GPIO) pins which can be used for endstops switches for example. In the gantry endstops switches were placed on both the axis to ensure that thy can not travel to far. The endstops were configured as normally closed, connected to +5 V and with pulldown resistor to ground, see Figure 52. This configuration was chosen since the most common failure mode for a mechanical switch leaves it open [63] and hence the machine will not move since it believes that the switch is pressed. Also if the cable breaks the circuit is left open and the machine will standstill until the problem is fixed. The switch used for the Y-axis was a Schneider Electric Telemecanique XCK-S, which was obtained from a local renovation of an elevator and was to be thrown away. For the X-axis a Omron D2F-L2 switch was used in conjunction with a 3D printed case. They can be seen in Figure 51



(a) Endstop switch for the X-axis

(b) Endstop switch for the Y-axis

Figure 51: Gantry endstops

One problem with mechanical switches is the bouncing effect as earlier mentioned in the SoTA 2.3.2. The oDrive has a built in software solution, were it waits for a given time duration before it start to read the input port again.

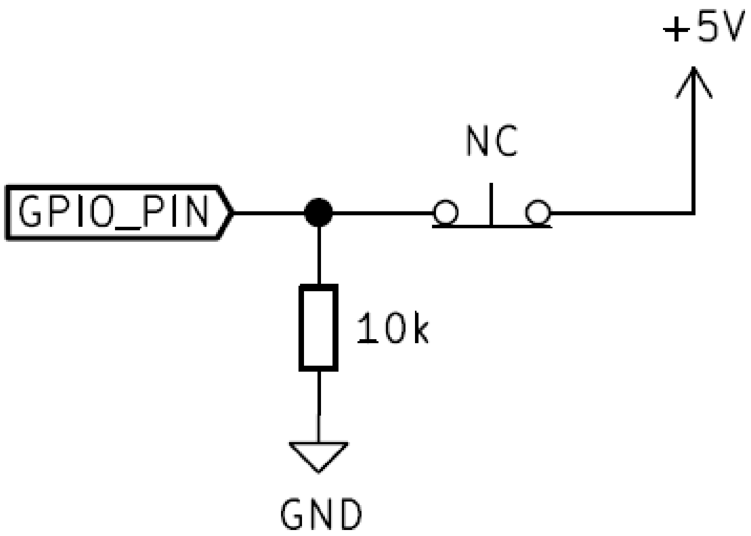


Figure 52: Endstop configuration

The use of endstops also provides the opportunity to enable homing of the axes. This procedure moves both the axes at startup until they hit the switches and offsets to a desired value. This offset from the endstop will then be the origin of the gantry, which will be constant for every startup of the machine. This fixed reference provides enhanced robustness for the automatic picking sequence, since the origin will be same for every refill of the machine an startup of the machine.

To program and control the ODrive the native protocol over USB in conjunction with python3 is recommended. But one can opt for ASCII protocol over UART or CAN bus instead if found suitable. In this project the oDrive is connected over USB to a Raspberry Pi 4(4GB edition) and controlled with python3. To program the parameters and calibrate the motors and encoders and alter control parameters, one can use the official tool **odrivetool** as well. This was frequently used in this project.

The Z-axis has one controller board that connects all the sensors and motors to the microcontroller. The sensors connect to the board via Molex connectors, which allows for easy connection and disconnections. The circuit board is shown in Figure 53.

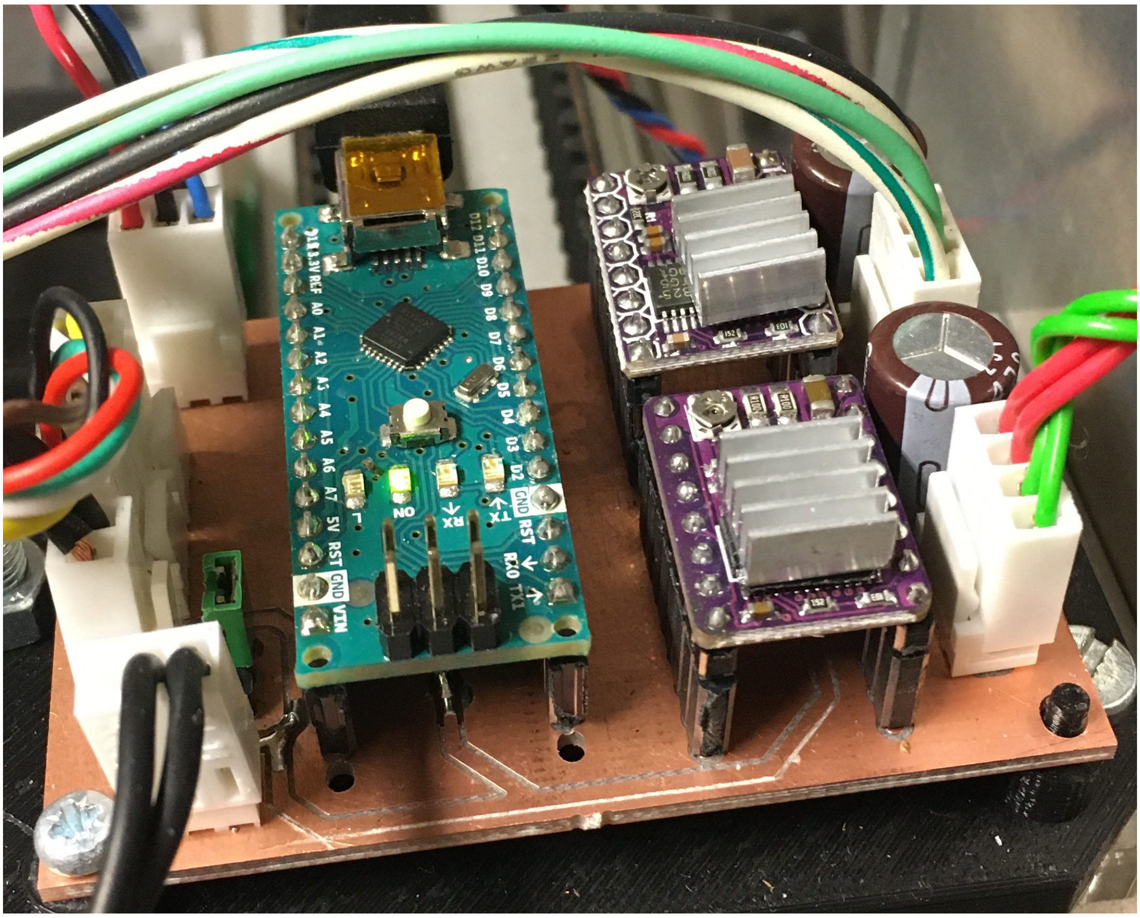


Figure 53: Z-axis circuit board

The connections required for the board to function is power and USB. The microcontroller is both powered and communicates via USB, while the stepper motors are provided with 24 V. The Z-axis controllerboard schematic is found in Appendix G.

STEPPER MOTORS The motor used for the Z-axis was a 2-phase hybrid stepper motor KH56KM2-801. The motor torque was estimated from Figure 54 by looking at the pulse rate. The pulse rate is the number of pulses per second that is used when driving the motor, which in this case is about 700. A pulse rate of 700 corresponds to a maximum torque of around 620 mNm.

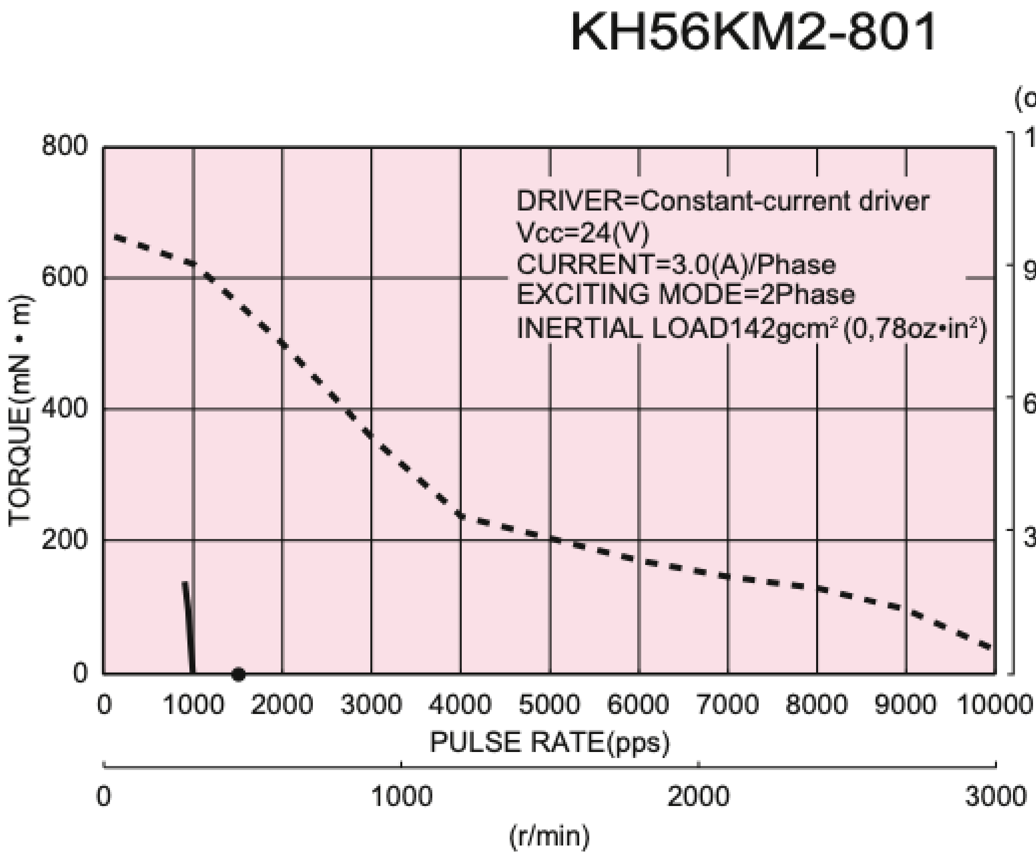


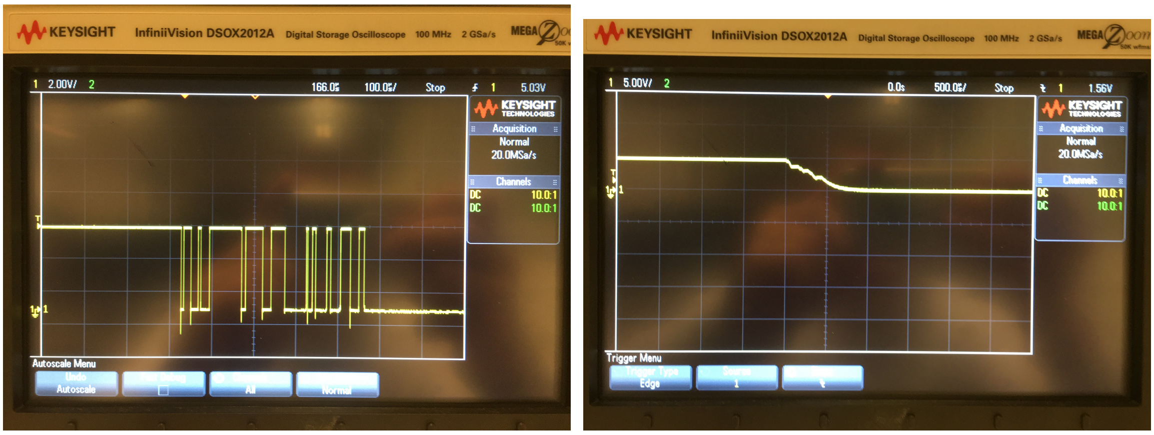
Figure 54: Torque vs velocity

This torque was sufficient to lift both the gripper and plants as shown in the Section 4.6.

MOTOR DRIVER The motor drivers chosen for the Z-axis and gripper was a DRV8825. The board manages currents up to 1.5 Amperes without external cooling. With an additional heat sink, the drivers can manage currents up to 2.5 Amperes [64]. It operates in a voltage range between 8 - 45 V. When testing the Z-axis under load, the maximum current consumption was approximately 0.6 Amperes. This board was chosen due to its small size and its specification.

MICROCONTROLLER The microcontroller chosen for the application was an Arduino Nano. It was chosen for its compactness, lightweight, easy to use, and its multiple GPIO. Multiple pins were needed since there were a lot of connections to be made to the controller.

LIMIT SWITCHES There are multiple limit switches connected to the main controller board. They are used to determine a fixed reference position. To mitigate the effect of debouncing, each limit switch signal is passed through a low-pass filter. The filter attenuates the high-frequency switching resulting in a smooth transition between the high and low states. Figure 55 demonstrates the filters effect.



(a) Without filter

(b) With filter

Figure 55: Hardware debouncing a switch

One thing to notice between Figure 55a and 55b is that the time frame differs. The trade-off with this low-pass filter is that it increases the time it takes for the signal to change state, due to the RC constant. The numerical values for the low-pass filter were chosen to

$$R = 10\ \mathrm{k}\Omega,\ C = 100\ \mathrm{nF},$$

as described in the Section 4.6. The circuit board can be seen in Appendix H.

4.4.2 *Gripper*

The controller board used for the Gripper system is shared with the one belonging to the Z-axis of the Gantry. The gripper housed a circuit board depicted in Figure 56 which consisted of five filters and the Voltage Common Collector (VCC) for the stepper motor. Due to the soil detection of each seedling being implemented using limit switches, these needed low pass filters in order to counteract the previously mentioned phenomenon of debouncing (refer to Section 4.4.1 for more in-depth explanation). The limit switch signals were carried to the controller board on the Gantry's Z-axis since the common state machine for the two subsystems was meant to effectuate a sequence of actions depending on the outputs of said limit switches. However, due to time constraints these soil detection limit switches were not mounted and thus not tested.

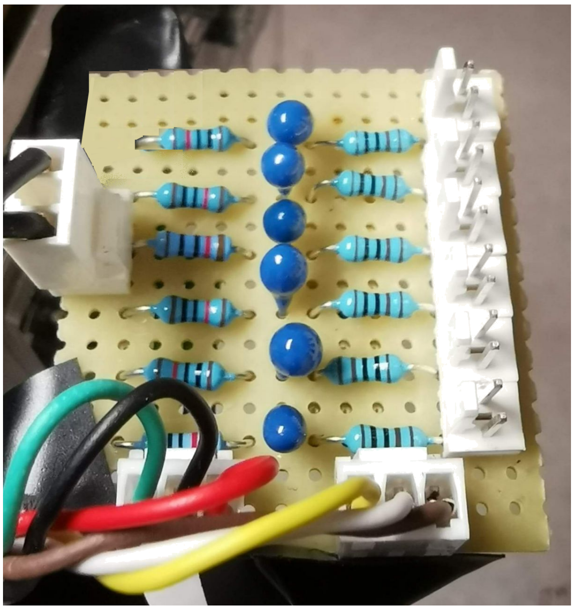


Figure 56: The circuit board mounted onto the gripper containing the power supply for the motor and the low pass filters for the limit switches

STEPPER MOTOR AND RESPECTIVE DRIVER The motor chosen for the gripper was a 2-phase bipolar stepper motor Sanyo Denki 103H5208-5210. The advantage of stepper motor is its simple but precise control. By controlling the number and frequency of the input pulses, the required angle and speed can be achieved, which is translated into accurate position control of the actuation plate. The performance of 103H5208-5210 met the gripper requirements most. Its basic specification are listed in Table 7:

Table 7: Specifications of Sanyo Denki 103H5208-5210

Model number	103H5208-5210
Holding torque at 2-phase energization	0.39 Nm
Rated current	1 A/phase
Wiring resistance	4.1 Ω /phase
Winding inductance	9.5 mH/phase
Rotor inertia	$0.056 \times 10^{-4} \text{kg} \cdot \text{m}^2$
Mass	0.29 kg
Motor length	39 mm

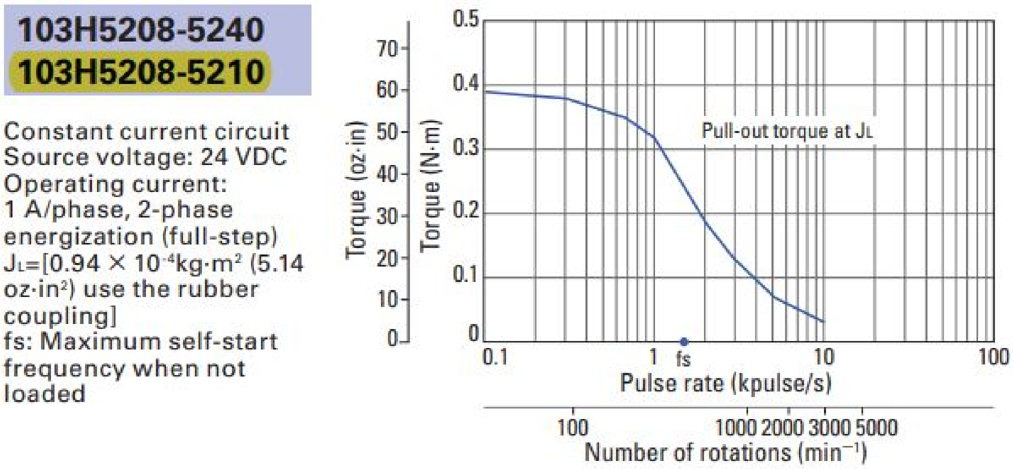


Figure 57: Torque VS. Pulse rate

The torque curve of 103H5208-5210 is shown as Figure 57. The gripper motor is locked most time in operation, so the holding torque is used to calculate the motor output. The motor shaft is connected with a lead screw by jaw coupling. When the gripper is handling the seedlings, the motor thrust is:

$$F = 2\pi\eta T/L = 1102.14 \text{ N}$$

where $\eta = 0.9$ is the transmission force of the lead screw, $T = 0.39$ Nm is the holding torque of 103H5208-5210 and $L = 2$ mm is the pitch of the lead screw. The result shows that the motor can provide at most 1102.14 N to the actuation plate.

Regarding the gripping and releasing process, the actuation plate moves back and forth between the origin and final position with a height difference of around 7.4 mm. Both of the grasping and releasing process should be finished in 1 seconds, which means the motor rotates 3.7 revolutions per second. In this case, the corresponding pulse rate is about 600 pulse per second, which corresponds to a torque of 0.35 Nm. In this state, the motor thrust is:

$$F' = 2\pi\eta T'/L = 989.1 \text{ N}$$

LIMIT SWITCHES Limit switches were also used in the gripper subsystem. One limit switch was mounted on the top of the gripper for defining the origin position of the actuation plate. When the gripper was moved to the its open position, the actuation plate was homed to the origin position (the upper limit of its linear displacement) where the fingers were open and able to be inserted in between the seedlings. This ensures that the gripper fingers would not push the seedlings away and cause gripping failure. Moreover, when the gripper moves to aligning above the Buffer subsystem, the actuation plate is homed in order to open the fingers to drop the seedlings. Thus, the limit switch defines the open position of the gripper fingers.

In addition to the limit switch for defining an origin for the actuation plate, they were also supposed to be used as probe-like components, almost like touch sensor in the gripper. As shown in Figure 39, in order to detect if the gripper had successfully gripped the seedlings or if the seedling had suffered slippage between the fingers it was designed for five limit switches to be installed at the bottom of the gripper. These binary sensors yield a high signal when in contact with the soil of a seedling in a cell of the cultivation tray (when the gantry's Z-axis lowered the gripper).

