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Industrial Electrical Engineering and Automation

Automatic Recovery in Robotic Pattern Creation

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Automatic recovery in robotic pattern creation

MASTER THESIS

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Abstract

English

A distribution equipment solution using a delta robot for picking and placing packages in a rectangular pattern into cardboard trays (blanks) is currently under development. In order to increase the robustness of this solution, concepts for handling a variety of performance problems in the grouping or pattern creation area without operator interaction, e.g. toppled packages or missing packages, needs to be tested and proven. The concepts are grouped together as “automatic recovery in robotic pattern creation” and are the basis for this master thesis.

This thesis work is divided into three main parts: identifying the performance problems and their causes, generating concepts for solving them and lastly testing and verifying these concepts. The thesis only needs to come up with proof of concepts, and it is assumed that a complementary computer vision system will be used together with all the recovery concepts in this thesis.

A tool attachment for the already existing gripping tool for picking single packages was designed to solve the simpler performance problems with fallen/rotated/misplaced packages in the pattern creation area. It was tested for robustness and speed and showed good conformability when picking angled surfaces. Around 20 packages can be picked within the allotted time of two minutes, which is the estimated time for operator interaction.

A second attachment for clearing the blank completely, to be used in cases where recovery would take too long or when the performance problem is judged too complex to recover from, was also designed and tested with success.

Two patents applications for the two attachments have been filed by the Company.

Swedish

Företagets avdelning för distributionsutrustning håller på att utveckla en lösning för att packa förpackningar i ett rektangulärt mönster i öppna tråg. Lösningen använder sig av en delta-robot med ett vakuumdrivet plockverktyg för att plocka och placera förpackningarna. För att öka robustheten i lösningen vill man ta fram och testa koncept för att automatiskt, och utan operatörsinteraktion, hantera diverse problem som uppkommer i mönsterskapningsområdet, vilket är målet för detta examensarbete.

Examensarbetet är uppdelat i tre olika områden; identifiering av mönster-relaterade problem och deras orsaker, generera koncept för att lösa dessa problem, och slutligen testning och verifiering av dessa koncept. Arbetet är avgränsat till att endast behöva bevisa konceptens genomförbarhet för framtida utveckling och behöver ej resultera i färdig produkt. Det antas finnas ett bildigenkänningssystem för att identifiera problem samt förpackningar i robotcellen och omfattas ej av arbetet.

Ett avtagbart tillbehör till det befintliga greppverktyget designades för att plocka undan enstaka förpackningar vid simplare fel så som fallna, roterade eller felplacerade förpackningar. Hastighet och robusthet för tillbehöret testades och visade god anpassningsförmåga avseende att plocka vid vinklade ytor. Omkring 20 förpackningar kunde plockas säkert inom den allokerade tidsramen av 2 minuter, vilket är den uppskattade tiden det tar för en operatör att själv hantera problemet.

Ett andra tillbehör för att rensa bort alla förpackningar i ett tråg har också tillverkats, för fall där problemet kommer ta för lång tid att lösa eller om det anses vara för komplext för verktyget att klara av.

Patentansökningar för de två verktygstillbehören har lämnats in av Företaget.

Preface

If you had only two minutes, what would you do? An operator by an equipment line would spend them on stop procedures, clearing a pattern creation problem and resetting the production line. But what if the robot could somehow manage this by itself?

This master thesis is about a pattern creating delta-robot and its ability to automatically recover from performance errors without operator intervention. During the course of this project concerning the topics of mechatronics, product design and development, automation, embedded programming, robotics and computer vision, the saying “jack of all trades, but master of none” comes to mind, but maybe that is what it means to be an engineer.

During my five months (September 2019 to February 2020) working on this master thesis I have learned much about how a large multinational company works, and how to plan, document and drive a project forward. It has also taught me the power of rapid prototyping, PowerPoint presentations and demonstration videos.

Special thanks to “DE_ Technology & Experts”; my scrum team at Distribution Equipment, for their support, feedback and cheerful spirits in an ever so changing Activity Based Working environment. I would not have made it this far without them.

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1. Background

Produced packages are to be packed into crates in a specific pattern (the 'pattern creation area'). This is currently done by a delta robot in a pick-and-place operation. The robot picks up a group of packages (the 'grouping creation area') and puts them in an open cardboard tray (the 'blank') using a vacuum powered suction cup tool head. However, errors (the 'performance problems') can occur in the grouping or pattern creation area such as misaligned, toppled or missing packages, causing a decrease in pattern quality or a complete crash of the production line. Currently the production line has to be stop and an operator has to correct the performance problem manually. To avoid stopping the line and involving operators the delta robot needs to be fitted with a robust error handling system (the 'concept') for handling the different performance problems in a safe manner with as few damaged packages as possible.

The aim of the thesis is to come up with concepts of automatic recovery from performance problems caused in the pattern creation or grouping area of the production line. The project should result in a mechanical and/or software proof of concept that can be further developed by the Company and incorporated into their equipment solutions. Methods of incorporating automatic blank removal or automatic package return will also be examined.

1.1 The packaging line

The pattern creation module with a delta robot is a part of a distribution equipment line. Upstream the pattern creation module there are other equipment modules for controlling the flow of incoming packages and releasing groups of packages to the pattern creation module. Several pattern creation modules can be used in the same equipment line to increase capacity. Figure 1 shows a schematic of the equipment line.

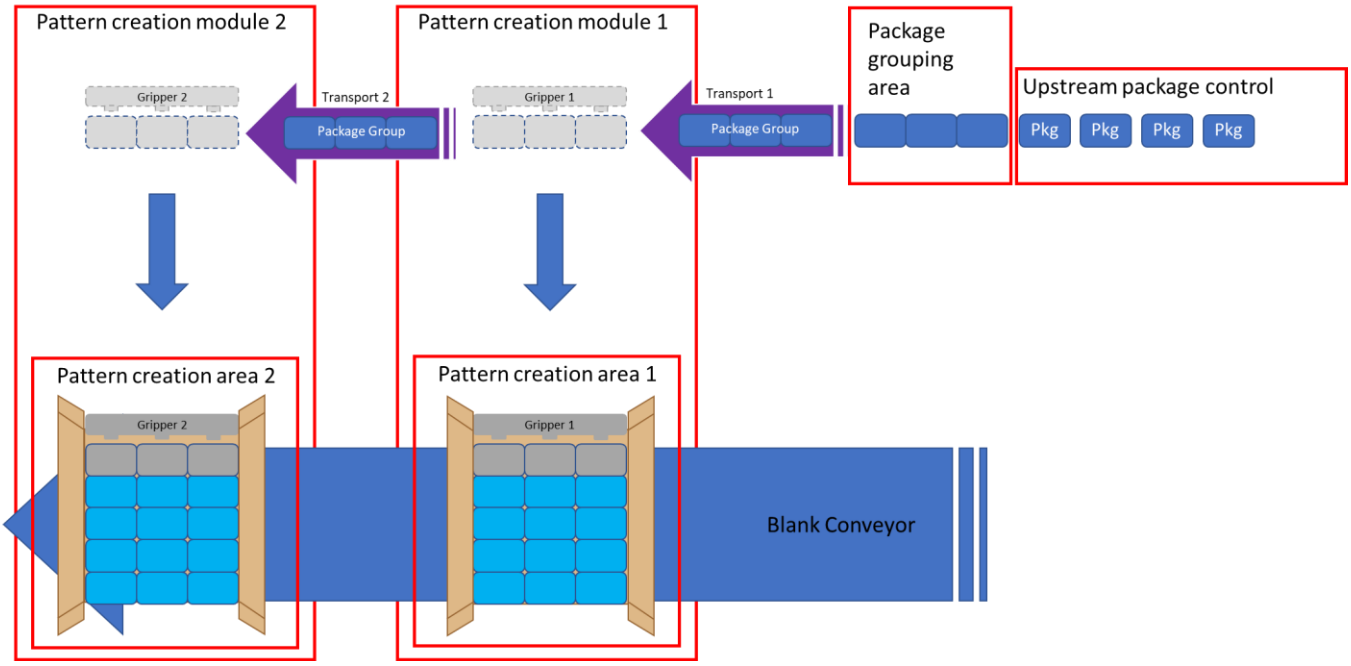


Figure 1: The equipment line

1.2 Scope and delimitations

- The project does not include developing methods for identifying the different performance problems, only the handling of these. Assume there are input signals for the different identified problems.
- The project goal is to result in (mechanical and/or software) proof of concept(s) for possible recovery actions, not final solutions ready for implementation into the packaging line.
- The project does not have to offer a concept(s) for every single identified performance problem, rather try to focus on performance problems that have the largest impact on line-performance in relation to its complexity.

1.3 Company way of working

The Company utilizes a working environment model called ABW - Activity Based Working. This is a flexible way of working that means open office spaces and no fixed seats. Individuals who are working with the same project sit together and can communicate freely, often in close proximity to the workstation of their project, if there is one. This model means that during this project the author has been partly located with the thesis supervisor and her team, and partly located by the test rig together with the people in charge of it.

Another corner stone of the Company is the AGILE way of working called “Scrum” [1]. One part of the scrum-methodology is to visualize and keep track of different assignments. Every day there is a short scrum-meeting where the individuals in the team aligns on their current tasks, starts new ones and ticks off finished ones. This has been very helpful in breaking down the project into smaller pieces that are easier to handle.

1.3.1 Design strategy

During the course of the project there has been a lot of iterative concept design, meaning concepts are taken from idea to prototype, tested and remodeled in a rapid pace. Not all concepts are evaluated together in order to rank their validity, rather they are realized and tested in practice to see if they are feasible. Generating concepts, produce simple prototypes and do quick and dirty tests is a chosen strategy of the company. By rapid iterations including prototype testing is a chosen strategy by the company since many concepts are tested and risks are detected before detail design and equipment module procurement are done. In this way time and cost are less compared with having larger design loops later. Workshops and meetings are frequent to keep everyone aligned and on the same page. Most of the concept generation and verification for this project have been done during workshops like these. To enable these fast design iterations the company uses 3D-printers, water cutting and other fast, on-demand manufacturing tools to quickly satisfy the needs of rapid prototyping.

A common method for finding root causes (RCA - Root Cause Analysis) is the “five why’s” method. It is a simple but effective method of breaking down a problem and categorize the different causes. An example could be:

1. Problem: Liquid in the production line. Why?
2. A package was crushed. Why?
3. The package was in the wrong position. Why?
4. It fell over. Why?

5. The vacuum was insufficient. Why? → The suction cup was leaking.

Of course, this reasoning could be taken further than just five levels, and usually a problem forks into several root causes, but often a lot of problems have similar causes on different levels that can be grouped together, meaning you can fix several issues by correcting just one root cause.

1.4 Tools/instruments

1.4.1 The test rig

The test rig is similar to the packaging line envisioned in the future solution, however there is only one picker robot. The robot is an Adept Quattro 650 mounted on a P30 platform. What sets this apart from other delta robots is that it has four arms rather than the conventional three, enabling a slightly larger workspace, higher speeds and some extra manipulation of the end effector [2]. The rotational and tilt degree of freedom of the robot in the rig have been suspended to decrease the complexity of its movements. The blank conveyor in the rig is not cyclical and can therefore only feed a few blanks before requiring a manual reset. It is connected to an encoder and a latch inside the cell that can keep track of passing blanks.

The robot workspace can be found in the user's guide [3] shown in Figure 2.

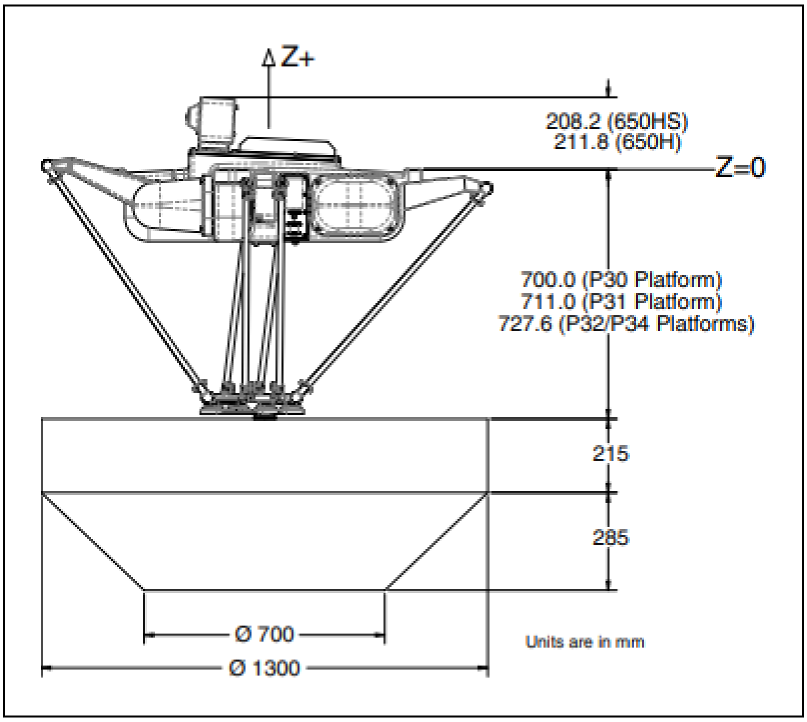


Figure 2: Robot workspace

The current packaging solution uses a special tool head (the 'Gripper head'), see Figure 3, consisting of a gripper mount (red) and several gripper units (green). The gripper head (yellow) is fully pneumatic and designed to pick a group of packages, see Figure 4. The pressurized air is converted to vacuum using standard venturi vacuum generators [4] attached to each gripper unit.

