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MF2058

Project Pinnacle

Final Report

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Abstract

The project is conducted as part of the MF2058/MF2059 Mechatronics Advanced Course at KTH in collaboration with LOX Container Technology. The current process of manual mounting and removal of twistlocks of shipping containers is labour-intensive and unsafe. This project aims to design and create an automated pinning station for shipping containers that can securely and efficiently mount and remove twistlocks in every corner of the container. The stakeholder for this project is LOX Container Technology, a company specialising in automatic, electric, and digitally controlled twistlocks used in the container shipping industry. They aim to automate and improve the safety of container handling operations. The requirements from the stakeholder called for a pinning machine concept that was reliable, safe and fast. It should furthermore be smart enough to detect errors and be easy to operate. The project was divided into two phases. The first phase involved comprehensive research into the current state-of-the-art automated pinning solutions for container transportation. Based on this research, many design concepts were scrutinized based on the stakeholder requirements. The design was optimized for reliability, simplicity and speed, and the initial phase of the project concluded with a complete theoretical concept for a pinning machine. The second phase was the construction of the proof-of-concept prototype: a single-corner full scale pinning machine, that demonstrates the concept of operation that was settled during phase 1. Mechanical schematics were drawn for the machine, the bill of materials was ordered and the mechanical, electrical and software development were done in parallel and combined to form a functional machine. The finished prototype met or exceeded every applicable stakeholder requirement, and the concept proved to be a good basis for further development of a full scale machine.

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This project would not have been possible without any of the support from the mentioned entities.

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List of Acronyms and Abbreviations

BOM Bill of Materials

HMI Human machine interface

ISO International Organization for Standardization

MAG Metal Active Gas

PCB Printed Circuit Board

PDU Power Distribution Unit

PLC Programmable Logic Controller

PM Pinning machine

PWM Pulse Width Modulation

RORO Roll-on/Roll-off

SOTA State of the art

SWOT Strengths-Weaknesses-Opportunities-Threats

TTL Transistor to Transistor Logic

1 Introduction

This chapter provides an overview of the project, covering its background, detailed aspects, scope, and relevant requirements that will serve as guiding principles for its success.

1.1 Background

When shipping containers are transported, they are secured together and to the transport vehicle using twistlocks in each corner. However, this process currently requires manual mounting (pinning) and removal (depinning) of the twistlocks before and after each transport. Workers must manually insert heavy metal twistlocks into the bottom corners of the container while it is suspended from a crane, making this process both labour-intensive and unsafe. This project aims to create an automated pinning station that can securely and efficiently mount and remove twistlocks, eliminating the need for manual labour and creating a safer working environment.

1.2 Project description

This research and development project aims to design and create an automated pinning station capable of securely and efficiently pinning and depinning twistlocks. This project is conducted as part of the MF2058/MF2059 Mechatronics Advanced Course at KTH in collaboration with LOX Container Technology, spanning the spring and autumn terms of 2023.

The project is divided into two distinct phases. The first phase involves comprehensive research into the current state-of-the-art automated pinning solutions developed for container transportation. This research will identify existing concepts, technologies, and best practices. Based on this knowledge, the project will proceed to design different innovative concepts and ideas for the pinning station.

The project's second phase is focused on developing and delivering a functional prototype for the pinning station and magazine, explicitly targeting one corner of the container. The prototype will be designed to meet the specified requirements identified during the research phase.

1.3 Scope

This project's scope includes creating a complete design of the pinning machine prototype, including all the required pinning stations and a full-scale magazine. On the other hand, due to resource limitations within the project scope, the implementation

will be limited to constructing the full-scale prototype of one corner, including a reduced-size magazine. This approach will allow an evaluation of the prototype's functionality and its feasibility within the constraints of the project.

1.4 Organisation

For the spring, the team was organised to have one team manager and all members to work in sub-teams of 3, having weekly meetings with the whole team and meetings with the stakeholders and the coach when necessary. The work began with the complete team working on the State of the art (SOTA) for two weeks; the aim was that every member understood the existing solutions that would benefit the proceeding preliminary design phase. For the mentioned design phase, the team was split into sub-teams of 3, and the goal was to develop a complete solution with three different points of view. The best aspects of each design were selected after detailed meetings with the stakeholders. The team was further split into reshuffled groups of 3 to focus on designing the three essential systems; the pinning station, the transfer bot and the magazine. In such a manner, the final concept for the spring term was established.

Upon finalising the concept, the team initiated the prototype design phase. Collaboration occurred within groups of three, conducting weekly meetings to deliberate diverse concept ideas and integrate various subsystems. Following the completion of the prototype design and the preparation of the Bill of Materials (BOM) list, the team reorganised into three primary domains: electronics and electric design (two members), mechanics and chassis manufacturing (four members), and software and Programmable Logic Controller (PLC) programming (four members). Allocation of team members was adjusted based on the remaining time and workload. Weekly meetings persisted to monitor ongoing tasks and ensure adherence to internal deadlines.

During the whole project, the team members rotated between different teams to ensure uniform learning and contribution.

1.5 Stakeholders

The stakeholder for this project is LOX Container Technology, located in Stockholm, Sweden. The company specialises in automatic, electric and digitally controlled twistlocks used in the container shipping industry. Their twistlocks are used to improve the speed and safety of container handling operations. The ability to be digitally controlled from a remote distance eliminates the need for manual labour

and reduces accidents. Their technology greatly speeds up the loading and unloading procedures, saving a lot of time, which is critical in the supply chain industry.

Lead by Magnus Carlmeister (CEO), the student team receives continuous and great support from Erik Leonton (Research and Development) and ex-employee Patrik Tiainen (Application and Embedded Software Engineer). With one stellar product in the market, LOX aims to step up the container shipping industry by bringing in more automation and safety.

1.6 Requirements

This section presents an overview of the requirements obtained by the stakeholders and extensive research. The requirements will serve as a guiding principle throughout the project, ensuring the final product meets the expectations.

1.6.1 Stakeholder Requirements

- Pinning machine (PM) shall be able to use for Roll-on/Roll-off (RORO) and Train segments.
- The PM shall work with LOX RCL twistlocks.
- The PM shall be able to handle 20ft and 40ft standard shipping containers.
- The PM should be able to handle 45ft standard shipping containers.
- The PM shall handle a pinning/depinning twist motion in less than or equal to 30 seconds.
- The PM shall handle a full pinning/depinning cycle in less than or equal to 90 seconds.
- The PM shall contain a magazine that holds a minimum of 160 twistlocks when full
- The PM shall be able to withstand 200G of impact forces when containers land on it.
- The PM shall be able to be moved with at least reach stacker or forklift.
- The PM will only be connected to external power.
- The PM shall have exception handling for when an error arise.

- The PM shall work without any human interaction, except for exception handling or change of magazine.
- The PM shall be implemented as either one pinning and one depinning machine or as a combined pinning and depinning machine.
- The PM main functionalities shall be evaluated with a prototype of at least one corner of the container.

1.6.2 Technical Requirements

The following is the technical requirements that have been developed through the project to fulfill the stakeholder requirements.

Dimensions

- The PM shall have a minimum dimension of 12.192 x 2.438 m (40 ft container).
- The PM shall handle a weight of at least 36 000 kg.

Features

- The PM shall be able to automatically check magazine status.
- The PM shall know the current magazine status
- The PM shall provide a minimum of one emergency stop button which stops all motions in the PM.
- The PM will provide a Human machine interface (HMI) for the operators.

Motors and actuators

- All motors in the PM shall be electronic.
- The vertical actuator shall be able to actuate 329 mm in a maximum of 10 seconds.
- The vertical actuator shall be able to push/pull 1650 N.
- The gripper shall be able to rotate 45°.
- The gripper rotation shall take a maximum of 10 seconds.

- The gripper shall be able to rotate with at least 5 Nm.
- The horizontal actuator shall be able to actuate 12 m in a maximum of 30 seconds.

Software and control

- The control system shall run on a PLC.
- The PM shall be able to detect error in magazine status.
- The PM should be able to detect collisions.
- The PM should be able to detect if a lock can not be inserted or removed.

2 State of the art

In order to avoid the pitfalls encountered by previous attempts at designing a twistlock pinning and depinning machine, solutions made by other teams have been thoroughly investigated and evaluated. Their respective strengths and weaknesses have been analysed to establish the groundwork for a prototype that may be robust, fast, and reproducible. Furthermore, the intended prototype's somewhat differing prerequisites regarding lock type specificity and working conditions have been explored.

2.1 Container design

Freight containers are highly standardized by the International Organization for Standardization (ISO) standard 668 *ISO 668:2020* [8]. This includes, among other things, the containers width, length, height, empty weight, and max loaded weight. Furthermore, the standard describes the dimensions and placement of the corner castings. There exists several different types of ISO containers with different dimensions. Common for all types are that they have the same width, 8 ft, and that they all have four corner castings, one in each corner used for connecting containers together. The 45 ft ISO container has 4 extra corner casting placed at the same positions as for the 40 ft container. The ISO standard dimensions can be seen in [appendix A](#)

2.1.1 Corner castings

Shipping container corners consist of two corner castings, one on the top and one on the bottom, made of high-strength steel that are welded to the container's frame at each corner, see [figure 2.1](#). They distribute the load of the container evenly across the frame, allowing for safe stacking, transportation, and handling. The corner castings also include holes for lifting lugs and interlocking mechanisms to prevent shifting during transportation. It is these corners that are interfaced with interlocking mechanisms, one solution being the container twistlock.

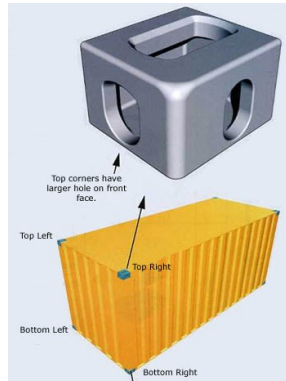
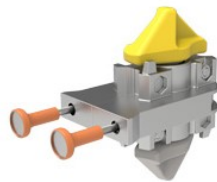


Figure 2.1: Corner castings, [3]

2.1.2 Twistlock

Twistlocks are components located on the corner castings of shipping containers that twist into place and lock containers together during transportation. They prevent containers from moving or shifting while in transit and are made of high-strength steel. Twistlocks are easy to connect and disconnect, and can withstand the forces generated during transportation. They are most commonly applied manually by an operator, which is both time-consuming and labor-intensive.



(a) Conventional Twistlock [2]



(b) LOX Twistlock [6]

Figure 2.2: Twistlocks

LOX Technology twistlocks are a smarter, more modern version of the conventionally used twistlock. LOX has built tracking tags and identities into their twistlocks. This makes them traceable and permits large scale data collection on transports and their lock locations. Additionally, the lower hooks can be electronically engaged and disengaged, saving valuable time and ensuring safety in the loading and unloading processes. Furthermore, they can provide status messages on their state, saving workers time on manual observation.

2.2 Harbour / Container terminals

RORO ships carry trucks loaded with containers; see [figure 2.3](#). These containers are loaded onto the trucks in harbours and container terminals using forklifts, reachstackers, movable cranes etc. To better understand the process of loading and unloading the containers at these harbours and container terminals, a dock worker was interviewed, see [appendix B](#). Some important information collected from the interview was that stacking a container upon another one was fully dependent on vision, without any guidance used.



Figure 2.3: RORO container handling, [7]

2.2.1 Pinning and Depinning

In order to secure the twistlocks to the underside of the container, an operation called pinning is performed. The twistlocks are inserted into corner castings on the underside of the containers, as mentioned in [section 2.1.2](#). After being inserted into the corner castings, the whole lock assembly is turned 45° , thus securing the locks in place. Similarly, the depinning is done in reverse: by first turning the twistlock inside the corner castings, the lock is released. The lock can then be lowered and removed from the container. A container generally has 4 corner castings; therefore, the pinning or depinning operation needs to be done 4 times per container. Many attempts to automate this process have been done, as described in [section 2.3](#). However, it still remains predominantly reliant on manual labour even to this day.

2.3 Current Solutions / Previous attempts

This chapter goes through some of the current solutions and previous attempts of automatic twistlock handling for containers.

2.3.1 Pinsmart

A solution developed by the company RAM Spreaders is the automatic twistlock handling machine, also called Pinsmart. The solution utilizes a bed with eight fixed pinning stations. The task of the pinning station is to provide the linear and twisting motion needed for pinning and depinning of twistlocks. The bed also utilizes gather guides that guides the container to the right position. The actuators used in the machine are powered with hydraulics. The machine can be seen in [figure 2.4a](#)

The machine can handle several kinds of twistlocks although requires manual reloading of the pinning stations. According to RAM Spreaders the reloading of the machine compared with manual pinning results in a 75% reduction in work [10]. The discharging of the pinning station after depinning is fully automatic. Furthermore the machine can handle 20 ft, 40ft and 45ft containers or two 20 ft containers simultaneously.

2.3.2 Pinsmart II

Pinsmart II is a further development of the original Pinsmart discussed in [section 2.3.1](#). It is a stationary solution with 7-axis robotic arms that performs the pinning and depinning of twistlocks, see [figure 2.4b](#). Similarly to the original Pinsmart it uses gather guides that guide the container to the correct position. The robotic arms will then perform the pinning or depinning operation. The robotic arms can also memorize the exact twistlocks used and their exact positions. The time it takes for Pinsmart II to pin/depin a twistlock is within 10 seconds, and the magazine can hold up to 2000 twistlocks. It is also designed to handle 20 ft, 40 ft and 45 ft containers.



(a) Pinsmart [9]



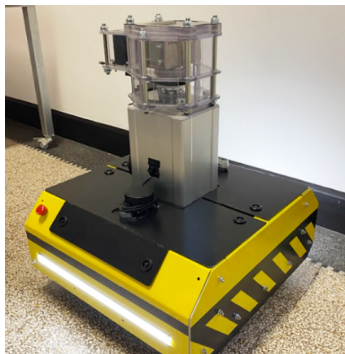
(b) Pinsmart II [11]

Figure 2.4: Pinsmart 1 and 2

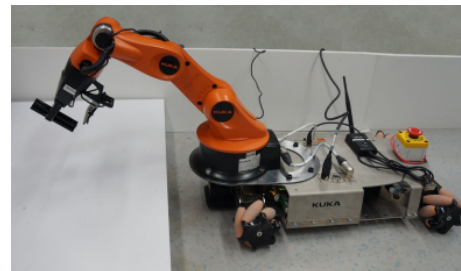
2.3.3 Autonomous vehicle

In cooperation with Siemens, a research project from the Technical University of Delft has created an autonomous vehicle able to do the pinning and depinning of twistlocks [12]. The project utilized a four wheeled vehicle able to navigate to the corner castings. The vehicle formed a platform for a linear actuator, able to insert the twist lock into the corner casting. How the final twisting motion is achieved is not clearly stated. However the linear actuator used was a TL3 industrial column. The TL3 is a rectangular lifting column with a maximum load of 4000 N and a speed of 13.7mm/s at the maximum load [13]. The TL3 was deemed suitable as it can handle high loads and operate in a rough environment such as ports. The project was considered a success and a working concept was presented to Siemens. A picture of the autonomous vehicle can be seen in figure 2.5a.

