Design of an Industrial Bin Picking Station

Jonathan Ramb

DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
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MASTER THESIS

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Jonathan Ramb

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Co-supervisor: Yiannis Karayiannidis
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Abstract

With the ever-increasing demand for automation, new ways to optimize production lines are needed. The aim of this thesis is to complete an industrial automation task by employing a concept in robotics known as bin picking. The concept involves organizing objects by picking them out of a cluttered bin using an industrial robot.

An industrial station is designed in which loose, foam cylinders are organized with the help of computer vision and an industrial robot arm with a suitable end-effector. Using a structured-light-based 3D scanner, these objects are localized and then grasped using a gripping tool which is attached to the robot. To reach the goal of the customer-oriented project, the specialized gripper is designed using Ulrich & Eppinger's design process and the vision controller is configured. These partial solutions are then finalized in a robot station concept. A needle-type gripper that uses ingression of the foam material as its gripping method was selected and implemented. The system showed a consistent ability to pick out cylinders of the bin and place them on a designated fixture. A layout of the robot station was created together with the steps of a program cycle.

A secondary bin picking application was also created for a different object to test the limits of the system. Small, plastic cups were used for this. The System struggled to perform consistently due to scanner noise caused by interreflections from the plastic surfaces.

The implementations showed potential for the technology to be used in industrial settings. The specific firmware used can be applied to objects with distinct geometries and low reflectivity. Objects with non-ideal characteristics may be applied in a system with the correct configurations and hardware.

Keywords: bin picking, computer vision, automation, robotics, 3D Scanning

Sammanfattning

Med ett ökande behov av automation inom industrin så ökar också intresset för att hitta nya sätt att optimera tillverkningsprocesser. Målet med detta examensarbete är utförandet av ett industriellt automationsprojekt som tillämpar konceptet *bin picking*. Bin picking innefattar organiseringen av föremål som ligger löst i en behållare. Detta genomförs med hjälp av en industriell robot, ett gripverktyg och datorseende.

En industriell station ska framställas där cylinderformade objekt i skum plockas och placeras i en fixtur. Med hjälp av en 3D-skanner som använder strukturerat ljus ska dessa objekt lokaliseras och greppas med ett gripverktyg som är fäst på roboten. Det kundorienterade projektets mål nåddes dels med utvecklandet av det specialiserade gripverktyget, där Ulrich och Eppingers produktutvecklingsmetodik användes och dels av konfigurerandet av styrenhetenerna och plockningsstationen. Dessa dellösningar sammanställdes sedan i ett robotstationskoncept. Systemet visade förmågan att löpande kunna plocka cylindrar ur en behållare och placera dom på en fixtur. Det slutgiltiga gripverktyget var en typ av nålgripdon som använder penetration för att greppa skumcylindrarna. Till sist designades en stationslayout tillsammans med en tillhörande programcykel.

Ytterligare en bin picking implementation med en annan typ av objekt gjordes för att testa systemets kapacitet. För detta användes små muggar av plast. Implementeringen visade en bristande förmåga att lokalisera muggarna på grund av skannerbrus från interreflektioner som härstammar från de reflektiva plastytorna.

Implementationen visade potential för att teknologin ska användas i en industriell miljö. Teknologin kan användas på föremål med distinkta geometrier och icke-reflektiva ytor. Objekt med icke-ideala egenskaper kan dock användas med rätt konfigurationer i styrenheterna och robust hårdvara.

Nyckelord: bin picking, datorseende, automation, robotik, 3D skanning

Acknowledgments

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Lund, December 2022

Jonathan Ramb

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1 Introduction

In this introductory chapter, the project boundaries are be laid out. It starts with a brief background on Odigo Consulting and the aim of the project. Afterwards, the approach to achieve the project goals is explained. Lastly, the contents of each chapter are explained in the Disposition chapter.

1.1 Background

1.1.1 **Odigo Consulting**

Odigo Consulting (Odigo for short) is a company with the mission of making automation more accessible to small- to medium-size companies. While larger companies have the resources to automate their production lines, small companies often struggle to keep up with the growing market. To give these companies access to higher production rates and better work environment, Odigo sells automation solutions that employ robotic arms to complete e.g., pick-and-place or fabrication tasks.