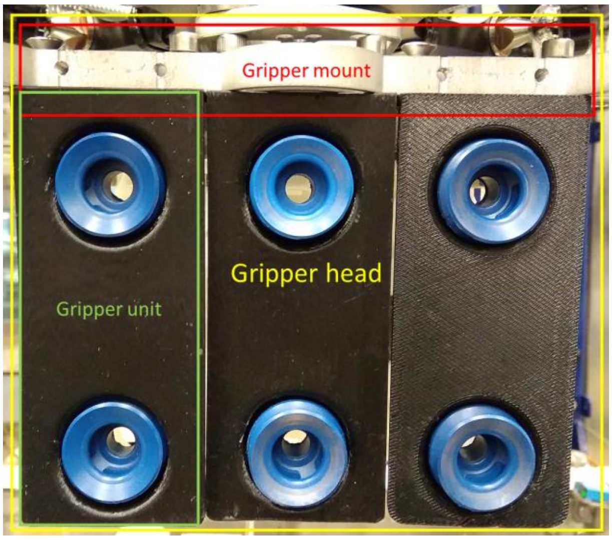


Figure 3: Gripper head

Figure 4: Picked group

The packages used in the robot rig are of type Tetra Brik Aseptic 200 Slim Leaf and are a standard 200ml Tetra Pak package. The dimensions are roughly 50x35x120mm. Straws are not attached to the packages used in the test rig (unless requested).

1.4.2 Robot software

The robot is programmed in a software called ACE (Automation Controlled Environment) [5] where you can design and simulate the movements of your robot. The software is developed and supported by Omron Industrial Automation and used to control their robots. It supports digital inputs and outputs to communicate with sensors and valves and other equipment collaborating with the robot. The robot can track the movement of the package groups and blanks via entry-signals from laser sensors and encoder signals synced to a common clock. The position of objects is simply the time difference from entry times the amount of and distance per encoder tick. There is no feedback regarding object positions.

The software allows for 8 digital outputs and 16 digital inputs as well as premade modules for Omron computer vision cameras and ethernet TCP/IP communication with other components such as PLCs and line controllers.

1.5 Project procedure

The project will be divided into three distinct parts:

1) Identifying the performance problems and their causes
2) Generating concepts for solving them
3) Testing and verifying the concepts.

When performing the last step of testing and verifying, the generated concepts (so far) will be run on the rig, software will be developed to support the testing, and the results will be documented. Tests will be run until either a) adequate results are achieved, or b) some design flaw is apparent and the concept will go back into the design phase (part 2). The entire process is a loop and concepts go back and forth between testing and design several times. This report will try to present the results in a chronological and efficient way that is easy to follow.

Due to the nature of this project there has been no need for severe benchmarking or a strict approach of concept design, such as the Ulrich and Eppinger "Product design and development"-procedure [6]. The thesis is based upon a need from the company, and as such much or all of the ground work for this specific need has already been made by different legal and development teams at the company. The need is to develop proof of concepts for solution to the performance problems, and that is what the thesis will focus on.

2. Identification of performance problems

The first phase of the project was to gather information about what problems could occur during the pattern creation process and where in the packaging line they would appear. The information was collected based on the experience of the people who worked with the rig previously and designed the original packing software. However, the gripper has since then been improved and some of the performance problems identified during this period have been (partly) corrected, see **Improved gripper** topic.

Table 1: Grouping problems

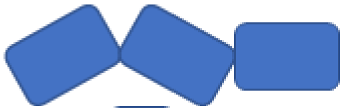
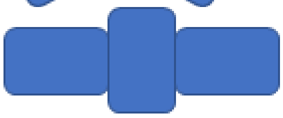
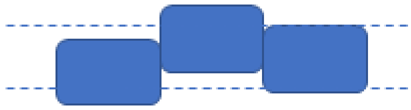
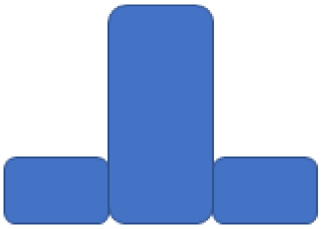
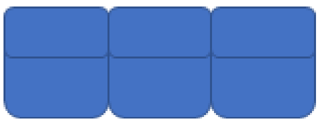
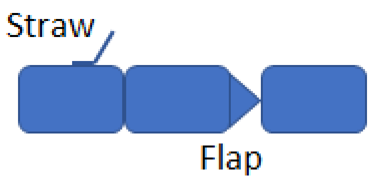
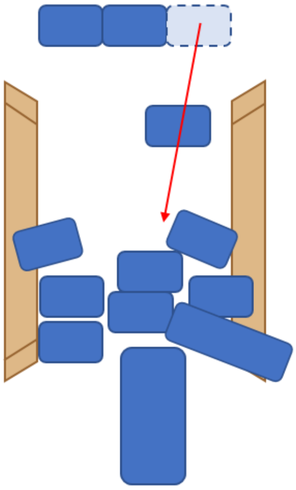
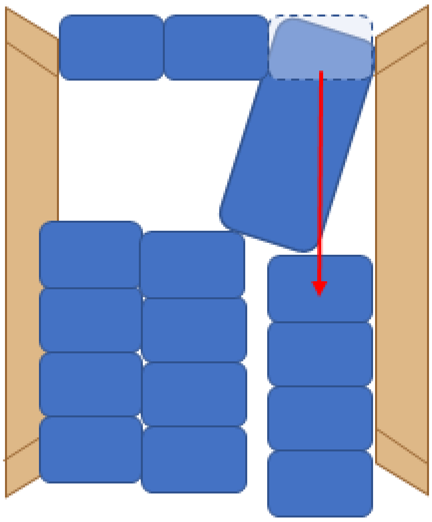
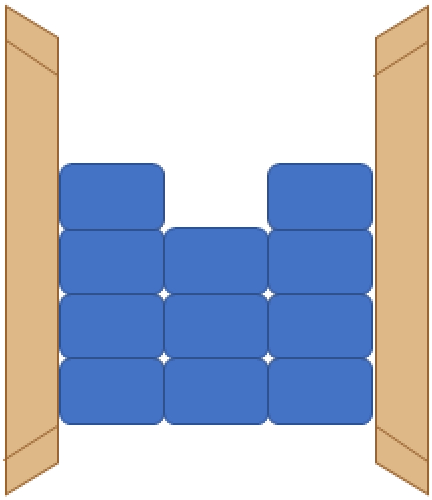
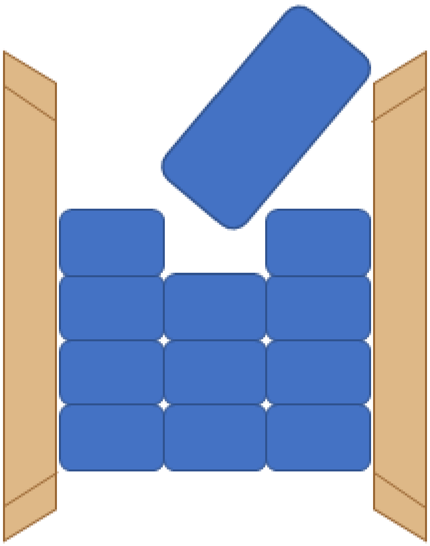
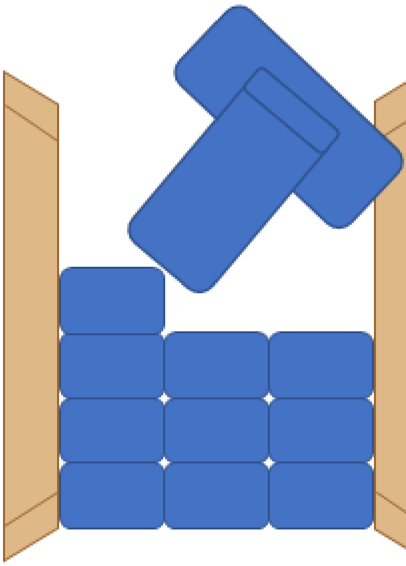
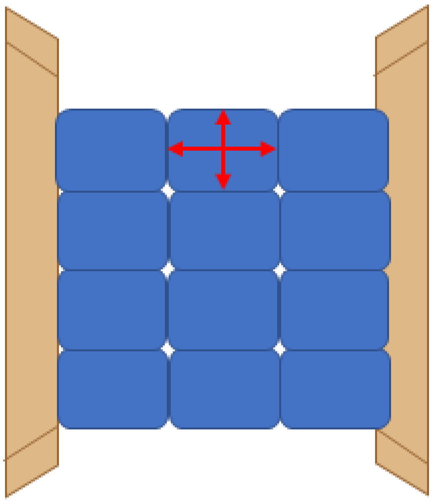
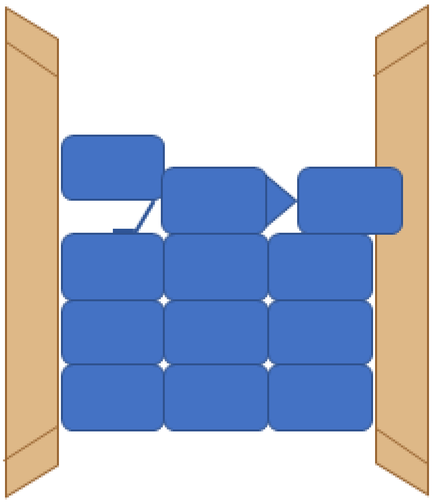
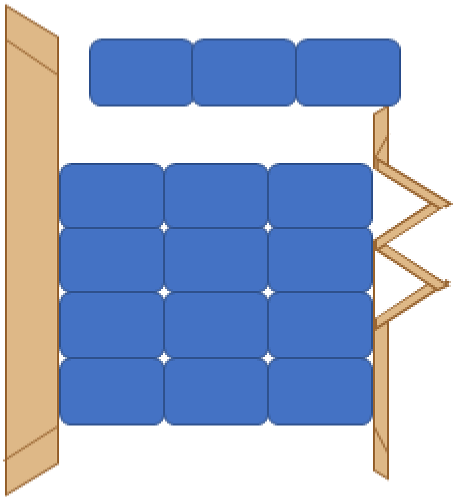
4 packages in a group	
Rotated packages: Slightly rotated packages (buckled group) Fully rotated package (90 degrees)	 
Group not straight	
Space between packages in a group	
Missing package	
Fallen package	
Other object/damaged package in group	
Package leaning	
Straw/flap/cap protruding	

Table 2: Patter creation problems

Bowling problem	
Pushing package into pattern	
Missing package in blank	

Fallen package in blank	
Fallen package in blank - special case: packages on top of each other or leaning on each other	
Packages too large	

Straw/cap/flap protruding from packages	
Gripper/packages colliding with blank side flap	

The problems were then broken down using the "5 why" method for finding the root cause of each problem and grouped together based on where the problem is most likely to occur. A few restrictions on the system were also identified:

- The package conveyor moves too fast to enable any kind of static interaction with the packages.
- The packing robots are too busy to do anything else other than packing when the line is running. If a robot is to perform any type of preventive or recovery action the line needs to be shut down. Operator intervention is estimated to take around 2 minutes, and thus this should be the maximum time required for an automatic recovery action.
- Due to the high speeds the robot tool head weight needs to be kept to a minimum. This means that adding permanent attachments to the tool head is not a favorable measure.

Shortly on the handling of conveyor belts and package flow: When handling packages on a conveyor belt without paddles or other section dividers to keep the spacing between packages, one should refrain from all types of static contact with the packages. In the current rig setup, there should preferably be no interaction at all between the railings and the packages after the grouping area, because every point of contact will mean friction between package and railing, which entails a big risk for interrupting the flow, especially in high speeds. If interacting with the package flow is required it is usually preferred to use dynamic contact like belts running at the same speed as the package flow, thus not presenting any fixed point for a package to stick to.

2.1 Root cause analysis

2.1.1 Grouping problems

4 packages in a group
This can happen when the belt brake does not give a sufficient space between two packages and the package grouping module thinks it is only one package, thus grouping it together with two other packages.

Group not straight, Rotated packages & Space between packages
These problems have very similar causes:

- The package might be released from the package flow control module with a slight rotation or slightly misaligned. The package might reorient back correctly during contact with the railings but be shifted to either side or create space to the next package.
- The package grouping module might rotate or push packages aside during grouping.
- Fallen or misplaced packages might affect other packages.
- The packages might shift during transport, either from contact with railings or a broken conveyor link. Packages can also be "dancing" on the conveyor belt, meaning they move around simply from vibrations in the conveyor.

Missing package
A missing package can be caused by the package falling on the conveyor after the grouping module, or from a failure in the grouping module.

Fallen package
Caused by the package falling on the conveyor after the grouping module due to packages moving on the conveyor.

Other object/broken package in group
Packages can have been damaged during any part of the packaging line. Other objects such as caps/straws or machine parts can appear among the packages for a multitude of reasons.

Leaning package
Package lean is created during the production of the packages. Slight package lean can be found on almost all packages and is inherent for the production machine and can depend on environmental parameters, material differences, glue inconsistencies, machine calibration etc. The leaning angle might change over time due to production parameters, and when it is too big it becomes a problem for the gripper to handle. Packages might also lean differently in the same group due to poor flatness in the bottom, usually due to the bottom flaps not being glued properly.

Straw/flap/cap protruding
Straws/flaps/caps protruding from the package is usually caused by poor manufacturing of the package, usually the glue is misplaced/missing or too weak causing the glued components to fall of/come loose. It can also be caused by mechanical interaction from the upstream modules.

2.1.2 Pattern creation problems

Bowling problem
This can be caused by the gripper not slowing down accordingly when delivering the packages, or from poor vacuum. Poor vacuum in turn can be caused by a malfunction of the gripper or any parts involved with generating the vacuum for the cups. It can also be caused by poor contact with the package, e.g. an uneven surface that the cup cannot conform to, or misaligned gripper where the cup is not centered on the package.

Pushing package into pattern
This soft version of the bowling problem has similar causes at lower speeds but could also be caused by a previous fallen package (or other object) in the pattern creation area getting pushed around by the gripper.

Missing package in blank
Usually caused by the gripper dropping a package on the way to the pattern creation area due to poor grip, either from faulty vacuum generation or poor alignment with group. A poor grip could also be caused by trying to grip an incorrect group.