A similar project was developed at Singapore Polytechnic [5]. The vehicle used was a KUKA youBot which uses a similar four wheeled platform with an actuator placed on top. The actuator was in this case a 6-axis robot. A figure of the used KUKA youBot can be seen in figure 2.5b.



(a) Autonomous vehicle from the University of Delft [13]



(b) KUKA youBot [5]

Figure 2.5: Autonomous vehicle

A key feature of the system is that it features a 3D scanning system that can estimate the pose of the twistlocks. The 3D scanning system is not mounted on the vehicle but in connection to the storage of the locks. The information can then be fed to the vehicle from the 3D scanning system. The vehicle can then use the robot arm to pick up a lock. Finally, the vehicle can locate a corner casting with the help of RFID-based autonomous localisation. When the corner casting has been found, the robot arm can perform the pinning motion.

3 Concept development

At first glance, the task appeared to be challenging in its complexity. The design of an automatic container twistlock applicator had to meet several requirements and constraints, from reliability to error handling. However, the problem was managed effectively by breaking it down into smaller, more manageable pieces. The most critical components of the product were identified and evaluated individually using a Pugh matrix; refer to [appendix C](#). This allowed for an objective assessment of the pros and cons of different design options and data-driven decisions were made. By breaking the task down into smaller parts and evaluating each individually, the project was tackled confidently.

3.1 Design concepts

The design of the PM was divided into three main parts: the magazine's development, the pinning mechanism and the transfer between those parts.

3.1.1 Lock Magazine

One of the stakeholder requirements was to have a magazine holding at least 160 locks. To achieve this, and to keep the loading process of the locks automated, four different concepts were generated.

Push Magazine The first concept made was the push magazine. The idea behind this concept was that along each long side of the container bed, there would be six chutes for each pinning station holding 40 locks each, see [figures 3.1a, 3.1b and 3.1c](#). The chutes would have traces for keeping the locks in place and in the proper orientation. For pushing the locks to the pinning station, three alternatives were discussed.

The first alternative for pushing the locks was to have a support at the end of the chute connected to a motor by a wire. To load the pinning station, the motor would then roll in the wire, pushing the locks towards the pinning station, see [figure 3.1a](#).

The second alternative for pushing the locks was to have the locks on a belt, see [figure 3.1b](#). This way jamming of the locks could be avoided and the needed force for pushing the locks would be reduced. Having a belt would also allow for depinning by switching the direction of the belt.

The third alternative for pushing the locks was to have a motor connected to a rotating spiral in the chute, see [figure 3.1c](#).

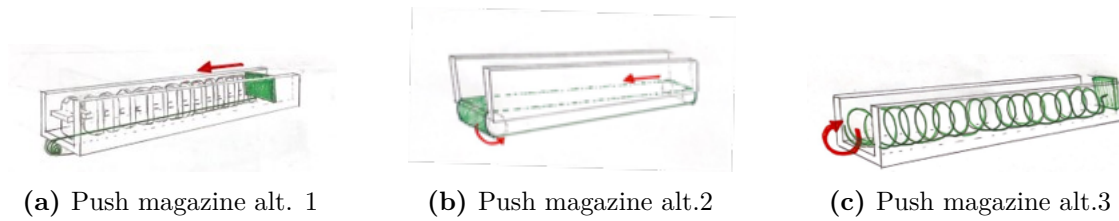


Figure 3.1: Push Magazine

Conveyor magazine with indexed positions Exception handling is one of the most important features of the machine, for example, rejecting a faulty lock; and it was challenging to incorporate such handling methods in the 'Push Magazine' due to its linear queue-type nature of dispensing locks. To counter this problem, a conveyor magazine concept was introduced. It was essentially a conveyor belt carrying 160 locks indexed into appropriate positions that ran in the middle of the chassis, refer figure 3.2.

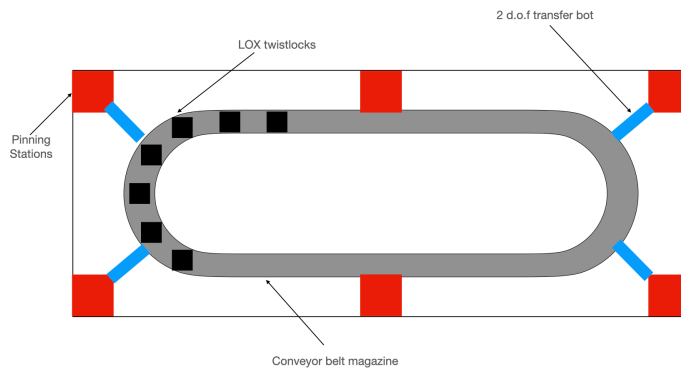


Figure 3.2: Conveyor magazine with indexed positions

This way, it was convenient to access any lock and, at the same time, reject a faulty lock. Transferring the lock from the magazine to the corner casting and vice-versa would be via a two d.o.f pinning station.

Fixed magazine To reduce the complexity of the magazine, a concept where the locks are in a fixed position in the magazine is developed. The locks are stored in the magazine hanging upside down, in the same way as in the corner castings of all containers. The locks can then be inserted into and removed from the magazine with

the same motion as the pinning and depinning of a container. The fixed magazine is illustrated in yellow in figure 3.3.

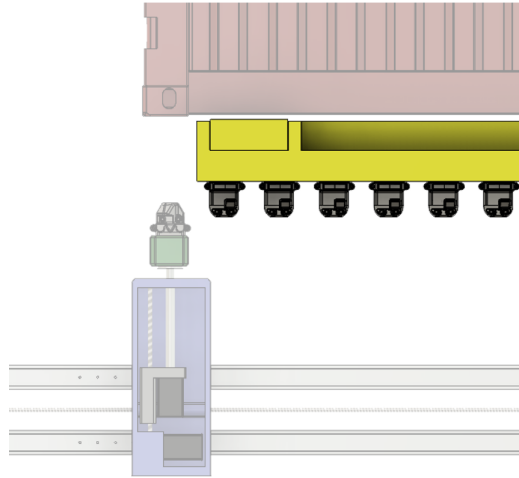


Figure 3.3: Illustration of the fixed magazine shown in yellow

3.1.2 Pinning mechanism

The pinning station must be able to perform a vertical linear and twisting motion to successfully perform a pinning operation and the same motion in reverse to perform a depinning operation.

Gravitational operated pinning station By utilising the gravitational force when loading the container on top of the machine, the pinning station could be powered via hydraulic pressure generated from the weight of the container. This would result in the pinning motion synchronous with the lowering of the container. Also, the pinning station would not need any external power to operate. To achieve the desired linear and twisting motion a cam and follower could be implemented as seen in figure 3.4.

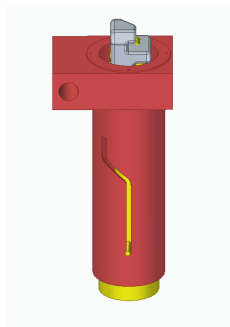


Figure 3.4: Pinning station with cam and follower

If a synchronous pinning motion is undesirable, hydraulic accumulators could achieve a non-synchronous movement. The hydraulic pressure could then be stored to be used when the container is fully in place. It should be noted that a cam and follower results in a gradual twist during the linear movement. This differs from the movement during manual pinning as it is first a strictly linear movement and finished by a strictly rotating movement.

Electrically operated pinning station By using two independent electrical actuators, the desired pinning operation could be performed for the linear movement and one for the twisting motion. A linear guide rail and a rotating lead screw could achieve linear movement. An independent electrical motor can achieve the twisting motion.

No matter what kind of actuation, the pinning station will require a solution for gripping and releasing the locks. This can be done using a claw mechanism that would need at least one more actuator. Using a box with a spring-loaded interior is also possible to clamp the locks by the hooks. The clamping mechanism would release when the linear actuator moves down after pinning. A CAD representation of an electrically-driven pinning station with the box-gripper can be seen in [figure 3.5](#).

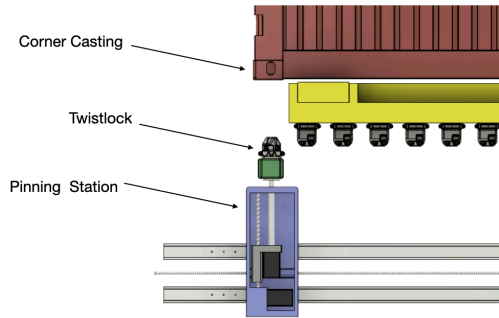


Figure 3.5: Electrical operated pinning station

Dampened pinning station Since the forces when loading a container on the pinning station are significant and potentially damaging, it could be suitable to include some kind of dampening in the pinning station. This could be done by mounting a spring under the pinning station. This could then absorb some of the forces when loading the container to the pinning station. The displacement of the pinning station could also be used to detect the presence of a container or errors. A conceptual design of this can be seen in figure 3.6.

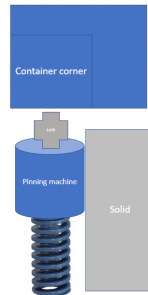


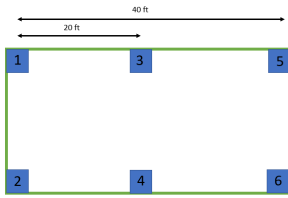
Figure 3.6: Dampened pinning station

Another way to protect the actuators from the forces when loading the container could be to use a compliant actuator. The force from the container would then simply push the actuators down. Both the compliant and dampened pinning stations would allow the locks to be raised while lowering the container. This allows the locks to be used as a guide when reducing the container; this is strengthened by the twistlocks having a cone-shaped head.

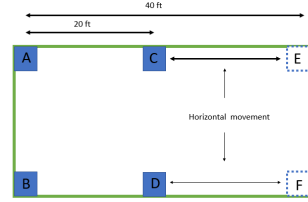
Positioning of pinning stations If the machine can handle both 20 ft and 40 ft containers, six fixed pinning stations are required, or two fixed and two pinning

stations that can move horizontally. In the case of six fixed pinning stations, 3 and 4 in figure 3.7a would be deactivated during the pinning of a 40ft container, and 5 and 6 would be deactivated during the pinning of a 20 ft container.

Allowing pinning stations to move would allow the pinning stations to adjust to the container size. During the pinning of a 20 feet container, the movable pinning stations would be in position C and D in figure 3.7b. If a 40 feet container were pinned, the pinning stations could move to positions E and F.



(a) Fixed pinning station -
Top view



(b) Movable pinning station -
Top view

Figure 3.7: Positioning of pinning stations

3.1.3 Magazine - pinning station interaction

There must be some interaction between the magazine that holds the locks and the pinning station responsible for performing the pinning and depinning. This interaction is achieved using a 'transfer bot'. The transfer bot's design heavily depends on the magazine's design. However, the most important part of this interaction was the orientation of the lock. The twistlock is heavy and does not have a stable centre of gravity; thus, suspending the lock is challenging.

It was decided that independent of the magazine design, the best way to interact with the lock is either using the top conical lock or the bottom hooks, refer figure 2.2b. This ensures the lock is always vertical, to eliminate the need for complex motions to correct the orientation of it.

Thus, the locks are suspended in the magazine despite its type, into a corner casting-like fixture. The gripper will too be similar to the corner casting. This greatly simplifies the interaction design.

3.2 Concept evaluation

To evaluate the different concepts for each subsystem, a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis was made; see appendix D. From that, the

strengths and weaknesses of each concept became clear. These were then compared to the requirements to choose the winning concept.

For the magazine solutions all different magazine solutions were also plotted in a graph comparing robustness and complexity. As seen in figure 3.8, the fixed magazine has high robustness and lower complexity compared to the other concepts, both desired features of the design.

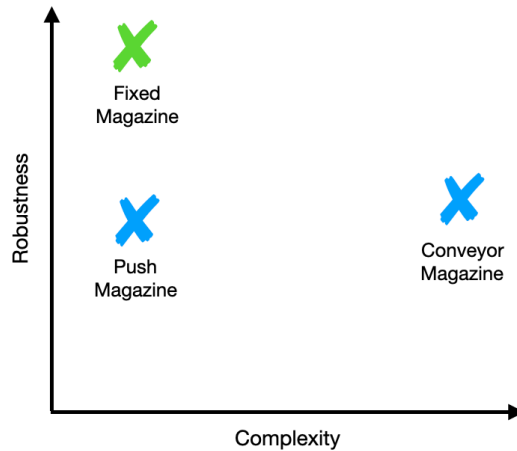


Figure 3.8: Evaluation chart of Magazine Concepts

3.3 Selected concept

The selected concept is a fixed platform designed to accommodate both 20 and 40 ft containers. It incorporates modular "pinning stations" and a twistlock magazine, providing a versatile solution for container handling operations. This section will overview the platform's key features and outline its capabilities.

3.3.1 Fixed platform

The fixed platform serves as a stable foundation for container handling activities. Its primary purpose is to hold containers of varying sizes, ensuring efficient operations securely. Designed to accommodate both 20 and 40 ft containers, the platform offers flexibility to adapt to different cargo requirements in logistics and transportation. Additionally, the platform is equipped with container fittings that enable it to be easily moved with a reach stacker. Figure 3.9 visually represents the fixed platform, including its dimensions and layout. To further illustrate the capabilities of the

selected platform, figure 3.10 showcases the platform with 20 and 40-ft containers placed on top of it.