Odigo uses collaborative robotic manipulators from Universal Robotics. Collaborative Robots is a fast-growing segment in the robotics industry today (Association for Advancing Robotics, 2022). Cobots, as they are often referred to carry a variety of advantages and disadvantages over the larger, industrial robots that are used in, for example the automotive industry. As described in Marrone's Msc thesis (Marrone, 2022, pp. 9-10) they function to collaborate with humans. Rather than operating in an enclosure, cobots are designed to work in proximity of humans at lower speeds and torques with integrated safety features. While many large robotic arms require to be set-up and managed by external companies, cobots can often be programmed and repositioned in-house. This flexibility at a low price-point is ideal for small companies or family-businesses that are looking to start their automation journey. (Marrone, 2022, pp. 9-10)

Bin picking is a challenge in robotics that spans over many disciplines. The idea revolves around picking objects from a bin and placing with the help of a robot. Selecting and picking the correct part in a disorganized bin autonomously is the main benefit of this and is highly desirable in the industry. This is because many industrial processes require parts to be ordered before or after the main production steps. This step is usually done manually, which, besides being monotonous also costs the company labor recources.

Odigo has multiple years of experience working with automation using robotic arms and are willing to expand their portfolio in new fields. The team has previously dealt with tasks using 2D vision, which concerns itself with detecting the location of features and objects using 2D images. Object localization using 3D vision adds another dimension to the problem. Using 3D scanning technology, a 3D map of the scene can be recorded. The so-called depth-map, containing the depth values, grants more information about the position and orientation of objects, making it possible to determine the position of objects in the z-axis.

1.2 Project

1.2.1 **Objectives**

The project comprises of two objectives, the primary (main) objective and the secondary objective. The primary objective is to complete a customer-centred project that focuses on solving the Bin-Picking task set by Odigo. The secondary, more holistic objective consists in exploring and understanding the area of 3D vision and bin picking. For this reason, there are chapters in this report that exist to explain the capabilities and limits of the technology.

1.2.2 **Primary Objective**

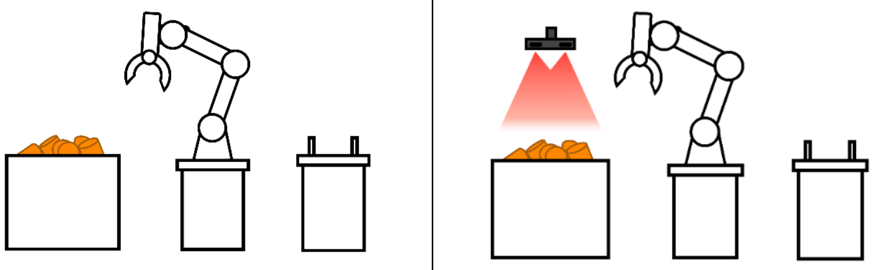
The main objective of the project is designing production line station for COG, one of Odigo's larger customers. COG wants to automate one of the pick-and-place processes using a robotic arm.

COG is a Laholm-based company, founded in 1977 that produces coated foam balls for the Toy and Sport Market. The production has been ramping up recently, making COG consider automating more production steps. For this pick-and-place task Odigo sees potential to implement a Bin Picking solution with the help of 3D vision.

The objective is to pick foam cylinders from a filled bin and place them on a table in preparation of subsequent production steps. This task is currently done manually with the help of a magazine instead of a placement table (image can be found in Appendix C.1.1). The cylinders will lie loosely with random orientations and positions. To effectively pick these cylinders a 3D scanner will be used in conjunction with a robotic arm to locate and place them precisely. This scanner will feed the 3D point cloud data into a vision controller that then communicates to the robot controller how the picking action should be performed. After the foam cylinder has been picked up, the robot arm will move the cylinder on the placement table.

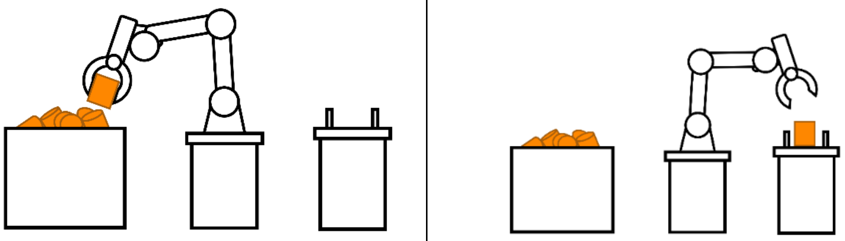
The task is completed when the following steps can be executed. The corresponding states of the robot station can be seen in Figure 1.

1. Localization – pickable cylinders are identified and position/orientation is calculated.
2. Picking – The System selects a cylinder and grasps it using a suitable end-effector.
3. Placement – The Robot places the cylinder on a table or designated fixture.



0. Box of loose cylinders are placed by the robot.

1. Localization



2. Picking

3. Placement

Figure 1.1 Schematic drawings of each step in the bin picking process including the initial state of the station.

1.2.3 **Secondary Objective**

The secondary objective to better understand computer vision is addressed by applying it to a different, more challenging object. Though it is not part of the main solution, it adds better understanding to the characteristics of bin picking. The solution includes a gripper design and a program in the software, Bin Picking Studio (BPS).