Fallen package in blank & special case
A fallen package in the blank can either be caused from falling after being correctly delivered by the gripper, or simply by incorrect delivery. If it falls after correct delivery it usually means it has an unstable bottom, which is a manufacturing problem. It can also be caused by the liquid sloshing around in the package; when the packages are delivered the liquid is pushed to one end of the package, and the inertia of the liquid might cause the package to fall over.

Straw/cap/flap protruding from packages
As in the grouping problem this is usually caused during manufacturing or mechanical interaction by upstream modules, if the problem is not detected before picking. It could also be caused by the gripper after grouping, most likely due to the packages touching the blank sides and caps/straws/flaps are peeled of/opened.

Gripper head hitting blank sides
Could be caused by signal problems where the blank sensor gives the robot a faulty position of the blank. More commonly though the blank side flap fails to open to the specified angle, and thus there is less space in the blank for the gripper head to enter. When the gripper comes in at an angle, there might be a collision.

2.2 Previous concepts

There have been some previous attempts to prevent different performance problems before this project started and they will be shortly explained in this section.

2.2.1 Alignment guide(s)

Ordinary side-guides (standard metal railings) were previously installed on the conveyor in the grouping area. This resulted in straighter groups, but also increased frequency of line crashes due to packages sticking to the railing, causing package jam stopping the production flow and overflowing the conveyor. The railings were removed and instead a very low guide made from a slicker material close to the conveyor, guiding the bottom of the packages was installed. This resulted in a lowered amount of friction between the package and railing and the point of contact is lowered to very close to the bottom of the package, effectively decreasing the lever distance of the friction forces acting on the package sides, minimizing friction problems like twisting or toppling torque.

2.2.2 Blank/Pattern ejection

There is no concept for ejecting blanks or clearing patterns completely, but some lines have a vision system before the sealing station where the crates containing the pattern are sealed. If an error is detected the system will decide if it will cause a problem in the machine or not. If there is a probability that the sealing operation will fail, the machine is stopped completely, and an operator will have to come and remove the blank. If the system does not think there will be a sealing error, but the pattern is incorrect, the crate will be sealed and put aside in the outfeed for an operator to manually repack/get rid of.

2.2.3 Improved gripper

The gripper has been improved to tackle some of the performance problems in the grouping area, such as leaning packages and slightly rotated packages. A more robust way of approaching, connecting to and delivering the packages have been developed and is currently being patented by the Company.

3. Concept generation

Due to a lack of test data for the system it was not possible to statistically rank problems with regard to frequency or severity and thus determine what performance problems are the most important ones to solve. Together with the engineers responsible for the robot and test rig it was instead decided to start looking at a simplified case of the pattern creation problem, taking into consideration only the packages from the most recently delivered group that fails to conform to the pattern without disturbing the previous pattern, not including packages falling on top of each other. This would mainly take care of fallen packages in blank and missing package in blank. Some consideration will also be put into preventive actions regarding the leaning packages problem and the previously developed alignment guide.

The pattern creation problem is considered a major risk for line crash and the line will have to be stopped in order to recover from this problem before a crash occurs. There is plenty of time to change tool head.

3.1 Tilted gripper

The gripper can pick up packages leaning slightly. It is dependent on how ductile the suction cups are. If it's very ductile and conforms to the angled surface well without pushing the package off the conveyor the gripping will succeed. Testing will have to be performed in order to find the maximum angle α_{max}, see Figure 5, that the gripper can handle.

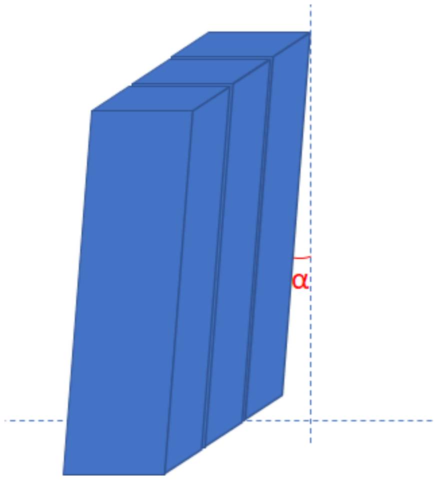


Figure 5: Leaning packages

The idea is to tilt the gripper head to have a slight lean in the same direction as the packages making the difference in angle smaller. Tilting the gripper head will allow for up to twice as large acceptable package lean due to straight packages leaning $\pm\alpha_{max}$ degrees in relation to the gripper, from no lean (-) to heavy lean (+) according to Figure 6.

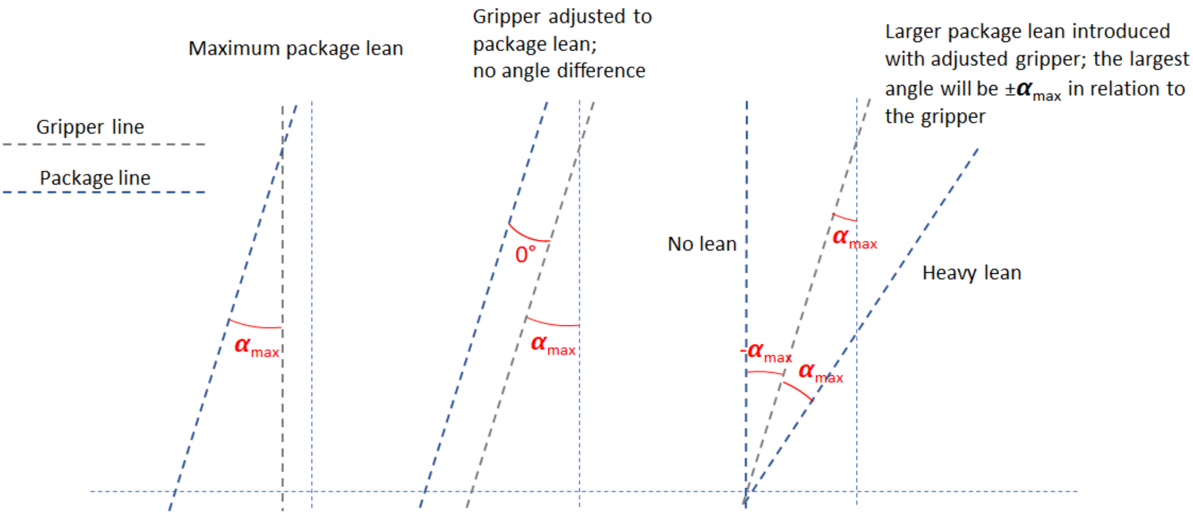


Figure 6: Angle visualization

Here it is assumed that the packages will always lean to the same side being caused mainly by manufacturing parameters.

3.2 Alignment guide

The package alignment guide has shown promising results but has not been thoroughly tested or calibrated. The guide is made from a long slab of plastic in order to keep the friction as low as possible.

Two design parameters to keep in mind when designing a package guide is how long the guide should be and how tight to fit the guide to the packages. The guide should be long enough to support the packages to reduce leaning and misalignment and prevent rotation of packages during the entire group creation process, but not too long so that it disturbs the packages after being released from the grouping mechanism. Areas where the package is propelled forward by other means than friction from the conveyor are suitable for alignment guides.

Some space between the guide and the railing is required for the packages to go through, and the more space there is the fewer friction problems there will be. However, more space gives larger room for misalignment and for rotated packages.

The test results from the tilted gripper concept below will help to determine how many degrees of rotation is acceptable for the packages (the suction cups are circular and will conform equally well to vertical and horizontal angle) on the conveyor. The maximum rotation angle can be used to help decide how wide to put the alignment guide, see Figure 7 below:

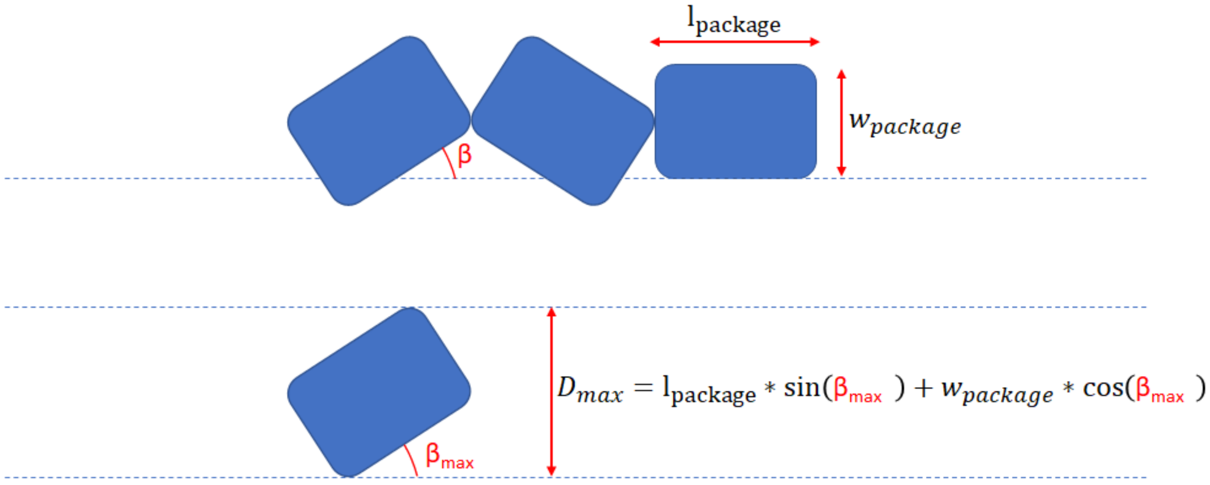


Figure 7: Alignment guide width calculations

Another concept for solving this problem is to have a belt on either side of the conveyor that aligns the group after the grouping module, much like a railing, but without the static friction problem. Ostensibly, this is a belt driven guide that does not slow the packages down, only follows them. However, this could cause new problems such as different detach times from either side belt, which can cause package rotation. It might also add space between the packages or create any of the other listed grouping problems and therefore is not a viable solution.

3.3 Pattern recovery

For this problem the package(s) must first be identified and located, then removed from the blank and put into a return-feed trough. After removing the fallen package there are essentially two options, either

1) remove the remaining packages from the faulty group from the blank, or
2) add package(s) to complete the group.

Alternative 2 would be preferable since it would not mean having to return packages that are already placed correctly in the blank, however alternative 1 is by far the simpler alternative since it does not involve picking a single package from a buffer of packages outside the line. A buffer would be required because the replacement package can't be taken from the groups on the conveyor since this would destroy the next group, ultimately returning the same number of correct packages as alternative 1. Picking and inserting the replacement package in the correct slot adds extra complexity compared to just picking and inserting a new group. The fact that rotation is disabled also creates trouble since the reservoir can't be behind the robot, it needs to be accessible from the front.

In order to pick up the fallen package a different tool head needs to be used. The main gripper head can only grip vertical surfaces due to the limited degrees of freedom of the delta robot. There is a possibility to pick up a fallen package from the side, but because the rotational axis of the robot end effector has been restrained it would be impossible to align with the fallen package. There would also be problems fitting the rotated gripper head inside the blank without disturbing the blank sides or the pattern, since the gripper head itself is as wide as the blank and the pattern. Picking the package from above appears to be the most viable alternative.

In order to keep things as simple as possible the new tool head will be pneumatic just like the current one. This simplifies the connections when switching tool head and reduces the number of components (and thus the weight) required on the "plate" of the robot. A simple design with a single suction cup oriented downwards will be tested for this purpose. A tool head with clamp grippers could also be designed, but if vacuum works then that is preferable due to the lower complexity and risk of damaging the package. One cup would be enough because the picked package does not need to be aligned in any specific direction when delivered to the return trough. This solution would be limited to only picking horizontal surfaces, with respect to the conforming angle of the suction cup. Highly ductile cups are available in the market giving large flexibility of picking angles. Some consideration has to be taken to picking packages on the side where the straw is attached since you should not pick on the straw (due to poor vacuum and/or straw falling off), only the package side. Contact needs to be made in either corner of the package, but this should be detectable by the vision system.

To lower the complexity of tool change the picking tool has been designed as an attachment to the current gripper head rather than an entirely new tool head, see Figure 8. The picking attachment can be easily gripped by the four outer suction cups of the main gripper head and the middle cups will provide the vacuum for the attachment's single cup. The attachment will be mounted inside the robot cell where the robot can reach it easily while not restricting the robot's movements.

Figure 8: Picking attachment

Package detection will be done using a machine vision system to be installed in the rig. Some concern has been raised about the computational speed of the vision system, meaning that it might not be able to detect problems with the pattern quick enough to stop the gripper from delivering the next group. If this is the case, a vacuum sensor can be added to each of the three vacuum channels on the gripper head. The sensor output can be compared to one of a correct pick-up and will detect if there are irregularities to the vacuum signal. If there are irregularities it would indicate that a package might have been dropped or released to early, giving reason to slow down the packing and give the vision system enough time to analyze the pattern creation area. Hopefully this will not be necessary since it will add weight to the gripper head.