Other solutions for detecting gripping results had been considered during the design process. One possible solution which was mentioned previously was to apply a strain gauge at the surface of the gripper fingers. This is a general method used in many existing robot grippers. However, since the object-to-be-gripped in this project is relatively small and arranged closely, the size of the gripper system is limited to a great extent. Therefore, installing the strain gauge and related circuit would need advanced processing technology and is not robust enough for extreme working environments and strong vibrations. In order to avoid direct contact with the seedlings, ultrasonic sensors and cameras were also considered. However, ultrasonic sensors can hardly be accurate enough to detect seedling stems with relatively small diameters, and may be compromised by debris [65]. Alternatively, ultrasonic sensors may be used to detect slippage by sensing the presence of the soil. However, this would entail positioning the sensor in a way that allows for this view, which proved challenging given the inability to place anything below the gripper. Doing so would compromise how close to the base of the stem the gripper would grip the seedlings. Similarly, cameras are voluminous, which makes installation impossible on the compact gripper. Another disadvantage is that it cannot work in a dark environment, and providing light may compromise the light-sensitive roots of the seedlings. Other viable alternatives include slotted optical sensors. Unfortunately, slotted optical sensor may rely too heavily on the seedlings in the cultivation trays growing in a consistent and uniform manner, which can not apply to existing cultivation trays.

4.4.3 Buffer

In this section, the electrical implementation of the buffer system is described.

MICROCONTROLLERS The system utilize two different types of micro-controllers in its system layout, low level (hardware control) on Arduino Nano, and high level (logic, communication, system decisions) on Raspberry Pi.

This separation is done to modularize the system. Separating the hardware control from the software logic control adds redundancy to the system, and makes it easier to scale the system with more hardware, since an Arduino only need a single serial USB connection.

STEPPER MOTORS The lead screw drive needs an active driving source. Servo and stepper motors were the best available options amongst all. The stepper motors are easy to control and were freely available from the previous year projects. Hence stepper motors were chosen as the primary driving source for the linear system.

Considering the maximum torque requirements of the lead screw drive and maximum desired speed, the motor was selected. There were motors available from previous year projects and from these, the Nema 23 KH56JM2-851 stepper motor, in Appendix D, was selected since it satisfied the torque and speed requirements. It is a bipolar stepper motor with holding torque of 0.5 Nm.The motor was coupled to the lead screw using jaw coupling. The lead screw was supported using roller ball bearings on both ends.

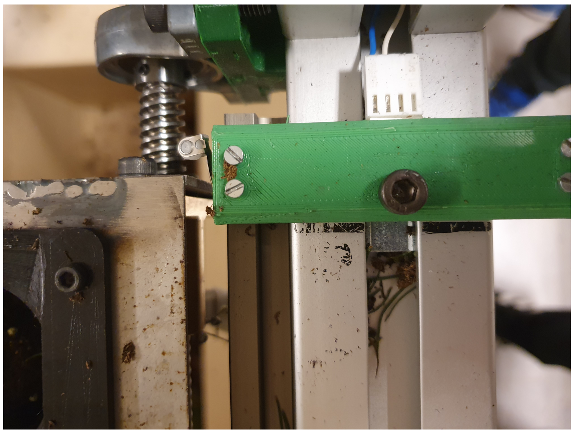
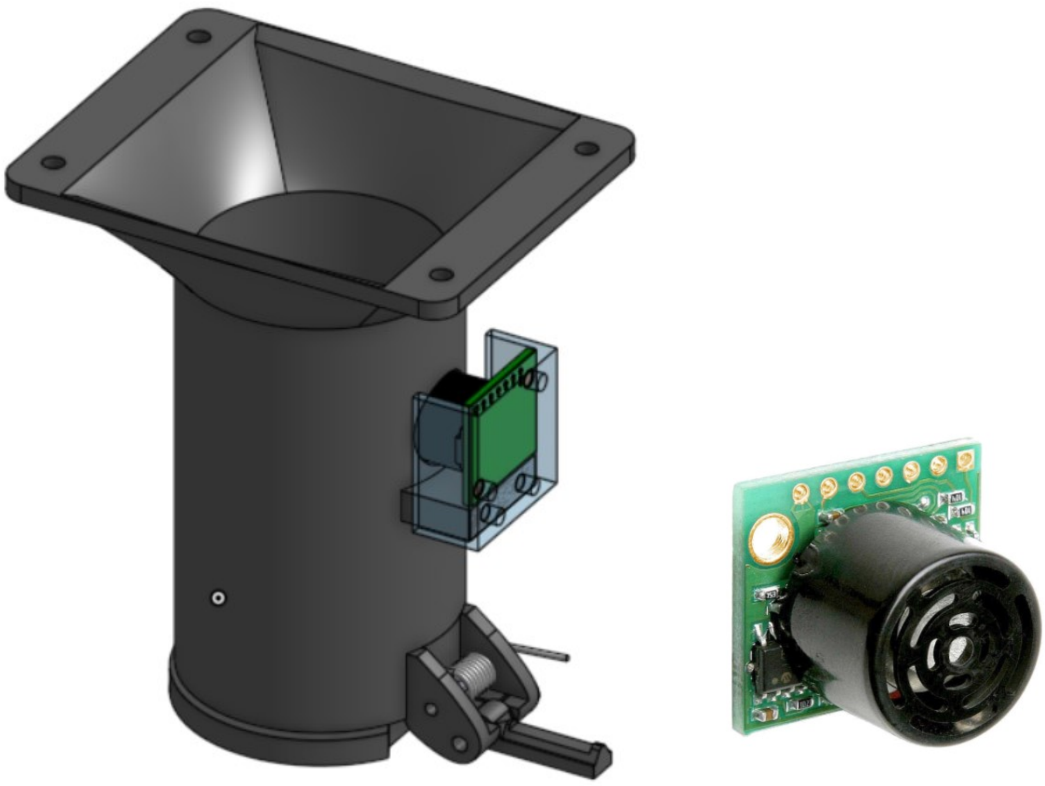


Figure 58: Buffer Limit Switch

LIMIT SWITCH The linear drive needed to calibrate the reference start position. Similar to the gantry Z-axis, a limit switch was used to do the calibration. Instead of using a Low pass filter based debouncing for the switch, Software dbouncing was implemented. A 3D printed mount was designed to fit the limit switch. As shown in the above Figure 58 it was mounted to the aluminium extrusion using M5 bolt. The black line as seen in the Figure 58 is the defined mounting position of this limit switch mount.

SENSORS IMPLEMENTATION The goal of this project was to be able to detect seedlings. The sensor thus had to be present in the cup or on its top surface. The chosen position of the sensors was to mount them in the cup, so that when a seedling would come in its proximity it could be detected. Since the performance of ultrasonic sensors is not much affected by rain, dust or lighting conditions they were an appropriate choice for this application.



(a) Ultrasonic sensor mounting **(b)** Maxbotix Proximity Sensor

Figure 59: Buffer system sensor

The ultrasonic sensor selected was a Maxbotix LV-EZ01 sensor, which has a single transducer setup, thus making the assembly more compact. These sensors are more accurate than the standard Hc-SR04 and are more resistant to noise.

ALL IN ONE CIRCUIT BOARD A circuit board was designed to connect all the sensors, stepper motor, motor driver, limit switches, servo motor and Arduino Nano. This made it simpler and easy to connect all the actuator and electronics in one place removing the mesh of interconnecting jumper wires. The system looked much compact and easier to understand with the addition of this circuit.

The board layout can be seen as in the Figure ??. It has an input connection for 24 VDC and 5 VDC. The 24 VDC is routed to the input of the stepper motor driver through a 470 uF decoupling capacitor. The Arduino's digital pins are routed to stepper driver. The SLP and RST pin of the driver are kept HIGH whereas the ENABLE is switched to high whenever the motor needs to be actuated. This ensures that the motor is not in locked position continuously, thereby keeping the stepper driver cool. The ultrasonic sensors are connected to the analog pins on the Arduino and they are powered by a common 5 V supply from the board. The limit switch is connected to high with a pull down resistor on the other end. The low on the switch is detected by the digital pin from Arduino. Moreover the servo is connected to a digital pin D11 on Arduino and is powered by 5 VDC supply from board. This connections in all make this board All in one.

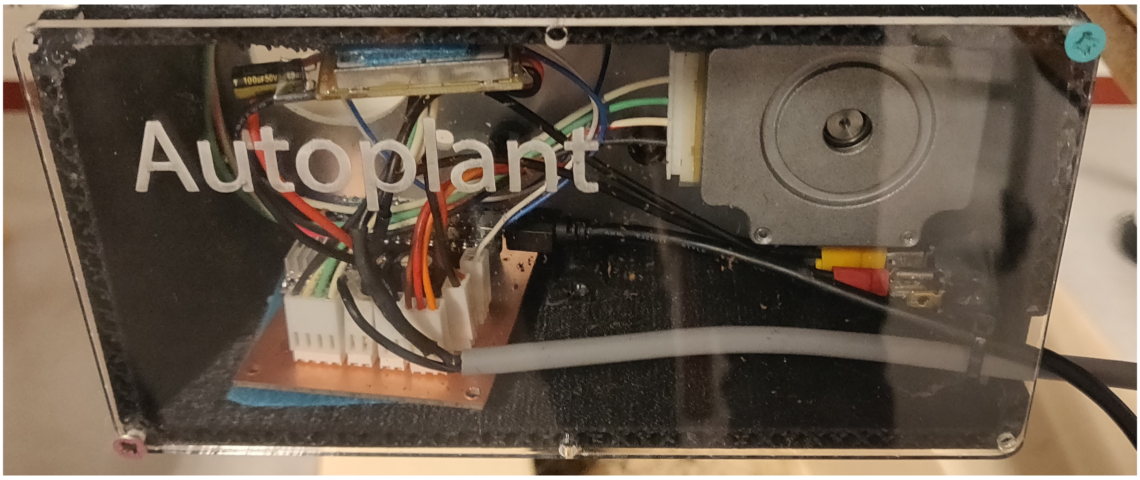


Figure 60: Buffer Electric Box

A 3D printed enclosure was made to enclose all the electronics, cabling and the power switch as shown in the Figure 60. The power switch is mounted on the right side of the box. This connects and disconnects the power for the complete buffer system except the Arduino, which gets power through the USB.

4.5 Software Design

The software design implemented in the solution is described in the following.

4.5.1 *System Architecture*

In this section, the overall software architecture is first described and then more detailed descriptions of the software implementations of the various parts are given.

To enable easy control of the machines all axis, monitoring various parameters and alter settings, a Graphical User Interface(GUI) was made. The main objective with the GUI was too have a practical tool. From the main view shown in Figure 61 the Gantry's axis can be stepped with a given step size. The Z-axis and gripper can also be manually controlled. One can also connect the ODrive from here and watch the endstop status. option to switch between manually and automatic control is in this view.

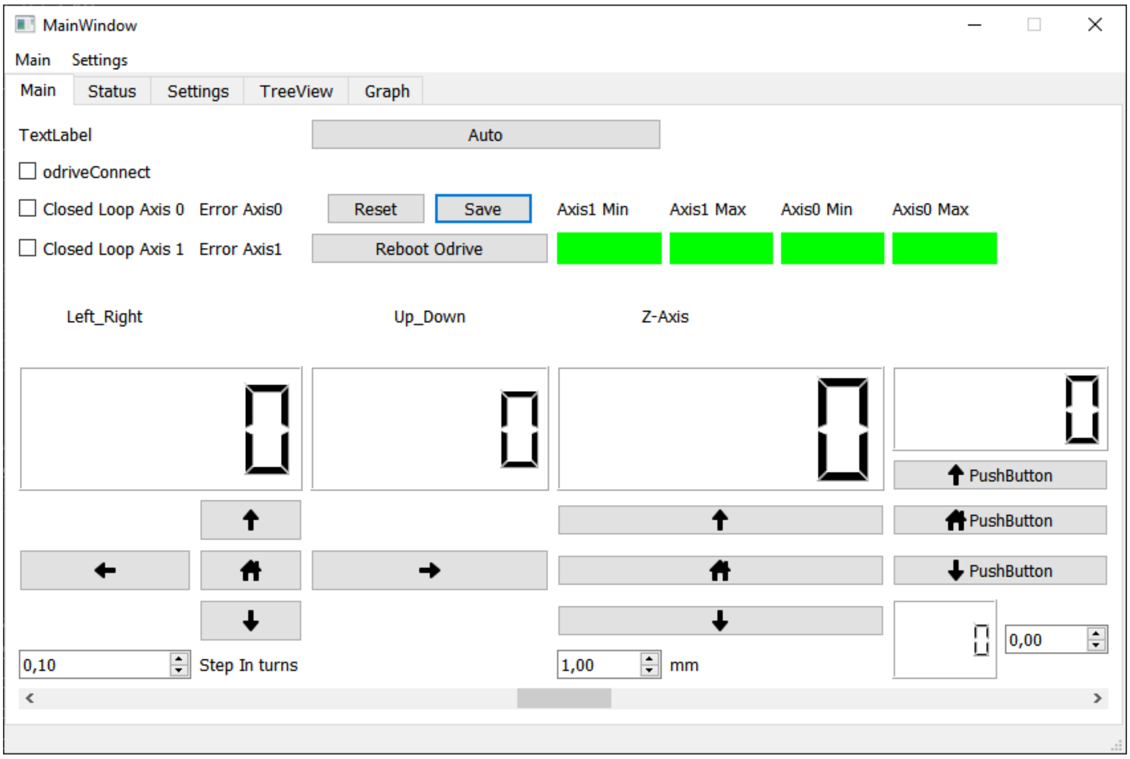


Figure 61: Graphical User Interface main view.

Another convenient view is the tab "TreeView" were one can see which plants are being picked depicted by the blue load icon instead of the normal tree icon, see Figure 62.

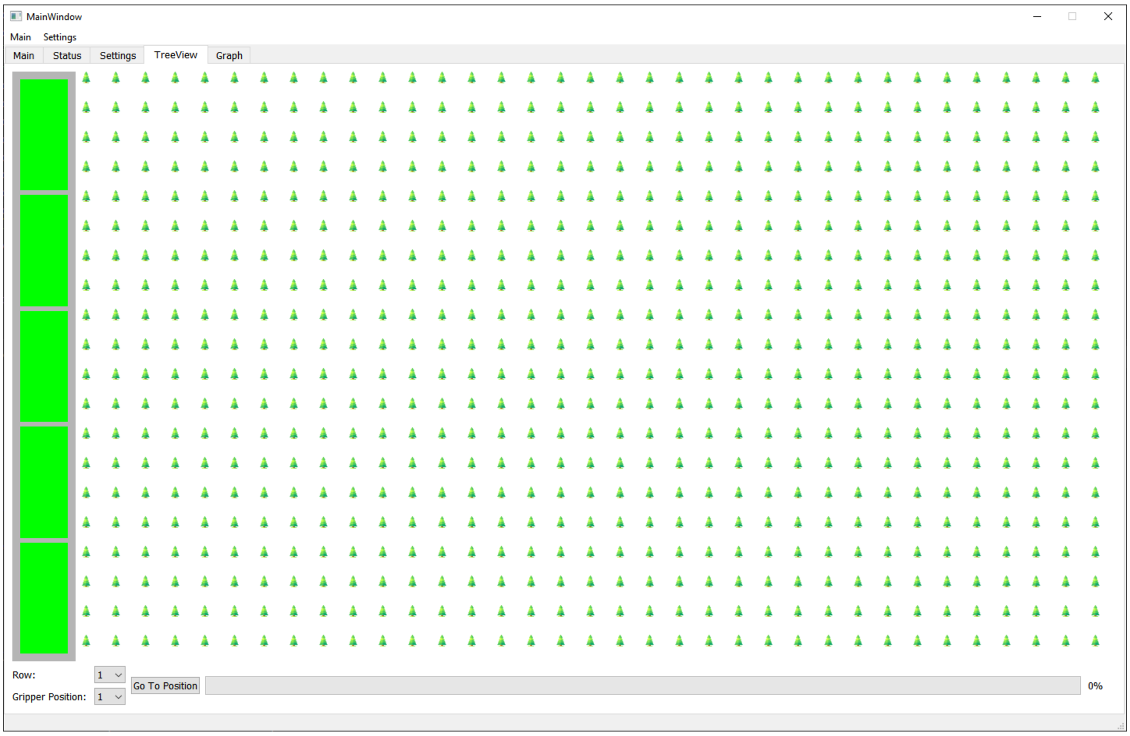


Figure 62: Graphical User Interface TreeView

The GUI was loaded onto the Raspberry Pi and was operated using a 7 inch touchscreen. The casing for the Pi and screen was 3D printed and seen in Figure 63

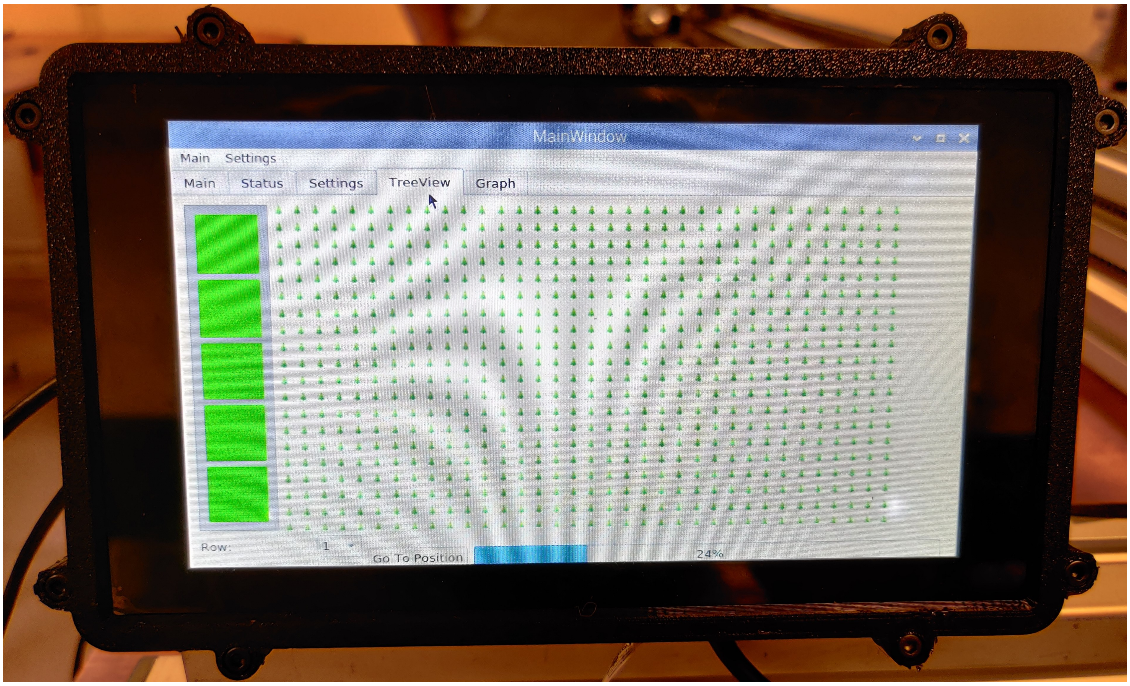


Figure 63: Casing for the Raspberry Pi

The GUI's design was made with a tool named QtCreator [66], which is free to use for non-commercial applications. The coding that connects the buttons, displays, etc to functions in the program was made with Python3 and the PyQt5 library was used to integrate the graphical design into the code. This library basically makes the design elements into objects that has its own methods and can be used to your liking.

When having a GUI it is important to use multi-threading programming. Why this is important becomes imminent when considering the case with only one thread. Then the GUI will lock up as soon as a function runs, since the program is sequential. Therefore it is important to have the GUI run in its own thread. Conveniently the PyQt5 library comes with its own implementation of threading that makes it relatively easy to create a new thread for a function or a set of functions.

Sometimes one wants to collect data or do something at a certain interval, then timers can be useful and PyQt5 comes built in with this functionality. For instance, data is plotted and battery voltage and errors are checked with the use of timers.