1.3 Approach

The primary task is divided into partial solutions. First, the gripper is developed and then the vision system. This order was chosen due to the times the equipment is available at the company. As Odigo has a leasing contract with the equipment suppliers, the equipment for the bin-picking-station was only available from the 18th of October on. This order is also logical as the Bin Picking Software requires a model of the gripper for to simulate the process.

An Adaptation of Ulrich & Eppinger method (Ulrich, T., & Eppinger, 2012) for product development was used to design the gripper tool. This way, different types of gripper tools can be methodically explored. Since the solution is commercial only, customer related process steps are omitted such as exploring customer needs and concept testing.

After setting up the robot test station, the vision system setup will be developed using a trial-and-error-style approach. The integration of the Vision System requires tweaking of many parameters and so, a solution can only be reached through structured experimentation. The partial solutions are lastly combined into a system-level solution by designing a station layout.

The Gantt-chart describing a proposed time plan for the project can be found in Appendix A. It contains the tasks and their corresponding time frames along with a comparison with the actual time plan.

1.4 Disposition

The project will be structured as follows:

The Theory chapter breaks down the themes of robotic manipulators from how they function to what role they play in the industry. A surface-level examination of the three overarching steps in bin picking is also included. The Gripper Design Chapter goes through the Ulrich & Eppinger's concept development steps (Ulrich, T., & Eppinger, 2012) to create and test a robotic gripper. In the end a suitable gripper is selected to be used with a UR robotic arm and the vision controller. The following chapter, Bin Picking, will start with an explanation of the working principles of the vision controller and Bin Picking Studio, with a schematic of the system-level solution. After that, a detailed explanation of how the Bin Picking Solution for the foam cylinders was created, containing the all the necessary steps in configuring the vision system and creating supplementary hardware, such as the fixture. The performance of the station is additionally measured and evaluated. The Robot Station Design will present a system-level solution, showing the station layout, the production steps and incorporated safety features. Many of the steps were repeated for the picking of plastic cups in a Bin Picking, new case but without the station design. This step serves to further explore the capabilities of the system and to complete the secondary objective. The Reflection sections of the chapters 3, 4 and 5 serve to evaluate the steps taken in the development process and discuss alternative solutions. The results are then summed up and presented in the sequential Conclusion chapters. In Future Work, possibilities for expanding the project will be discussed.

2 Theory

This section will cover some relevant theory around robotic manipulators, computer vision and Bin Picking. The robotic manipulator subchapter explains the variants of industrial robots and the roles robots play in the industry. In the computer vision part, the three significant steps in bin picking are explained: Perception, Cognition and Action.

2.1 Robotic Manipulators

2.1.1 **Industry**

Industrial robots (also called robotic manipulators) are defined as *"automatically controlled, reprogrammable multipurpose manipulators programmable in three or more axes,"* by the International Federation of Robotics (International Federation of Robotics (IFR), 2022). These robots are characterized by their ability to perform specific, repetitive automation tasks in sectors ranging from packaging to pick-and-place to manufacturing. The demand for automatic tasks has steadily increased over the years. Modern, industrial robots offer certain advantages over other automated systems: (Tilley, 2017):

- **Ease of integration**
- **Highly variable tasks**
- **Complex tasks**
- **Possibility for low volume production**

2.1.2 **Working Principles**

Industrial robots are defined by their axes that are connected by a series of joints to form a *kinematic chain*. The number and alignment of the axes define the *degrees of freedom* that the robot has, which is an indicator of its manoeuvrability. Many degrees of freedom are good if the robot needs to access e.g. a workpiece from many angles with its so called *end-effector*. At the end of the robotic arm, a tool, also known as *end-effecto*r, is mounted on the tool-flange. The type of tool can be, among other things, grippers, welding tools and spindles. The *workspace* of a robot (seen in Figure 2.1) represents every point that the end-effector can reach to fulfil the robot's task. This size of this space often scales with the degrees of freedom that the robot has. The calculation of what angle each of the axes must have to result in a certain end-effector position is called the *inverse kinematics* and usually has multiple solutions. Typical industrial robots such as the KR series robots by KUKA or the IRB robots by ABB use 6 axes with 6 degrees of freedom.