3.3.1 Design iterations

The attachment was tested inside the rig and has been shown to work, however some packages are squished due to incorrect z-coordinates and the fact that the attachment has a rigid trunk. To counter this problem a spring-loaded trunk, see Figure 9, will be implemented. A ready-made component (the 'spring cylinder') has been identified and consists of a longer inner pipe and a shorter outer metal cylinder with a spring integrated inbetween the two. The outer cylinder will be attached to the attachment, allowing the inner part to move freely (within its physical constraints). When picking packages in the blank area only packages in the middle of the blank could be reached due to the trunk being too short. The spring cylinder will be connected to the air supply via an 8mm air hose from the connector on the white part, instead of being directly connected to the air

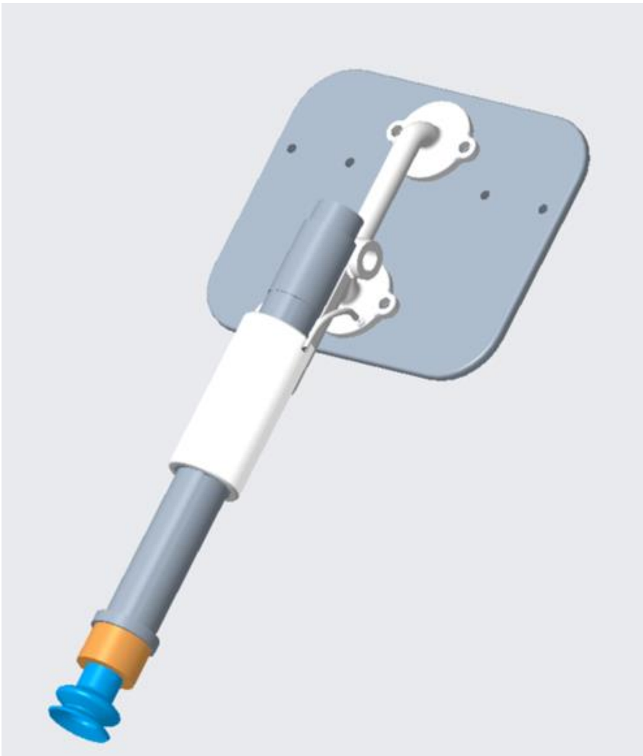


Figure 9: Picking attachment with spring-loaded cylinder

flow from the gripper head suction cups. The suction cup was changed to a 2.5 bellow one, enabling the attachment to pick packages at a larger angle.

Due to robot workspace limitations the elongated trunk had to be shortened slightly, making sure it fits the workspace criteria but is still long enough to reach packages in the sides of the blank. The air hose connecting the spring cylinder with the connector on the white component was replaced with a chamber that encloses the end effector of the spring cylinder. The chamber is connected with the air supply via a channel incorporated in the component. The new version can be seen in Figure 10 and a closeup on the white part in Figure 11. One concern with this design is that the spring cylinder bearings would not be airtight and vacuum would be lost, and in that case a shortened version of the hose design would have to be used.

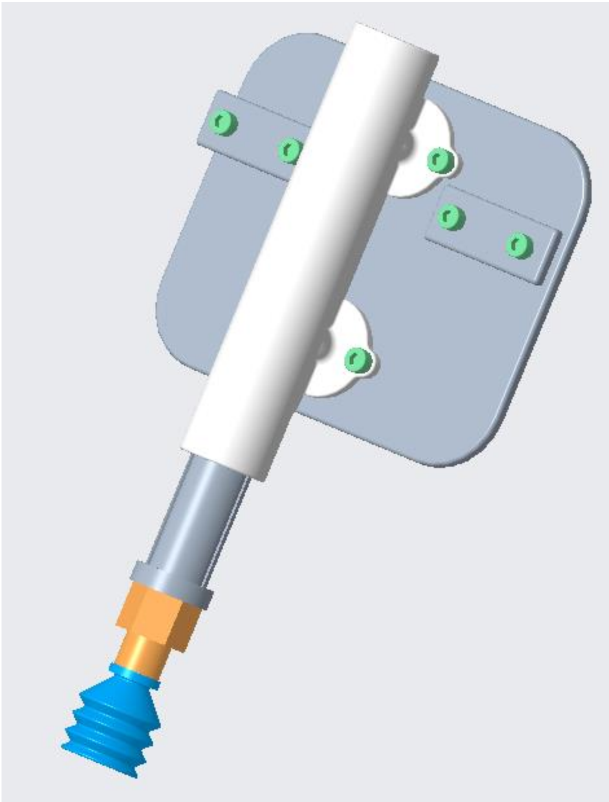


Figure 10: Air chamber and 2.5 bellow cup

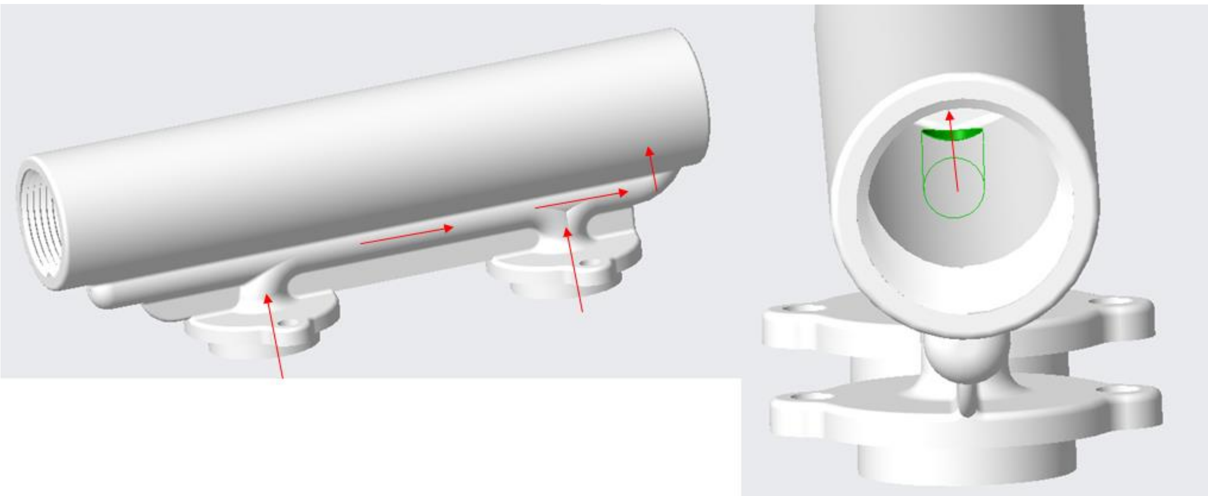


Figure 11: Air chamber close-up

3.3.2 Holder and attachment plate design

The first holder design was made from three layers of plate aluminum to keep the design modular and simple, see Figure 12.

Semi-circles were added to the attachment plate to be able to align it with the V-shaped guides in the holder, making sure it is always fixed X-direction (coordinate system in the bottom left of the picture). Two L-shaped plates (only the right one shows in the figure for display purposes, one more is mirrored on the left side) will keep the attachment fixated in the Y-direction. The attachment will be picked up in the Z-direction which is the only available degree of freedom.

Of course no design is ever flawless, and this was no exception. To allow for the attachment to be gripped while still providing Y-direction alignment the attachment plate had to be made wider than the gripper head itself. This increases weight and will increase the risk of collisions. Another problem is the V-shapes that might accumulate dust or liquids during production.

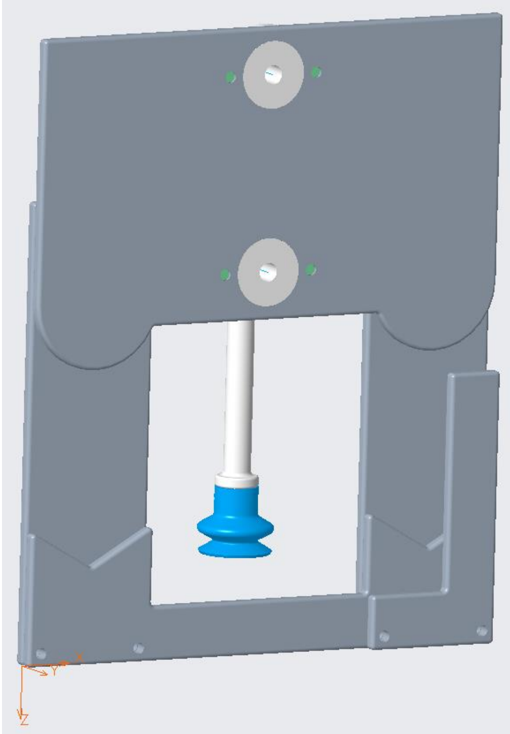


Figure 12: Attachment holder

To fix these problems the design was inverted, see Figure 13: the V-shapes were turned upside-down (and eventually replaced with bars) and the holder was transformed to more of a "hanger". The attachment will be hung on the holder while still utilizing the X- and Y-direction alignment concepts from the previous design. The hanging mechanism will be placed on the opposite side of the attachment plate compared to the last design to not disturb the gripping.

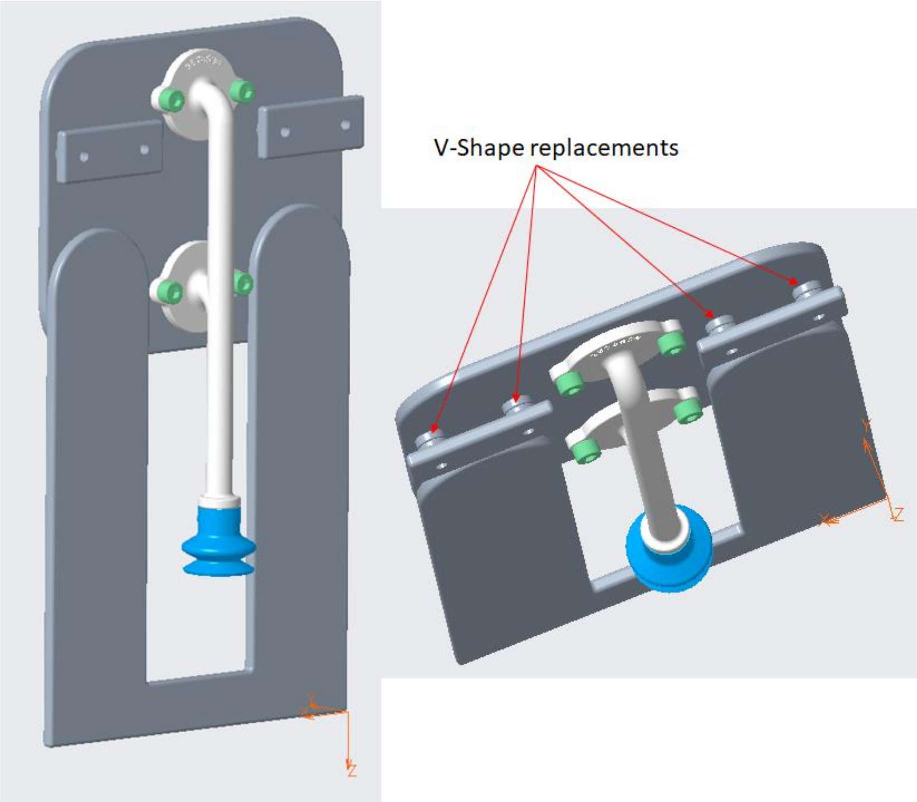


Figure 13: Holder with inverted design

3.3.3 Holder placement

In order to keep the attachment available for the robot with very short notice, but not allow it to interfere with the robot's movements, it was decided to make a dynamic holder for the tool attachment. A static holder would limit the space where the robot can move and increase the risk of collision.

The dynamic holder can be designed in several ways, for example with a simple linear cylinder from the bottom, an arm on a door hinge from the side, or like a draw bridge coming down from above. Either option is viable and have their pros and cons. However, this is only a proof of concept and only has to work in the test rig. Taking this into consideration, the design choice of a linear pneumatic cylinder from below seems like the simplest concept, mainly because it involves very few parts and presents no need to fasten the dynamic holder to the robot cell chassis. There are some problems with presenting the attachment from below; mainly that packages could fall down on the attachment during unsupervised production and present problems when picking up the attachment, but since this is only a proof of concept for the supervised test rig it is not considered to be a problem.

The holder plate has been redesigned to be attachable to a piston, see Figure 14 (left side). The piston will be moving in the Z-direction with the attachment, see Figure 14 (right side).

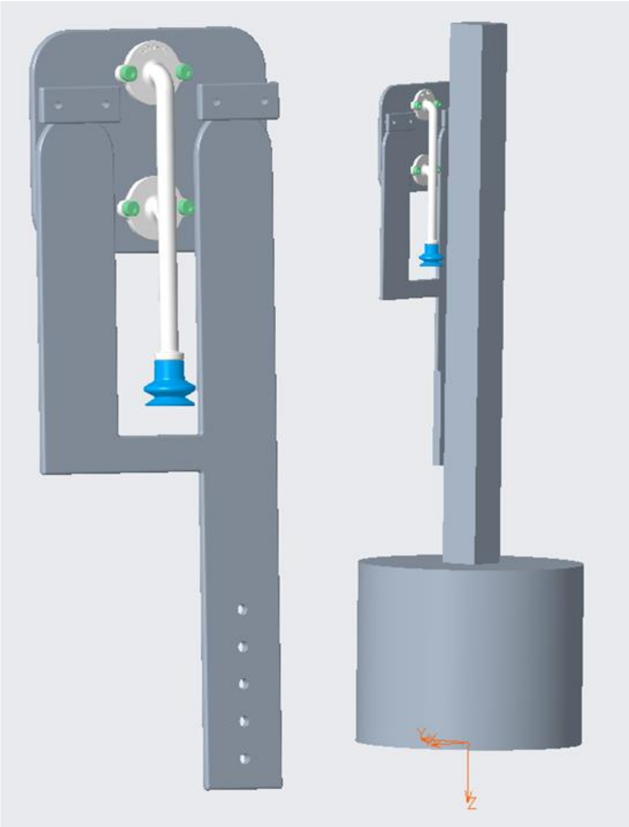


Figure 14: Holder mounted on piston

3.3.4 Application to the future solution

The final version of the packaging equipment will be more compact than the test rig and will include way more features. Therefore the holder placement has to be considered. Not all areas of the cylindric robot working space are used by the robot motion during the normal packing cycle, thus they would make good areas to place the attachment holder.

An option to fastening the holder in the robot cell floor and resenting the attachments from underneath is to place it placed in level with the tool head in a periphery part of the robot workspace, presenting the attachment from the side. The holder could be fastened in the robot cell frame which would minimize the risk of packages falling on the attachments, however there might be problems with fitting a piston with a stroke of at least 150-200 mm horizontally in the robot cell. For this reason it might be simpler with a drawbridge design shown in Figure 15 where you don't occupy as much horizontal space in the cell.