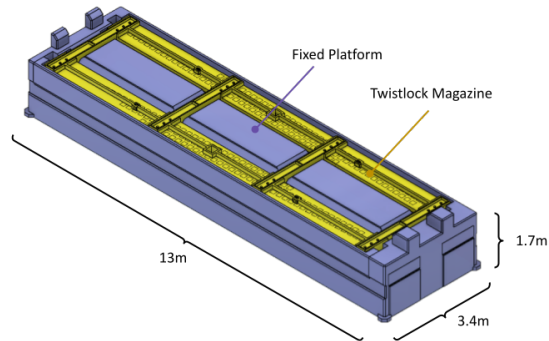
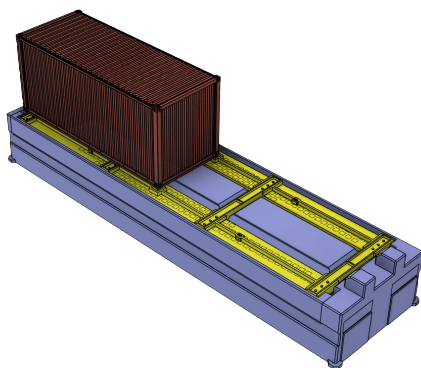
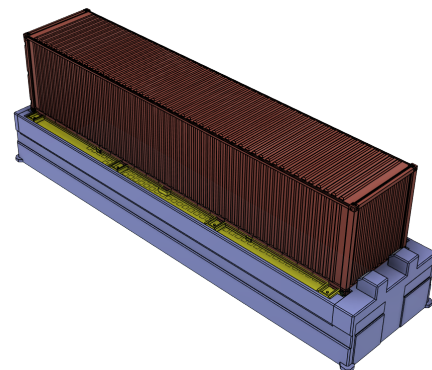


Figure 3.9: Final concept - Fixed platform



(a) Fixed platform with 20ft container



(b) Fixed platform with 40ft container

Figure 3.10: Platform with stacked containers of different sizes

3.3.2 Modular pinning stations

The actuator system of the platform consists of six modular pinning stations, with one station positioned at each corner of the container. These pinning stations enable precise three-axis motion control, allowing for vertical, horizontal, and rotational adjustments. Refer to figure 3.5 for a visual representation of a pinning station and figure 3.11 for their integration into the fixed platform, providing a better understanding of the actuator system's design and functionality.

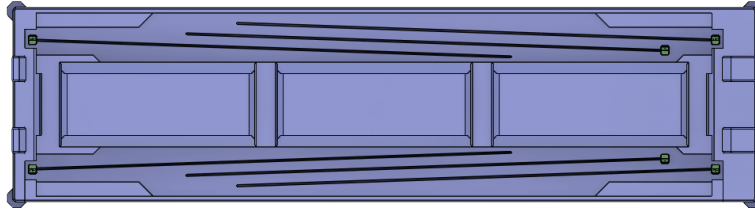


Figure 3.11: Horizontal paths of the pinning stations

3.3.3 Twistlock magazine

The magazine serves as a crucial component in our container handling system, responsible for housing the twistlocks used to secure containers. Its loading and unloading operations depend on the ongoing activities at the harbor. When the harbor is either loading or unloading containers, the magazine is accordingly loaded or unloaded.

To ensure flexibility and adaptability, the magazine must be designed to be modular and removable. It must have the capacity to accommodate 40 twistlocks per corner, given our machine's support for 20ft and 40ft containers. Additionally, the containers are always aligned with one of their sides, necessitating the magazine to have space for at least 240 twistlocks (6 corners \times 40 twistlocks).

We can achieve this by incorporating a twistlock magazine, as shown in figure 3.12. The magazine features slots that are designed similarly to standard container corner castings, securely holding the twistlocks in place. Each pinning station includes 40 twistlock slots, providing a sufficient supply for container pinning or depinning operations. The current concept, depicted in the figure, utilizes a diagonal arrangement of the magazines to optimize space utilization. However, alternative configurations are feasible, such as a parallel placement. This parallel layout not only enables the potential inclusion of support for 45 ft containers but also addresses the issue of half-full magazines during magazine switching.

The twistlock magazines are stackable, allowing for convenient storage and transportation of the twistlocks. This feature promotes operational efficiency and minimises equipment storage's required space. Furthermore, the twistlock magazines can be easily transported using a reach stacker, ensuring seamless integration into the container handling process.

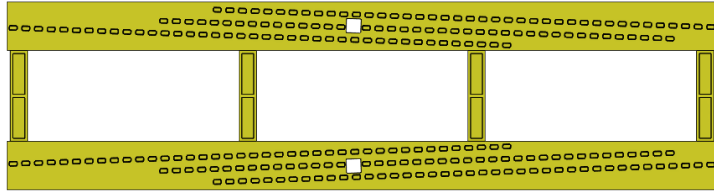


Figure 3.12: Twistlock magazine viewed from the bottom

4 Single corner prototype

The Stakeholder requirements were planned to be fulfilled via designing and developing a 'Single-corner' prototype, that would fulfill all the other requirements but only for a single corner. This prototype would serve as a tangible representation to test its effectiveness, safety measures, and operational efficiency in real-world applications.

4.1 Concept development

To start the development of a single corner prototype a detailed concept was created. This included all parts of the prototype and the development of detailed requirements of all parts and the decisions of what parts to be used to fulfill this requirements.

4.1.1 Chassis concept

The frame of the prototype, see [figure 4.1](#), for the automated pinning station was designed to be simple and robust. It would serve as an enclosure for all the components to ensure they were held in place during operations. In order to achieve this, the main structure of the frame was made of square steel tubing. This provides a cost effective and strong frame, although care must be taken while welding to ensure the corners of the machine maintains the design critical right angles. Even slight non-parallelism in critical parts like the linear actuator, linear guide, magazine, or corner casting, would result in failure of operation. The magazine needed to be able to withstand the rough handling of the twistlocks, whose springhook latches can take significant vertical force before actuating and allowing the lock to fall into the gripper assembly, therefore it was decided to use a steel U-beam, see [figure 4.2](#).

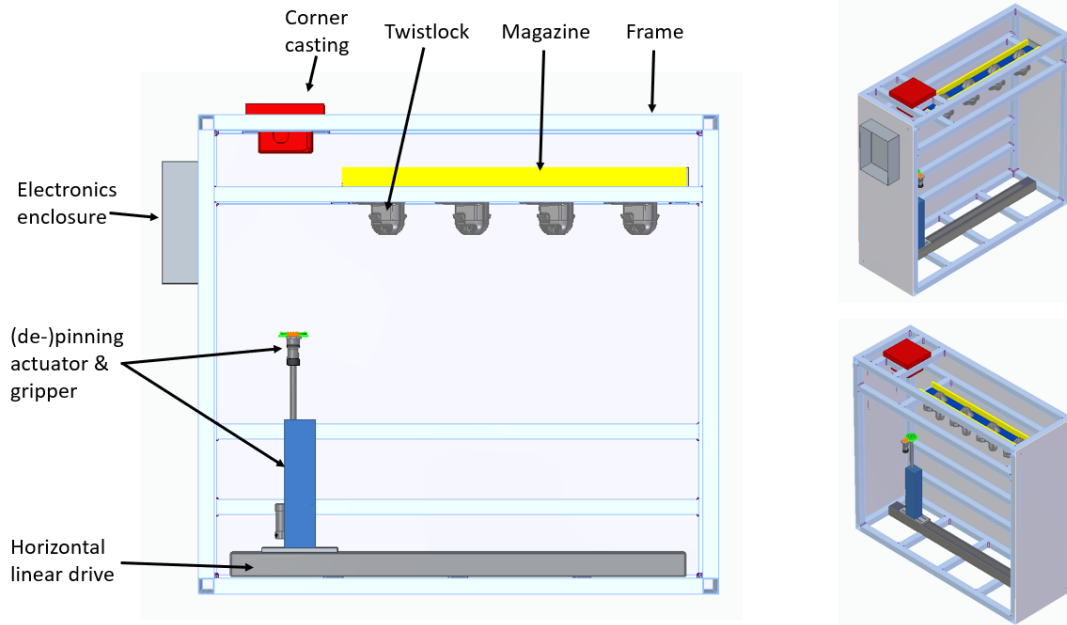


Figure 4.1: Chassis concept for the prototype

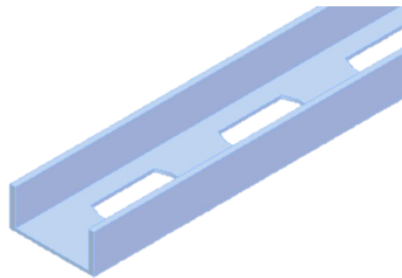


Figure 4.2: Concept for the magazine using U-beam

4.1.2 Pinning arm concept

The general requirement of the 'pinning-arm' was to pick up a twistlock from the magazine and pin it into an empty corner casting of the container and/or depin a twistlock from the container and place it back into the magazine within a stipulated time.

Two actuation axes were to be designed, the vertical motion henceforth referred as Y-axis and a rotational motion; henceforth referred as ϕ -axis. The Y-axis motion was responsible for pulling the twistlock out of the magazine/container and/or hoisting it up into the magazine/container. While the ϕ -axis was responsible for rotating the gripper holding the twistlock to lock/unlock it into the magazine/container.

Y-axis actuator The force needed to overcome the spring force of the twistlock when inserting it into the gripper is given from LOX to be approximately 1000 N. The weight of the twistlock is 8 kg and the weight of the gripper is 2 kg. A safety margin of 50 % gives that the vertical actuator need to handle at least 1650 N.

The stroke length needed for the vertical actuator is determined by the height of the twistlocks. When inserting a lock from the magazine to the container, the lock needs to be lowered below the locks in the magazine and then raised into the corner casting of the magazine. This length is, as seen in figure 4.3, 329 mm and is hence the minimum stroke length needed for the vertical actuator. The reason the lock needs to be able to go below another lock in the magazine is because a potentially faulty lock might be left in a position closer to the corner casting than the first functioning lock.

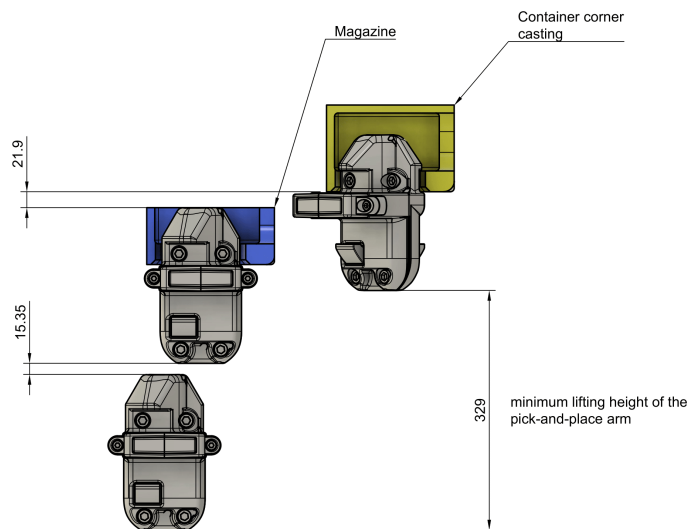


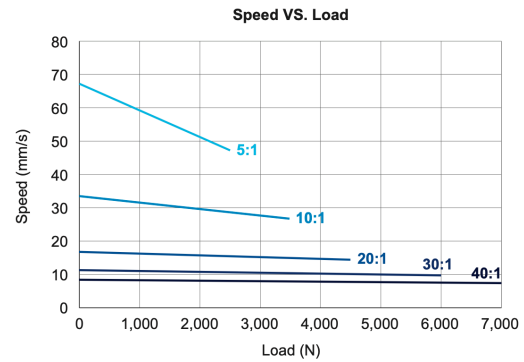
Figure 4.3: Minimum Y-axis stroke length

According to the technical requirements the Y-axis actuator must be able to actuate 329 mm in 10 seconds. This gives that minimum speed of the Y-axis actuator is $3.3 \frac{mm}{s}$.

After an extensive market research and considering the requirements, it was decided to go ahead with a 24V ball-screw linear actuator with a gear ratio of 5:1 from OEM motors. The ID10 Linear Actuator fit all the requirements w.r.t. stroke length, speed of operation and load capacity.



(a) Device



(b) Speed vs. Load characteristics

Figure 4.4: ID10 24V ball-screw actuator

ϕ -axis actuator: The requirements of the ϕ -axis is on the torque needed to rotate the twistlock to locked/unlocked position in the corner casting and the related speed to rotate 45° . To determine the needed torque a series of test were performed. A twistlock inserted inside into a corner casting was rotated by a force applied via a load cell. The test was performed 20 times for locking and unlocking respectively, the result can be seen in figure 4.5. This resulted in a maximum measured torque of approximately 2.5 Nm, since the method had quite some uncertainty a safety margin of 2 was chosen, giving the minimum required torque to 5 Nm. The time for a 45° rotation was set to be 10 seconds based on the technical requirements defined in section 1.6.2. Consequently, this necessitates a minimum rotational speed of 0.75 RPM for the ϕ -axis.

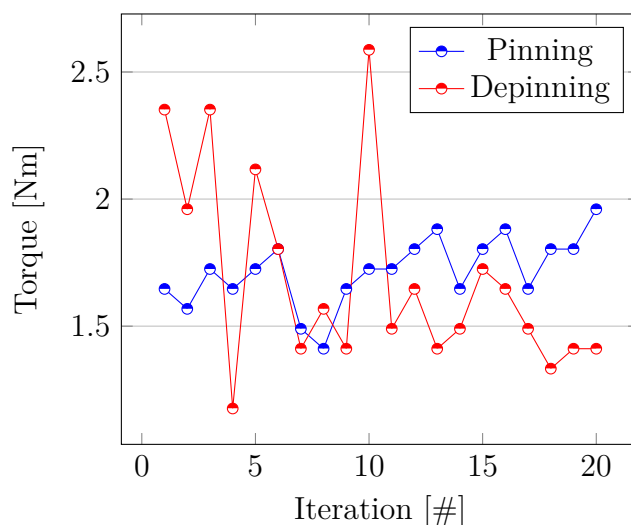


Figure 4.5: Torque needed for pinning/depinning

Considering the simplicity of the requirements and ease of availability in the market, the actuator of choice was a 24 V DC motor. Specifically, the DC motor chosen was a 24 V motor, delivering 2.7 Nm and a maximum speed of 45 RPM from Micro Motors. The mentioned motor fit all the requirements w.r.t. torque and speed if an additional gear of a minimum ratio of 1.85 is added. Due to concerns of controlling a fast rotation with open loop control it was decided to use a gear ratio of 4.7. This gives a rotational speed of 9.6 RPM and torque of 12.7 Nm which fulfills the requirements with a safety margin.



Figure 4.6: Micro Motors DC motor 'E192-24-91'

Gripper Assembly The gripper must be able to firmly hold onto the locks and rotate with the speed and torque as discussed above. There were two main options

for achieving this rotation: one being an in-line ϕ -axis actuator and the other being a side-mounted ϕ -axis actuator with a gear train. The two options are seen in figure 4.7.