To plot data from the ODrive pyqtgraph was used, which is a library for highly efficient plotting. This was great for integrating into the overall design.

In the PyQt5 library there is support for a Virtual Network Computing (VNC) server of the GUI. VNC is a tool for sharing the computers screen and remotely control the device [67]. This made it possible to run the program on a device without a physical screen and remotely control the interface from another computer. The GUI could be viewed using a VNC viewer software. This was used when developing the interface and main program.

The software was written on another computer and transferred onto the Raspberry Pi over Secure Copy Protocol (SCP). SCP is way of securely transferring files between two machines and is based on the Secure Shell (SSH) protocol [68]. This made prototyping the code on the intended hardware very fast.

Since a lot of network services were used, a firewall was installed on the Raspberry Pi to limit access only to specific ports. The firewall used was Uncomplicated Firewall (UFW) [69].

In Appendix L there is a manual for how to run the program in the Rapsberry Pi.

WEB INTERFACE To make a simple web interface for controlling basic functions of the machine MQTT 2.5.1 in conjunction with a framework called Node-RED was used. Node-red makes it easy to program various buttons and other elements to send and receive MQTT messages. This also auto generates a simple web page with these control elements. The node-red server was hosted on the Raspberry Pi 4 that was used for the local GUI as well. With the use of port-forwarding in the router it was made possible to access this web interface from outside the local network.

The interface shown in Figure 64 has functions for controlling the axes of the gantry and gripper. It also shows the estimated state of charge for the battery pack and the percentage of plants picked. The switch is for turning the X- and Y-axis motion off.

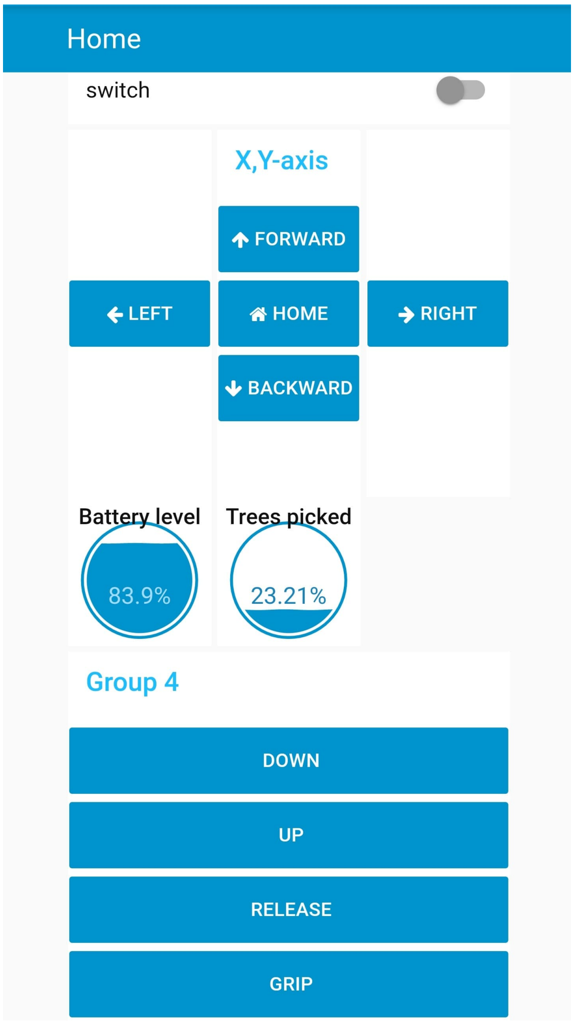


Figure 64: Web interface created with Node-RED shown on an mobile phone

4.5.2 *Gantry*

To control the Gantry's X- and Y-axes, code for controlling the ODrive was integrated into the main program. This was easily done since the native protocol for ODrive has a library written in python.

CODE FOR STEPPER MOTOR The software for driving the Z-axis was written in C++. It was written in a modular way so that it could be used with the gripper as well. The working principle of the code is a state machine. The state machine waits for a serial command from the main computer. When a command is sent, it performs the task and lets the computer know that it is completed. A simplified flowchart of the system is shown in Figure 65.

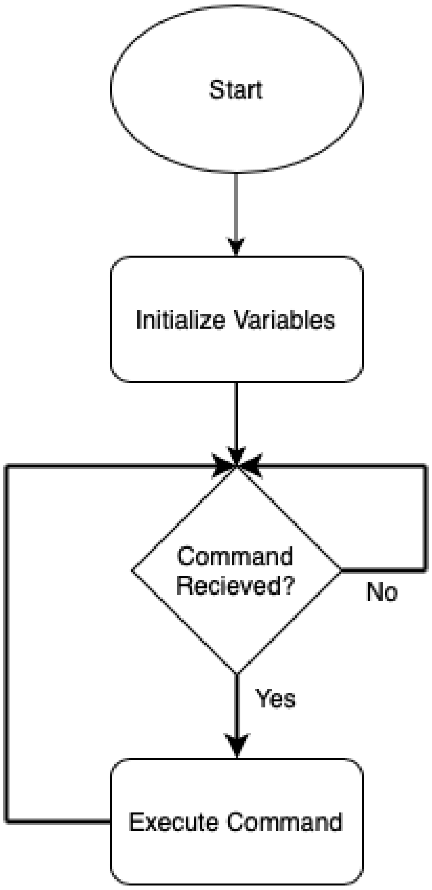


Figure 65: Z-axis flowchart

The motors used in both the Z-axis and gripper are stepper motors. The chosen stepper motors are open-loop, they lack feedback. This makes it important for the Z-axis to know where the carriage is located. This is done by letting the machine home itself i.e. let it run until it hits the limit switch. This becomes the machine's reference position, all the distances will be referenced from this position.

There are multiple safety features of the code. It has an internal position tracking, that keeps track of where the carriage is located. Before the machine can move, the carriage must be homed.

The code also features a maximum distance, which the operator can choose. If one tries to move the carriage further than, the software will stop it. There are multiple features included that can be controlled from the GUI. The operator can move to an absolute position, or move relatively. This was proven to be very useful when calibrating the machine for the automatic process.

CONTROL The BLDC motor driver mentioned in 4.4.1, uses an cascaded position, velocity and current control loop as shown in Figure 66. Every stage is a variation of a PID controller. [70] The gain parameters was almost perfect for the setup by default, but some was altered slightly to enhance performance. This was done by manual tuning with resulting values seen in Table 8.

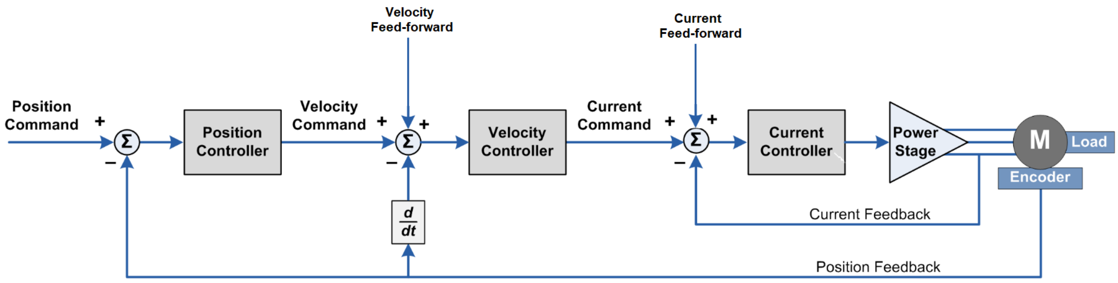


Figure 66: Control loop used in the motor driver [70]

Table 8: Tuned control parameters

Axis	Y-axis	X-axis
Proportional gain position	20	20
Proportional gain velocity	0.5	0.5
Integrator gain position	0.25	0.333

4.5.3 *Gripper*

The whole sequence of transporting the plants from the trays to the buffer system was performed in an auto sequence controlled from the GUI on the Raspberry Pi. It moved the gantry into the correct XY position and sent the instructions to the Arduino that controls the Z-axis and gripper. As mentioned previously, the software enabling the gripper actuation is a state machine. The main states used for the gripper mechanism are opening or homing and closing the gripper. The sequence began with the gantry moving down along the Z-axis. The gantry then moved towards the trays and positions itself into the correct Y position of the seedlings it intends to grip. Then it moved forward to to the correct X position. When the gripper was perfectly aligned with the plants it moved down further along the Z-axis in order to grip them as near the roots as possible. After reaching the correct positioning the gripper was closed and the gantry moved up bringing the plants with it out of the trays. After that it moved to the buffer system where it aligned with the buffer and released the plants.
Another state machine sequence for the gripper which was never tested but created was to check if it had gripped the plants. The sequence for this is shown in Figure 67. Once the gantry had moved into the correct X- and Y-position and before the gripping action could be performed the gantry moved further down in order for the limit switch to be able to reach the soil inside the cells. The system then checked if the limit switch yielded a high signal, this was then recorded in order to see how many plants the limit switch sensed in the beginning. Once that was done, the gripping process began and the fingers would grip the plants and remove them from the tray. Once the roots had moved 2 cm up, the gantry's Z-axis would stop and the limit switch outputs were checked again. If the limit switch was still yielding a high signal then the gripping was successful, but if the limit switch yielded a low signal it would be compared to the initial state of the limit switch. If the initial and second state differed, the gripper would release all the plants and the whole gripping process would be repeated. This

sequence would only be performed a total of 2 times after which the plants that were not gripped successfully would be left. If the limit switch yielded a low signal in the beginning the gripping reattempt would not be performed. One exception to this is if all the limit switches yielded a low signal. The reason the seedlings were to be moved up 2 cm before checking the limit switch output was due to the first 2 cm of seedling extraction being the most challenging. This can be explained by the cell diameter of the seedlings being the widest at the top.

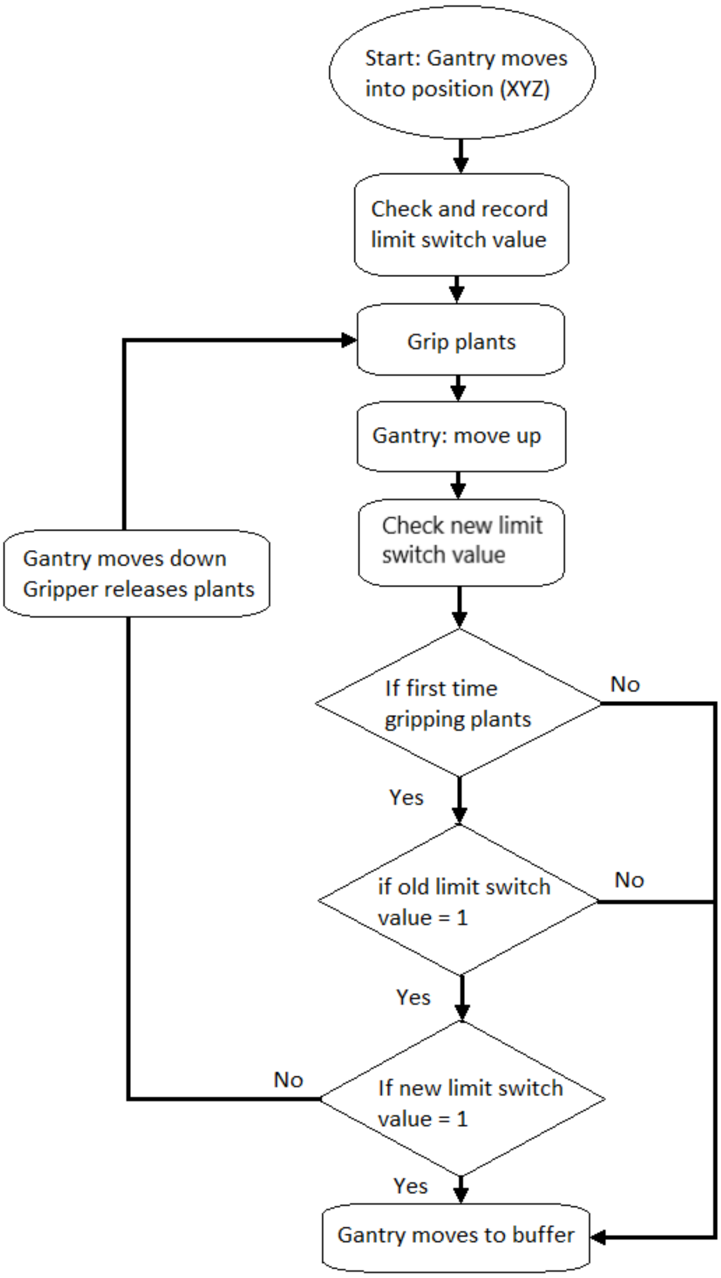


Figure 67: Flow chart of limit switch code for the Gripper

4.5.4 *Buffer*

In the following paragraphs, various topics of the buffer system software implementation are described.

SOFTWARE ARCHITECTURE The software in the buffer is separated into two parts, low level hardware control that will be performed on an Arduino Nano platform, and a high level state machine that will be performed on a more computationally capable Raspberry Pi.

HIGH LEVEL – STATE MACHINE The high level logic commands are implemented as a state machine on the Raspberry Pi in python code. A simplified state machine for the buffer can be seen in Figure 68. The state machine involves movement from one side of the tray to the other, with cup opening sequences, restock seedling sequences and occasionally a homing sequence.

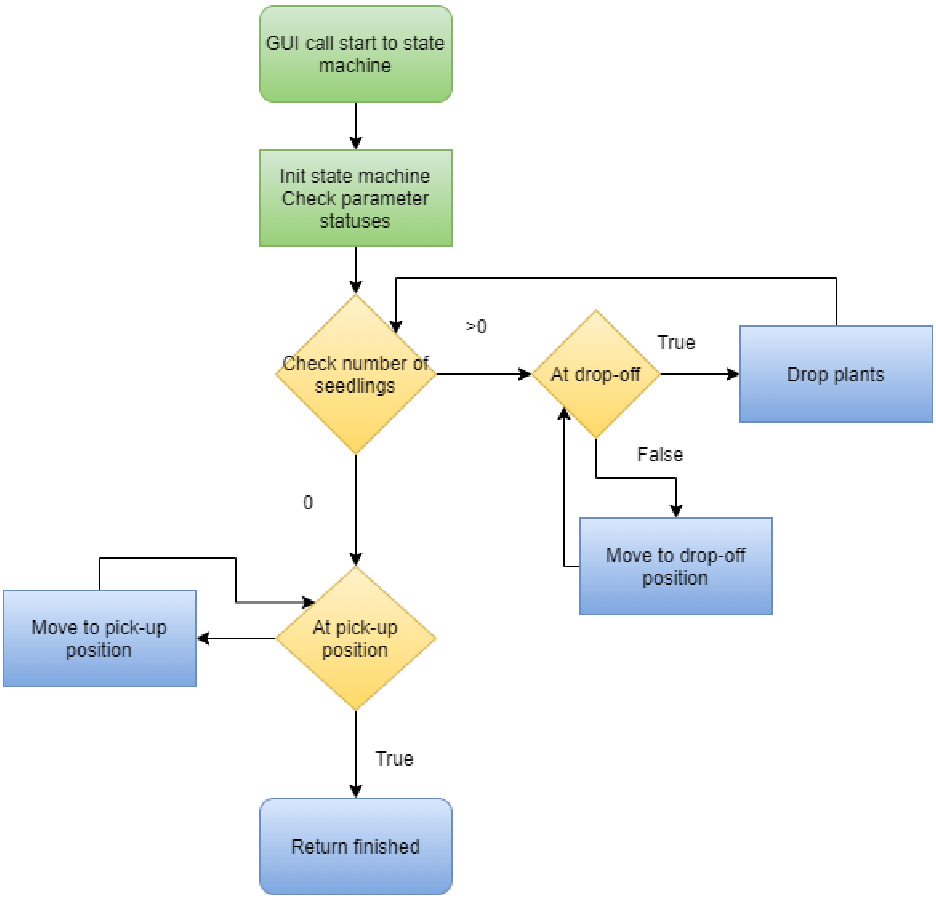


Figure 68: State Machine Flowchart

Why the use of a state machine? A state machine is a way to divide a complex set of instructions into more manageable pieces, where each state is responsible for performing a set of instructions. Each new state is determined by the previous state. The state machine implementation was chosen because it enables a more modular approach to handling of different tasks. By separating tasks into states, each task can be designed and tested independently from another. A state machine can be used as a way to model abstraction, instead of having a set of tasks that would need to state explicitly each action, by grouping each task under a state, the state machines creates an abstraction that is not necessary for the user on a higher level.

A state machine operates on conditions, depending on which conditions are fulfilled or not after a state, another state will be chosen to be performed.

State machines have some disadvantages. One is that when a state is removed, all the state which have a dependency to lead from or lead to the removed states need an update. Another disadvantage is that the state machine is based on a visual graph representation, and if there are too many states, it can be hard to follow. For the scope of this project, the amount of states were deemed to be low enough that there would not be any problems with the visual representation. One of the biggest issues with state machines is that the reuse ability is low. If some conditions are inside a state, using the state machine across different projects becomes difficult [71].

Each opening sequence implements a movement of the tray to correct position, query sensor data if the seedling is in the cup, if a seedling is in the cup, open, hold and close actions are taken and then followed by another sensor query to check if the seedling has successfully been dropped. If there is no seedling in the cup before the cup is opened, the tray will skip the opening sequence and move on to the next state. If there is still a seedling in the cup after the open, hold and close sequences are performed, each sequence will be repeated. A possible but currently not allowed action is to perform a clearing sequence. This was included in the early concept design, but was not created for the final prototype design that this project spans, due to being deemed not to be a necessity. The clearing sequence performs the same actions as the cup opening sequence, but at another position. In this position the cup is not in the hand-over position between the Autoplant 1 and Autoplant 2 projects, but rather intended to be an open to the ground position where waste/dirt can be removed from each cup.

After each run through of the state machine, the final state is the restock sequence, here the state machine calls to the gantry positional system that it is ready to receive plants, and which position it currently is in (there are two predetermined restocking positions for the Buffer system), so that the system knows where to move the seedlings to for drop-off from gripper to buffer subsystem.

At every second run of the state machine there is a short calibration performed to remove any possible drift in the tray system position that can cause miss-alignment, this is necessary since the current prototype design has a small slippage upon startup cause by a spike in torque upon launch.

STATE MACHINE API The high level controller offer API that can be called for query of current tray status (ready or not ready) and at what position it is currently at. There is also an API that allows the GUI to perform manual movement outside the preset position of the state machine, these can be seen in Table 9. Any optional arguments defaults to tray number 1. In case one of the trays are not operating, the optional argument will default to information about the current running tray.

Table 9: Buffer API

BufferControl class API	Input parameter	Return
get_tray_status	tray_ID (Optional 1 | 2)	Boolean, Tray ID
get_tray_position	tray_ID (Optional 1 | 2)	position mm, Tray ID
set_state_machine	tray_ID	None
set_movement_manual	tray_ID, length, direction	None
set_open_cup_manual	tray_ID	None

THREADING Since the system needs to be performing concurrent actions, each tray is designed to be controlled as a thread during concept design. The high level controller is designed as to be used as an individual tray that can be scaled for each tray that the system has. By assigning a thread to each tray controller, the system can handle unforeseen behaviour such as interrupts or subsystem malfunction. Another advantage with using threading for the high level controller is repeat ability, since by having a thread to control and monitor each tray, the difficulty for individual control during manual mode is reduced. The design of threading is also by necessity, since parts of the opening sequence can introduce delay in action if the python code was not threaded (this due to internal delays or waits).