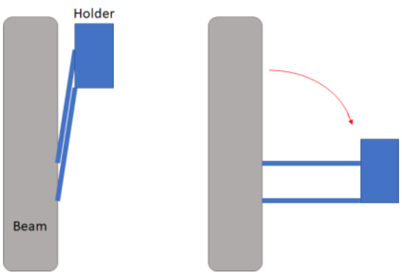


Figure 15: Drawbridge concept

3.4 Blank ejection/Pattern clearing

For cases where the pattern have been destroyed to a point where it is no longer viable or even possible to recover it with the single pick and place method there needs to be a way to eject or clear the blank before it reaches the sealing station where the crate is sealed, so that the sealing station will not shut down and have to call an operator.

A few different ways of approaching this will be examined, and each concept consists of two parts: clearing the pattern and ejecting the blank.

- **Internal ejection**: The robot will handle both pattern clearing and blank ejection. Does not increase line footprint but will require complex concepts for the robot.
- **External ejection**: Let the entire "unrecoverable" pattern go through the robot cells and be ejected externally. This would require an external machine between the sealing station and the robot cells and would therefore increase the total footprint of the production line. Designing any external machines are out of scope for this thesis project.
- **Semi-external ejection**: The robot will clear the pattern and only let the empty blank pass through the robot cells, letting an external station handle the ejection of blanks. This would make both the robot's and the external ejector's job easier and less complex but would still increase the footprint of the production line.

Something to take into consideration when designing the concepts are where to put the ejected material. Packages and blanks when ejected inside the robot cell needs to be transferred out of the cell. The drop area where the recovery action drops packages is not available since the packages are already deemed too many/damaged for single pick operation.

3.4.1 Internal pattern clearing

The simplest way to clear all the packages would be to simply push them off the end of the blank like a bulldozer. In the current rig that is not possible due to the way the blanks are fastened to the conveyor, see Figure 16.

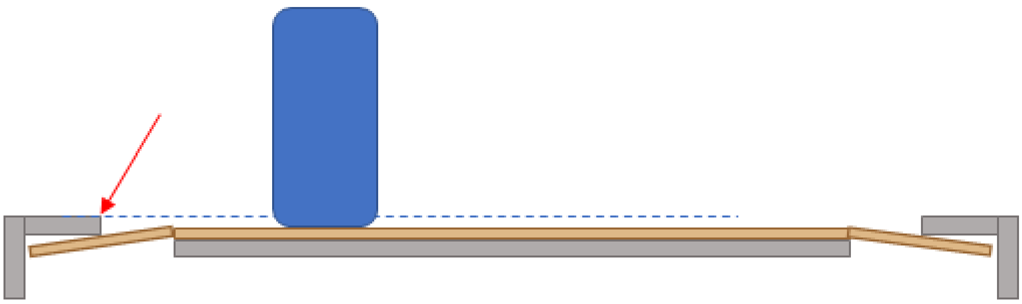


Figure 16: Blank conveyor railings

When pushing the packages of the edge they will get stuck on the small threshold created by the conveyor railing (in grey, Figure 17). One solution could be to make the conveyor level (right) or wedge shaped (left) as in Figure 17.

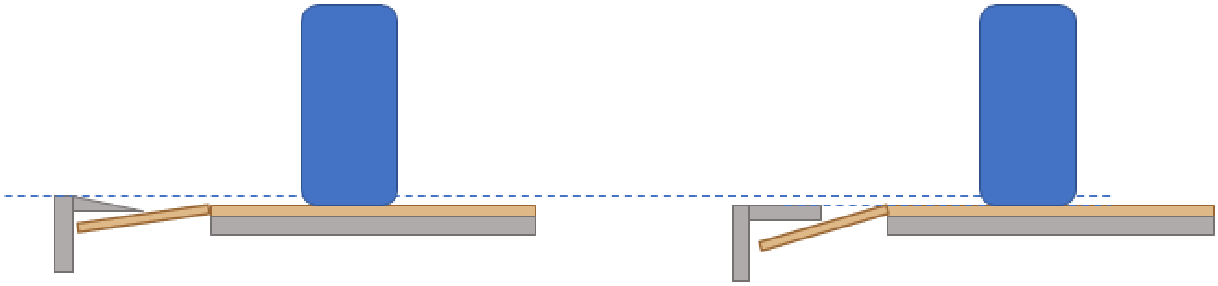


Figure 17: Blank conveyor railing design modifications wedge (left) and lowered (right)

The pattern cannot be pushed off the blank at every blank position due to the robot workspace, see Figure 18.

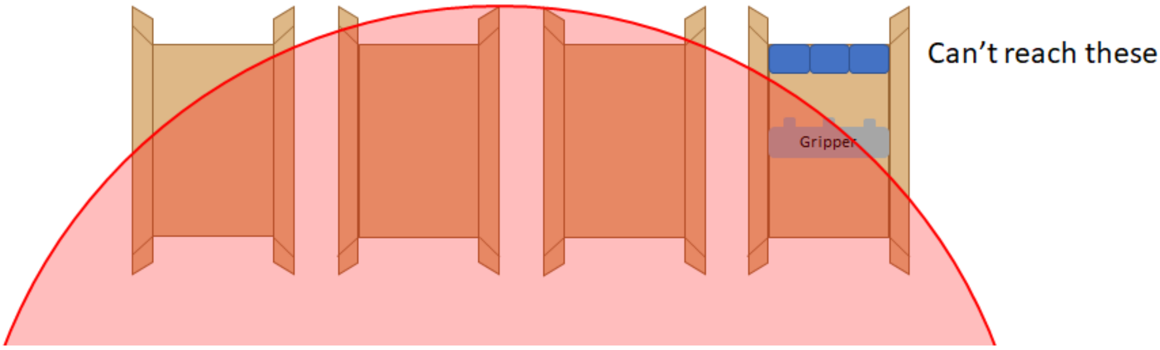


Figure 18: Robot workspace

To solve this a shovel-like attachment will be designed that simply extends the grippers reach, see Figure 19.

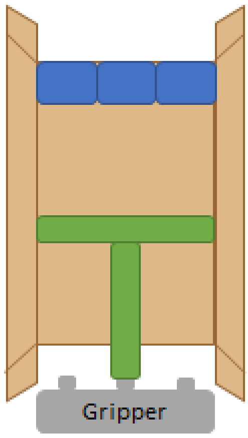


Figure 19: Push attachment concept

Due to the limited workspace the shovel cannot be as long as the blank, and therefore it might still not be able to clear the blank regardless of blank position. Measuring distances in the robot cell shows that the push attachment cannot be too long, or it would not fit between the package conveyor and the first group of packages in the blank. Calculating how far the blank can be allowed to travel is shown in Figure 20 where x is the attachment's length, b is the blank conveyor rail width, L is the blank length, R is the robot workspace radius, c is the distance between the workspace center-point and the blank and y is the furthest coordinate the blank can be allowed to travel before the last row is out of reach. $y = \sqrt{R^2 - (c + L + b - x)^2}$. This means that if a problem occurs when placing a group beyond this distance, the robot will not be able to clear the pattern. The next robot in the line could potentially clear that pattern, but it would not work for the last robot in the line. Some limitations on how far the blank is allowed to travel during pattern creation could be implemented to make sure no pattern is built outside the recovery reach.

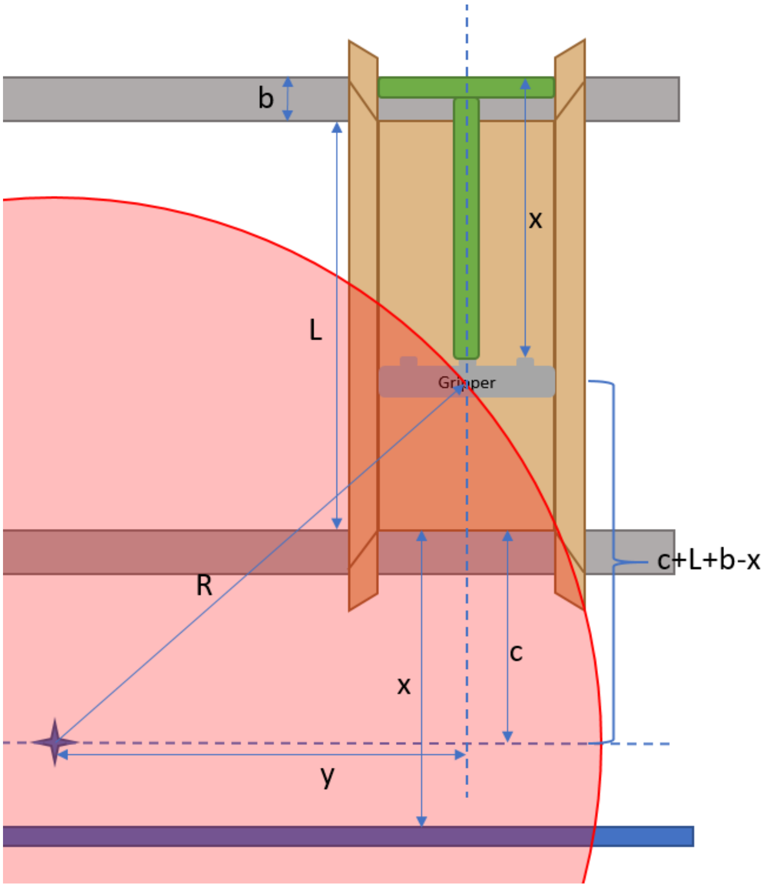


Figure 20: Robot reach calculations

3.4.1.1 Push attachment design

The push attachment has been designed in a similar fashion as the picking attachment with a 5 mm aluminum water cut plate for the gripper head to connect to. Three struts are connected to the plate, and another water cut plate is mounted in the end. As much material as possible has been cut away from the end plate in order to reduce weight. The attachment assembly can be seen in Figure 21.

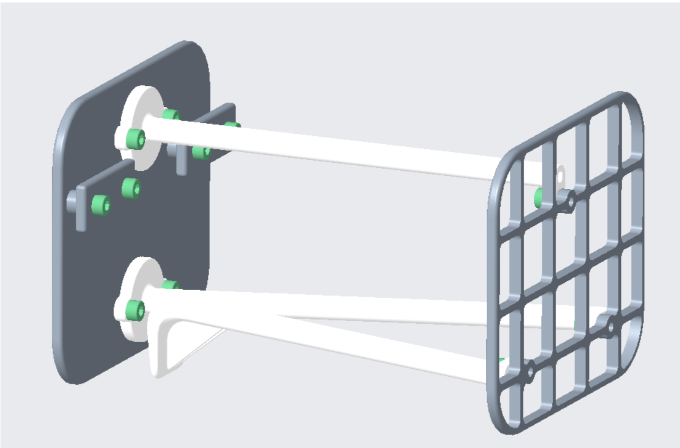


Figure 21: Push attachment assembly

3.4.1.2 Holder design

The push attachment will be kept on the same holder as the picking attachment, and therefore the design needs to be changed slightly. The same alignment principles will still be used, but the holder plate will be doubled to fit the second attachment, see Figure 22, where the right side is the original holder, and the left side is the extension for the push attachment.

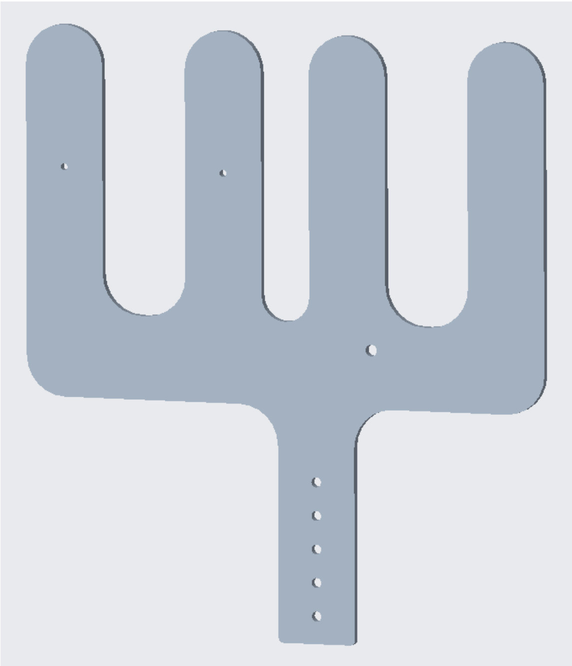


Figure 22: Holder plate

Some alterations had to be made to the push attachment design in order for it remain horizontal on the holder. Due to the pivot point of the attachment being so close to the back plate it would simply fall down into a non-horizontal position where the gripper cannot pick it up, see Figure 23. To counter this, an extra support plate was attached to the holder and a brace plate to the lower strut of the attachment.