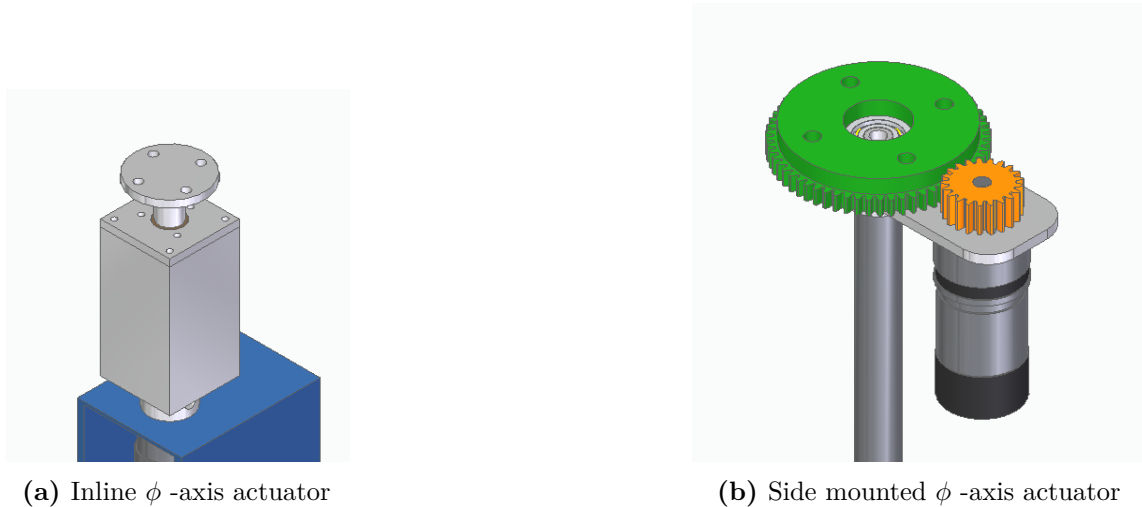


Figure 4.7: The two suggested ϕ -axis actuator setups

Due to the added length required for the inline actuator, as well as concerns about the axial load being too large, the side-mounted version was deemed suitable. The gears were dimensioned according to the power and torque of the motor E192-24-91, using a gear module of 1.5 mm with Solid Edge Engineering tools. The exact input parameters and output can be seen in figure 4.8.

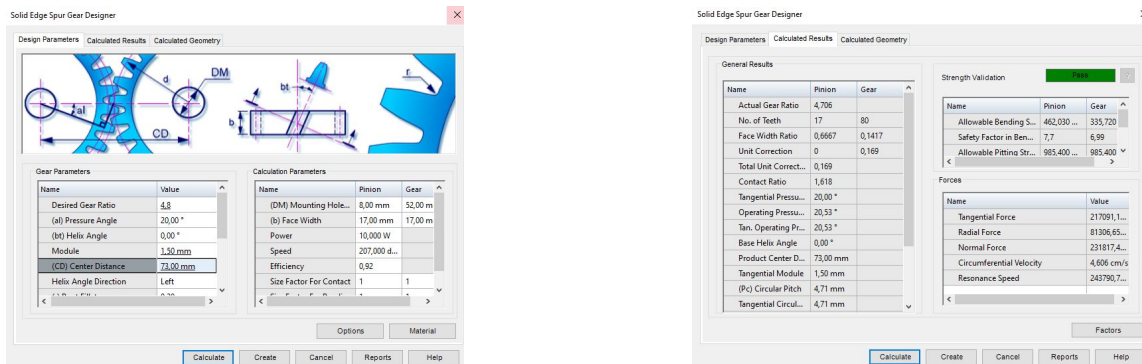


Figure 4.8: Input and output of gear dimensioning

The actual gripper was then designed to be mounted on the gear. The gripper has the same inner dimension as a twistlock with retracted lugs. The friction force

was then assumed to be enough to hold the twistlock in place. The gripper also features a mounting hole for an inductive sensor, indicating if a lock is in the gripper and facilitating the indexing of the magazine. The suggested design of the gripper can be seen in [figure 4.9](#). Note that this design was modified; more details can be found in [section 6.1.2](#).

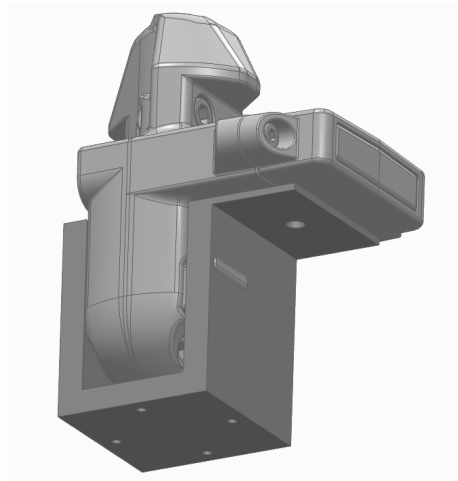


Figure 4.9: First design of gripper

Control Considering the simplicity of the requirements, it was decided not to invest in a closed-loop system but rather use an open-loop control with a feedback from sensors. For control over Y-axis, it was planned to use the inbuilt potentiometer of the linear actuator to give feedback of the position. While the angular displacement of the ϕ -axis was planned to be controlled via inductive sensors indexed in appropriate positions.

4.1.3 Horizontal drive concept

The design of the horizontal drive system needed careful consideration of several critical factors, namely the travel time of 30 seconds for moving 12 m, mitigation of mechanical friction in the axis, and adherence to permissible positioning tolerances allowed when inserting a twistlock into a corner. Addressing these factors was critical for ensuring the desired performance of the machine.

Several actuator options were considered, such as rack and pinion drives, belt drives, and ball screw bearings. While all three actuator options can achieve the necessary horizontal velocity, ball screw bearings are unnecessarily precise, meaning

expensive, for this application, considering that the positional tolerance is approximately 1 cm. Furthermore, a more readily available belt driven actuator was selected over the rack and pinion alternative.

For driving the belt drive a synchronous motor was used after a dynamic simulation made by B&R Automation showed that it was more than capable of powering the horizontal drive when paired with a planetary gearbox with a ratio of 40:1.

A compliant jaw clutch was introduced between the gearbox and the belt drive in order to lighten jerk loads on the horizontal axis.

4.2 Mechanical design

Due to high demands for parallelism in frame construction, parts of the frame design discussed in [section 4.1.1](#) were changed to be able to adjust the position of components during the course of the project. This was mainly done because of expected warping during welding. To achieve this, slots were suggested to be milled into the frame instead of fixed holes. The parts with critical placement requirements are the X-axis actuator, X-axis linear guide, and the magazine, and are therefore mounted in slots. The relevant components are highlighted in [figure 4.10](#).

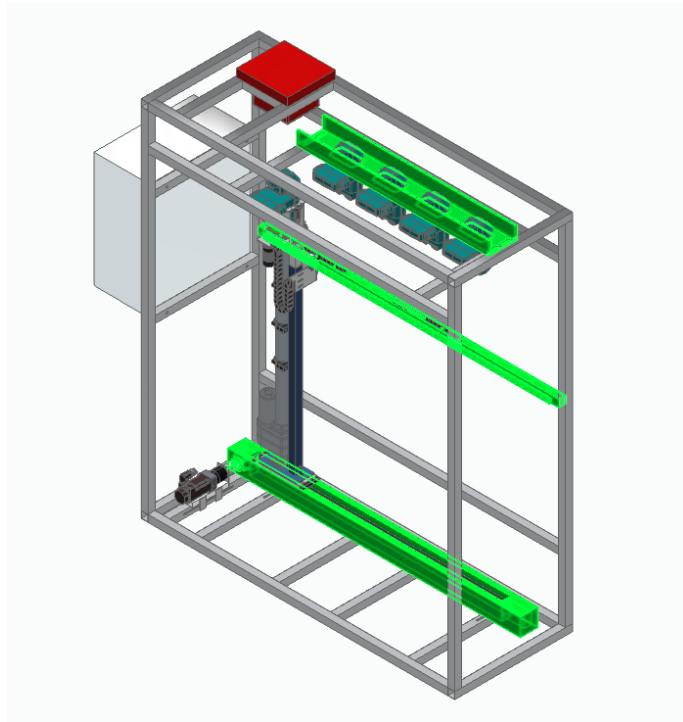


Figure 4.10: Adjustable parts in the mechanical construction

The frame could also be constructed using aluminium profiles, offering greater adjustability and eliminating the need for welding. However, as previously mentioned, due to budget constraints and the solid mechanics discussed in [section 4.2.1](#), this option was deemed unsuitable, and steel tubing, while more challenging to assemble, was chosen.

It was discovered that the Y-axis actuator was able to rotate around its axis. This could potentially lead to the entire gripper assembly rotating along with the movement of the Y-axis. To counteract this, the rotation of the Y-axis had to be locked. This was achieved by attaching a tube to the Y-axis actuator that locks the rotation. The tube in question also retracts into the tube that mounts the Y-axis actuator body, much like a telescopic arm. The solution is shown in [figure 4.11](#).

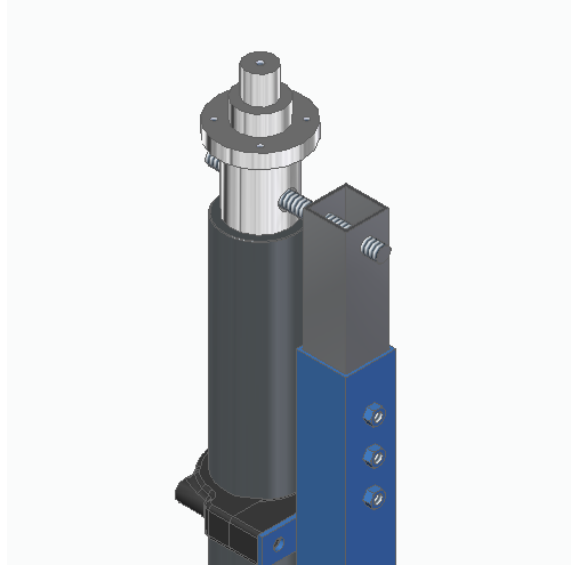


Figure 4.11: Telescopic arm that locks the rotation of the Y-axis actuator

4.2.1 Solid mechanics of the frame

To determine a suitable dimension for the tubes in constructing the frame, an analysis of the stresses in the tubes can be conducted. When the force from the Y-axis actuator acts on the vertical beam, it can be simplified as a beam bending problem, as illustrated in Figure 4.12. Subsequently, an analysis of the stresses can be carried out.

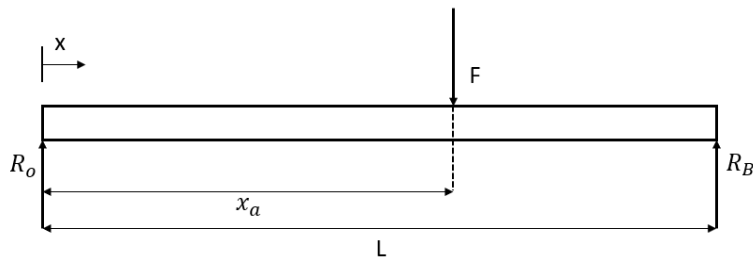


Figure 4.12: Free body diagram of forces acting on horizontal bar

In order to calculate the reaction forces R_O and R_B force equilibrium can be formulated as in equation 4.1.

$$R_O + R_B - F = 0 \quad (4.1)$$

Moment equilibrium around the applied force F can be described as follows:

$$R_B(L - x_a) - R_O x_a = 0. \quad (4.2)$$

Combining the force and moment equilibrium gives the following expressions for R_O and R_B

$$R_O = \left(1 - \frac{x_a}{L}\right)F \quad (4.3a)$$

$$R_B = \frac{x_a}{L}F. \quad (4.3b)$$

Performing a cross section of the beam along the X-axis as shown in figure 4.13 gives the internal moment as described in equation 4.4.

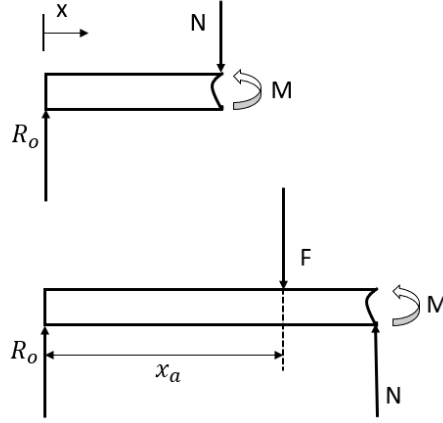


Figure 4.13: Free body diagram of internal moment of the horizontal bar

$$M = \begin{cases} R_0 x & , 0 \leq x < x_a \\ R_0 x - F(x - x_a) & , x_a \leq x < L \end{cases} \quad (4.4)$$

Finally the stresses in the beam can be calculated as in equation 4.5 where c is the distance to outer shell of the beam, where the stresses will be the largest and I is the second moment of inertia of a 35x35 KKR tube.

$$|\sigma(x)|_{max} = \frac{|M(x)| \cdot c}{I} \quad (4.5)$$

In figure 4.14 a plot of the maximum stress $max(\sigma(x))$ with the point of applied force x_a varied from 0 to L . Two cases were simulated, one for normal operation where

the estimate force to insert or extract the locks is 1000N and when the maximum force of 2500N from the actuator is applied to the beam.

The lengths where the corner casting and magazines slots are located are marked with red dots, i.e where the machine is operating under normal conditions. The red lines indicated the yield strength of the material.

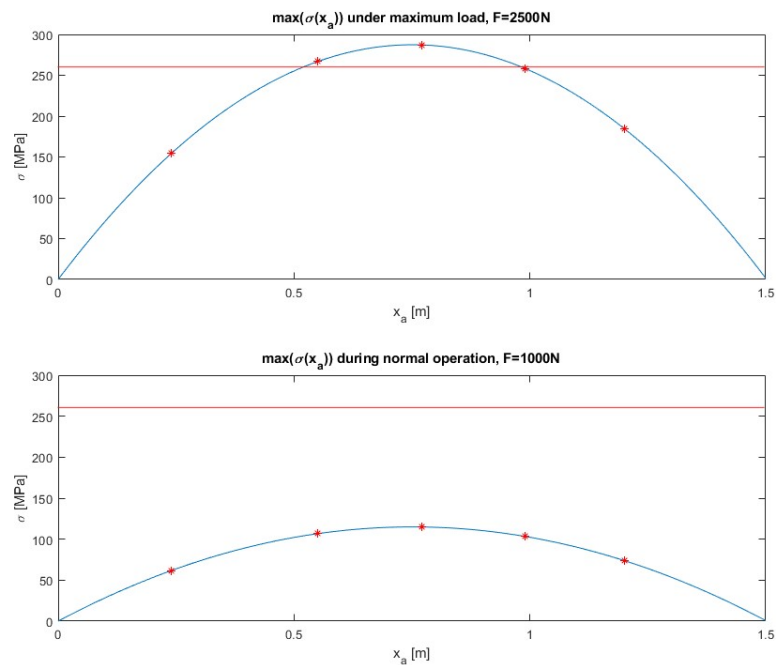


Figure 4.14: Plot of simulated stresses in the horizontal beam

From the plot it can be observed that during normal operation the frame is not at risk of permanent deformation. Although if an error would occur and the full force of the Y-axis actuator would be applied it could cause permanent deformation depending where the force is applied. It's relevant to note that the electrical fuses implemented in the power delivery unit (PDU) protects the machine from this fail mode, since the abnormally large currents during this error state would quickly exceed the fuse rating and cause them to blow, stopping the motor from further bending the frame.