COMMUNICATION METHOD The high level controller communicate with the low level controller using serial communication, this is done via the Python serial API through the use of the usbCommunication class. Unlike the Modbus communication method discussed previously in the SOTA in Section 2 and concept design, this was later changed due to the decision to not use the initial concept of ROS as programming language responsible for communication and control, but instead the system uses C++ on Arduinos and Python on Raspberry Pi. Since serial communication is very easy to use and clearly defined, it was decision made to reduce complexity. To physically perform the serial communication, the Arduino boards are connected to the main Raspberry Pi via USB.

LOW LEVEL As mentioned, the low level hardware control is handled by an Arduino. Because of the limitations of pins on an Arduino, each buffer will require its own. The units controlled by the Arduinos are the tray movement stepper motors, the lid servo, the homing limit switch, and the seedling sensors. A possible design improvement would be to connect the limit switch to the Raspberry Pi as well as to the Arduino, for a faster trigger of interrupt routines. On the low level controller all of the safety features (example limit switch that prevent movement outside geometrically allowed scope) that are required to ensure there will be no damage to the system in case of movement outside perimeter.

The low level controller is responsible for interface and interaction between hardware and software (analog to digital signal processing), as well as providing API between the low and high level controllers.

The API between the high level and low level is due to simplicity based on sending strings over a serial communication, and then parsing the strings. On the low level controller this is done using the Arduino C++ serial package [72].

To implement the state machine from the high level controller, the low level controller has its own state machine implementation that activates different cases depending on how it parses the string based on Table 10, where the strings used by the state machine is presented. The first character is the tray identifier. The second defines which action is being taken and the third form a set of strings to move to up to 9 preset positions, currently 6 defined. Four to six enable movement to any position up to 999 mm from homing position (origin), and the seventh string parameter control the position of the cup opening servo. The Arduino returns the string "999" when it has successfully performed its task, or "666" if something prevented the tasks execution.

Table 10: Buffer Serial string API

Buffer Low level Control	Control string output	Arduino return string
Drop-off position 1-5	11X0000 (X = 1|2|3|4|5)	999|666
Homing	0000000	999|666
Move to restock position 1	1110000	999|666
Move to restock position 2	1160000	999|666
Open Servo	1800001	999|666
Close Servo	1800000 (X = 1-9)	999|666
Query current position	1600000 (X = 1-9)	999|666 + position (mm)
Query seedling status	1600000 (X = 1-9)	999|666 + XXXXX (X = 0|1)

4.6 Simulation

To verify that the BLDC motors received would be capable of driving the X- and Y- axes, a Simscape/Simulink model of the mechanical system was designed. The model only consists of one of the axes, namely the Y-axis, since it moves the heaviest load. The motor was modeled as an ideal angular velocity source. The belt was modeled as translational springs and dampers in parallel. A spring rate of 6 GPa and a damping coefficient of 8.2 kN/m, typical values for timing belts [73], where used. The X- and Z- axes as well as the gripper constitutes the mass that the Y axis moves, this was modeled as a mass in Simulink, the mass of 12 kg was calculated by setting the correct material parameters in Onshape and looking at the mass properties. The pulleys were modeled as ideal Simscape pulleys, meaning they are friction- and inertia-less. An ideal torque sensor was added to the driving pulley to sense the torque needed to drive the mechanical system at the velocity specified. A picture explaining the mechanical system that was modeled can be seen in Figure 69 and the equivalent Simulink block diagram can be seen in Figure 70.

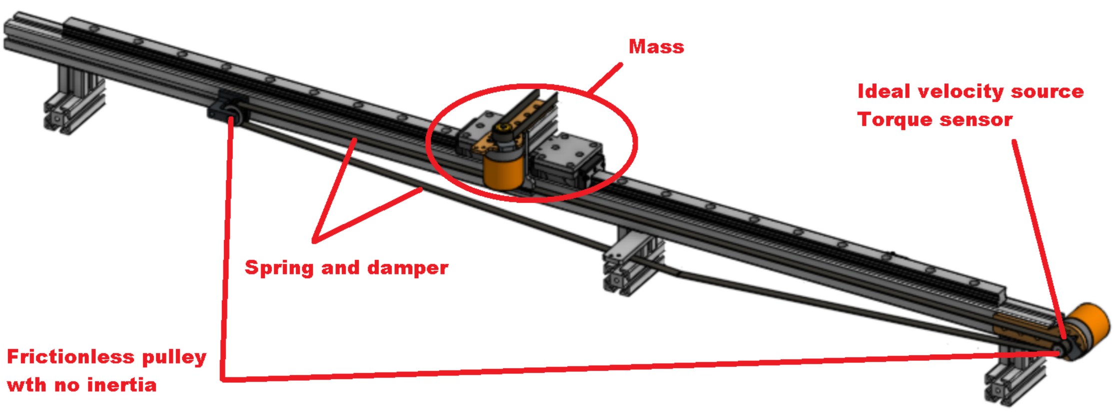


Figure 69: Descriptive picture of the physical equivalent of the simulink model.

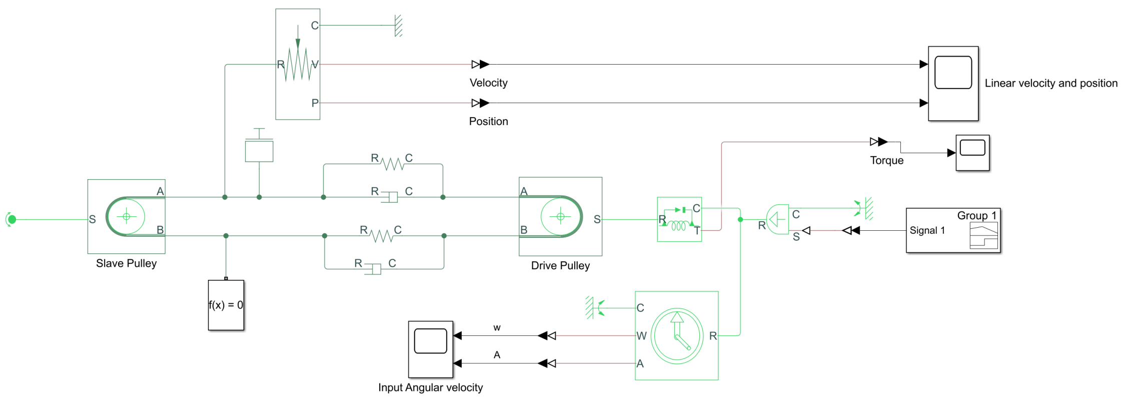


Figure 70: A Simulink/Simscape block diagram of the mechanical system

In Figure 71 the torque plot for a step input of 100 rad/s at second 2 and a step down to 0 rad/s at second 3, can be seen.

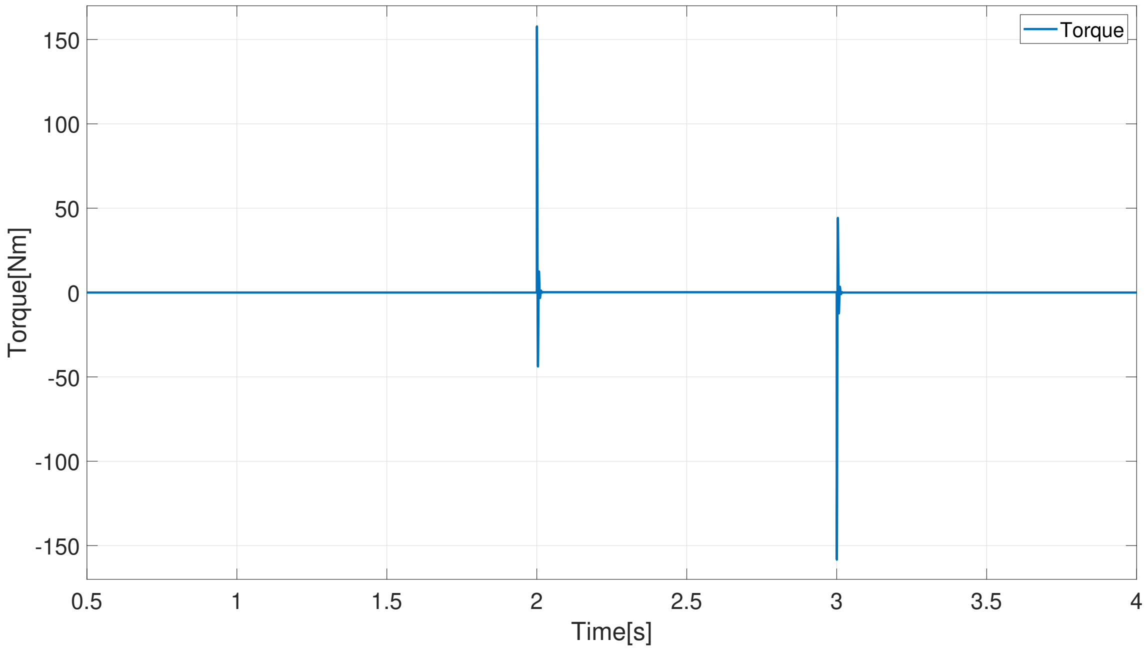


Figure 71: Needed torque to perform a step input

It can be observed that massive spikes of torque are required at the time when the step occurs. The motors can not supply this amount of torque. However commanding a step input is not a good idea for several reasons. The torque and current will peak at the step time even if can not go to the required level, which will put unnecessary stress on both the mechanical and electrical system. Instead a trajectory planned input is commanded, consisting of a ramp from 0 rad/s at time 1 second to 100 rad/s at time 2 seconds. The velocity is then kept constant for one second before it ramps down from 100 rad/s at 3 seconds to 0 rad/s at 4 seconds. As can be seen in Figure 72 the require torque is now much less, at a maximum of around 0.4 Nm. The motors are capable of handling 3 Nm of torque as can be seen in Appendix C and are thus well equipped to handle the torque required to move the mechanical system.

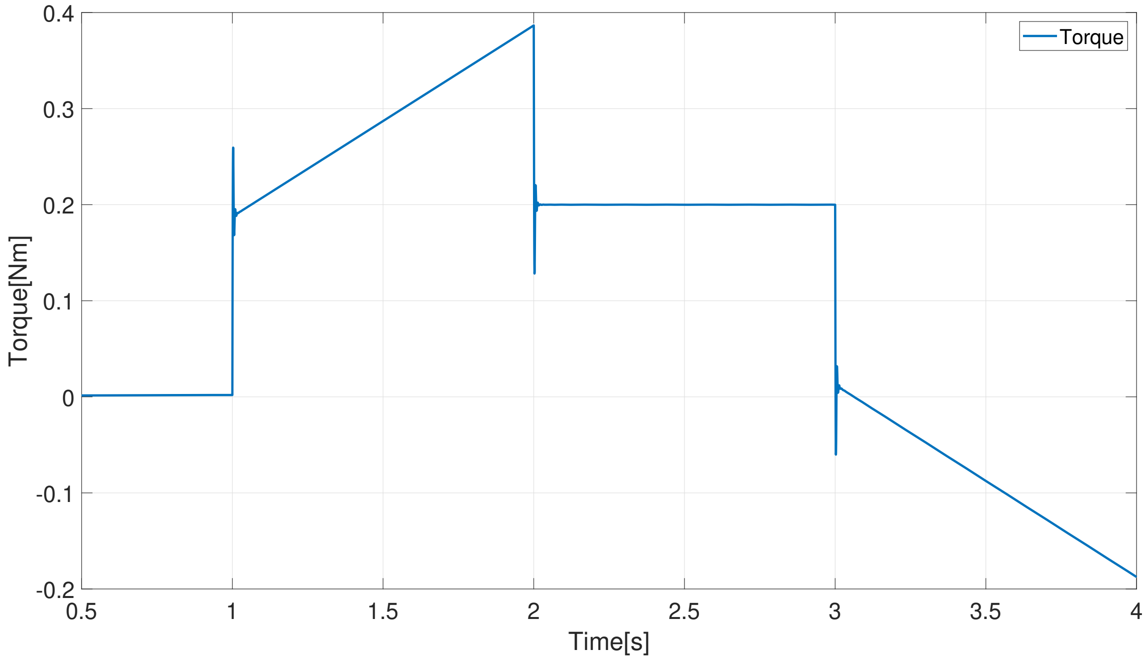


Figure 72: Torque to perform a ramp input

The stepper motor on the Z-axis needs to be able to handle the weight of the carriage and gripper. To verify this, a Simulink model of the leadscrew was created as shown in Figure 73. The model estimates the lifting force, which is presented in Figure 74.

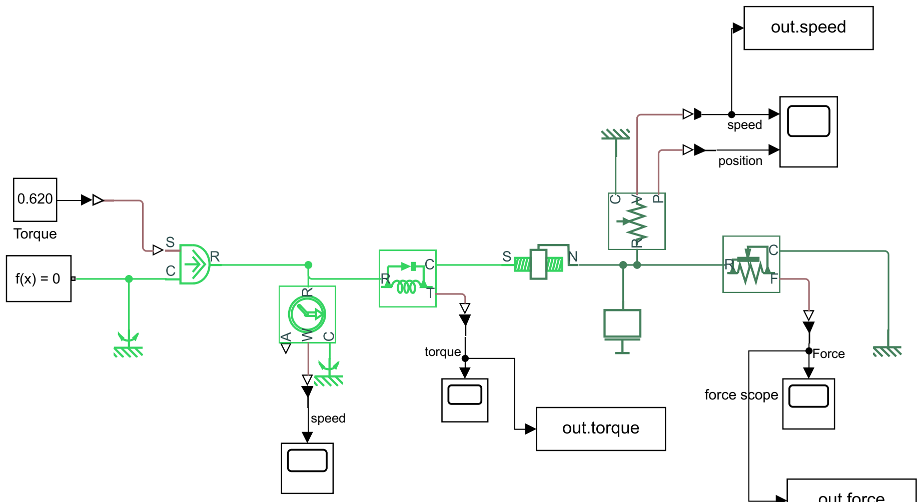


Figure 73: Simulink model

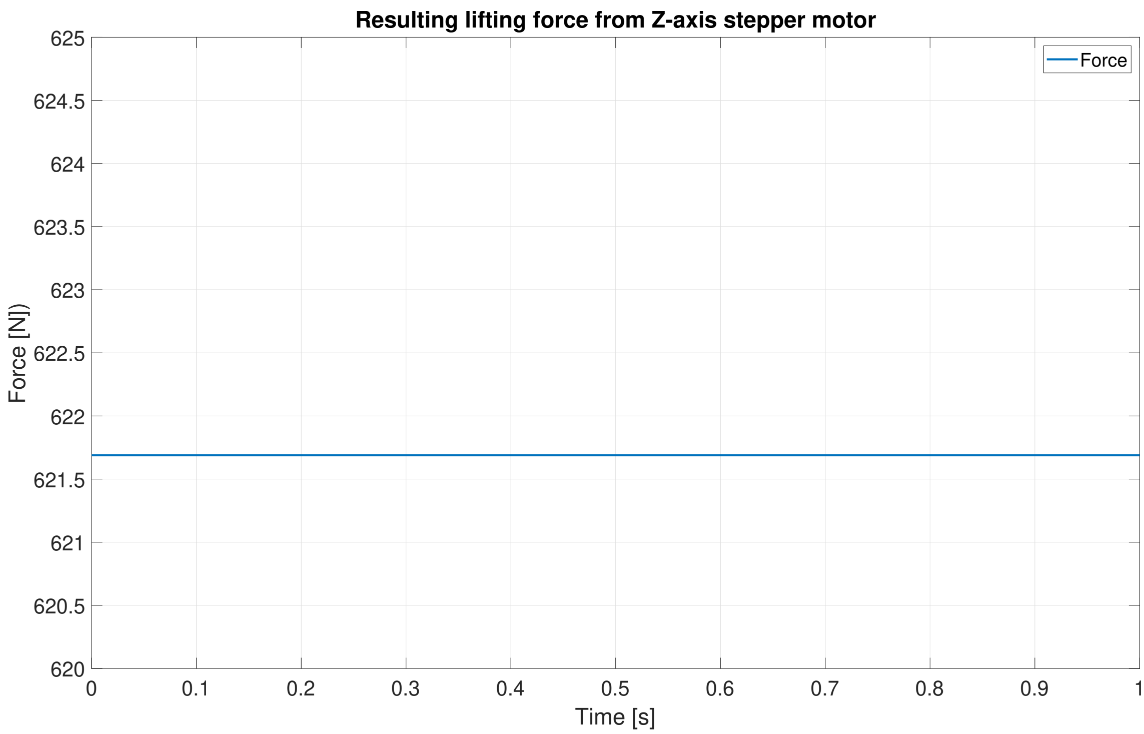


Figure 74: Lifting force simulation

As seen in Figure 74 the stepper motor can produce a lifting force of approximately 621.7 N, which is more than enough to lift both the gripper and plants, which were estimated to weigh less than 12 kg.

To mitigate the effect of deboucing, a simulation of a low-pass filter was created. The low-pass filters was designed according to Figure 75. It consists of two resistors and one capacitor. The resistor R_1 and capacitor C_1 form a low-pass filter, with $R_1 = 10\ k\Omega$ and $C_1 = 100\ nF$. These numerical values were found by testing different values while monitoring the results on an oscilloscope. The purpose of R_2 is to limit the current when the capacitor is discharged through the limit switch.

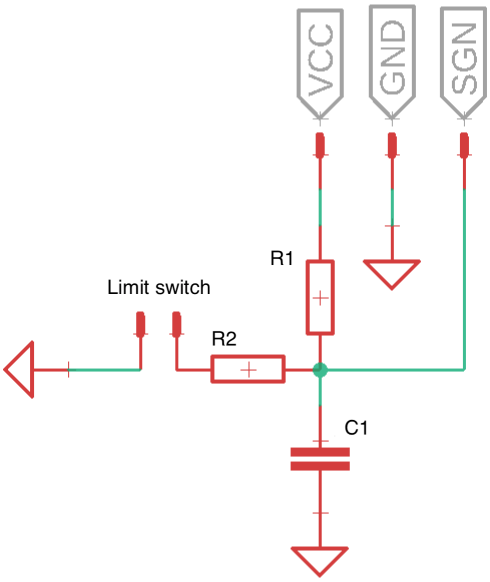


Figure 75: Low-pass filter

The Laplace equation of this circuit is shown in equation (1).

$$SGN = \frac{R_2}{R_1 R_2 C_1 \cdot s + (R_1 + R_2)} \cdot VCC \tag{1}$$

One thing to keep in mind when choosing numerical values for this circuit is that R1 and R2 form a voltage divider. The final value theorem shows that the voltage of SGN when the switch is pressed is determined by:

$$SGN = \frac{R_2}{R_1 + R_2} \cdot VCC. \tag{2}$$

The microcontroller used uses a 5 V Transistor–transistor logic (TTL), which means that a logical zero is 0.8 V [74]. To achieve this, the resistor has to be dimensioned according to equation (3)

$$SGN < \frac{R_2}{R_1 + R_2} \cdot VCC \rightarrow R_2 < \frac{R_1 \cdot SGN}{VCC - SGN} \tag{3}$$

The equation yields that the maximum value for R2 is approximately 1.9 kΩ. To make sure that the threshold of the TTL level is never crossed, the value of R2 has to be less than this value. The value was chosen to 1 kΩ. This choice of resistance should result in $SGN = 0.\overline{45}$ V which is confirmed in the simulation shown in Figure 76.