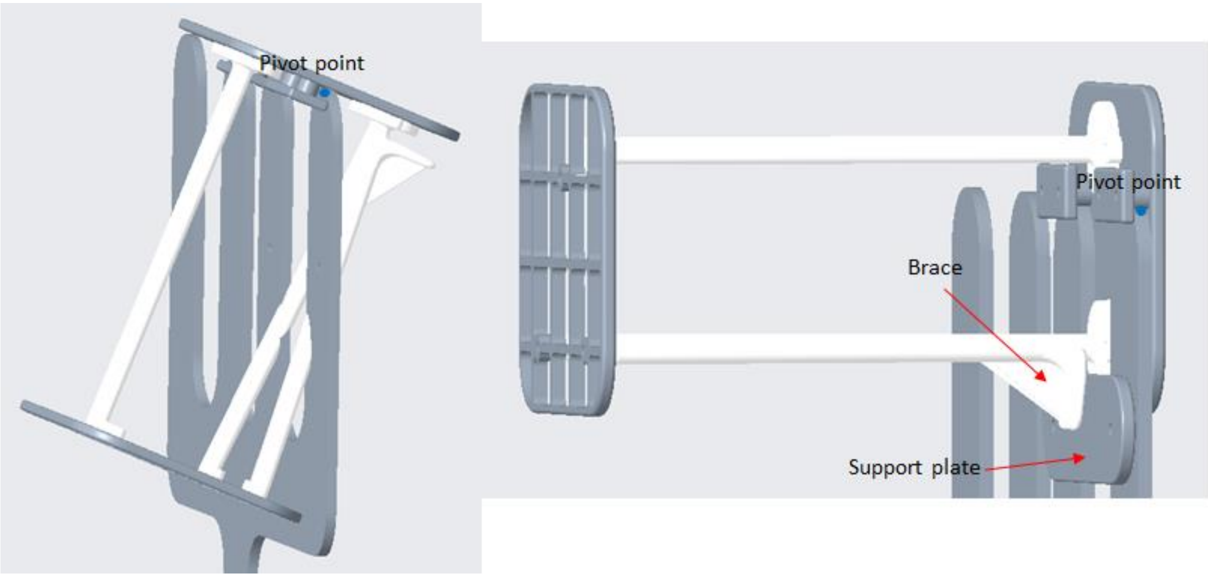


Figure 23: Push attachment with brace and support plate

3.4.1.3 Holder placement

There are not a lot of positions available for picking up the push attachment due to its size and the fact that it has to be picked from behind since the tool head cannot rotate. Presenting it from above is not possible due to the robot arms being in the way. This more or less only leaves presenting from below at the position shown in Figure 24 below.

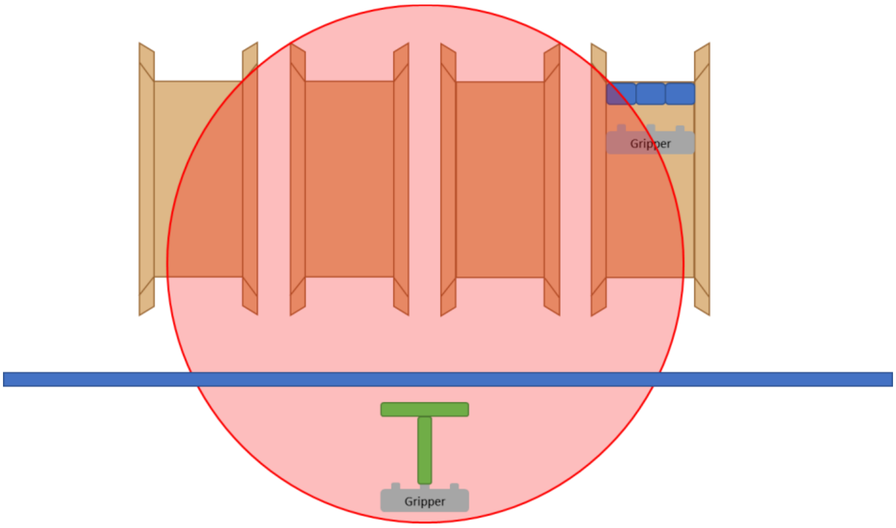


Figure 24: Holder position

3.4.2 Internal blank ejection

Empty blanks can be easily removed from the conveyor using a large (or a set of) suction cup(s), but the real problem appears when the blank is damaged. Damage can occur during the process of clearing the pattern, it can be hit by the gripper, or it can be contaminated by product from leaking/broken packages. In these cases, the blank will need to be removed and cannot be reused. The blank can be in any condition after being damaged, and it is not sure that a suction cup or a custom gripping/clamping tool can attach to the blank properly. Some type of ejection system that does not depend on the condition of the blank will be required, e.g. bursts of pressurized air or a large spatula-looking tool.

3.4.3 Application to the future solution

There are some different possibilities when it comes to implementing this concept, since the final production line could contain several robot cells in concession. In the case of several robots one idea could be to let the last robot handle all of the ejection, which would only require one set of attachments and one ejection point. Another idea would be to let every robot handle its own ejection. This would of course mean more equipment duplicates and ejection points but might increase overall capacity of the packaging line. While the problematic blank travels to the last robot cell the robot would have to wait for a new blank regardless; the blank feed rate is such that another blank will not arrive in the robot cell until the first blank is “full”. The blank will then have travelled almost the entire length of the robot workspace. If however there is a problem early in the pattern creation, and the blank has to be cleared, the robot would still have to wait for the blank to travel the entire workspace before a new blank is presented. For this reason, it might be preferable to allow each robot to clear patterns.

Drop point(s) could be designed like a simple trough leading to a conveyor or storage where an operator would have to go through the packages manually. Preferably a similar trough connected to the same conveyor will be used for the recovery drop point. One could also cover the entire robot cell floor with a return conveyor, which would also feed out packages that fall off the package conveyor.

4. Proof of concept

4.1 Tilted gripper

External design improvements made to the gripper head during the course of the project made the gripper able to handle grouping problems with leaning packages. The improvements to the gripper head made the tilted gripper concept unnecessary and it was never tested.

4.2 Alignment guide

This concept is already known to the company and is used as a general method for preventing grouping problems in package flow, whereas the aim for this thesis project is to develop new strategies for recovery and determine what is possible and viable, and what is not, using the new robotic solution. It was therefore decided to not do any further testing on the alignment guide concept.

4.3 Pattern recovery

The final picking attachment held by the gripper can be seen in Figure 25. In line with the company's chosen design strategy, all the white components are 3D-printed from a nylon-based plastic that is very durable. The metals parts have been water cut and sanded down.

Figure 25: Picking attachment, attached

The piston and holder extended, retracted and with the attachments can be seen in Figure 26. The holder has been fitted with throttle valves to smoothen the end motion.

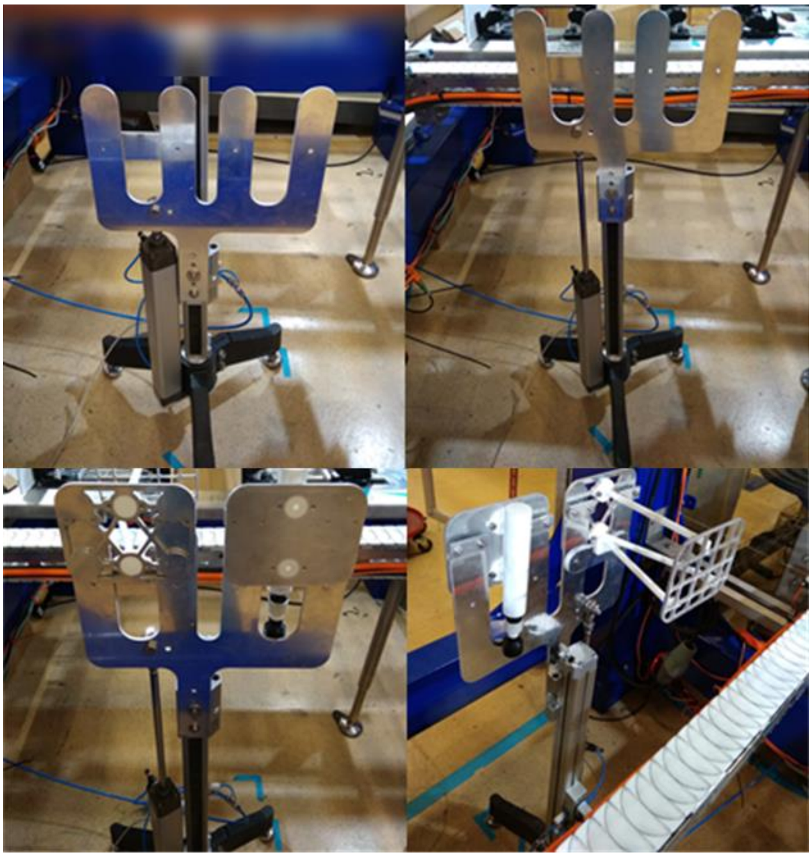


Figure 26: Holder retracted (upper left) & extended (upper right), with attachments back (lower left) & front (lower right)

4.3.1 The pick-and-place program

A program for the recovery action was created and incorporated in the current pick-and-place program. The “fallen package” will be placed in a known location in the robot cell since there will be no coordinates received from a vision system. When the recovery-signal is activated, the robot will finish its placing sequence and go to the attachment pickup location (1) in Figure 27, attach (2), move to the package location at safe height (3), pick the package (4), exit the blank to the safe yellow transfer area (see Figure 28) at safe height (5) and finally drop the package at the drop position (6).

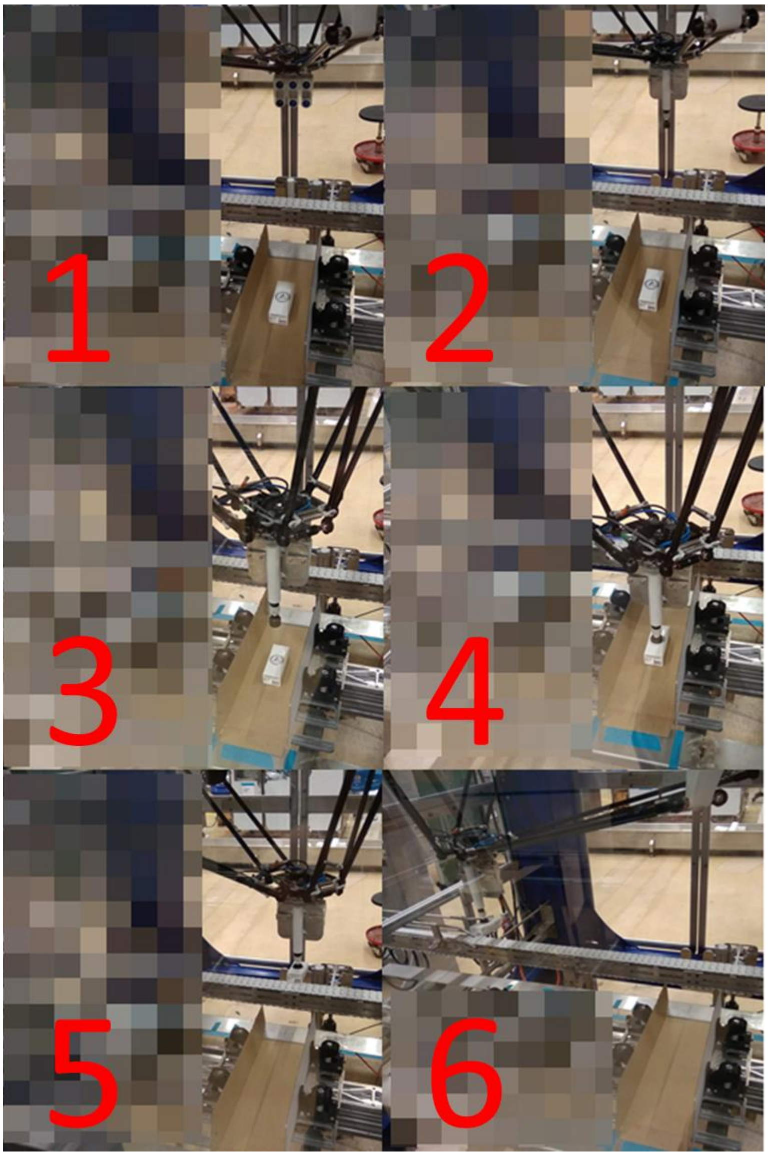


Figure 27: Pick and place sequence

The pick-and-place program is designed so that the robot will always move around the rig at a safe height, and then move straight down at the desired positions. In order to minimize the risk of collision, a safe “transfer area” (yellow area) in the robot cell was identified, see Figure 28.

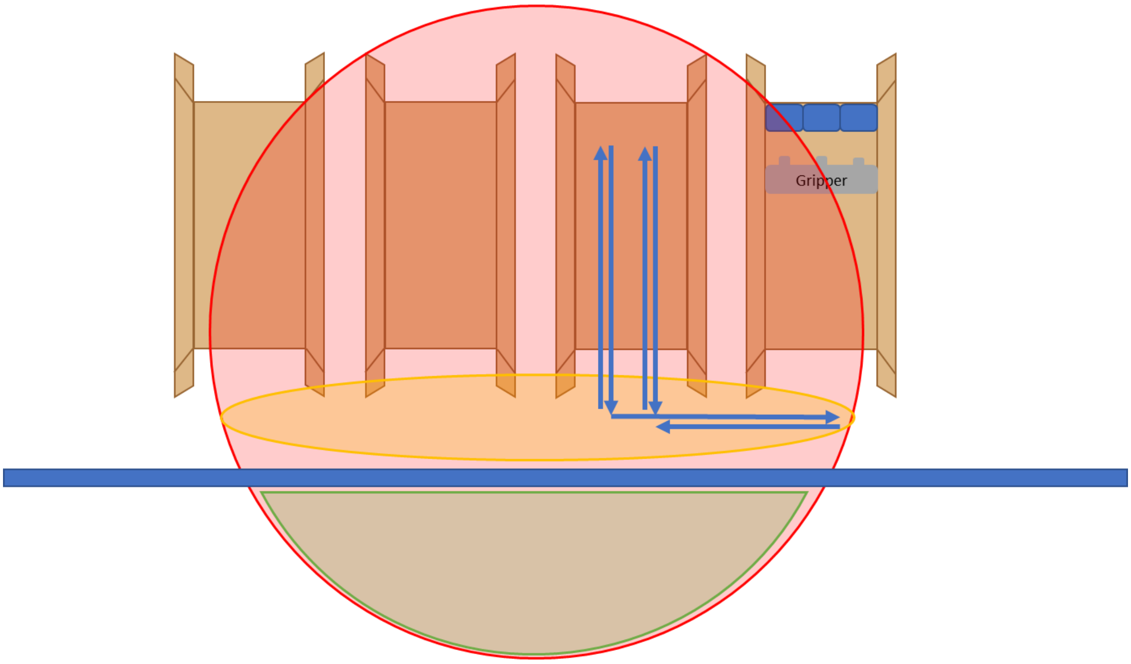


Figure 28: Robot safe transfer area (yellow)

In this area there will never be any packages or equipment, because it is where the robot usually moves around when packing. The same area can be used for moving around safely when recovering. The recovery motion is very similar to the packing motion; moving along the conveyor to the desired y-coordinate, then entering and leaving the blank from the front, shown by the blue arrows in Figure 28. The drop of location for the demonstration was put in the far right end of the yellow area where it is less likely to cause any problems. This does increase the distance that the robot has to travel and therefore the time consumed, but for the sake of proving the concept it does not matter greatly.