Due to the reduced weight and the fact the tube will not deform during normal operation the 35x35 mm tubing was deemed suitable for the building of the frame.

This assumes that the welds in the frame are stronger than the actual material. This was verified by applying a large force to a test-weld replicating the welds in the

final frame. The results from this test can be seen in [figure 4.15](#). The test showed that the welds are stronger than the tube and therefore the tube itself will be the weak point from a mechanical perspective.



Figure 4.15: Test of mechanical properties of weld and tube

4.3 Electronic design

The actuators were chosen based on the technical requirements, so accordingly the electronics needed to support a smooth operation of the actuators. The goals of the electric system were as follows:

- Provide electrical protection to necessary components.
- Provide all the necessary power supplies and input signals to all the components.
- Provide necessary signal conditioning to communicate with the controller.
- Choose appropriate sensors.
- Cable management and wiring harness design.

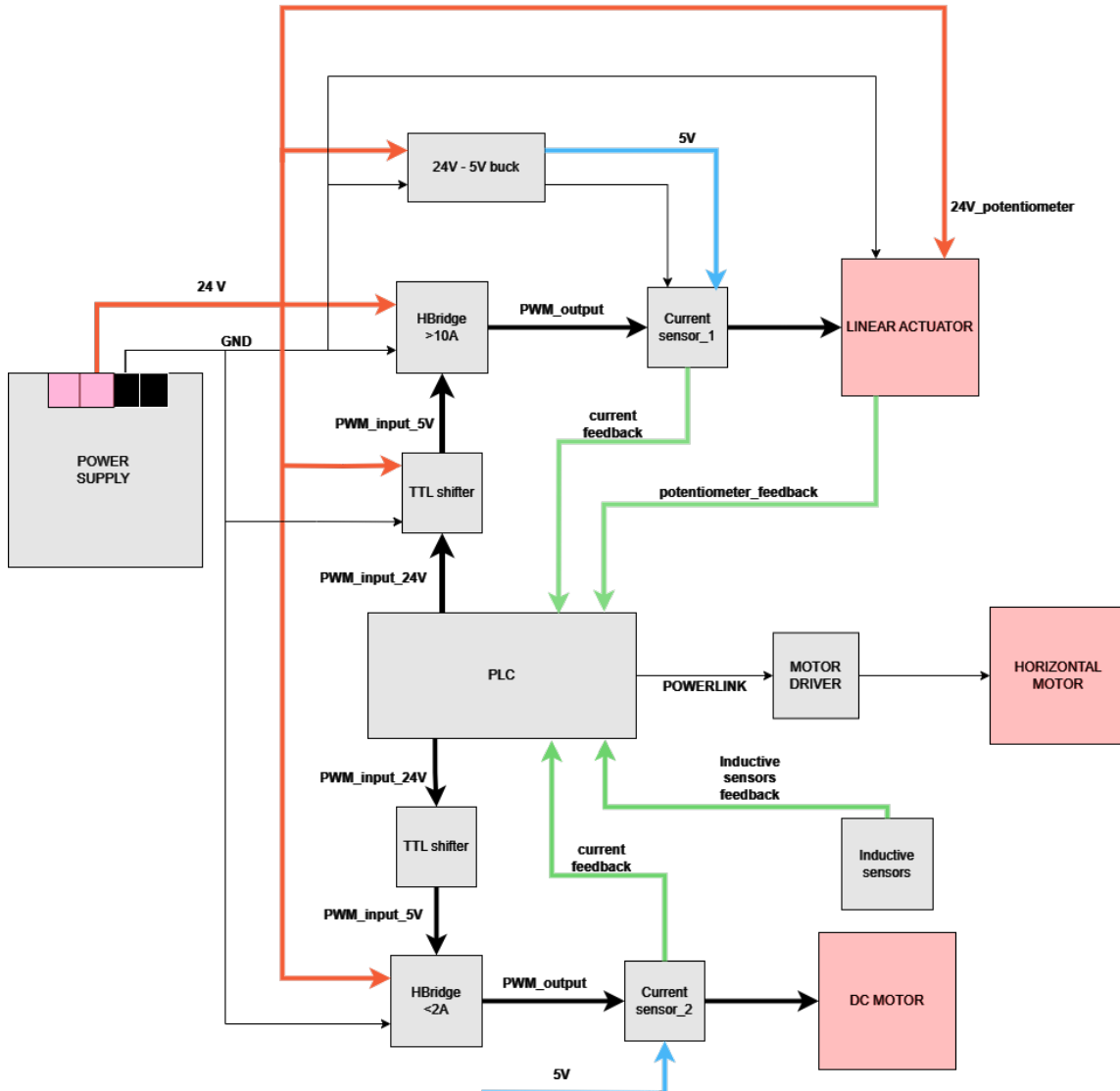


Figure 4.16: Scheme of the electronic design.

The electrical circuit, see [figure 4.16](#), was designed to control and operate three main components: a linear actuator, a horizontal motor, and a DC motor. The circuit integrated a power supply, PLC, motor drivers, and various sensors and components to ensure that the motors were powered and controlled efficiently, with feedback systems in place for real-time adjustments.

The circuit was powered by a 24V power supply that provided power throughout the circuit, including 24-5V buck converters to supply the low-level voltage compo-

nents. There were two main paths from the power supply; one led to a linear actuator responsible for the Y-axis and another led to a DC motor responsible for the ϕ -axis. Both paths included H-bridge circuits for controlling the direction of the motors movements. PLC inputs were used to control the speed of the motors. Since the chosen PLC only sent Pulse Width Modulation (PWM) signals of 24V, Transistor to Transistor Logic (TTL) shifters were included in both paths to adjust signal levels from 24V to 5V. Current sensors provided feedback on the amount of current flowing through each path of the circuit. The sensors would provide a security measure in case over current was drawn by the system. The motor responsible for the X-axis was directly controlled and powered by a off-the-shelf motor driver, which took the inputs directly from the PLC via 'Powerlink' and was powered with 230 V.

A PLC was planned to be central control unit for this setup, receiving inputs from various sources; including current feedback, inductive sensors or the potentiometer feedback from the linear actuator, and then sending control signals accordingly.

4.4 Software design

This chapter discusses the rationale behind the choice of using a PLC for the control system as well as using software states for the various operational modes of the machine.

4.4.1 Control System

PLCs have become the standard in industrial applications due to their design focused on reliability and capability to withstand harsh environmental conditions. This robustness is critical in demanding settings like port and container handling operations. This inherent durability ensures reduced downtime and prolongs the operational life of the system, presenting a distinct advantage over alternatives such as microcontrollers, which may not offer the same level of industrial-grade reliability and robustness.

In terms of scalability, integration, and cost considerations, the modular nature of PLCs allows for scalable solutions. As operational demands evolve, integrating additional modules without overhauling the entire system is feasible. This scalability, coupled with the ease of programming and maintenance, makes PLCs a more flexible choice compared to microcontrollers. PLCs offer a more intuitive programming environment and have extensive support and comprehensive documentation, significantly reducing maintenance efforts and troubleshooting time. Furthermore, PLCs excel in their ability to integrate with HMIs, a critical aspect for efficient operation and exception handling. This integration capability is more robust and user-friendly compared

to microcontrollers, facilitating effective monitoring and control of the automation process. While PLCs are more expensive than custom microcontroller implementations, the long-term benefits of reduced development time, lower maintenance costs, and operational efficiency justify the initial investment. The efficiency and reliability of PLCs make them a cost-effective solution over time [4].

For the purposes of this project, a PLC from B&R Automation has been utilized. B&R Automation is a leading global solution provider for automating machines and factories [1], It is important to note that the selection of B&R as the PLC provider is not central to the project's goals or outcomes. However, the report will incorporate B&R-specific terminology and references.

4.4.2 Software States

A big part of the project was to make the solution automatic, running selected sequences for different tasks such as pinning, depinning, and calibration of the magazine. To achieve this, a detailed state machine diagram was developed, outlining the software and machine behavior across various scenarios, as depicted in [figure 4.17](#). The different states depicted in the flowchart are:

- "POWERON" - The initial power-on state encompasses the machine's startup procedures, primarily initializing the X-Axis motor. A crucial prerequisite for transitioning from this state is the setting of the machine's home position, ensuring that the system is correctly aligned before any other actions are taken.
- "IDLE" - In the idle state, the machine is primed and awaiting input. When entering the IDLE state the machine is moved to its home position, readying itself for the execution of automated tasks or to respond to user commands.
- "MANUAL" - When manual intervention is required, whether for ad-hoc tasks or following a system error or emergency stop, the machine enters the manual state. This mode grants the operator the ability to perform manual jogging and other tasks, providing a layer of control and flexibility.
- "CALIBRATION" - The calibration state is critical for the system operation. Triggered from the idle state through the HMI, the system performs a count of the twistlocks present in the magazine. This process is fundamental to ensure the availability of the locks for the pinning and depinning tasks.
- "PINNING" and "DEPINNING" - In the pinning and depinning states, which the machine enters from the idle state, it carries out the core functions for which

it was designed: the secure mounting and efficient removal of twistlocks. These states are central to the machine's operation, addressing the primary objectives of this project. The detailed pinning and depinning flowcharts are presented in sections F.1 and F.2, respectively. These diagrams systematically illustrate the operational logic of the automated pinning station. During the pinning process, coordinated movements along the X, Y, and ϕ -axis are executed sequentially to align and secure the lock onto the corner casting of a container. Conversely, in the depinning process, similar sequential movements across the X, Y, and ϕ -axis facilitate the lock's safe detachment from the container.

- "EMERGENCYSTOP" and "ERROR" - Safety is critical, and thus, pressing the emergency stop and entering the error states is designed to halt all operations instantly, stopping all motor axes. This immediate response is crucial to safeguard the system and its operators from potential hazards. As previously mentioned, after an emergency or error state is resolved, the machine automatically transitions to the manual state. This requires an operator's verification and potential corrective actions, ensuring that the machine does not resume automated tasks without human oversight.

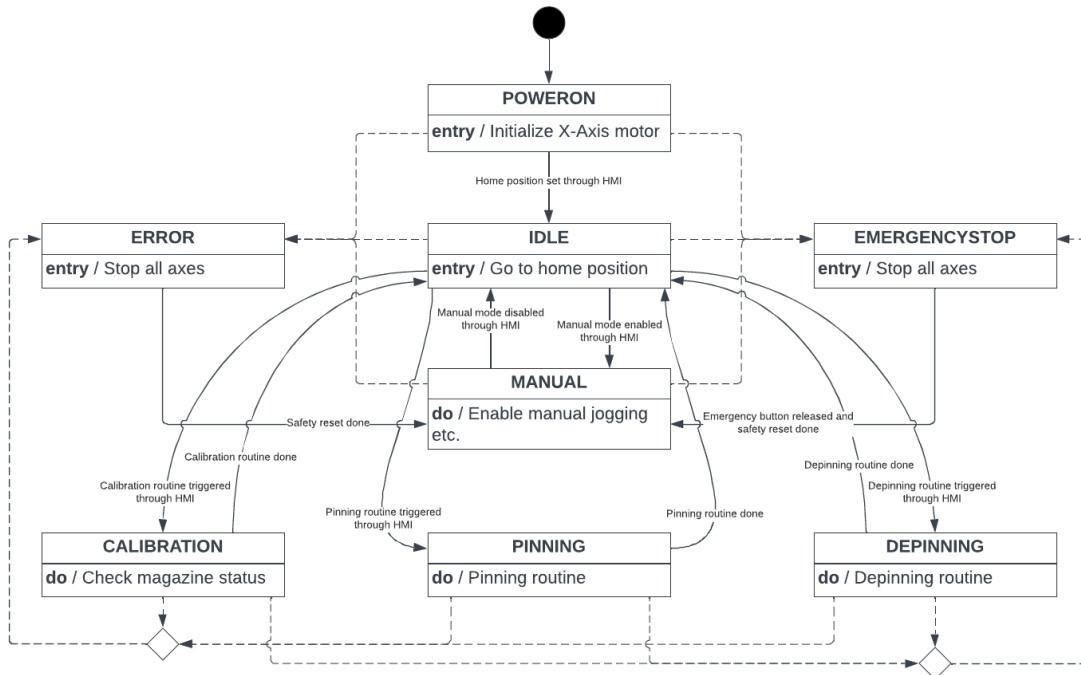


Figure 4.17: States of the pinning/depinning machine.

5 Method

This chapter outlines the steps taken such as; time plan, risk assessment, and budgeting. It aims at providing a clear overview of how the project was organised and managed our project to ensure its success.

5.1 Time plan

Roughly the fall period will consist of the following major activities:

- Recap final concept
- Detailed CAD of concept
- Research components
- Order components
- Building
- Assembly
- Testing
- Report writing

The detailed time plan can be found in [appendix E](#). The aim is to finalise the detailed design and CAD within the first few weeks and then build, assemble and test the prototype. The two most critical tasks are ordering components and testing due to their unpredictable nature. Thus, these tasks will run in parallel to other tasks. The report will be written congruently with other tasks. The team aims to build a working prototype for one corner and develop a complete conceptual solution for the whole machine. A buffer period of 7 days is kept in December to ensure the project finishes ahead of schedule and there is a safety margin.

5.2 Risk assessment

The risks of critical parts not arriving on time were prevalent during the implementation phase of the project. The most critical component, provided by subcontractors, was the Y-axis actuator. If the Y-axis actuator proved inadequate in terms of speed, power, or other specifications, it would be difficult to meet the project requirements.

To proactively address this issue, thorough research was conducted on the specifications of the actuator, and the subcontractor was contacted to ensure that the actuator would meet the requirements and arrive on time.

In the event of the worst-case scenario, where the actuator could not be delivered on time, there was a contingency plan to potentially build an actuator. However, this would be time-intensive and might not meet the desired requirements. Fortunately,

due to the research and timely ordering, this situation did not occur during the project.

The electronic system was responsible for the smooth operation of all the actuators and sensors. Since the system was capable of drawing very high currents of up to 10 A plus, there would always be a risk of a component burning up, which might lead to the damage of the other components associated with it. The replacement of the components would mean hold-up in the further processes like testing. This risk was tackled in two manners; first by designing the electronics in a way that if a high current was to be drawn enough safety measures like current sensors and fuses were provided in the path. The design was made such that any susceptible component could be easily replaced from the electronics board. Second way was by ordering extra components that were prone to damage e.g. fuses, buck converters, etc. such they would be easily available.

The mechanical design was anticipated to pose significant integration risks due to tolerance considerations, particularly concerning the frame. Extensive discussions took place on this matter, involving consultations with multiple external professionals.