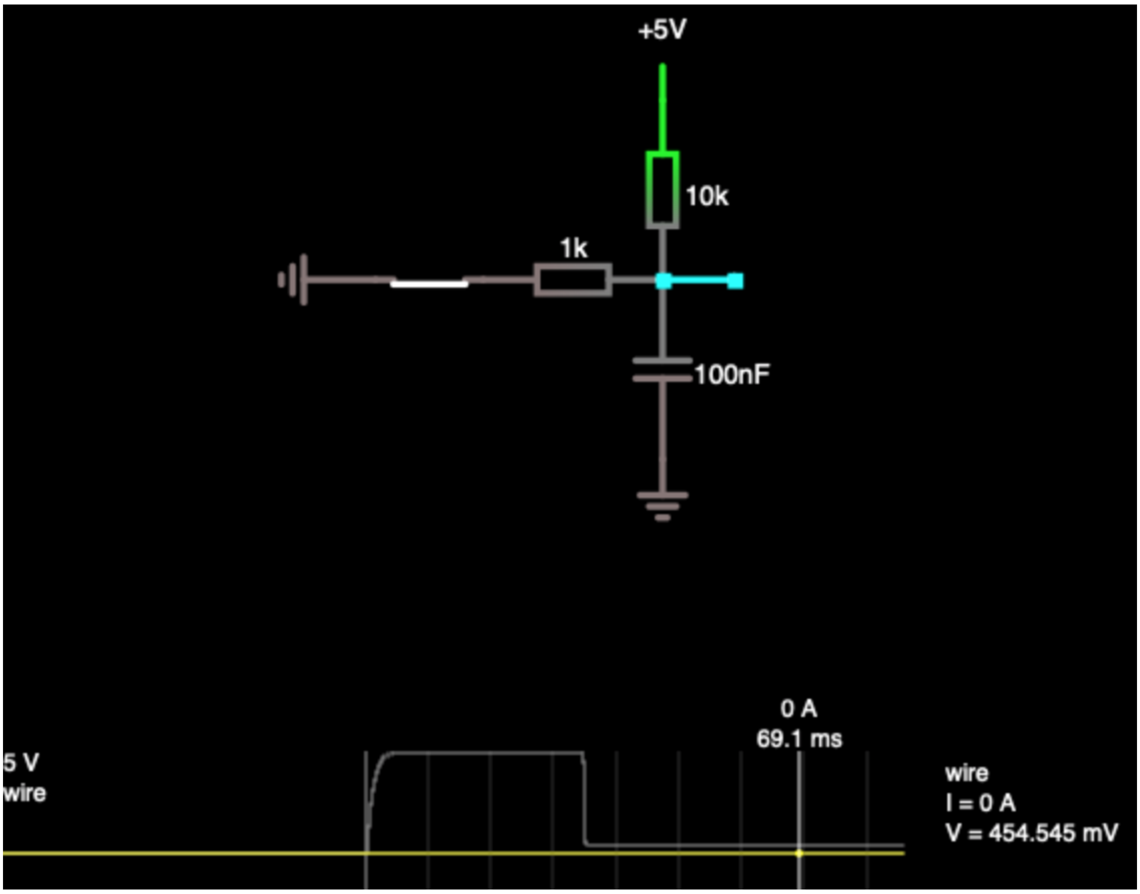


Figure 76: Limit switch Simulation

5 VERIFICATION AND VALIDATION

The technical requirements of the system listed in Section 1.3 describes the overall system requirements. To successfully test whether they were met or not, they have to be broken down further

- The system should be able to output 400 seedlings per hour.
  - The Buffer system should be able to output one plant every ninth second.
  - The Gantry and Gripper systems should be able to deliver plants to the buffer system every 45th second.
- The system should be functional in the given environment.
  - The Gantry system should be able to handle shocks without losing position.
- The system should be autonomous.
  - The Gantry needs to automatically go through every gripping position accurately.
- The system should handle seedlings safely.
  - The Gripper system should extract plants from the cultivation trays safely.
  - The Gripper system should be able to detect extraction successful or not.
  - The Gripper and Gantry system should be able to transport plants from the cultivation trays to the buffer system safely.
  - The Gripper system should be able to drop down plants into buffer system safely.

5.1 Seedling output speed

In the following paragraphs, the stakeholder requirements dealing with seedling output speed and the tests that were performed to verify and validate the fulfillment of those requirements are discussed.

THE GANTRY AND GRIPPER SYSTEMS SHOULD BE ABLE TO DELIVER PLANTS TO THE BUFFER SYSTEM EVERY 45TH SECOND To verify that this requirement was met, the time it took for the different movements was measured. The times can be seen in Table 11.

Table 11: Time measurements

Task Number	Task	Time [s]
t1	Lift/lower Z-axis	5
t2	Grasp plants	1
t3	Release plants	1
t4	Accelerate/decelerate in X/Y-direction	0.5
t5	Travel 1m in X/Y-direction	4

The actions presented in Table 11 can be paired together in a specific order to represent the steps that the machine takes to pick up plants and bring them to the buffer system. This combination of steps and total time can be seen in Table 12. Note that in step 2 and 7, when performing task t5, a travel length of 1 m is assumed, which is approximately the longest travel length for the X- and Y- axes in the scaled down version that was built. The resulting time was 22 seconds. In a full scaled version the longest X and Y travel length would be longer, approximately 3 meters. This would add 8 seconds to step 2 and 7 respectively, increasing the total time to 38 seconds, which is still fast enough to satisfy the requirement. It is worth noting that the travel speed of the X- and Y- axes was capped quite low, and is capable of traveling at far greater speeds.

Table 12: Auto sequence steps

Step	1	2	3	4	5	6	7	8	9	10	
Task	t4	t5	t4	t2	t1	t4	t5	t4	t1	t3	Total
Time	0.5	4	0.5	1	5	0.5	4	0.5	5	1	22

THE BUFFER SYSTEM SHOULD BE ABLE TO OUTPUT ONE PLANT EVERY 9TH SECOND

The possible output of seedlings from the buffer depends on two factors: the speed of the linear movement of the buffer and the time required to open and close a seedling container. The linear movement speed was tuned by doing a unit testing on the linear drive as discussed in section below. Whereas the time required for opening and closing of the seedling container was dependent on speed of Servo motor and delay required to ensure successful plant drop. The servo motor speed was set to maximum, while the plant drop delay was set by Trial and error. Multiple dryrun tests of the complete buffer cycle from Restock to all seedlings dropped were performed. One complete cycle took 45 sec to complete whereas the time between each dropoff was noted to be 5 sec. This converts to the plant dropoff rate of around 720 plants/hour.

STEPPER UNIT TESTING FOR SPEED The stepper motor in the buffer system was individually tested for the maximum travel speed. For this testing the motor was connected to the lead screw and linear rail setup with the tray mounted on the rail. The time taken for the tray to travel between two consecutive drops was measured. The delay between the steps and the voltage input are the two factors the stepper motor's speed is dependent on. The voltage input was set to 24 V and the delay time was varied to check the speed performance. It was observed that the linear travel of the tray was fastest at 500 us step delay and it took 2.8 s to travel from 1st drop position to second, but it was noisy. Finally after many alterations in delay time 550 us step delay performed the best both in terms of travel speed and less noise. It took 3.02 s between two drop positions. Based on this test data, a respective delay time and voltage was implemented in the actual buffer setup and tested to reach the 720 plant drop/hr benchmark.

5.2 Environment compatibility

As discussed, the system will operate in a harsh environment. Because of limited time and monetary funds, the physical adoption to these requirements was part of the delimitations of this project. However, some functional measures have been taken to ensure the systems compatibility with the harsh environment.

THE GANTRY SYSTEM SHOULD BE ABLE TO HANDLE SHOCKS WITHOUT LOSING POSITION The ODrive uses feedback from the encoders to maintain the position of the motors. If displacement occurs, the controller will try to counteract it to maintain its position. In other words, the motor is in closed-loop control. This feature was tested by manually displacing the axis. The test was successful, and the motors returned to their initial position.

The Z-axis is open-loop. To maintain its position, holding torque of the stepper motor is enabled whenever the Z-axis is not moving. To test this, the carriage was manually pushed when the holding torque was active. The motor successfully held its position.

5.3 Safe seedling handling

In the following paragraphs, the stakeholder requirements dealing with safe seedling handling and the tests that were performed to verify and validate the fulfillment of those requirements are discussed.

THE BUFFER SHOULD BE ABLE TO HAND OVER A SEEDLING TO THE PLANTATION SYSTEM To fulfill the task of handing over a seedling to the plantation system, the opening mechanism of the seedling container must be functional. As discussed, the containers are held closed with a torsional spring, and then opened using a servo and levers.

The appropriate preloading angle of the torsional spring was found through manually changing the angle and then testing seedling drops. The reasoning behind this approach was that the achieved container prototypes were 3D printed and hence not perfect. The alternative, to calculate an accurate angle, therefore was not as pragmatic as physical testing. To ensure sufficient opening of the containers, the servo was tested in a similar fashion. As discussed, the servo was selected considering the force needed to open the container and counteract the spring. But the needed angle of the servo had to be found. This was done through iteratively changing the value sent from the Arduino until a satisfactory corresponding value and angle was found. The servo and spring configuration was tested physically and found to fully open the containers.

THE GRIPPER SYSTEM SHOULD EXTRACT SEEDLINGS FROM THE CULTIVATION TRAYS SAFELY The seedlings in the project were delicate and had a relatively small diameter. However it was also noticed that the seedlings were fairly flexible. Therefore, the skewed gripping fingers arrangement was implemented as well as rubber material on the gripping contact area. When the gripper closed, the seedlings were bent and not squeezed by the fingers in the same place from both sides of the stem.

To test if the gripper was able to extract seedlings from the cultivation trays safely a number of tests were performed. First the gripper system was manually tested, meaning that both the XYZ-positioning of the gantry was performed through observation and when the seedlings were perfectly aligned with the gripping fingers the closing of the gripper was controlled manually. The tests were performed both on the taller and smaller seedlings as well as on seedlings that had been pulled out before and on seedlings that were brand new. After the manual tests the gripping and extraction of the seedlings was also performed with the automatic sequence where the gantry positioned itself before gripping the seedling. These tests were performed first without the buffer system in order to test as many gripping sequences as possible without delays and later also with the buffer in order to see the whole system working together. The automatic sequence would run until the the system had picked the seedlings of one whole tray. The tests were mainly performed with the tray locking mechanism in place but the system was also tested when the mechanism was absent to observe the difference in the performance. The tests were also performed when only the plants that were supposed to be gripped were in the cultivation tray as well as when the whole tray was filled to see the difference. It was monitored when and why some issues occurred as well as how many plants the gripper was actually able to grasp successfully.

THE GRIPPER SYSTEM SHOULD BE ABLE TO DROP DOWN SEEDLINGS INTO THE BUFFER SYSTEM SAFELY As before to test if the gripper system was able to drop seedlings of into the buffer system safely the whole system was performed both manually and autonomously. The manual tests were performed while the buffer system was standing still while the test during the automatic sequence were performed with the buffer system active. During the testing it was monitored if the system was able to successfully lower the seedling into the correct cup, if the seedling was damaged in any way and what the main reason was for this damage if it did occur.

5.4 System autonomy

In the following paragraphs, the stakeholder requirements dealing with system autonomy and the tests that were performed to verify and validate the fulfillment of those requirements are discussed.

THE GANTRY NEEDS TO AUTOMATICALLY GO THROUGH EVERY GRIPPING POSITION ACCURATELY To operate autonomously the gantry needs to know every position it needs to go to and accurately go to all those positions in automatic mode without failure. The software provided an automatic mode and it was tested on the fully assembled hardware. To test the entire auto sequence of the gantry in isolation the test was performed without picking any trees and without running the buffer system. This way it could be tested much faster since it did not have to wait for the buffer system to finish outputting plants. Through observation it could be see that the gantry positioned itself so that the grippers fingers where correctly positioned over the cups in the cultivation trays for every possible position.

THE GRIPPER SYSTEM SHOULD BE ABLE TO DETECT SUCCESSFUL AND UNSUCCESSFUL EXTRACTION OF SEEDLINGS Unfortunately due to time constraints the system that was designed to detect a successful extraction was not able to be implemented. The planned system included limit switches for soil detection in and out of the tray. The detection sensors on the buffer were also not able to be implemented due to non delivered components and were thus not tested.

THE GRIPPER AND GANTRY SYSTEM SHOULD BE ABLE TO TRANSPORT SEEDLINGS FROM THE CULTIVATION TRAYS TO THE BUFFER SYSTEM SAFELY For this requirement the system was also tested both manually and autonomously. The gantry system moved between the cultivation tray and the buffer system multiple times. The main focus of these tests was if the gripper system could successfully hold on to the seedlings without dropping them or without them slipping down while traveling between the cultivation tray and the buffer system. It was also observed if the gripper was able to hold the seedlings for a longer time during which the buffer system would perform it sequence. During the automatic sequence the gantry stops and starts to move several times while holding the seedlings and it was monitored if the gripper was able to hold the seedlings during these sequences.

SENSOR UNIT TESTING The concept of plant detection was tested on a easily available HC-SR04 ultrasonic proximity sensor. The sensor was mounted in a similar way as maxbotix on the side of the cup, and the transducer protruding from holes in the cup.

The HC-SR04 has four pins namely 5 V, Gnd , Trig and Echo. It was powered using Arduino 5 V out. The trigger and echo pins were connected to digital pins on Arduino as shown in Figure 59a. A constant PWM pulse was sent out through the trig pin. Whenever a plant was in the proximity of the sensor, the change in pulse width on the echo pin could be observed. The software code in the Arduino tracked this respective change in pulse and therefore detected a plant. Once the plant is detected, it prints Plant detected on the serial monitor which is read and processed further by the lower level code of the buffer system.

5.5 Software Verification

The software has been designed according to the methods taught in the course MF2013 Embedded systems for mechatronics for verification, using unit tests and mock test. The theory is that the initial test has to return a failure (preferably before any actual code is written), after which the code will be iterated until the tests return a pass, this to make sure that the code is working successfully and that the code works as intended.

Each high level API towards the low level (C-code on Arduino) has a unit tests that makes sure the code output is the expected, and vice-verse for input (if proper input is received, does the code perform expected functionality). After hardware was put in place, integration testing and system testing was performed to ensure designed capability was in place. As an example an integration test that was designed was to connect an Arduino, Raspberry Pi and a stepper motor and ensure that given a high level command, the hardware executed the expected amount of turns [75].

To perform system integration test between the API aimed towards the GUI 4.5.4, the API was first tested using unit tests and then finally tested in the final system integration test where by the complete design was tested.

6 RESULTS

The entire process was automated and could be controlled remotely via the internet. However, sometimes the gripper would not successfully grip all the plants it intended to grip and sometimes it would pick more than intended. The seedlings were safely lifted from the cultivation trays and safely transported by the gantry, however sometimes they were held in a skewed way so that the plants were damaged when they were put into the buffer system. Therefor, the stakeholder requirement of safely transporting the seedlings to the plantation arm was not completely met. The system was successful in delivering 400 plants per hour and it is believed that the system could be improved to deliver 750 plants per hour with only software changes and up to 1200 plants per hour with some hardware modifications, which will be discussed in Section 7.1 and 8.

The stakeholder requirements of operating all year around except for when the ground is frozen was not met as it was considered to be a too big task. The focus of the project was instead put on the other parts. It could be argued that the stakeholder requirement of being able to solve disturbances was partly met, as the machine can be operated manually, remotely over the internet, and thus there is a limited possibility of manually solving disturbances such as objects becoming lodged by manually gripping them or pushing them. However, no automatic, or robust disturbance handling system was designed in the project.

The finalized machine can be seen in Figure 77 - 79.

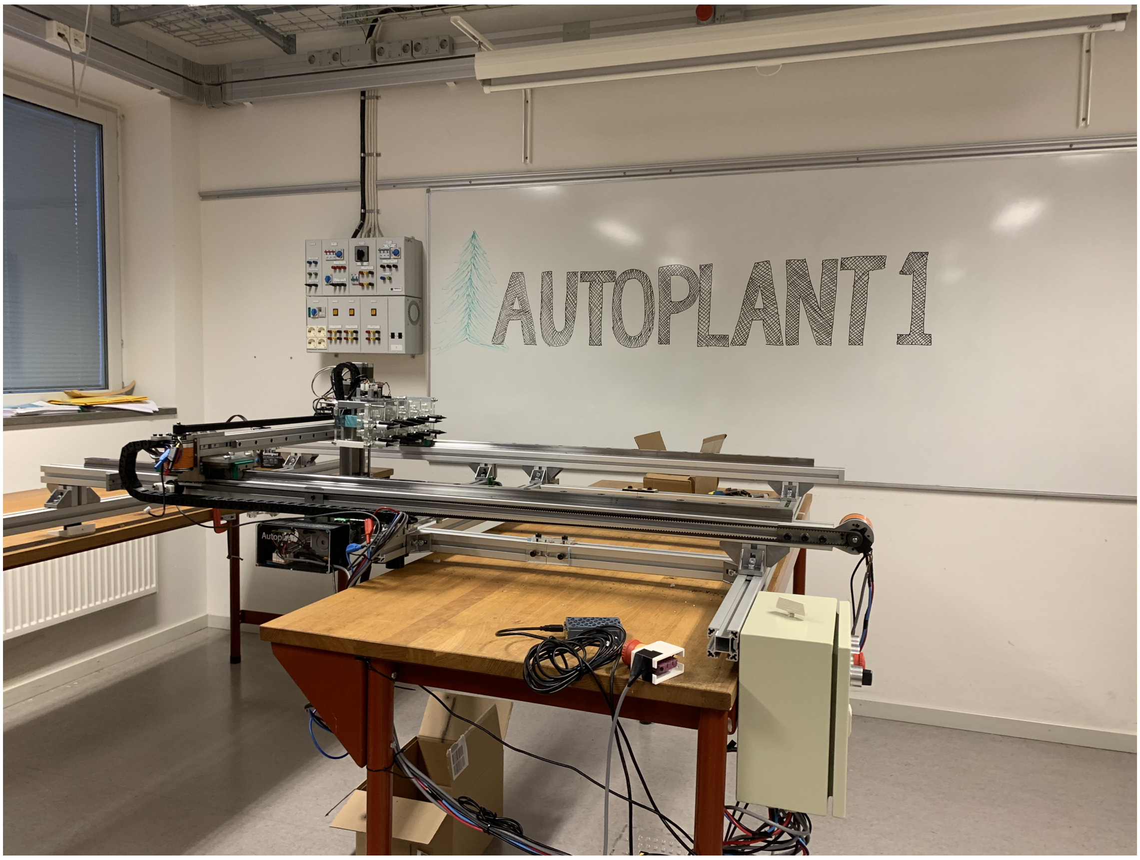
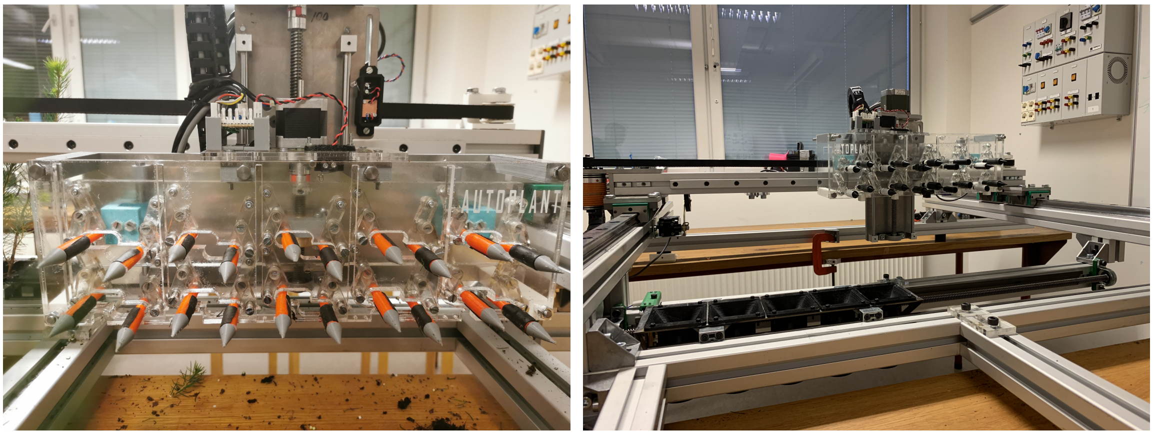
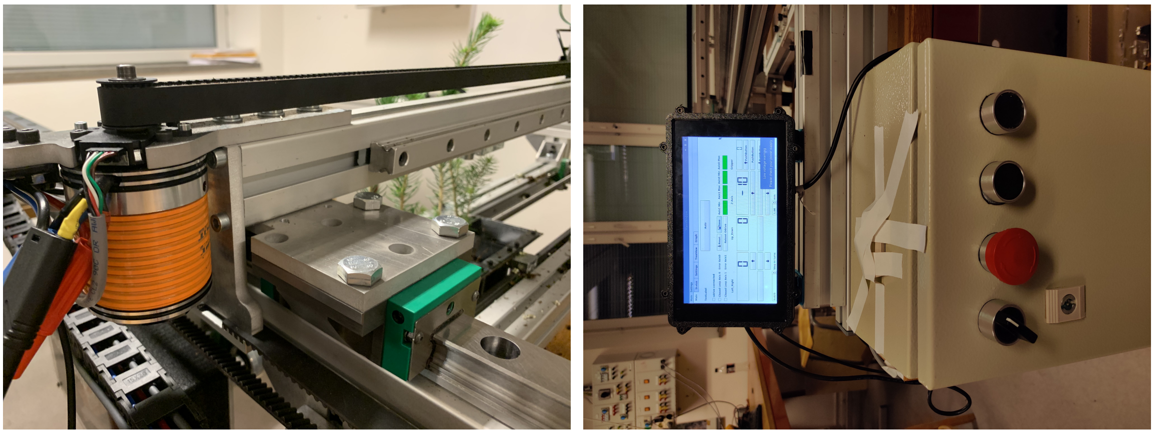


Figure 77: Complete view of the machine



(a) Front view of the Z-axis and gripper (b) View of the Z-axis, Gripper, and Buffer

Figure 78: Front view of the Overall System



(a) BLDC motor that drives the X-axis (b) Electronic cabinet and control unit

Figure 79: X-axis and control unit

6.1 Stakeholder requirements

Table 13 shows the stakeholder requirements, requirements that are fulfilled are noted with ✓, X if they are not fulfilled and - if it could not be verified.