4.3.2 Robustness

For this concept to be viable it needs to be able to connect to surfaces that are not perfectly horizontal. To test the capacity for picking angled surfaces packages were placed in different angles, shown in Figure 29. Simple software for picking (moving straight down onto the package surface) and dropping each package was written and the test was performed until a high repeatability without errors was achieved.

Figure 29: Angle test setup

The suction cup showed great conformability and could grip even the steep 55-degree surface, shown in Figure 30. No larger angles than 55 degrees were tried because of the package's 90-degree corners; if one side is angled at x=55 degrees, that will result in the another edge angled 90-55=35 degrees, see Figure 31. Given this argument there is no need to test angles greater than 45 degrees, but because of the difficulties with picking the top of the package (as explained in the following paragraphs) it was increased slightly.

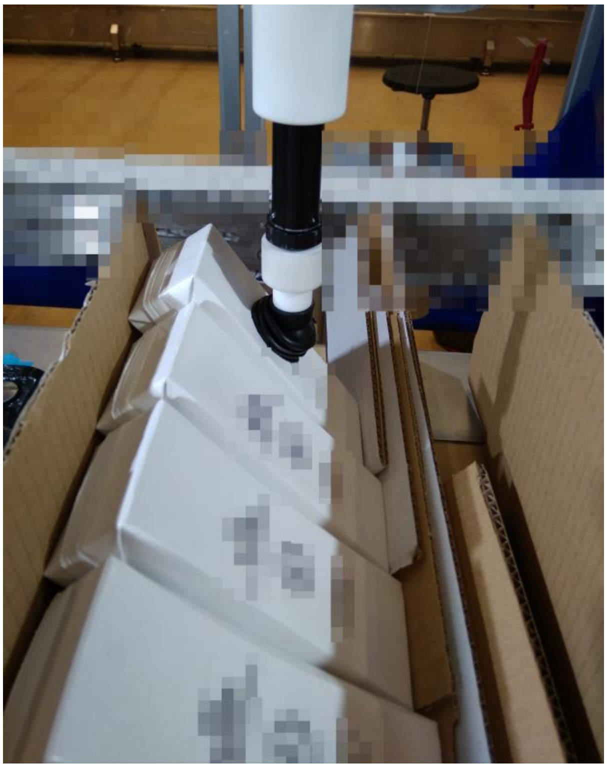


Figure 30: Suction cup conformity 55 degrees

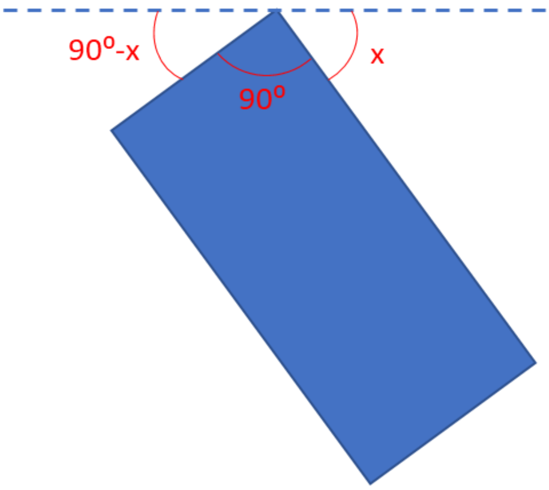


Figure 31: Angular test, angle calculation

Picking standing packages is proving more difficult than toppled ones due to the large seam that runs across the top surface, see Figure 32 (left). The leakage is too large to establish enough vacuum for gripping over the seam; thus, the cup has to grip next to the seam where there is barely enough surface area, shown in Figure 32 (right). The green circle represents the inner diameter of the suction cup, which has to be inside the red borders to achieve vacuum.

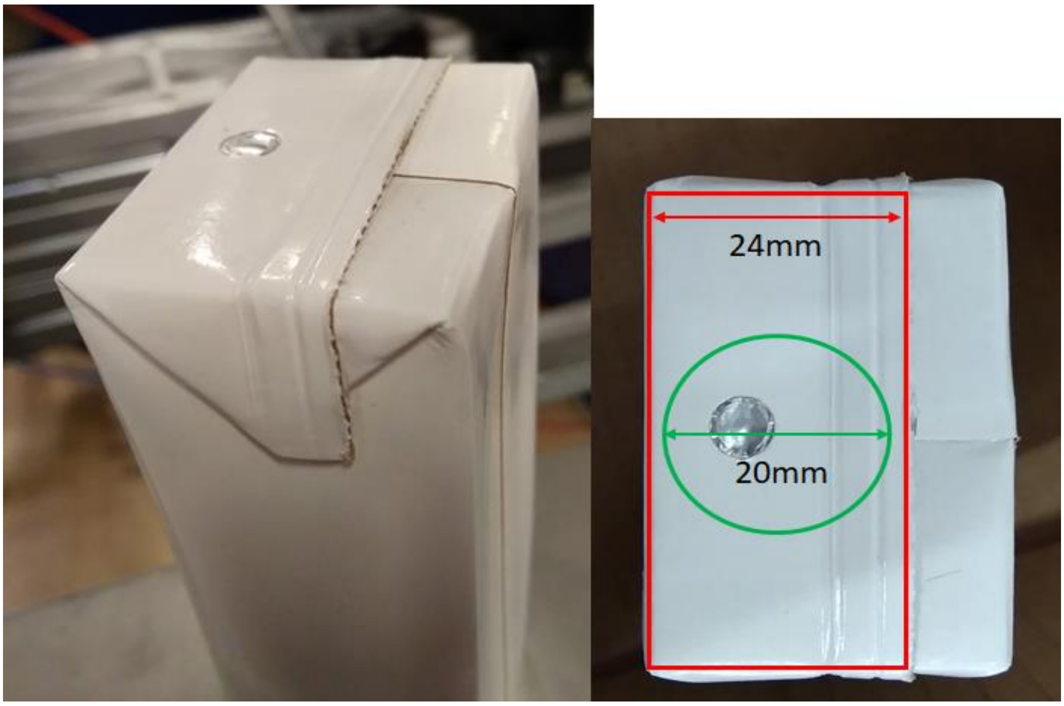


Figure 32: Package top

Following the same logic, a package can’t be picked up via the bottom surface using the current 20mm diameter suction cup due to the several seams, see Figure 33.

Figure 33: Package bottom

Solutions to this problem could be using a smaller diameter vacuum cup and moving slower with the packages and giving the cup sufficient time to establish vacuum when picking the packages. Another concept developed after this test was to topple the standing packages with the picking attachment and then pick them on the side instead. The procedure for this toppling-test is shown in Figure 34 below.

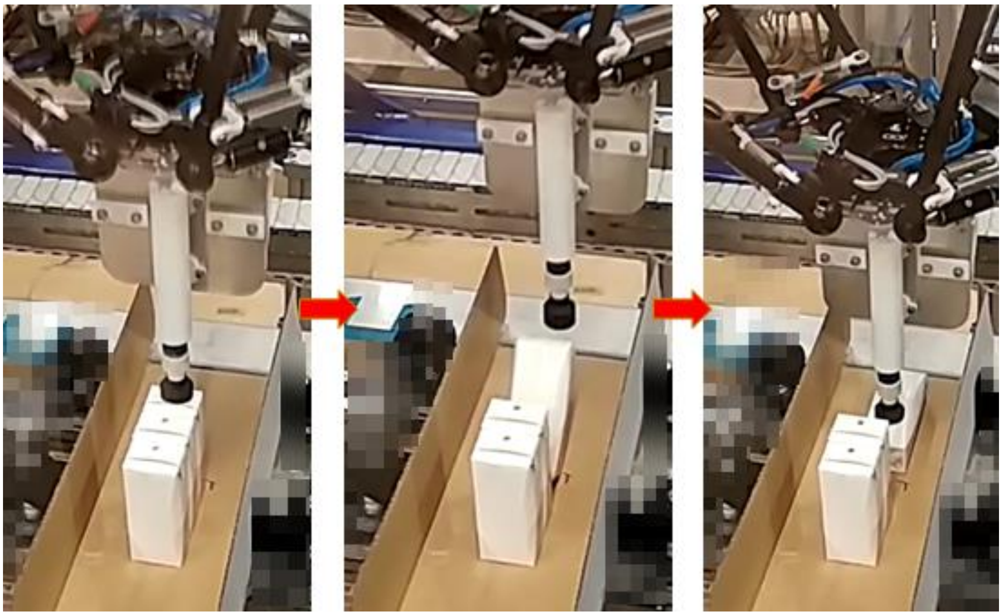


Figure 34: Topple and pick procedure

This procedure took 17 seconds, with 8 seconds of tool change and then 3 seconds per package pick and drop action.

4.3.3 Recovery speed

During a workshop in week 13 it was decided to run two different scenarios at the highest possible speed (without dropping packages) in order to get an estimate of how fast errors could be cleared. The robot speed was successively increased until the test could no longer be done without dropping packages (or dropped packages where the cause was obvious and correctable), and that speed was decided to be the highest safe speed. The two scenarios were a single fallen package (scenario 1), see Figure 35, and a package fallen on top of another (scenario 2), see Figure 36. Seven errors were introduced on the three blanks in the rig and they were then picked in concession. Due to the robot reach it was not possible to pick on nine positions (the lower position in the left and right blank were out of reach).

Figure 35: Recovery speed - scenario 1 setup

Figure 36: Recovery speed - scenario 2 setup

The picking sequence for scenario 1 was to pick the fallen package with the picking attachment, and the other two with the gripper head. This is possible since they are still correctly oriented. The sequence for scenario 2 is to first pick both fallen packages with the picking attachment, and then the remaining package with the gripper head. Scenario 2 was also run using only the picking attachment for all three packages. This would be required if the standing packages are rotated from their original orientation.

Some modifications were made to the pick and place program to increase the speed of clearing; mainly that instead of going into the blank in an L-shape via the safe area, the picking attachment will go straight to the pick position, but move out of the blank in an L-shape after picking the package. The trunk is short enough to move over the blanks unobstructed when it is not carrying a package.

Scenario 1 took about 1 minute and 20 seconds to pick (about 12 seconds per error), and scenario 2 about 1 minute and 30 seconds (about 13 seconds per error). Scenario 2 has one more pick action in order to clear the error, so it should take longer than scenario 1 where the two standing packages are gripped together by the gripper head. There were some problems with dropped packages in scenario 2; two packages were dropped before reaching the drop point. Both packages dropped were the angled ones, and it was probably caused by not being centered over the angled package when gripping, thus gripping closer to the short end of the package instead of the center of gravity. This makes the package swings around much more in sharp turns which results in a larger torque for the vacuum to handle. If the gripper was more centered on the package it would not have been a problem. Had there been a vision system installed in the rig it would have to give more accurate positions than the pre-programmed ones, thus gripping more accurately.

Scenario 2 run using only the picking attachment took about 2min 20seconds to pick (about 20 seconds per error). The large increase in time is due to a decrease in general transfer speed from 8->7 (12.5% decrease) when carrying packages, and a speed of 4 (compared to 8, a 50% decrease) when picking and carrying the standing package. Due to the small picking window it was decided to give the vacuum more time to attach to the package. Carrying a standing package means more forces when moving around due to the package swinging around more, and thus requires lower speed than the horizontal packages to not drop packages.

To enable free mobility over the blanks even with a package the spring in the cylinder device was removed, so that the cylinder will retract itself when a package is picked, see Figure 37. This is a very neat solution that cuts the length of the trunk by about 40mm (when holding a package), thus giving much needed clearance when moving around in the rig, enabling the packages to be transferred straight over the blanks. However, with no spring load to extend the cylinder once vacuum (and package) is released, it is not guaranteed that the weight of the suction cup and the inner cylinder part alone will be enough to extend it again, especially after many cycles when the internal bearings starting to wear down a bit and internal resistance increases. Depending on where on the package it is gripped it will hang down from the suction cup to some degree, making it difficult to determine exactly how much clearance there is after each picking action. When testing the non-spring-loaded version it became clear that it was not a working concept because while being able to pick horizontal surfaces, it could not even grip the 20-degrees angled packages. This is because some amount of force is required to press the suction cup down over the angled surface to conform in order to achieve vacuum. Without the spring load there is no such force, and the cup never conforms, vacuum is not established and no packages are picked. When picking horizontal packages the attachment retracts nicely and gives good clearance and could potentially be used in special cases.