Ultimately, the strategy employed was to pinpoint critical dimensions for heightened scrutiny. Additionally, the emphasis was placed on accommodating variability by e.g. over-sizing screw holes or substituting them with slots.

Moreover, additional material was procured as a precautionary measure to address worst-case scenarios where encountered integration issues couldn't be resolved through modifications to the manufactured parts.

The biggest risk associated with any project is the project not finishing within time. To handle this risk, it was identified that a proper time plan would be mandatory. Thus, whenever deciding a deadline, two deadlines were considered, a real deadline and an acceptable deadline. The acceptable deadline would be one week prior to the real deadline thus giving the illusion of urgency to the work and if any delay occurred, there would always be the real deadline to make sure the project is on time. The final deadline of the project was pushed one week prior to the expected deadline in December and all deadlines were derived based on this new deadline.

5.3 Budgeting

The resource acquisition for this project was accomplished through a combination of purchases and the utilization of borrowed equipment. [Table 5.1](#) provides a comprehensive list of the items procured, with the total cost amounting to 25 199 SEK.

Alongside these purchases, additional resources were sourced from the KTH stock.

Table 5.1: Bill of Materials

| Component | Part Name | Supplier | Quantity | Unit price SEK | Total cost SEK |
|-----------------------------------|--|----------------|----------|-------------------|-------------------|
| Mechanical components | | | | | |
| Linear actuator | ID 10 | OEM | 1 | 4 514 | 4 514 |
| Mounting bracket | MB30 | OEM | 1 | 336 | 336 |
| DIN rail 250 mm | RND 465-00764 | ELFA | 4 | 24 | 96 |
| UPE140 Steel beam | UPE-140 balk 1,4m | Bromma Stål | 1 | 1 028 | 1 028 |
| Ball bearing | 4304 ATN9 | Kullagret | 1 | 423 | 423 |
| Steel plate 1000x500x1.5 mm | Stålplåt 1,5mm 1000x500mm DC01 | Montano | 2 | 272.5 | 545 |
| 35x35x2 Square steel tubing | 35x35x2mm KKR | Montano | 5 | 511 | 2 555 |
| Pinion Z=17 M=1.5 | Cylindriskt Kuggjul | Noremlem | 1 | 65 | 65 |
| Gear Z=80 M=1.5 | Cylindriskt Kuggjul | Noremlem | 1 | 455 | 455 |
| Cable Carrier | DJ15 20x29 R28 | JBCNC | 2 | 107 | 214 |
| T-Slot Nut | XCAN 8 | FlexLink | 10 | 19 | 190 |
| Linear rail | Simple Select | Mekanex | 1 | 5 600 | 5 600 |
| STSCoupling Jaw clutch | Kloppoling | Mekanex | 1 | 1 316 | 1 316 |
| Planetary Gearbox | 8GP50-050-040S2L2 | B&R Automation | 1 | 2 968 | 2 968 |
| Cost mechanical components | | | | | 20 305 |
| Electrical components | | | | | |
| Emergency Stop | FB1W-YW1B-V4E01R | ELFA | 1 | 332 | 332 |
| 20 A Breaker | 5SL4120-6 | ELFA | 1 | 159 | 159 |
| Glass fuse 800mA | 0217.800MXP | ELFA | 20 | 3.6 | 72 |
| DC motor | E192-24.91 | ELFA | 1 | 1 399 | 1 399 |
| Power Cable | RND 465-00953 | ELFA | 1 | 58 | 58 |
| Inductive sensor | E2BM12LS04WPB22MOMI | ELFA | 5 | 258 | 1 290 |
| Power supply 24V 20A | NDR-480-24 | ELFA | 1 | 1 152 | 1 152 |
| Motor driver 10A | Cytron MD13S | Botland | 1 | 144 | 144 |
| Motor driver | DRV8871 | Botland | 1 | 96 | 96 |
| Current sensor | DFRobot Gravity: Analog 20A Current Sensor | Botland | 2 | 96 | 192 |
| Cost electrical components | | | | | 4 894 |
| Total cost | | | | | 25 199 |

This stock includes a variety of components and tools that were essential for the execution of the project. Furthermore, a collaboration was established with B&R Automation, a partnership that facilitated the borrowing of PLCs among other essential equipment. The details of these borrowed items are presented in [table 5.2](#). While these resources were vital for the project, they are not included in the cost calculation as they were not purchased.

The budgetary planning for the project was strategically focused on cost-effectiveness. This involved a careful balance between the necessity of purchasing materials and the advantageous use of borrowed equipment. The financial allocation for the project primarily concerned the items listed in [table 5.1](#). This approach ensured an efficient use of funds while maintaining the project's technical integrity.

Table 5.2: No-Cost Bill of Materials

| Component | Part Name | Supplier | Quantity |
|------------------------------|--------------------|----------------|----------|
| Mechanical components | | | |
| Linear Rail | Unknown | SKF | 1 |
| 3mm stainless steel sheet | N/A | KTH | 1 |
| 6mm steel sheet | N/A | KTH | 1 |
| Bolts, nuts, washers, etc. | Various | KTH | 1 |
| 7075 aluminium alloy rod | N/A | KTH | 1 |
| Electrical components | | | |
| Servo Motor | 8LSA25.D9060S000-3 | B&R Automation | 1 |
| Control system | | | |
| PLC | X20CP1586 | B&R Automation | 1 |
| Digital Input Module | X20DI6371 | B&R Automation | 1 |
| Digital Input Module | X20DO4332-1 | B&R Automation | 1 |
| Digital Output Module | X20DO6322 | B&R Automation | 1 |
| Analog Input Module | X20AI4622 | B&R Automation | 1 |
| Safety Module | X20SLX410 | B&R Automation | 1 |
| Servo Drive | 8EI2X2MWTS0.XXXX-1 | B&R Automation | 1 |
| HMI | 6PPT50.101E-10B | B&R Automation | 1 |

6 Implementation

This chapter presents a detailed examination of the implementation and construction of the Pinning machine, segmented into comprehensive subsections dedicated to its mechanical, electrical, and software components.

6.1 Mechanical implementation

6.1.1 Frame

The construction of the frame consisted of four main steps, those being:

- Cutting of tubes
- Milling and drilling
- Welding
- Verification

In the first step the 6 m stock of 35x35 mm KKR tube was cut to length according to the design discussed in section 4.1.1. To ensure minimum waste material an online cut planner tool was used. The rough length of the tubes were cut in a horizontal metal bandsaw and finally grinded down to the exact dimension.

Thereafter slots and holes where necessary were milled and drilled in a metal milling machine. In tubes where both ends were supposed to welded shut, an extra hole was drilled to allow hot air to escape and avoid an explosion.

The frame was then spot welded with a Metal Active Gas (MAG) welding machine. The construction was continuously measured and adjusted before the final fillet weld

was applied. Fillet welds were only applied on the most load bearing welds, i.e the top tubes, tubes holding the magazine and the vertical tubes. This was to introduce as little warping as possible into the construction.

Finally the measurements of the frame were verified. It was observed that the diagonals differed by 3 mm which was deemed satisfactory.

6.1.2 Gripper Assembly

The gear and pinion of the gripper assembly lacked some holes. These were drilled and lathed. The hole for the ball bearing was noteworthy as it was press fitted it required tight tolerances. Furthermore the mounting adapter between the Y-axis actuator and the gripper assembly was lathed out of aluminum stock.

The gripper was originally thought to be milled out of solid aluminium, but due to material waste and technical difficulties it was decided to modify the gripper to be made of welded steel plate.

The parts for the modified gripper were water jet cut out of 3 mm stainless steel plate. The parts were then welded with MAG. Additionally chamfers were angle ground into the gripper to make it easier for the lugs of the lock to retract when inserting the lock. The finished gripper can be seen in figure 6.1.



Figure 6.1: Final implementation of the gripper

6.1.3 Electrical cabinet

The plates for the electrical cabinet were cut out of 1.5 mm steel sheet. These were then welded, and since the plate was thin, power and feed rates during welding had to be kept low to avoid melting through the material. DIN rails were subsequently mounted in the cabinet to facilitate the easy installation of electronics inside the box. Finally, the box was mounted on the frame.

6.1.4 Magazine

During exploration of various manufacturing techniques, it was recognized the importance of cost-effectiveness and ease of production. Consequently, it was decided to opt for a standardized component approach for the main part of the prototype magazine. After thorough research, we identified a suitable standard U-Beam, known as "UPE 140", which is able to accommodate the twistlocks. For detailed specifications of the UPE 140 beam, refer to figure 6.2.

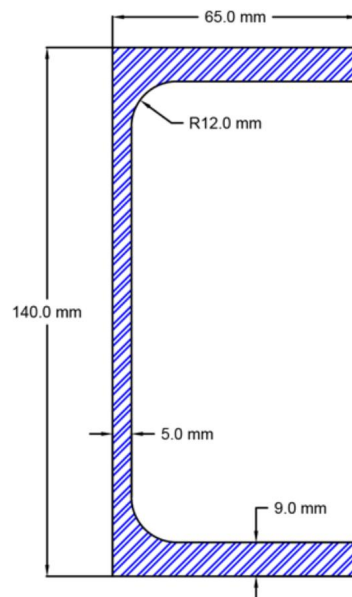


Figure 6.2: Cross-section view of a UPE 140 beam

The prototype magazine accommodates four twistlocks, a decision based on the dimensions of the twistlocks and the travel length of the linear rail. Its manufacturing consisted of water jet cutting the UPE 140 beam. The final design can be seen in figure 6.3.



Figure 6.3: The manufactured prototype magazine, mounted to the frame and with twistlocks attached

6.1.5 ϕ -axis actuator mount adaptor

Attaching the gripper sub-assembly to the Y-axis actuator proved difficult using simple manufacturing methods (e.g. water jet cutting or bolting). This is because the gripper needed to be mounted firmly along the Y-axis, requiring tight tolerances both to accommodate the Y-axis actuator as well as the bearing for the ϕ -axis.

Thus a " ϕ -axis actuator mount adaptor" was turned and milled out of a 7075 aluminium alloy rod. The central hole, used for axially constricting the bearing with a washer and bolt, was threaded. The same goes for the four mounting holes for the ϕ -axis actuator mount. As stated above tight tolerances were required, thus both radial attachment points were dimensioned to H7/h6 clearance fits. Figure 6.4 shows the adaptor mounted in an incomplete assembly for reference.



Figure 6.4: The ϕ -axis actuator mount adaptor mounted on the Y-axis actuator, ϕ -axis actuator mount and bearing

6.2 Electronic implementation

The smooth functioning of all the actuators and sensors demanded a robust electronic system. It was decided to develop an electronic board that would house all the necessary components. The electronics board, power supplies, motor driver and the PLC were strategically placed in an electronic box located on the wall of the machine. The goal was to have all components outside the actual operating zone to make troubleshooting easy as everything would be at one place. The electronics board was prepared according to the goals listed in Section [section 4.3](#) and then connected according to [figure 4.16](#).

Because the stakeholder required high reliability of operation, when choosing proximity sensors, inductive sensors were chosen. These binary sensors are staples of industry automation, that trip very consistently and reliably when metal is detected within their field of influence.

The master schematic of the electronics was built in Autodesk Eagle found in [Appendix G.1](#).

It was identified that the signals could be classified mainly into 3 categories: signals coming from the PLC, signals going to the PLC and signals going to the

actuators. To facilitate ease of cable management it was decided to have only two bus terminals from the electronics board: One responsible for sending and receiving signals from the actuators and one for sending and receiving signals from the PLC. Multiple components demanded an individual 24V supply, so a Power Distribution Unit (PDU) was made in-house that provided a 5 channel fused 24V power supply. All the required Printed Circuit Board (PCB)s were developed in-house using prototype boards. LEDs were placed on appropriate signals to provide power status, making troubleshooting faster. The buck converter modules were installed using pin headers instead of soldering them in permanently, which allowed for quick replacement, if one should fail. To reduce the wiring, a common ground bolt was introduced which acted as a local ground for the components. All the components and PCBs were mounted on the board via threaded PCB mounts, the idea being ease of access for servicing and replacement. For a picture of the developed electronic board, see figure 6.5.

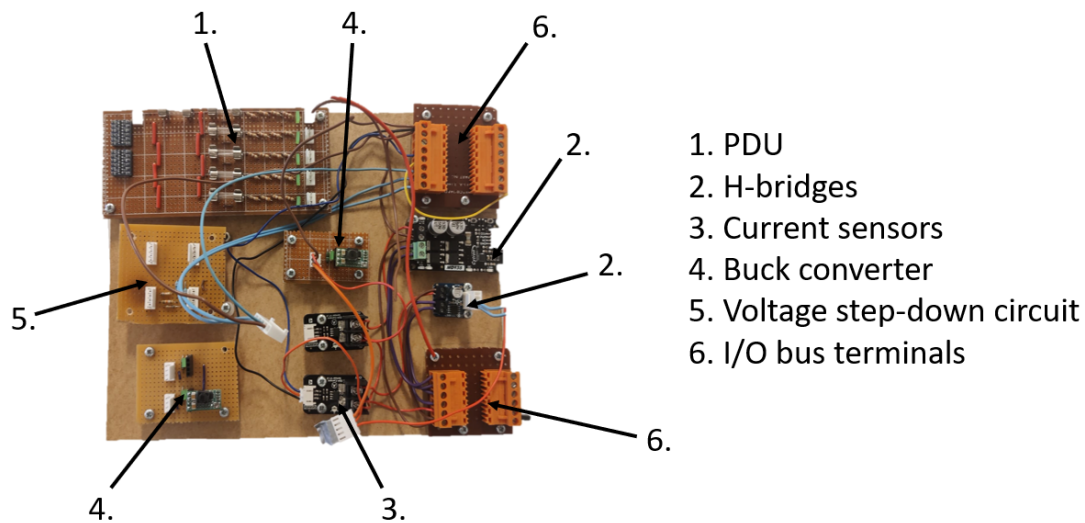


Figure 6.5: Electronics board developed.

It was noted during operation that the DC motor was not able to run on certain PWM frequencies and neither was it operational for a 100% duty cycle. The reason was identified as noise in the system as multiple PWM signals were clustered together in one area. To solve this, normal wires were replaced with shielded cables.

For vertical actuator controller feedback, an internal linear potentiometer built into the actuator was considered. Testing proved that the linear potentiometer for vertical actuator position feedback did not satisfy the EMS requirements for stable

operation by the PLC, leading to erratic movements and non repeatable final positions of the actuator. Shielding the cables mitigated the issue, but did not eliminate it. Replacing the potentiometer with an inductive sensor made the linear actuator very reliable in finding the top position with sub-millimeter accuracy. The potentiometer was still used to find the bottom position, since the required position had a large acceptable tolerance.