Table 13: Stakeholder requirements

Requirement	Fulfilled
Extraction of the seedling from the cultivation tray without damage	✓
Transport seedlings safely to the plantation arm subsystem.	X
The entire operation should be automated	✓
The system should be able to solve disturbances, such as objects be-coming lodged, as much as possible.	-
Ability to remotely control and overview the process	✓
Ability to extract and deliver 400 plants per hour	✓
Operate all year around except for when the ground is frozen	-

Overall the gripper worked quite well. It was able to grip most seedlings and deliver them safely to the buffer system. Out of the three requirements of extracting, transporting and delivering the seedling to the plantation arm it succeeded with two. There can of course be improvements with the first requirement of extracting the seedlings since the gripper was not always successfully in this but it did not harm the seedling. It was noted that the gripper did not break the tree stalks during the whole process and the roots stayed mainly intact even on the seedlings that were stuck in their respective cells. The only moments when the roots were affected and the seedling lost all the soil was when they had been picked and replaced into the tray multiple times. As for the second requirement of transporting the gripper did succeeded very well as the seedlings did not break during the Gantry's movement. The third requirement is the only one where the seedlings were sometimes damaged since they were not lowered in correctly the roots were in danger of being flattened. The third requirement is closely related to the first and if the seedling is not gripped correctly it was more difficult to perform the last task. Some of the resulting issues that were documented were:

- Gripping at an angle due to lack of soil or only gripping with one set of fingers as seen in Figure 80
- Slipping of the fingers and therefore not picking up the seedling
- Trouble picking up seedlings due to previous plants left in the tray
- Gripper fingers missing the seedling due to pushing it away or the fact that it is hard to reach because of where it grows
- Gripping seedlings on the rows behind or gripping the wrong seedling

(a) Seedling askew due to only being gripped with 2 fingers

(b) Two seedlings in one buffer cup due to tilted plant

Figure 80: Issues in Gripping process and seedling drop

7 DISCUSSIONS AND CONCLUSIONS

In this report, the design of a subsystem used for a tree-planting machine was presented. The functions of the subsystem mainly focused on extracting and delivering seedlings from a cultivation tray to the plantation manipulator. However, in the present market of planting machines that was investigated, the seedling transporting from storage to delivery system is not done autonomously, so the concept designs are inspired by combining existing solutions to a wholly automated subsystem. Considering the industry status and labour costs, the planting system was developed to be completely automated on the existing basis. In order to meet the requirements given by stakeholders, multiple aspects were considered during the design process.

GANTRY The prototype that was built of the gantry was delimited in the way that it was not made for continuous outdoor use, due to the limited time and resources. For example, the linear rails are very high precision and they would most likely not have a long lifetime in a dirty environment or where the temperature fluctuates. However, it was chosen because of its wide availability and because they are very easy to install on aluminium profiles. Instead of a belt, the X- and Y-axes could have been driven by chain, but because a belt was available at the beginning of the course, as well as being easier to work with, it was chosen as the means of transmission.

Regarding the electronics, the focus were towards getting a robust and well functioning base for future iterations. The electric foundation for the machine was made flexible and expandable with the use of an IP66 classed electrical cabinet with panel mounted connections. This will hopefully make it easier to add additional features to the machine in the future as it evolves. The system was designed around a 24 VDC voltage source, since this is a very common standard for industrial equipment. One thing to note is that the prototype was not made to be fully compliant with outdoor use, since this would have required additional cost and development time that was not deemed necessary at this stage of development. It had exposed PCBs and electrical connections that was not IP rated. If this product were to be deployed to a real world scenario this is an aspect to take under consideration.

The Z-axis was designed so that the non moving part of it hovered just above the top of the cultivation trays. This means that the Z-axis could not travel over plants, only above spots where the plants have been removed, increasing its possible travel zone as more plants are picked. This design choice was made for several reasons. The Z-axis would have to have a very long stroke in order to travel over the plants, around 500 mm. There would also have to be a very long offset between where the gripper attaches to the Z-axis and the actual gripper. These two facts in combination make for a less robust design in the face of shocks and vibrations. Further, the benefits of being able to move above the plants are not great, since the gripper could not pick up plants in the middle of a populated cultivation tray anyways, as it would destroy the surrounding plants. Neither could it pick up plants from the back, as this would require the gripper to be able to turn 180 degrees, which would require an additional degree of freedom and hence an increased level of complexity.

When running the machine it was capped at a considerably slower speed than it was capable of. This was due to several reasons where one was the fear of braking parts before it was known that all parts worked in the intended manner. Another was the part of damaging plants, where it was known that they had to be treated carefully. However it was noted that the speed could be increased a lot before they would seem to take damage, but the exact limits were not investigated due to time limitations. It was noted that the acceleration was the part that was most harsh towards the plants and is the parameter that should be kept at a reasonable level. This gives the conclusion that if the system is to be scaled up the velocity limits can be increased as long as the acceleration is reasonable.

The limiting speed factor for the overall design of the gantry is the stepper motor used in the Z-axis. One could have opted for a BLDC motor here as well and gained both speed and feedback control, but at the expense of higher price.

GRIPPER There are examples of grippers used to manipulate seedlings as demonstrated with the Risutec APC machines in Section 2.1. Although, most efforts towards mechanised forestation seems to have been aimed towards the plantation process. The Risutec solution which includes mechanical finger type grippers are in line with the research covered on grippers. These grippers are simple and not dependant on the shape or material of the seedlings, which could pose a problem with other types of grippers.

A gripper translates a force into a grasping movement, and therefore needs some sort of actuator. The review of available actuators concluded that the most appropriate solution would be electrical or pneumatic, and this selection could come down to precision versus price. Since the seedlings are not completely uniform, a force closure gripper (gripping by using friction) is most sensible. This can likely be improved by the choice of material of the fingers. Choosing a pliable material can also make the grasping more delicate, which is highly relevant to the task.

Possible improvements relevant for the gripper system are discussed hereon. One disadvantage of the chosen mechanical design with the linkage mechanism is how unforgiving it is towards tolerances in the construction. Several iterations were needed in order to achieve a prototype that did not have unstable gripper fingers caused by screw hole tolerances. This may be avoided with another design altogether which does not utilise linkage mechanisms or by improving the presented solution having this in mind.

The initial mechanical design included gripper fingers with wider diameter compared to that one of the final solution's. This resulted in the gripping fingers not overlapping as much, instead having a more skewed grip on the seedlings. The final solution differed from the initial design proposal with an increased vertical distance between the fingers which caused the seedlings to be tilted when gripped and extracted from the cultivation tray. The tilt could cause unsuccessful insertion of the seedlings into the buffer system cups as seen in Figure 81. It is recommended to further test this phenomenon to verify its cause since this may also be a consequence of gripping the same seedlings multiple times, causing loss of soil and thus a lighter weight that is unable to counteract the skewed grip. Otherwise, if the skewed grip is the main culprit the fingers could be modified into an elliptic cylinder shape. This would cause some overlapping of gripping contact area and reduce the produced tilt in gripped seedlings.

Figure 81: A problem encountered with the gripper subsystem were tilted seedlings when gripped. This would cause failure in inserting the seedlings into the buffer system cups appropriately. The pink outline highlights the buffer cup opening the seedling was supposed to be inserted into. The tilt of the seedling is highlighted by the blue line.

Another way to counteract erroneous insertion of seedlings into the buffer cups is implementing seedling separators into the gripper mechanical design. The gripper would then rely less on how straight the seedlings are when gripped which may be more viable when operating under heavy vibrations.

The stability of the actuation plate in its linear motion proved satisfactory due to the linear shafts limiting the motion to a vertical one. However, this may not be the case when operating in its intended environment: very rough terrain. To remedy this, mounting two linear bushings for each shaft may prove effective in stabilising the linear movement despite vibrations and shocks.

When extracting the seedlings from their respective cells, the tray would often be lifted alongside the upward pulling movement. A robust and autonomous solution for this was not implemented. Instead, clamping components were manually installed to fasten the cultivation trays onto the Gantry for successful seedling extraction. An alternative solution of utilising compression springs were considered. This would entail mounting compression springs at the base of the gripper which would apply force onto the cultivation tray while the seedling were being withdrawn. A suitable spring stiffness would result in the cultivation tray remaining static in equilibrium. This may still prove insufficient since the cultivation trays would not be secured the remainder of the time. The risk of the trays shifting whilst the common platform navigates rough terrain must be considered.

Another major issue faced when gripping the seedlings was the fact that each individual gripper would sometimes grip multiple seedlings including those on the next row. This would cause an issue for the buffer since there would be multiple seedlings in the same cup. To combat this phenomenon the fingers need to be further modified. One solution is to have them shorter, however this would increases the likelihood that the correct seedling might not be gripped at all due to the fact that some seedlings are pushed back when the gripper is aligned with the seedling. This in itself was also a big concern. To combat this the cone shaped fingertips were attached to the gripper fingers to make it easier for the gripper to slip by the seedlings without disturbing them. While this solution did seem to make it easier for the finger to avoid bending the trees back too much it also meant that some seedlings on the rows behind could be gripped with these finger tips.

What made the grasping more difficult was the fact that the seedlings often grew in different positions in their respective cells. Therefore it is harder to grip some seedlings that for example grow near the edge where they are at risk of getting pushed back. It was noticed that the position of some seedlings also meant that the gripper was not aligned with them at all when performing the auto sequence. The discussed solution to this would be to have some sort of sensor, for example a photo interrupter, that could sense if the seedling was present in between the fingers. The issue with adding sensors is their positioning on the gripper. As the mechanism looks now there is little space to add sensors where they are needed the most, in between the fingers. There is also the question of how to distinguish when the gripper has missed to grasp a seedling and when there is no seedling at all in the cell. The solution would be to have a sensor as close to the roots as possible and have it check the whole cell, but that might hinder the finger from grasping the seedling near the root.

It was also noticed that there was some slipping when the gripper tried to remove seedlings from their tray. This was not a huge issue and mainly happened if the seedling was firmly stuck in the tray and was difficult to remove. The solution used for this was to have a rubbery material on the fingers in order to increase the friction between the fingers and the seedlings. This did not always work since the needles on the trees were very slippery. Another solution to this would have been to grip the seedlings even closer to the roots where there are no branches. With the current design this was not possible since the mechanism that secured the tray, i.e. the clamp, was in the way. In order to avoid this there needs to be a different kind of mechanism securing the trays.

The fact that the seedlings would slip might also be caused by the fact that some seedling stems are wider than other. Since there is only one motor it would only move until one of the grippers would grasp its seedling. If one seedling is wider than the rest only that gripper has a tight hold of its seedling while the rest are more loose. With just one motor the grippers also seemed to move differently based on their position. The grippers at the ends would have a more narrow opening than the one in the middle. With a wider opening range it would be easier to avoid the seedlings getting pushed back and away from being successfully gripped.

Most of these issues might be solved with the introduction of sensors that can tell if a seedling has been successfully gripped or if the seedling is in the correct position to be gripped. For this project the limit switch sensors were considered but due to time constraints not implemented or tested. Upon further inspection it was also noted that the since the tray contains rows of both 9 and 10 seedlings the last limit switch would run into some problems on the shorter rows where there is no cell. It would then be lowered down onto the trays edge and might break. Therefore a different kind of sensor would be a better option.

It is important to continue to develop a system to check if the seedling was successfully gripped or not since when there are missed seedlings it becomes harder for the gripper to get the rest of the seedlings in the tray. The gripper then pushes on the remaining seedling and bends all the seedlings on the rows after. This is especially noticeable when gripping smaller seedlings with longer needles. When testing on such seedlings the gripper became inefficient on the columns where one seedling was left in the tray.It was unable to grasp the majority of the seedlings after (column-wise) the missed seedling. There was more success with the taller and thinner pine trees but it still makes it more difficult to grasp the correct seedling if there were unpicked seedlings left.

BUFFER The buffer subsystem is a concept to ensure a delivery of a seedling at each specific time based on the technical requirements, once every 9 seconds. Since the time it takes the gripper to get seedlings and deliver is dependent on the place it will take the seedling from its tray and this is changing, the buffer system has a store of seedlings that it can "buffer" and deliver at the required timings. The system can be said that it achieves this target goal of delivering a seedling at the set out requirement, in fact the result is quicker than the stakeholder requirement, one seedling can be delivered every 5 seconds. This result should be noted that it is a fairly simplistic implementation, since while it achieves the timing requirement, it is not a 100% success rate on dropping seedlings out of the cups. There are two current limitation that lowers the success rate, the seedlings itself and the physical setup of the Autoplant1 system.

Some seedlings have branches that extend further to the side than the width of the cups. These branches act like flexible beams that holds the seedling by pushing on the sides or the top edge of the cups and hold the seedlings floating. Since there is no system implemented to help the seedlings drop out of the cups other than gravity, this is not always enough, which leads to the seedlings not dropping out of the cups as intended. Some possible suggestions on how to ensure drop of seedlings are discussed in the future work Section 8.

The other limiting factor to success is the difference in height between the buffer and the X-axis beam on the gantry. Since the height difference is not big enough to ensure that the gantry passes above the seedlings when it returns to pick up more seedlings from the cultivation trays, it will bend the tops as seen in the Figure 82 and cause them to rest at an angle rather than the straight up-down pose that is preferred for a pure gravitational drop out of cups.

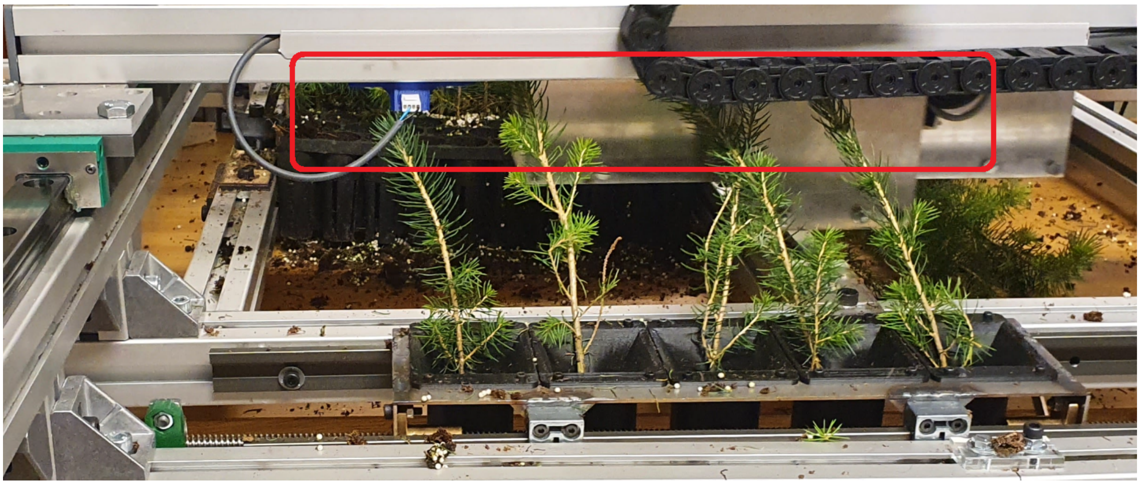


Figure 82: The seedlings get bent due to the X-axis beam on the gantry, causing it to get stuck in the seedling containers

This problem also has causes, but outside the buffer control. When the seedling is being gripped by the gripper, it can get gripped at angle and then be lowered towards the buffer at an angle, depending on how large the angle is, the earth with the root system can in some cases be compressed into itself, or straight up miss the cups and end up in another cup or completely miss the tray. There are some ideas on how to perform a better gripping in Section 8. Any problem that has an impact on the seedlings root system should be solved, since affecting the root system can often lead a fatality for the seedling.

There is nothing similar to this currently in industry, this project was a concept evaluation to investigate the possibility to automate forest plantation of seedlings and to gather experience and knowledge required to achieve this task. The buffer system has found some problems that have solutions. The project stakeholders and sponsors Skogforsk and Brake forest are very pleased with the progress and experience gained by the project.

7.1 Ethics & sustainability

In the following paragraphs, ethics and sustainability are discussed in relation to autonomy and environmental issues.

AUTONOMY There is always an ethical issue when dealing with autonomous machines. If the machine cause any damage or harm, who is responsible? The intended operational environment of the system in question is a further incriminating factor in this regard. Because the system would be operating in a very uncontrolled environment, it is much harder to prevent people, animals or property to come in harms way. Additionally, since the machine would not be kept under surveillance, there could be a risk of sabotage towards the system. It could simply be a question of someone stealing valuable equipment, or possibly tampering with the system to damage the seedlings or others. In either regard, the autonomy and the unsupervised operation of the system should be thoroughly considered from an ethical perspective.

ENVIRONMENTAL ISSUES Today, development of forestry technology is a hot topic all over the world. Although Sweden has the world leading level afforestation, many parts of the world are suffering from desertification and environmental pollution. Higher forest coverage helps reduce the adverse effect from industrialization and excessive carbon emission. Most of the existing planting methods still need manual operation, which is limited in cost-efficiency and labour shortage. Research on advanced autonomous planting machines can free up manpower and increase productivity. Higher planting quality and efficiency produced by optimized planting machines provide bright prospects to forestry development in the future. Predictably, application of autonomous forestry machines will accelerate afforestation and thereby make great contribution to sustainability.

8 FUTURE WORK

There are a lot of possibilities for future work in the area of automatic planting. This is due to the fact that the majority of the planting of trees is still done manually. A big part that can be automated is discussed in this very paper, the transfer of the plants from a cultivation tray to the planting machine.