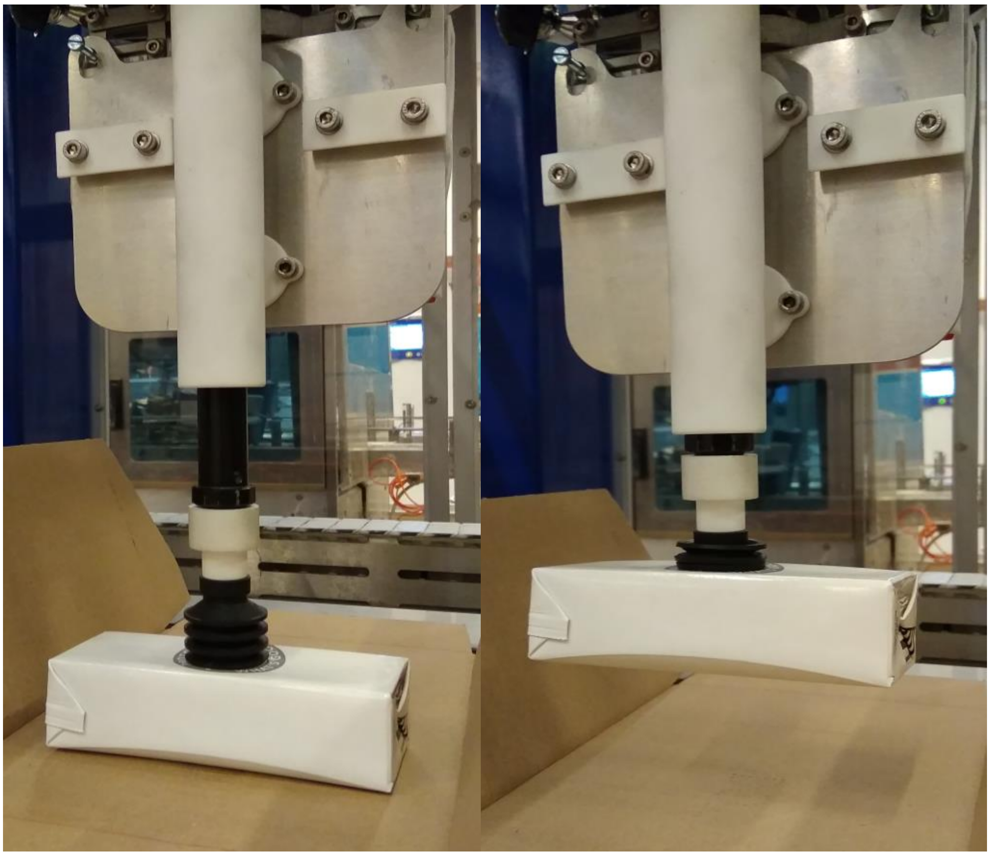
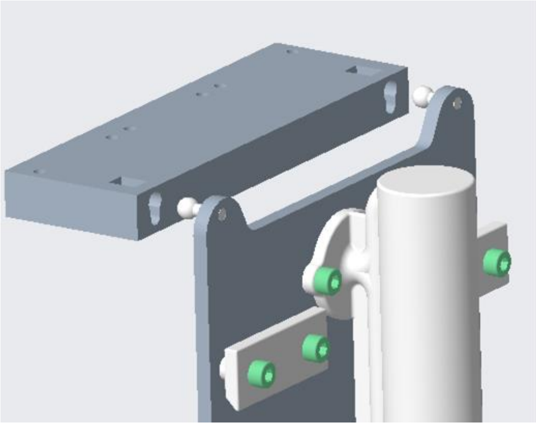


Figure 37: Non spring-loaded cylinder vacuum off (left) and vacuum on (right)

4.3.4 Application to future solution

The vacuum for the future solution is most likely not going to be individually controlled like in the current one. This means that the attachment cannot be held with two suction cups and gripping done with one, rather it will grab hold to the attachment and activating the vacuum all at once. It is no problem to keep the vacuum running at all times, but does pose a problem when releasing a package, since we then also need to release the entire attachment. In order to prevent dropping the attachment some kind of hanger/latch/clip design needs to be implemented so that it is kept in place during the short period when a package is being dropped. The vacuum can then be activated again and the attachment gripped before the robot starts moving again. So, this design only has to keep the attachment while the robot is static but must not interfere with the gripping function of the original gripper unit. Some design ideas using a keyhole shaped lock mechanism can be seen in Figure 38 below where the attachment will hang from the gripper mount while the vacuum is off.



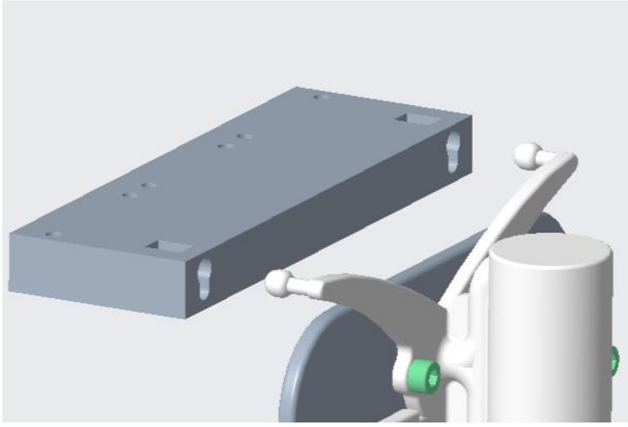


Figure 38: Hanging keylock mechanism with extended plate (left) and arms (right)

Another version with the knobs on the mount and the keyholes in the attachment plate was also suggested, see Figure 39.

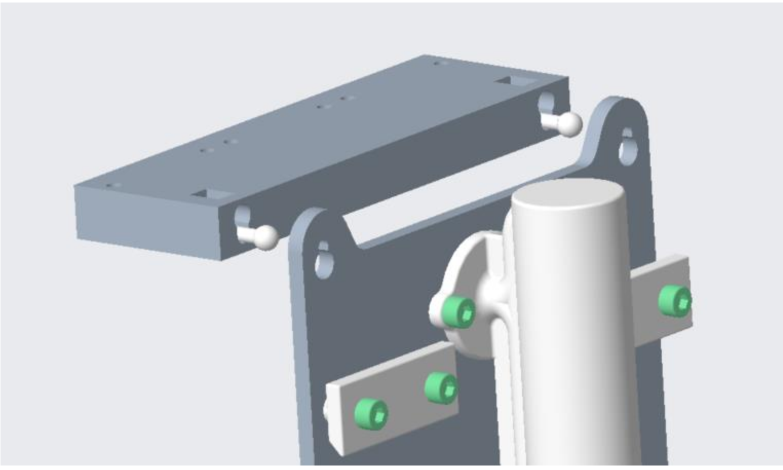


Figure 39: Hanging keylock mechanism, inverted design

Some other ideas using dynamic mechanisms activated via contact with the holder plate or using magnets were also considered, but required more complexity and more parts than the static keyhole concept.

It was decided to put the knobs on the mount rather than on the attachment plate, and the design was modified to fit the mount better; screws already present on the mount (for fastening a pair of leaf springs) were extended and used instead of the "knobs" and the keyholes were replaced with simple slots. The resulting design can be seen in Figure 40 below. With this design there will be a slight gap between the attachment plate top side and the gripper mount bottom due to the "keyhole" diameter being larger than the pin-diameter, but it will only be in Z-direction because of the same self-aligning method as in the holder.

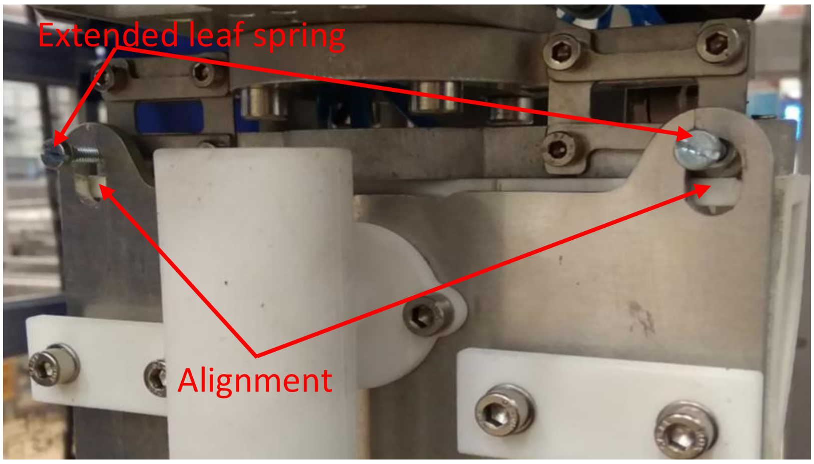


Figure 40: Hanging mechanism

4.4 Blank ejection/Pattern removal

The push attachment attached to the gripper can be seen in Figure 41. The attachment is lowered down in the yellow area in front of the blank to avoid crushing packages, then pushes packages down the entire length of the blank and off the edge of the grey blank conveyor guide rail as described in Figure 42. When the motion is finished it moves back to the holder position at a safe height.

Figure 41: Push attachment attached to gripper head

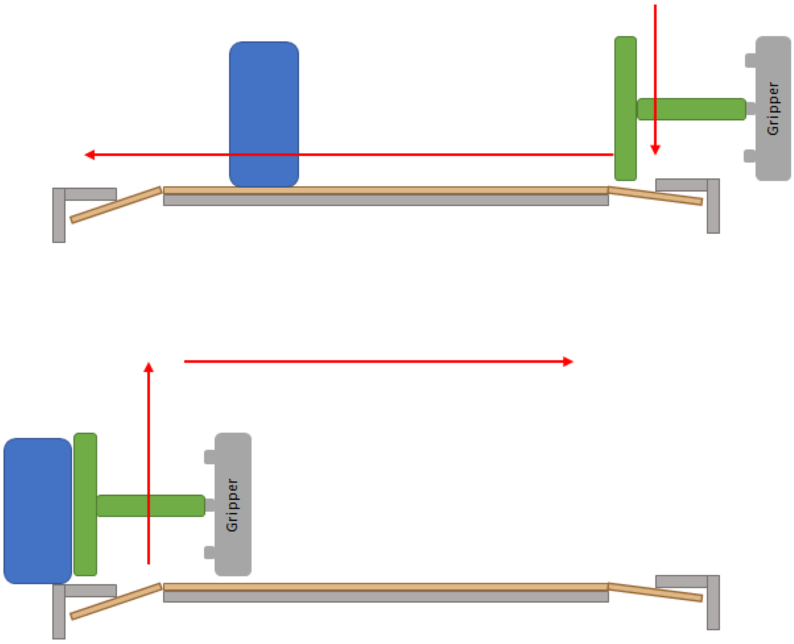


Figure 42: Push sequence

For the blank ejection it was decided to go for external ejection, mainly due to the complexity of clearing ruined blanks with the robot. The robot does not have enough degrees of freedom for very actuated movements, and since a ruined blank can be torn/wet/folded etc. it would be very difficult to make a "one-in-all" concept. Since the frequency of destroyed blanks is very low compared to pattern-related performance problems it was decided to keep the focus on those problems.

4.5 Proof of concept conclusions

Conclusively, one picking action takes about one second for fallen packages, and about three seconds for standing packages. Given a tool change of about 8 seconds, it means that the robot could theoretically pick between 112 and 36 packages depending on orientation over the course of two minutes. The speed is also dependent on how far the blank is from the drop point; comparing the closest point to the furthest one the time difference for clearing one error is about 36% more (11 and 15 seconds respectively for scenario 2) for the total time, but given 8 seconds tool change (tool change is rather constant due to the central position of the holder) the difference would be 133% (3 and 7 seconds respectively, 2.33 times longer) more spent on picking. Given this worst-case scenario, the robot would only be able to pick about 48-15 packages in two minutes.

Picking the standing packages using the toppling-method also takes around 3 seconds per action, however it can handle picking packages standing upside down, but does require a surface for the package to fall down onto. The vision requirements for this method are way lower since the attachment no longer needs to be within the narrow "picking window" on the top of the package.

Not using any spring load in the cylinder makes the tool retract about 40 mm when picking a package and enables it to move over blanks and packages. It can however no longer pick packages that are not completely horizontal and loses quite a bit of robustness.

The static hanging mechanism for keeping the attachment when suction is off works as intended but does make picking and delivering the attachment more complex. This in turn requires a bit lower speed when changing the tool.

No proof of concept for blank ejection or package return has been developed but will be discussed more in depth under the following “Discussion” headline.

5. Discussion

During the project it became clear that in order to actualize “automatic recovery” the focus had to be on the problems caused in the pattern creation area and after package grouping, not problems occurring inside the package grouping or control modules. These problems rarely created problems inside the robot cell, and thus could not be recovered using the robot, mainly because they often resulted in package jam before entering the robot cell. Surely there are improvements to be done with the package grouping and control modules, but it is not in the scope of this thesis.

The maximum speed of the robot depends on several parameters such as how well the motions are blended, sudden stops or change of direction, package orientation when picking, where on the surface it was picked etc. The total recovery time is also highly dependent on how far the packages have to travel between drop point and pick-up point, and could motivate having several drop points, or one large drop point all over the cell.

The tool change can be improved but is mostly significant when clearing low amounts of packages. To skip waiting for the cylinder would allow for lower duration but would mean the risk of colliding with the piston/attachments on the holder. A faster cylinder could be used, but it needs to be tuned correctly so that the attachments don’t jump off the holder when extending. Other types of tool changers could be used to improve the safety and speed of the final solution, including lock mechanisms and digital handshaking and software feedback when retrieving or delivering the attachments.

Picking standing packages is more difficult and two different methods have been tested. The toppling method works well and takes about 3 seconds per package. The difficulty with this concept is to get a controlled fall of the standing package. This concepts also allows for picking up-side-down packages, however this is a very unlikely event. Picking the packages without toppling also takes about 3 seconds per package but requires more precision from the vision system and the picking position. This concept cannot pick up-side-down packages. Smaller suction cups with lower speed/higher vacuum/slower speed could also be tested.

A package drop point/tool pick-up point in front of the blanks was examined and seems to be possible given the current workspace in the test rig. This drop point would be preferred to the current one in the yellow “safe zone” since this area will most likely be covered with a metal plate in the future solution, in order to prevent packages from falling down on the robot cell floor. It does not work with the current concept since there is not enough clearance to lift hanging packages over the standing packages in the blank. Furthermore, the pressurized air that generates the vacuum is released straight out from the bottom of the gripper, thus blowing packages away from underneath it when passing over them. This is however being remedied in coming versions of the gripper design.

Throughout this project it has been difficult to say what will work in the future solution since this is not fully developed yet, and therefore the presented concepts are only shown to work in the test rig. Some consideration has of course been put into integration with the final solution, but it is all speculative at this point and has not been the focus of the thesis work.

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