The minimum bottom position was the fully retracted position of the linear actuator, and the maximum bottom position was where the held twistlock just barely cleared the bottom of the magazine twistlocks. As can be seen in figure 6.6, these positions constituted a span of 58mm, which was within the ability of the noisy potentiometer to target reliably. The erratic movements mentioned earlier were eliminated in software.

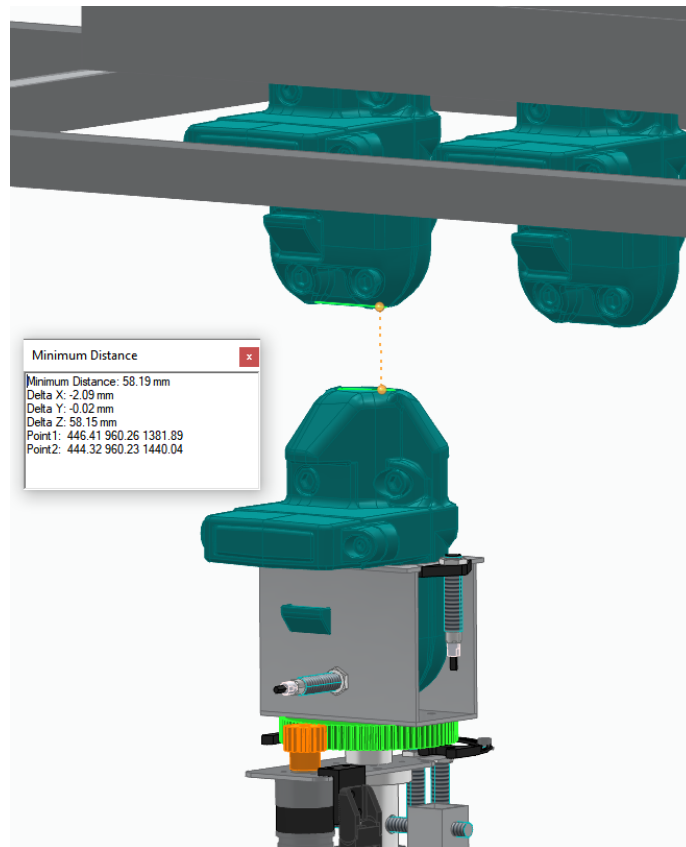


Figure 6.6: The minimum bottom position of the vertical actuator, and the distance to the maximum bottom position.

The TTL shifters were not able to shift PWM signals from 24V to 5V, thus they

were replaced with a simple voltage divider. The final implementation of electrical cabinet can be seen in figure 6.7.

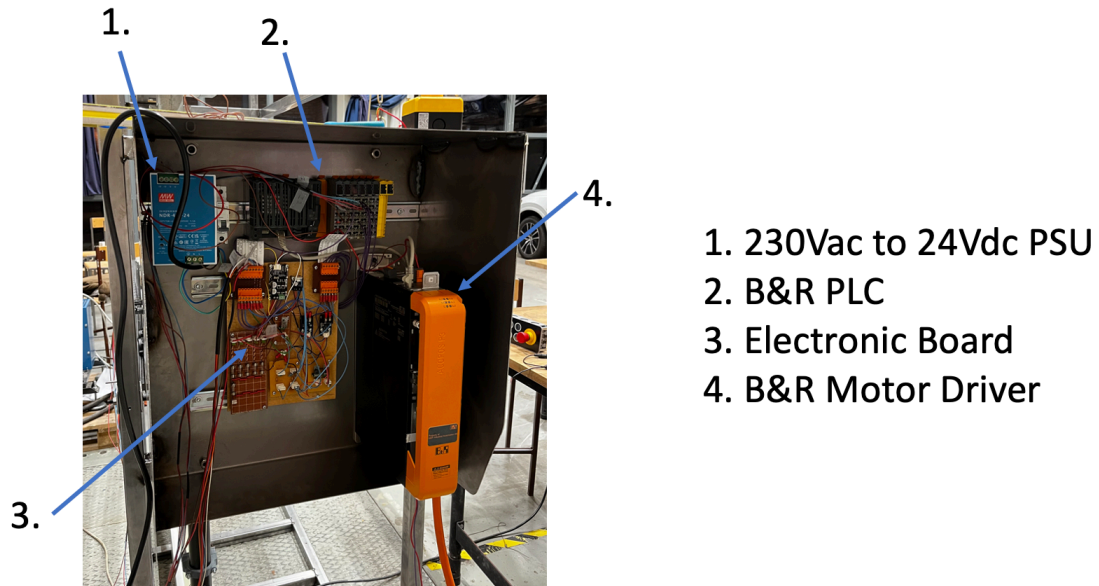


Figure 6.7: Final implementation of the electronics box.

6.3 Software implementation

This section describes the software implementation of the machine, consisting of the implementation strategy, HMI layout, exception handling and safety implementation through software.

6.3.1 Modular Software Design

This chapter delineates the software implementation strategy for the automated pinning machine. Initially, a comprehensive hardware overview was established in Automation Studio, as depicted in figure 6.8. Note that other hardware components are integrated through "I/O" mapping of each PLC module, and are not visible in this picture. The programming phase utilised Structured Text, a high-level language advantageous for its clarity and efficiency in industrial automation applications.

The software was systematically divided into distinct modules, each dedicated to a specific motor. These modules, equipped with individual interfaces, autonomously managed their respective motor operations, including the handling of limit switches

and current sensors. This modular design facilitated independent operation and ease of maintenance.

At the system's apex, a main program was implemented, functioning as the central command unit. It integrated the operations of each motor module, ensuring coordinated and efficient system performance. This architecture not only provided robust functionality but also established a foundation for future scalability and adaptability.

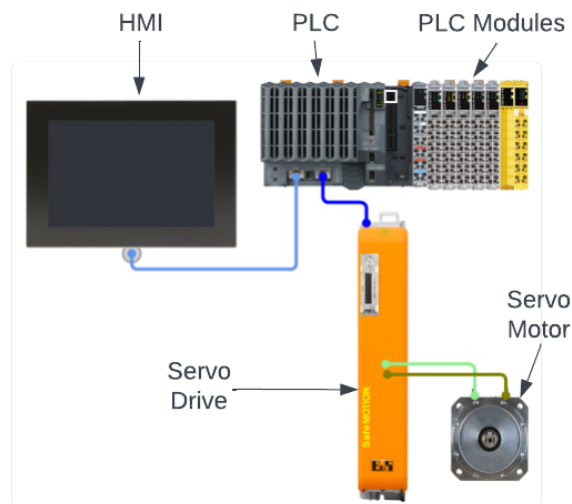
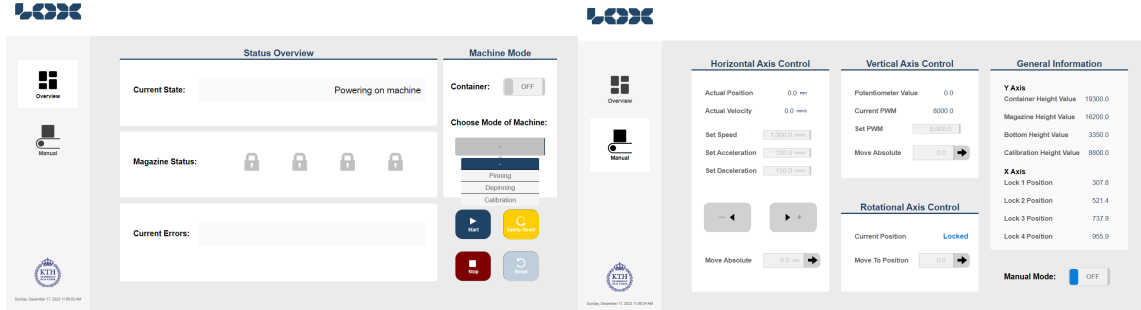


Figure 6.8: Hardware Overview in Automation Studio.

6.3.2 HMI and Exception Handling

The program was then connected to an HMI, making it easier to operate. On the HMI there are different modes to choose to run, that is, pinning, depinning, calibration and then a start button to start the chosen mode. There is also a stop button on the HMI for immediately stopping the whole machine and a reset button to make the machine go back to home position. The HMI also contains a page for jogging the X-axis and the Y-axis positions. For pictures of the HMI, see [figure 6.9](#).



(a) HMI Overview

(b) HMI Manual

Figure 6.9: HMI pages

In the states Calibration, Pinning and Depinning, the machine uses both the structure of the flowcharts seen in Appendix F and a state machine. The state machine is added to ensure that the machine is only actuated in a given sequence and hence prevent crashes if a input signal would become wrong.

One of the main requirements for this project was exception handling, so this needed to be addressed in the program as well. To do that, all the different issues that could occur first had to be thought of. One possible issue that could occur is if the physical magazine status is not matching the magazine status in the memory. This is handled both by checking if the gripper detects a lock when raised into the magazine for picking a lock up in the pinning state. And by detecting if the current is too big for the Y-actuator when trying to insert a lock into the magazine in depinning. In both these cases the machine is aborting and moving to its home position and raising an error. To detect if a twistlock gets stuck in the magazine or corner casting a combination of a current sensor on the ϕ -axis actuator and the inductive sensor in the gripper detecting if a lock is inserted is used. If this happens the machine should be stopped and an error arise.

To avoid any safety issues and components breaking, the program was first simulated in Automation Studio to see that every sequence functioned as wanted etc. When everything worked in simulation it was time to test it on the physical machine. First each motor was tested on its own, before testing the whole system. To address safety issues, there were always at least two people present during testing of the machine. Also, when the machine was running, no one was allowed to stand inside the frame, or touch anything on the machine.

6.3.3 Safety Through Software Implementation

In applications involving automated machinery, such as container twistlock handling, it is crucial to embed safety directly into the software design. This section explores the strategies for incorporating safety into software functionalities.

A significant portion of the software's safety features are implemented using B&R Automation's SafeMOTION. This system offers a range of safety functions vital for protecting both personnel and machinery. SafeMOTION achieves safety by integrating safety measures at the drive level, ensuring quick reactions to potential hazards and maintaining a secure operational environment.

Key safety features implemented using SafeMOTION include:

- **Emergency Stop Functionality:** Triggering the emergency stop promptly discontinues control signals to the motors, effectively halting their operation.
- **Monitoring Safe Speeds and Positions:** SafeMOTION constantly monitors the safe speeds and positions of the horizontal axis. The software utilizes this feature to keep the system operating within safe boundaries, intervening if these limits are breached.

Apart from SafeMOTION, other safety aspects are addressed through general software measures:

- **Motor Current Measurement:** The software actively measures motor currents to detect overcurrent conditions, which is crucial for preventing mechanical overloads.

To ensure the reliability and efficacy of these safety features, they were initially tested in simulated environments using Automation Studio. This simulation phase is critical for assessing the software's responses under various scenarios and confirming that all safety measures work as planned. Following the simulation, on-site validation tests were conducted under actual operating conditions. These tests are essential for verifying the practical effectiveness of the safety measures.

7 Validation and verification

The validation and verification process started by individually checking and validating each component.

In terms of electronics, each component underwent thorough checks to ensure expected behaviour and proper current and voltage levels. Before integrating the electronic board with the entire system, tests were conducted simulating the expected inputs in a real-world scenario. This approach helped confirm the accuracy of the design and ensured the desired outputs, mitigating the risk of damaging other components due to potential malfunctions in the electronic board.

Regarding the chassis, tests of the mechanical properties of the weld and the tube were also performed to verify the robustness of the frame.

Finally, the software was also tested and troubleshooted by subtasks, ensuring the correct behaviour and performance of the system.

Following this, the entire machine was tested to understand how all components interacted. Lastly, to ensure that all project requirements were met, validating the overall functionality and integrity of the system.

8 Results

The results of the pinning machine prototype are presented in this chapter. In summary, all stakeholder requirements are fulfilled for the full-scale concept. However the requirement on the withstanding 200G of impact force still needs to be fulfilled for the single-corner prototype.

Overall, the mechanical construction proved to be sturdy and stable. During the testing and calibration of the machine, both the frame and the magazine demonstrated resilience against substantial forces applied by the pinning machine, even when a lock was inserted slightly off-centred. No breakages or deformations occurred during the testing and operational phases, indicating that the frame and magazine were well-dimensioned and effectively welded to withstand the applied forces.

The movement of the three axes worked as desired. For the Y-axis, the machine moved between the bottom height and the magazine height in 4.10 seconds and between bottom height and corner casting height in 4.95 seconds. The ϕ -axis made the pinning/depinning rotation of 45° in 0.75 seconds. This fulfills the requirement of being able to rotate 45° in a maximum of 10 seconds. The X-axis moved from the corner casting position to the fourth lock in the magazine (with and without a twistlock) in 5.05 seconds.

The software program also showed to work as desired and fulfilling the requirements of automatically checking the magazine status, keeping track of the current magazine status and being able to detect if the physical status do not match the stats in memory. Furthermore the software stops all actuators when a emergency-stop is triggered as well as detecting if something gets stuck or requires too much torque to move.

The machine displayed exceptional repeatability during every pinning, depinning and calibration cycles. The accuracy was maintained and every task was completed as expected.

9 Discussions and conclusions

Taking into consideration the paramount need for a robust machine, the option with the fewest moving parts and simplest mechanisms became the obvious choice.

Throughout the design process, the most recurring point of resistance has been manipulation from one moving system to another moving system. That is, the interaction between the magazine and pinning station. The decision to keep the magazine rigid has simplified the system significantly in contrast to a moving magazine.

Additionally, each pinning station only contains one moving unit. This means that the HMI along with diagnostics and manual intervention should be more manageable.

The operational speed of the machine may be a point of concern due to the long travel distance required when the magazine is nearing empty. However, the subsequently increased precision and lowered failure rate makes up for lost speed in a long term perspective.

Also, further investigation has to be made into dimensioning the pinning machine for a container's impact forces in order to verify the impact requirement. This was deemed out-of-scope as the prototype is not designed to accommodate a full-scale container, meaning that there is no way to verify this requirement.

The concerns that remain to be addressed through prototyping or testing are the aspects regarding operator container positioning and making a practically feasible magazine. The angled magazines meet the number of locks specified by the product requirements. On the other hand, their total weight is concerning. Furthermore, although operators that work with stacking containers are highly precise according to first hand sources, without a well-tested guide, there is no way to know how the machine will impact operator precision.

The final prototype was able to achieve the applicable requirements given by the stake holder.

9.1 Ethical aspects

The development of an automated pinning machine introduces a range of ethical considerations, particularly in its potential impact on employment. While the automation of certain tasks may risk displacing jobs, it is crucial to frame this discussion within a broader ethical context, considering the well-being and safety of workers in high-risk environments.

One ethical consideration involves the potential displacement of human workers as a consequence of automation. The implementation of an automated pinning machine

may reduce the need for manual labor in certain tasks traditionally performed by workers. This raises concerns about the socioeconomic impact on individuals and communities that rely on such employment. On the other hand, the machine will still require workers for controlling the HMI.