In the near future one of the previously mentioned concepts will be chosen. This will be done in collaboration with the stakeholders since in order to make an informed decision more requirements need to be obtained. The question that needs answering is what degree of automation do the stakeholders require? This will determine what concept the group will moves forward with. After the concept is chosen the necessary components need to be acquired so that the process of developing the prototype can start as soon as possible.

GANTRY As mentioned earlier, the gantry that was built during the project is not ready for continuous outdoor use. For this to be fully accomplished several things need to be considered. The linear rails would need to be changed to a more suitable option, perhaps V-groove wheels, that was mentioned in the SoTA but that was not implemented in the project. All parts would need to have proper surface treatment to keep it from corroding.

To make the electronics compliant with outdoor environment one must make sure it can withstand water and moisture as well as varying temperature. If equipment are bought then it must be checked that it has the proper IP-rating to withstand things like rain and particles [62]. In this prototype the PCBs and the cabling and contacts mounted onto these are not IP-rated. This would be a good improvement for next iteration. One could opt to use conformal coating [76] for the existing PCBs or look for alternatives on the market to buy.

One problem that was observed during the testing of the system was that the X-axis sometimes touched the top of the trees in the buffer system, which would sometimes keep them from properly falling through the buffer system cups. This can be seen in Figure 82.

This problem could be mitigated by raising the X-axis higher or by lowering the buffer system. It did not seem the damage the plants when the X-axis touch the top of the trees, so another fix could be to either make the gripper more compact in the Y-direction so that the X-axis could move further forward before it reaches the first row of plants in the cultivation trays or to make the "safe zone" longer in the Y-direction. However the best solution is probably to make the plants not touch the X-axis at all.

The speed limitations of the Gantry are mainly due to the Z-axis. Which is primarily due to the choice of motor and lead screw. Changing one or both of these components could further increase the speed. By changing the lead screw to another type with a greater lead would change the distance traveled per revolution, which would result in an increased velocity. The cost of increasing the velocity this way is the resolution reduction. This might not be an issue since the Z-axis does not needs to be precisely positioned, it just needs to be able to move the carriage up and down. Another way to further increase the speed would be to change to another type of motor. If the motor is changed, one might also need to implement feedback to make the system closed loop. The advantage of using feedback is the possibility to monitor the carriages exact position, which might be of interest when operating in a harsh unforeseeable terrain.

The machine that was built in the project was a scaled down version. In order for the machine to take an entire steel frame of 60 cultivation trays, the X- and Y-axes need to be longer. This should be relatively easy to implement with the current design. The only thing to keep in mind is that when the length of the X-axis is increased, it might be necessary to have a belt on the other side of the Y-axis as well, the master and slave setup might not work if the X-axis gets too long. This could be achieved by attaching a long shaft on the backside of the motor that reaches over to the slave side of the Y-axis.

The cultivation trays need to be held down when several plants are separated from the cultivation tray at the same time, otherwise the tray may lift. In this project, clamps were installed that require manual operation. Since the long term goal is to fully automate the process, in a future version, automatic clamping would be required.

BUFFER SYSTEM IDENTIFIED PROBLEMS AND POTENTIAL SOLUTIONS During design of the buffer system, there has been a number of problems identified. Some of them have potentials solutions that has not yet been implemented due to the projects time coming to an end. Here they will be described and if any solutions are though off, they will also be suggested based on experience gained during the project.

The buffer system has a lot of possible growth at its current state. Some problems were discussed in the Section 7, one of main flaws discussed with the buffer system design was the lack of system implementation to remove the seedling from the cup, it was only using gravity. A solution discussed with the stakeholder was the use of a quick burst of pressurized air to the seedling a boost out of the cup. This would also have the positive side-effect of being able to remove any debris that is left in the cups from seedlings, like dirt and needles. There is room for further exploration in this area.

A problem that has an easy solution is the height difference between buffer and gantry X-axis not being large enough, it can be fixed with adding a distance in the mechanical design, but care should be given to possible instability that this can cause if the Z-axis is raised. One of the main improvements to the buffer efficiency would be adding seedling drop feedback to the system. At its current state, there is no feedback implemented into the buffer system, however there are plans for sensor feedback that can allow the state machine to query if a seedling is in the cup or not. These were not implemented due to lack of hardware, the sensors were not delivered in time before the end of the project. Delivery time was more than one month, likely due to Covid-19 situation stressing out the infrastructure of deliveries.

The buffer seedling drop sequence can be further developed, especially with a more developed communication between system. To ensure that there will not be any crash in future integration between the Autoplant 1 project and the Autoplant 2 project platforms, care should be taken to ensure communication from platform to platform when the seedling plantation system is ready to receive a seedling. This is a problem that the Plantma X 7 has regularly, it tries to plant a seedling, but is not always success full and then does not accept another seedling from its buffer system until the seedling is planted with success.

GRIPPER There is a lot that can be done to improve the gripping system. The main thing that was considered and discussed during the course of this project was the addition of sensors that can identify if a plant has been successfully gripped or if there needs to be a second try to retrieve it. As mentioned before the two main sensors considered during this project were photo interrupter or slotted optical sensor and limit switches. However there are also other options that are worth considering.

One such option is to use some sort of camera to localize the plant. The camera adds to the software complexity but with its help there might be a possibility to identify if plants have been gripped, if there are plants in the cells in the first place and also determine the positioning of the plant. The camera might be able to pick up if the plant is askew or not once gripped and with that information there might be a way to correct the problem so that the plant and the roots do not get damaged when placed into the buffer. This could with some adjustment be accomplished by adjusting the positioning into the buffer system or this could entail a more complex solution.

A more complex solution would be to have the five grippers more actuated individually. This would mean that the right amount of force could be applied for each individual gripper to extract the plant and thus avoid the issues with different stem sizes.

Another aspect that could be implemented if the gripper would be individually actuated is for the system to also be able to separate horizontally before placing them in the buffer system. That way the buffers cups can be bigger and it would be easier to place the plants in the correct cup even if they are askew when gripped.

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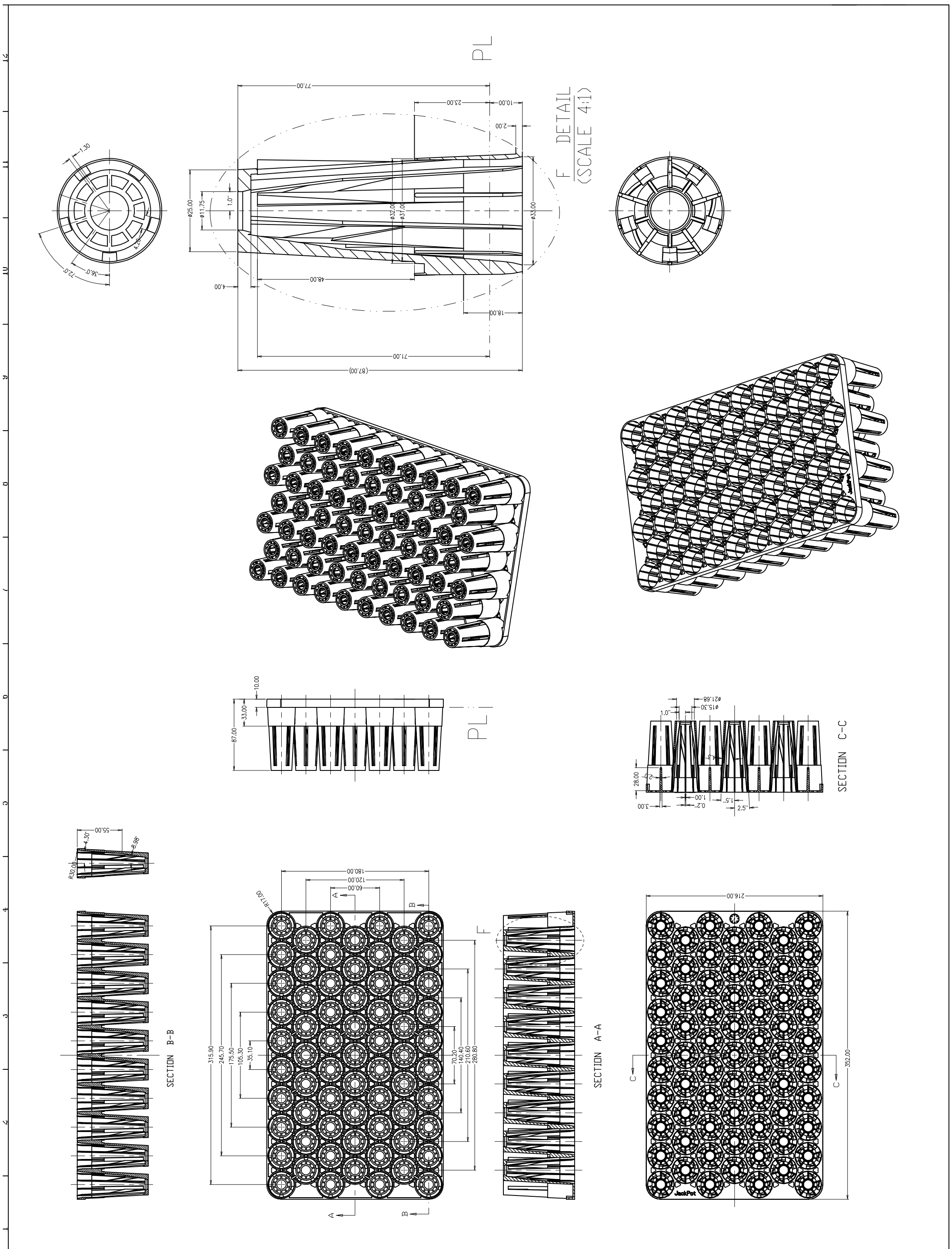
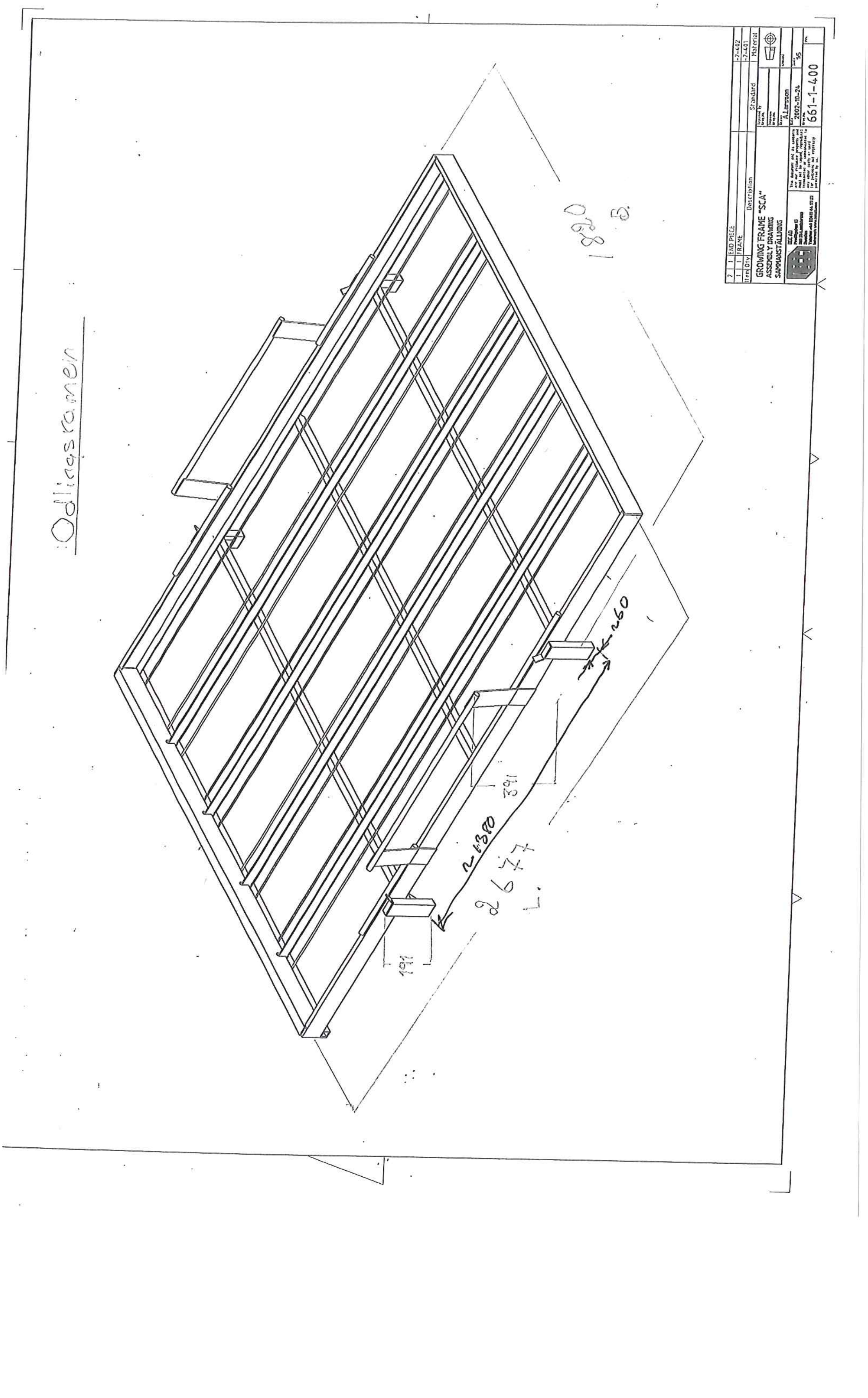
APPENDIX

A THE JACKPOT CULTIVATION TRAY

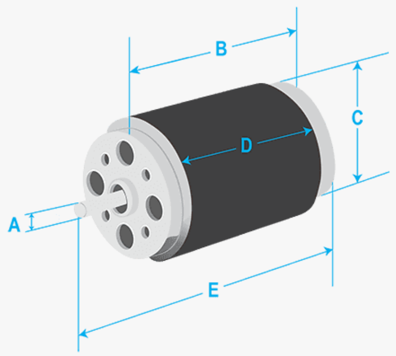


B A PICTURE OF THE REAL RACK.



C BLDC MOTOR TURNIGY D5035-125KV

Kv(rpm/v)	125.00	Max Current (Motor) (A)	45.00
Resistance (mh)	90.00	Max Voltage (V)	45.00
Power (W)	2000.00	Shaft A(mm)	8.00
Length B (mm)	71.00	Can Diameter C(mm)	62.50
Can Length D(mm)	54.80	Total Length E(mm)	108.50

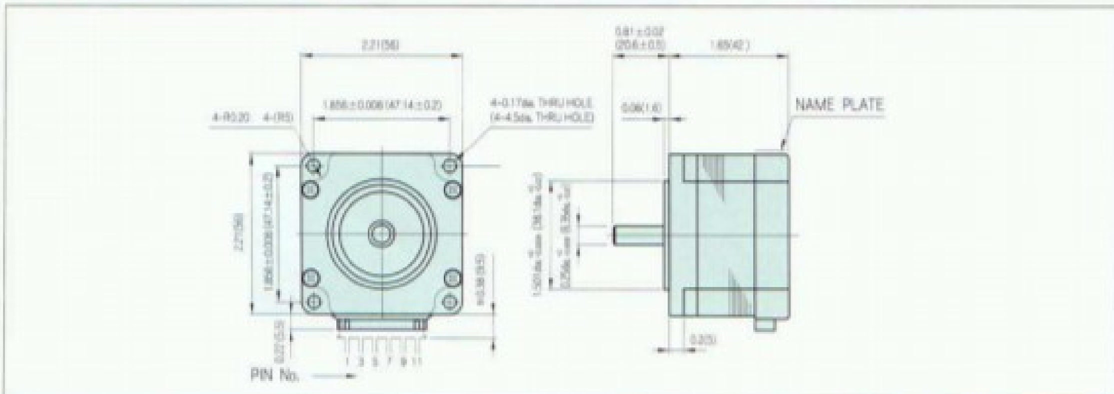


D STEPPER MOTOR DATASHEET

■ STANDARD SPECIFICATIONS

MODEL	UNIT	KH56JM2			
		-801	-802	-803	-851
DRIVE METHOD	———	UNI-POLAR			BI-POLAR
NUMBER OF PHASES	———	2			2
STEP ANGLE	deg./step	1.8			1.8
VOLTAGE	V	1.65	2.5	4.8	3.51
CURRENT	A/PHASE	3.0	2.0	1.0	1.3
WINDING RESISTANCE	Ω/PHASE	0.55	1.25	4.8	2.7
INDUCTANCE	mH/PHASE	0.6	1.2	5.9	5.6
HOLDING TORQUE	kgf · cm	4.3	4.3	4.3	5.0
	oz · in	60	60	60	69
DETENT TORQUE	gf · cm	250	250	250	250
	oz · in	3.5	3.5	3.5	3.5
ROTOR INERTIA	g · cm²	140	140	140	140
	oz · in²	0.77	0.77	0.77	0.77
WEIGHTS	g	400	400	400	400
	lb	0.88	0.88	0.88	0.88
INSULATION CLASS	———	JIS Class E (120℃ 248° F) (UL VALUE : CLASS B 130℃ 266° F)			
INSULATION RESISTANCE	———	500VDC 100MΩ min.			
DIELECTRIC STRENGTH	———	500VAC 50HZ 1min.			
OPERATING TEMP. RANGE	℃	0 to 50			
ALLOWABLE TEMP.RISE	deg.	70			

■ DIMENSIONS unit = inch (mm)



E AMT10-CUI ENCODER

For more information, please visit the product page.

CUI INC

date 10/10/2018
page 1 of 8

SERIES: AMT10 | DESCRIPTION: MODULAR INCREMENTAL ENCODER

FEATURES

- patented capacitive ASIC technology
- low power consumption
- CMOS outputs
- 16 DIP switch selectable resolutions
- index pulse
- modular package design
- straight (radial) and right-angle (axial) versions
- 9 mounting hole options for radial version
- 8 mounting hole options for axial version
- -40~100°C operating temperature

RoHS

ELECTRICAL

parameter	conditions/description	min	typ	max	units
power supply	VDD	3.6	5	5.5	V
current consumption	with unloaded output		6		mA
output high level		VDD-0.8			V
output low level				0.4	V
output current	CMOS sink/source per channel			2	mA
rise/fall time			30		ns

INCREMENTAL CHARACTERISTICS

parameter	conditions/description	min	typ	max	units
channels	quadrature A, B, and X index				
waveform	CMOS voltage square wave				
phase difference	A leads B for CCW rotation (viewed from front)		90		degrees
quadrature resolutions[1]	48, 96, 100, 125, 192, 200, 250, 256, 384, 400, 500, 512, 800, 1000, 1024, 2048				PPR
index[2]	one pulse per 360 degree rotation				
accuracy			0.25		degrees
quadrature duty cycle (at each resolution)	256, 512, 1024, 2048 48, 96, 100, 125, 192, 200, 250, 384, 400, 500 800, 1000	49 47 43	50 50 50	51 53 56	% % %

Notes: 1. Resolution selected via adjustable DIP switch, pre-set to 2048 PPR. All resolutions are listed as pre-quadrature, meaning the final number of counts is PPR x 4.
2. Some stepper motors may leak a magnetic field causing the AMT index pulse to not function properly (non-magnetic version available with 8 pulses per revolution).

F LEAD SCREW CALCULATIONS

Lead Screw Calculations

Torque

$$M_d = \frac{F * p}{2000\pi \, * \, \eta s} \quad [Nm]$$

$F = linear\ force\ [N]$
$p = pitch\ [mm]$
$\eta_s = efficiency\ *$

Critical speed

$$n_c = k_d * \frac{d_i}{L_K^2} * 10^8 \quad [1/min]$$

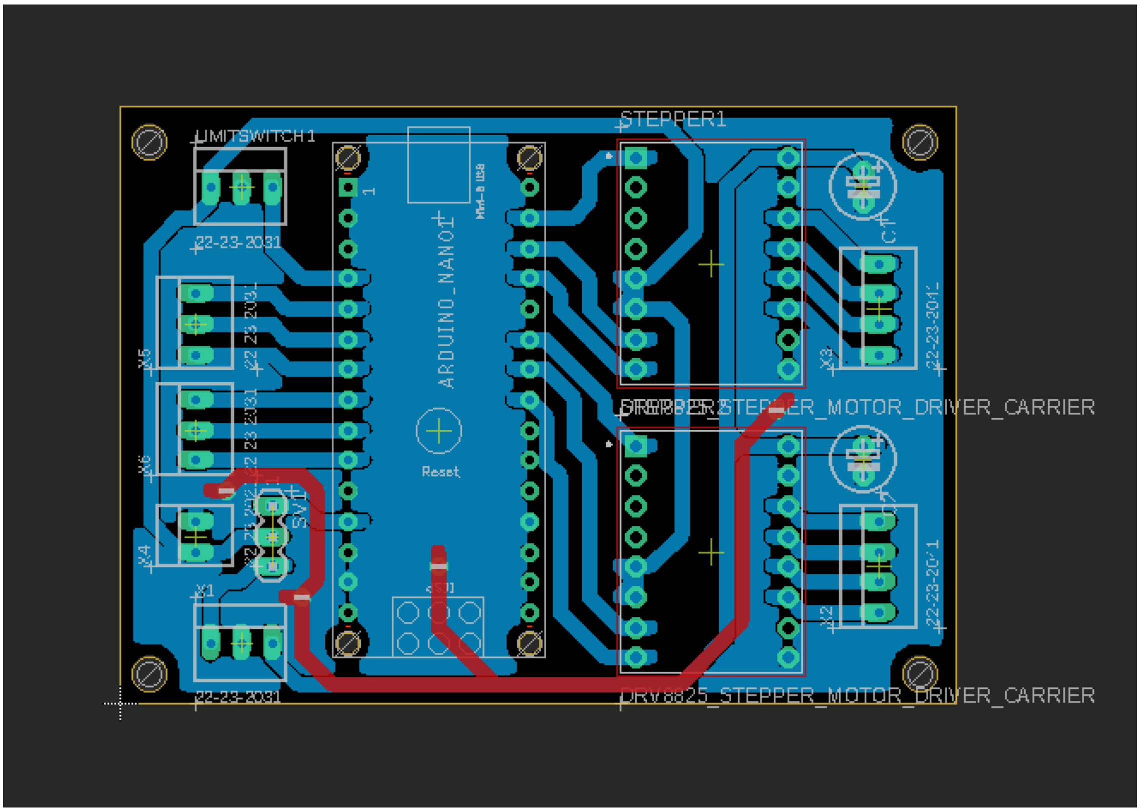
$L_K = lead\ screw\ length\ [mm]$
$k_d = support\ factor$ [-] (see table below)
$d_i = screw\ diameter\ [mm]$

Support	**Factor**
Both sides radially and axially fastened.	2.74
One side radially and axially fastened, one side radially fastened.	1.88
Both sides radially fastened.	1.22
One side radially and axially fastened, one side not fastened.	0.42

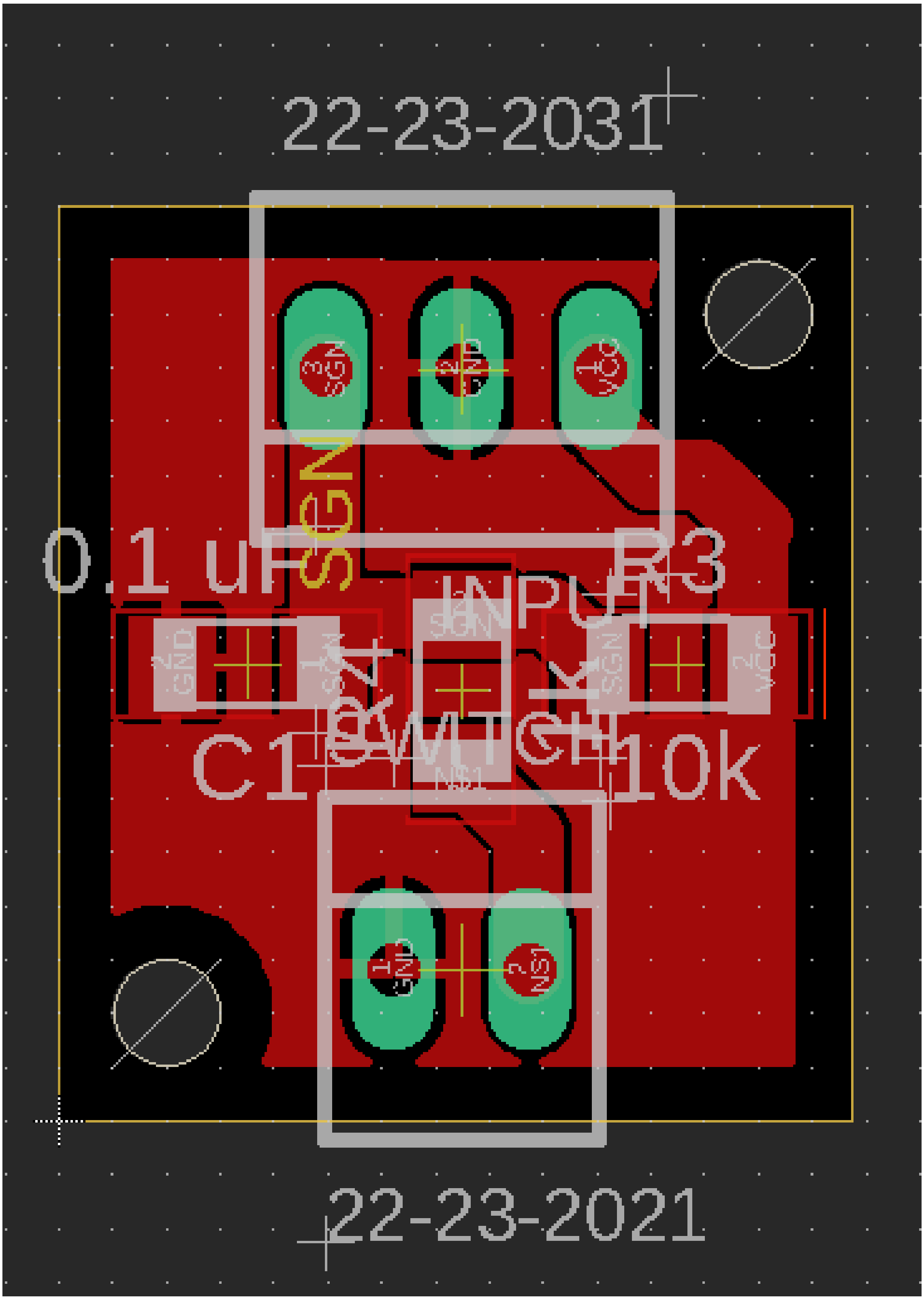
*Recommended maximum efficiency 20%.

Sources:
https://www.mekanex.se/berakningar/vridmoment-for-en-rorelseskruv/ [2020-12-10]
https://www.mekanex.se/berakningar/kritiskt-varvtal-for-rorelseskruvar/ [2020-12-10]

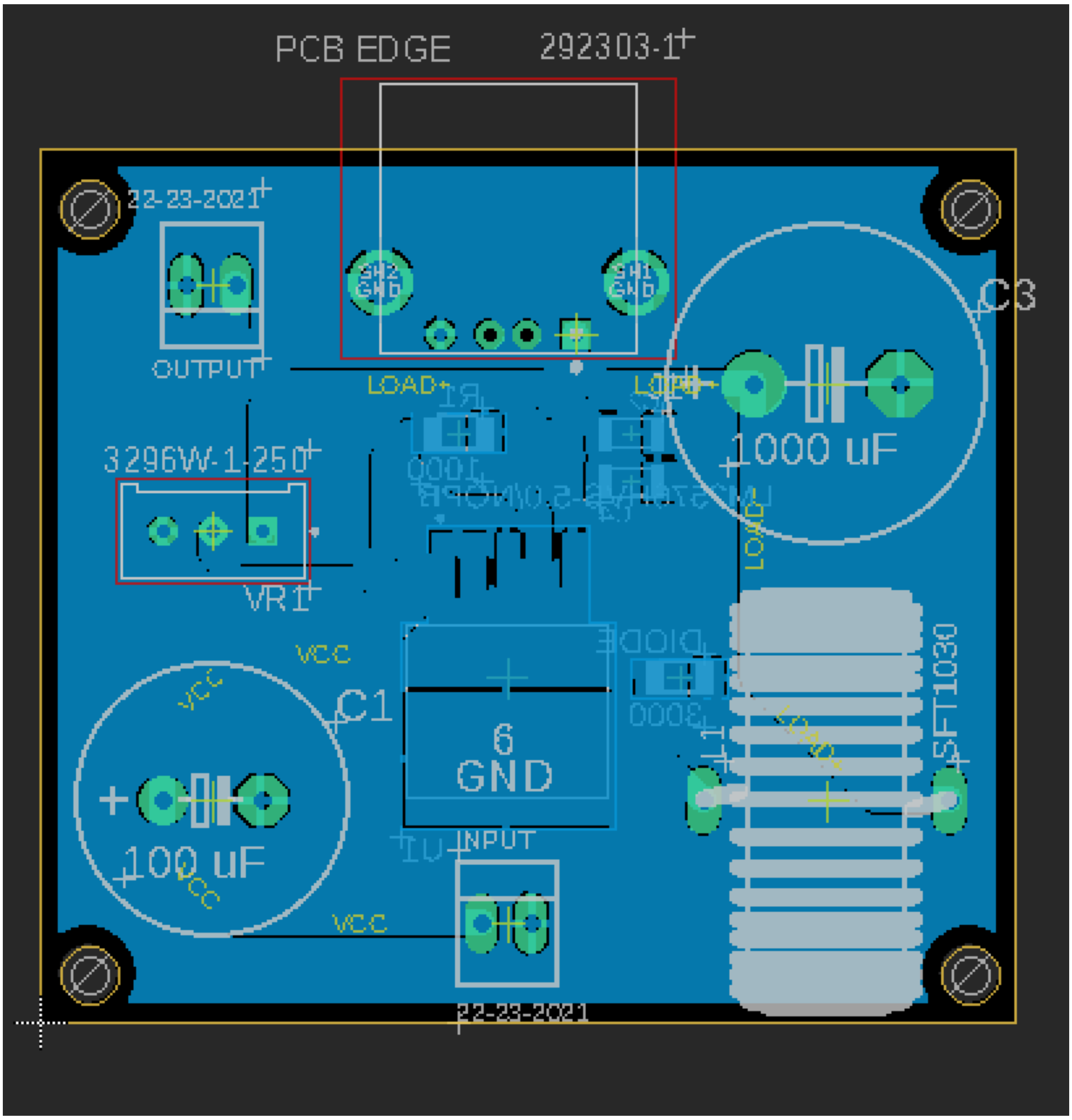
G Z-AXIS CONTROLLER BOARD



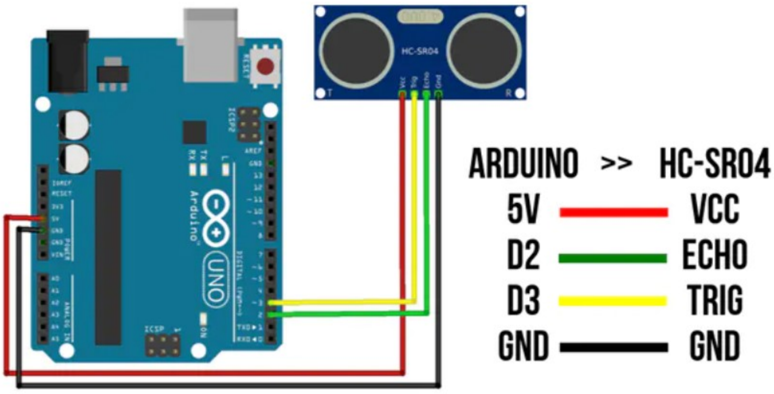
H LIMIT SWITCH BOARD



I 5 V REGULATOR BOARD

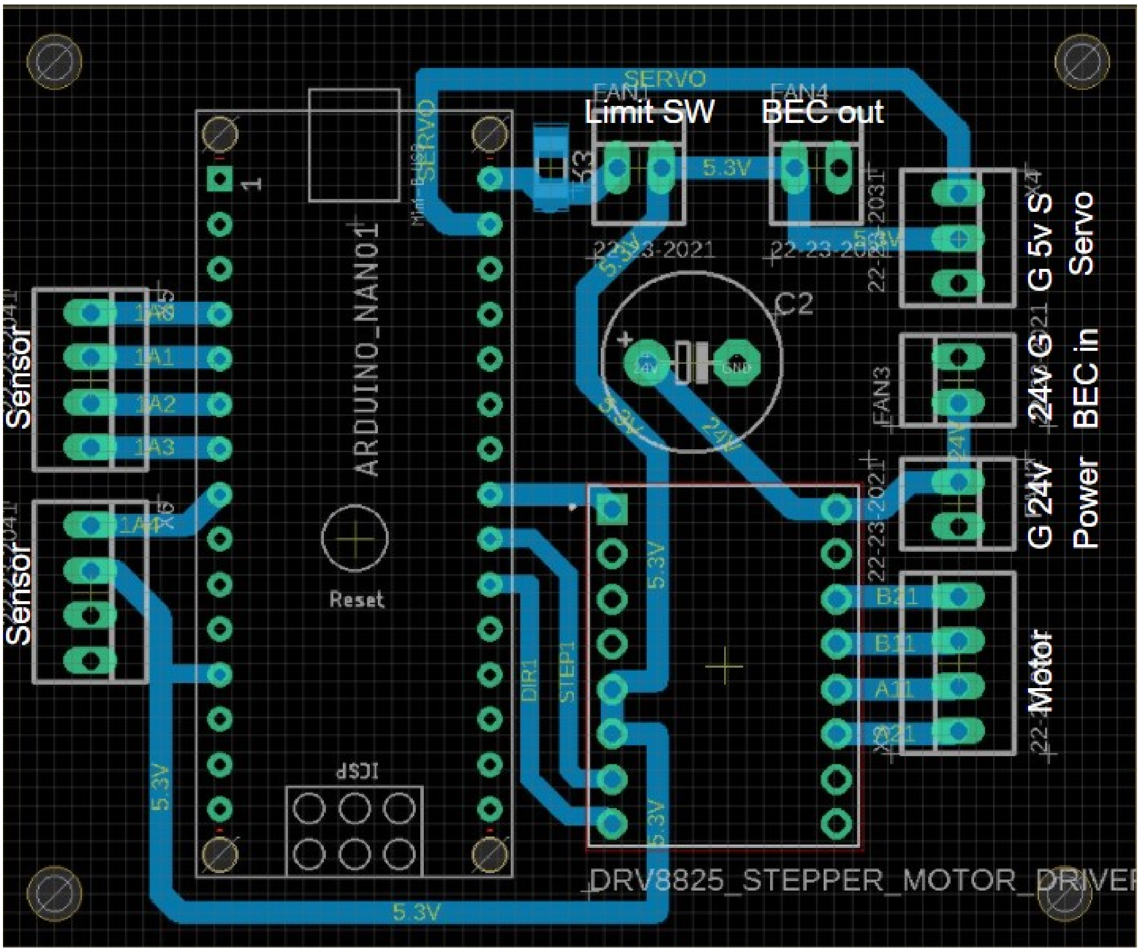


J ULTRASONIC SENSOR UNIT TESTING



Connection of Arduino UNO and HC-SR04

K BUFFER ALL IN ONE BOARD



L MANUAL FOR GUI

To start the GUI one must first turn the power on. Then wait for the Raspberry Pi to boot up to desktop. Ensure that both the buffer and Z-axis Arduino are plugged into the electrical cabinet. For starting the GUI it is easiest to access the Raspberry over SSH and run the following commands in a terminal window:

- `cd Gantry\gui`
  If one want the web interface to work then run this
- `mosquitto -d`
  After this optional step one can start the gui either on the local screen or as a VNC session. For local use run:
- `export DISPLAY=:0`
- `python3 gui.py`
  or if one want to use VNC type:
- `python3 gui.py -platform vnc`
  Then open up Remmina if on an Ubuntu based desktop enviroment or VNC viewer of your choice and connect to the Raspberry's ip.

M BUDGET

Mechanical Parts			
Name	**Cost/Piece**	**Quantity**	**Total**
Hardned axle, W10, L=1000 mm	106.65	1	106.65
Hardned axle, W8, L=130 mm	16.50	2	33
Linear rail,800mm and 2 wagons type FNS	1910.88	1	1910.88
Linear ball bearing	58.46	4	233.84
Timing Belt	259.9	2	519.8
T-mutter	189.78	2	379.56
Leadscrew D=10 L=300 mm	100.54	1	100.54
Pulleys 14-5M-15-6F-ST-S,8 mm hole	100	3	300
Pulleys 14-5M-15-6F-ST-S,10 mm hole	100	2	200
Axle coupling	69	2	138
Hardened axle	124.29	2	248.58
Cable chain 10x15 mm, 0.5 m	129	1	129
Nut for leadscrew	382.77	2	765.54
Trapezoidal nut	451.62	1	451.62
Aluminium profiles	80	11	880
Linear ball bearings	58.46	2	116.92
Hardned axle, Diameter = 8 mm, L = 108 mm	65	2	130
Leadscrew Tr10x2, L=1000 mm	97.61	1	97.61
Nut for leadscrew	371.62	1	371.62
Jaw coupling + spider, D1 = 8 mm, D2 = 5 mm	349.324	1	349.324
Anti-vibration pad	173.82	1	173.82
Igus linear wagon	60.46	10	604.6
T-mutter	552.75	1	552.75
Torsion spring	650	1	650
Igus linear rail	394	4	1576
Axle coupling	700	1	700
Trapezoidal nut	261	4	1044
Leadscrew. D = 12 mm, L = 300 mm	236	1	236
Schaeffler KUVE 30B	1432.5	4	5730
Schaeffler linear rail M8	6230	2	12460
Electrical Parts			
3 pole A-coding M8 panel mount	53.9	4	215.6
3 pole M8 cable	77.1	4	308.4
5 pole M12-panel	69.1	2	138.2
5 pole M12 cable	208.01	2	416.02
Molex Encoder	3.4	4	13.6
USB-Mini 5 m	51.59	2	103.18
USB-B panel mount	94.9	1	94.9
Electrical cabinet	397.89	1	397.89
Raspberry Pi display	571.5	1	571.5
USB-A to USB-A panel mount	52	3	156
USB-C cable 2 m	99	1	99
Raspberry Pi 4B	524.76	1	524.76

Raspberry Pi power supply	77.03	1	77.03
SD-card 64GB	361.86	1	361.86
Battery crocodile	178.84	1	178.84
Arduino Nano	170.38	3	510.76
USB PCB	8.252	5	41.26
Stepper driver	79	3	237
Stepper Motor Nema 23	422	1	422
Stepper Motor Nema 17	537,4	1	280
Micro switch	24	6	144
Limit switch	34,5	1	34,5
Schneider Electric Telemecanique XCK-S	379	1	379
ODrive	1200	1	1200
Encoder	390	2	780
Ultrasonic sensor	259,42	10	2594,22
Capacitive moisture sensor	70	2	140
Miscellaneous cables and crimps	700	1	700
Services			
Water jet cutting	400	2	800
Manual machining	500	2	1000
Total cost			46389.57 SEK (excl. VAT)

Table 14: Cost of parts and services.