Furthermore, the ethical imperative to prioritize worker safety and health must be acknowledged. The tasks associated with pinning stations often expose workers to hazardous conditions and environments. Automation has the potential to eliminate these risks by removing the need for human involvement in physically demanding or dangerous processes.

The prototype also introduces some ethical considerations as it could be dangerous if not handled correctly. The design introduces risks of getting squeezed or jammed between components if not careful, and the safety implementation in the control system is not thoroughly implemented to safely avert such events.

9.2 Sustainability aspects

As always, the development of products introduces impacts on the climate and carbon dioxide emissions.

The primary impact stems from the production process of the product, involving the extraction of raw materials, manufacturing of components, and subsequent shipping. To comprehensively assess the overall impact of this product, a thorough analysis of material flow and life cycle is imperative.

Additionally, if the product would lead to an incentive to increase the capacity to ship goods across the globe, it could have an indirect impact on the climate.

10 Future work

The Pinnacle prototype is not a finished product, but it does prove that the concept chosen is a sound basis for continued development of a full-scale container pinning machine. Its high speed, reliability, ease of use, error handling and, not least, increased occupational safety, is evidence that all these features can be implemented into the future product. While some features just need to be scaled up in the step to the full scale machine, others will have to be developed from scratch. These include:

- Interchangeable magazines, so that continuous operation can be done with an arbitrary amount of locks.
- Weather proofing, so that the machine can endure the harsh conditions in the harbor.
- Compliance with of worn and damaged containers, so that the machine can pin and depin containers of all tolerable conditions.
- Market certification and qualification, so that the machine can be approved and implemented safely.

All of which are significant engineering challenges that need to be overcome in order to finalize the product.

It is important to note that the current testing protocol is tailored for the "one-corner"-prototype version of the machine. In the pursuit of refining the prototype into a full-scale machine, key considerations also extend beyond mere technical enhancements. The design and overall functionality should be subjected to thorough review, incorporating the knowledge and active participation of the workers. This collaborative approach ensures that the final product aligns with the practical insight of those who will directly engage with the machine on an everyday basis. This is crucial to ensure that the safety measures are fully effective and cover all necessary aspects of the machine's operation.

There is a lot of work left, but that work can be done knowing that the concept is fast, stable and reliable, and that the completion of the project and implementation of the machine would lead to a safer occupational environment for harbor workers worldwide.

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Appendix A Container standard dimensions

Table A.1: Container dimensions

| Name | Length | Width | Height | Empty weight | Max weight |
|-----------------------|--------------------|--------------|----------------|--------------|------------|
| 20 ft standard height | 19'10.5" (6.058 m) | 8' (2.438 m) | 8'6" (2.591 m) | 2200 kg | 36 000 kg |
| 20 ft high cube | 19'10.5" (6.058 m) | 8' (2.438 m) | 9'6" (2.896 m) | | 36 000 kg |
| 40 ft standard height | 40' (12.192 m) | 8' (2.438 m) | 8'6" (2.591 m) | 3800 kg | 36 000 kg |
| 40 ft high cube | 40' (12.192 m) | 8' (2.438 m) | 9'6" (2.896 m) | 3935 kg | 36 000 kg |
| 45 ft standard height | 45' (13.716 m) | 8' (2.438 m) | 8'6" (2.591 m) | | 36 000 kg |
| 45 ft high cube | 45' (13.716 m) | 8' (2.438 m) | 9'6" (2.896 m) | 4500 kg | 36 000 kg |

Appendix B Interview

Interview with a dock worker from Gothenburg

May 15th 2023

Questions

1. Where have you been located during these 17 years? At a port area?
[swe] *Vart har du varit stationerad under dom här 17 åren?*

At a port area in Gothenburg

Vid en hamn i Göteborg

2. What have your roles and responsibilities looked like?
[swe] *Hur har dina roller och ansvarsområden sett ut?*

Been working with straddle carrier, high trucks that moves containers in the port. Also he's been driving container cranes for many years, loading and unloading ships. Now he works as a mechanic for the cranes.

Jobbat med gränsletruck, höga truckar som flyttar containrar i hamnen. Också kört containerkranar i många år. Lastat och avlastat fartyg. Nu är han mekaniker på kranarna.

3. What type of locks are you using currently? Has it always been the same?
[swe] *Vilka typer av lås använder ni idag? Har det alltid varit så?*

Been using a lot of different locks, both manual and half-automatic.

Använt massa lås. Både manuella men även halvautomatiserade lås

4. Can you describe the current working procedure for the locking?
[swe] *Kan du beskriva den nuvarande lösningen för låsningen?*

When placing a container you look at the corners of the containers for placing them correctly, there's no cone that you can use for guidance. So the procedure for placing the containers is fully visual. Small boats can swing a lot so in those cases a lot of fine touch is needed for placing the containers correctly.

There's been one crush accident on a workers arm relative the pinning procedure, however the worker did not follow the right procedure that they were supposed to.

Vid placering kollar man på hörnlådorna för att placera rätt, finns ingen "tratt" som man kan använda för guidning. Rätt placering sker rent visuellt. Fidebåtar (små) kan gunga mycket så där krävs det mycket känsla för att placera containrarna rätt.

Olyckor har hänt 1 gång, en som klämt handen när de gjorde på ett sätt man inte fick.

5. What is the attitude towards today's solution among the workers?

[swe] Hur upplever du inställningen till dagens lösning bland arbetarna?

The dock workers actually like pinning and depinning locks, they see it as a nice break to all the other work they do. He believes no dock worker in the world wants automated locks since that would remove job opportunities for them. However, he can see there is a risk by doing it manually since the containers easily can swing around when bad weather, especially the empty containers.

Ingen hamnarbetare i världen som vill ha automatiserad låsning. Hamnarbetare tycker det är skönt att gå ut och plocka koner (lås), så det gör de gärna. Containrarna kan lätt hamna i gung vid blåst, speciellt tomma containrar.

6. How long would you say it takes for a reach stacker to lower a container onto another container? How many containers are handled per hour?

[swe] Hur lång tid skulle du säga att det tar för en reachstacker att sätta en container ovanpå en annan container? Hur många containrar hanteras per timme?

The time to lower a container onto another one totally depends on the type of ship, nowadays the goal is to be at 30 containers/hour.

It is possible to carry 2 of the 20 ft containers at once, which improves the effectiveness a lot rather than handling only 40 ft containers.

Tid att sänka ner en container på annan beror helt på typ av båt, nu för tiden mål att ligga på ca 30 containrar i timmen.

Kan bära 2 st 20 ft samtidigt, så då blir effektiviteten mycket snabbare än om man bara hanterat 40 ft containrar.

Appendix C Concept development Pugh Matrix

| Criteria (0-5) | Importance | pinning action | | pinning/deconning same m/c | | Pinning stations | |
|---------------------|------------|----------------|-----------------|----------------------------|----|------------------|-------------------------|
| | | Synchronous | Non-synchronous | Yes | No | Sliding stations | Fixed multiple stations |
| Convenience | 3 | 4 | 3 | 5 | 2 | 3 | 3 |
| Exception handling | 4 | 1 | 4 | 3 | 4 | 2 | 3 |
| Cost | 2 | 4 | 2 | 3 | 2 | 3 | 4 |
| Safety | 5 | 2 | 5 | 0 | 0 | 1 | 5 |
| Reliability | 5 | 2 | 3 | 2 | 4 | 2 | 5 |
| Adaptibility | 4 | 0 | 0 | 5 | 0 | 5 | 3 |
| Speed | 4 | 5 | 3 | 0 | 0 | 2 | 4 |
| Automatic | 3 | 4 | 3 | 2 | 4 | 4 | 4 |
| Magazine capability | 3 | 0 | 0 | 5 | 1 | 1 | 4 |
| Total: | | 76 | 90 | 84 | 61 | 81 | 131 |

| Guide channel | Guides | | Common bed for 20/40ft | | Magazine deconning lock goes in place | |
|---------------|----------------|----|------------------------|----|---------------------------------------|----|
| | Free placement | | Yes | No | Yes | No |
| 5 | 2 | 5 | 2 | 4 | 2 | |
| 4 | 2 | 3 | 3 | 3 | 3 | |
| 2 | 4 | 4 | 2 | 3 | 4 | |
| 4 | 2 | 4 | 4 | 0 | 0 | |
| 5 | 2 | 3 | 4 | 2 | 4 | |
| 1 | 4 | 5 | 1 | 3 | 4 | |
| 0 | 0 | 0 | 0 | 4 | 1 | |
| 0 | 0 | 2 | 4 | 5 | 1 | |
| 0 | 0 | 2 | 4 | 5 | 3 | |
| 84 | | 58 | 102 | 90 | 98 | 78 |

Appendix D SWOT analysis

D.1 Lock Magazine

| | Strength | Weakness | Opportunities | Threats |
|--|--|---|--|---|
| Push magazine. Alternative 1: Push on locks | Simple to implement. Space efficient. Easy to change magazine. | Only possible to select first lock in line (need somewhere to get rid of malfunctioning locks) | | The locks can jam when pushed forward. |
| Push magazine. Alternative 2: Belt | Less force needed to move locks forward. Space efficient regarding locks. | Only possible to select first lock in line (need somewhere to get rid of malfunctioning locks). Harder to change magazine. Magazine takes up a lot of space. | | |
| Push magazine. Alternative 3: Rotating spiral | Simple to implement. Easy to change magazine. | The locks risk not keeping the exact orientation. Only possible to select first lock in line. | | |
| Magazine belt | Possible to select which lock should be used (and not used) in each corner | Complicated Hard/complicated to change magazine. | | May require manual loading of magazine in the machine. |
| Fixed magazine | No moving parts for the magazine. Very simple to change magazine. Space efficient. | Difficulty fitting 40 locks length wise inside the bounding box of the m/c | Possible to design the pinning stations/transfer mechanisms so that more than one corner can use same set of locks. Possible to select which lock should be used. | May require more motions and complexity from the pinning station/transfer mechanism |

D.2 Pinning mechanism

| | Strength | Weakness | Opportunities | Threats |
|--------------------------------------|--|--|---|--|
| 3-axis pinning station | Flexible with magazine type | Lots of moving parts | | Can be damaged by impact forces |
| Spring loaded Pinning station | Container can be loaded directly upon lock | Finding suitable dampeners can be difficult. Can not take horizontal loads | | Linear rod might get deformed if load is not axial |
| Pinning station Platform | Should be able to handle impact forces | Finding suitable dampeners can be difficult. Can not take horizontal loads | Can position container directly on the lock | |
| Box gripper | Removes the need for horizontal movement | Requires good synchronization with the belt | | |

Appendix E Gantt chart

E.1 Spring semester

I

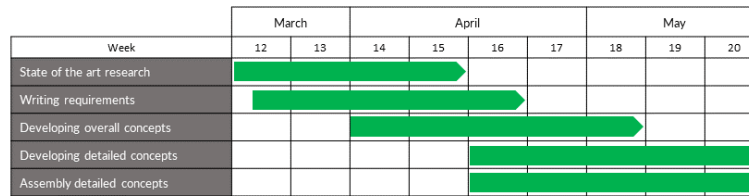
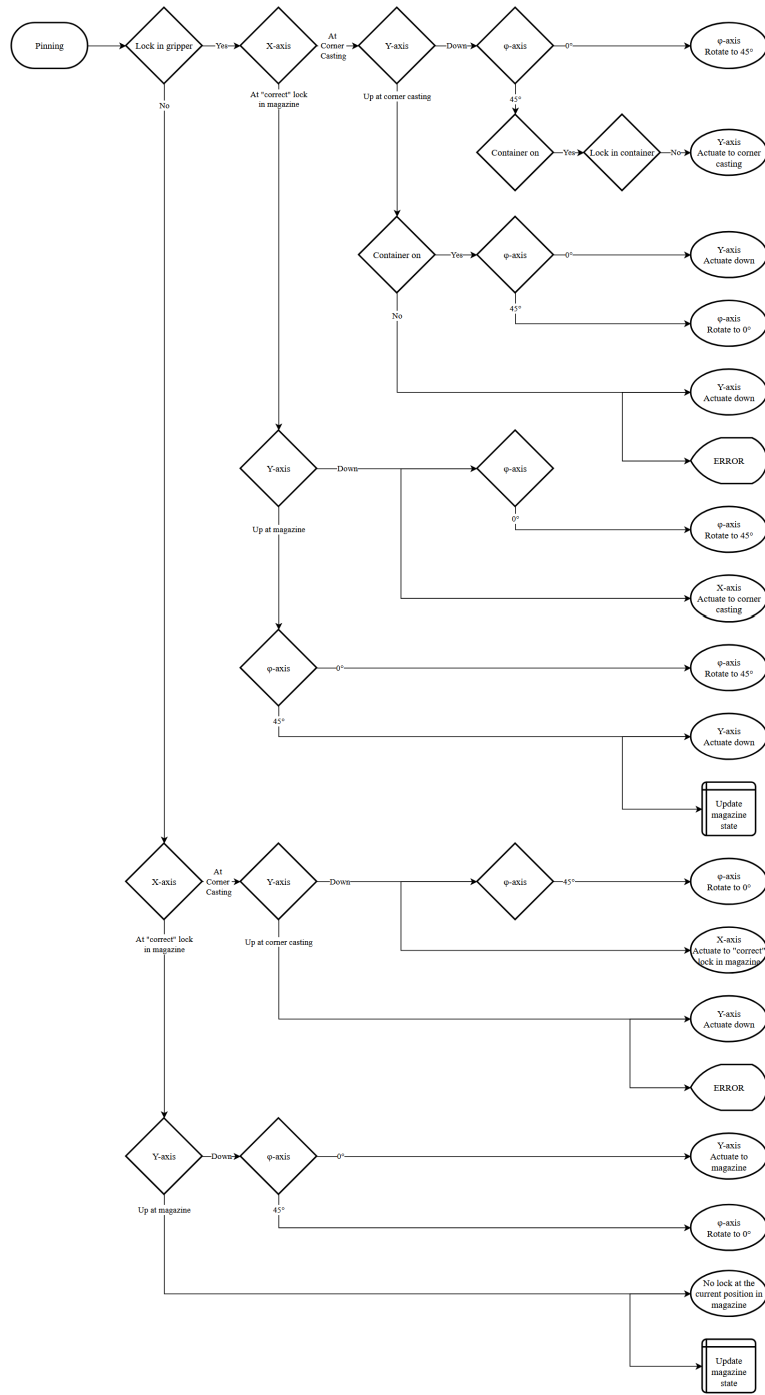


Figure E.1: Gantt chart for the spring semester

F.2 Pinning flowchart



Appendix G Electronic Schematic

G.1 Electronic Board