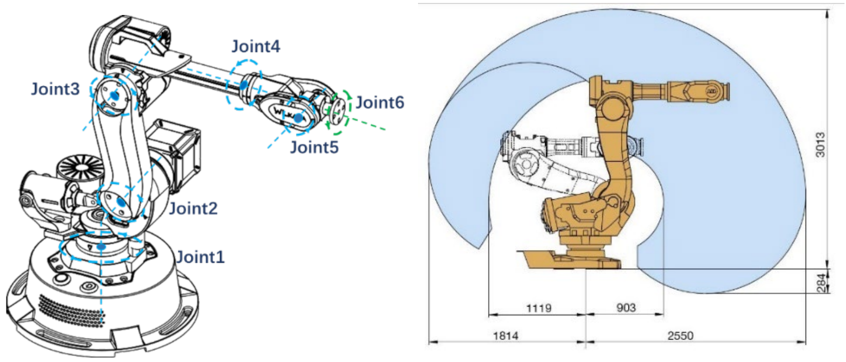


Figure 2.1 Left: Model of a desktop WLKATA robot. The arrangement of the 6 joints (axes) gives the robot a full 6 degrees of freedom. The end-effector is mounted on the tool flange, where Joint 6 is located. From: (Lin-Nice, 2020) Right: Image depicting the working space of an IRB robot from ABB. From: (Robots Gallery, 2022)

2.1.3 **Industrial Robot Types**

The robot configuration can look different depending on the required task to be done. Generalist robots, like the articulated robot type can be adjusted to perform many different tasks. The disadvantage of this robot type is the sophisticated control systems and high price due to the large motors required. Robots that have less degrees of freedom, such as a cartesian robot type are simpler to control and design. These robots can be used for tasks such as pick-and-place operations and packaging but also 3D printing. A large chain of joints often results in less rigidity and more compliance. Such is the case for the SCARA and the Articulated robots. Depending on the type of application, this can be an advantage or a disadvantage. (NRTC, 2021)

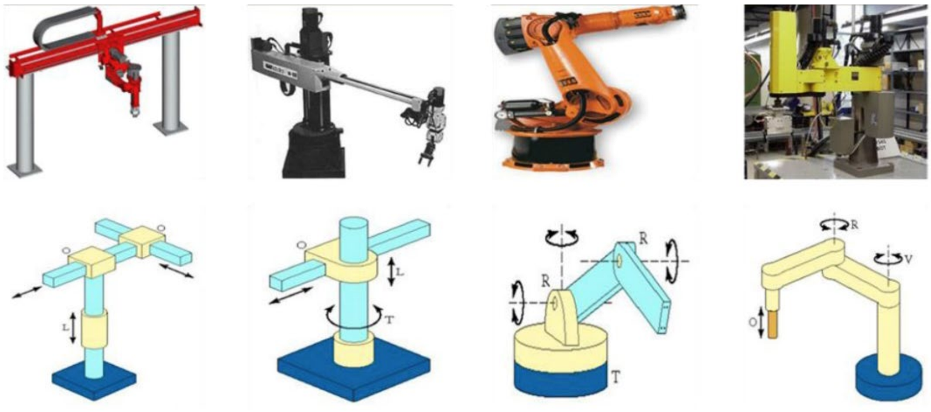


Figure 2.2 Four Different types of industrial robots and their corresponding link configurations. a) cartesian type, 3-axis b) Cylindrical, 4-axis c) Articulated, 6-axis d) SCARA, 4-axis. From: (Tallinn Industrial Education Center, u.d.)

2.1.4 **Collaborative Robots**

Collaborative robots are a branch of robotics that has been increasing in demand in the last years. The industry for collaborative robots reached a worth of 600 million dollars in 2018 and is expected to take up 29% of the whole robotics market by 2027 (Association for Advancing Robotics, 2022).

Collaborative robots (also known as cobots) differentiate themselves from regular industrial robots by specializing in *Human-Robot Collaboration* (HRC). The idea behind HRC is to allow humans safely to work in proximity with the robots. Large, industrial robots are known to work at high torques and speeds, which necessitates a surrounding enclosure. This concept was born from the need to implement fast and flexible automation to remove tedious or hazardous that were previously performed by humans.

Many of these robots have built-in safety features, such as e.g., safety paddings, low number of pinch-points (where limbs or clothing can get trapped) and force sensing technology. To meet the requirements of a collaborative robot, maximum speed and torque limit requirements must also be met.

Since Universal Robots introduced the first cobot, UR5 in 2008, many other companies such as KUKA and ABB have released their own variants to the market.

2.2 Computer Vision & Bin Picking

2.2.1 **Computer Vision**

The field of computer vision spans over many computer science disciplines. The central idea behind it is retrieving information on one or multiple images and to reconstruct its lightning, perspective, and colour. How this is accomplished is through probabilistic and mathematical models to find potential solutions. While humans and animals can do this effortlessly, this task remains a challenge for computer vision algorithms.

Computer vision has found itself in a wide variety of applications. Applications can be found in the automotive, medical, military and online marketing sectors among many others. These are examples of typical applications. (Szeliski, 2010, p. 5)

- **Optical character recognition** – used for recognizing handwritten text on packaging or letters.
- **Medical imaging** – used to study state of organs and to detect tumours or cancer.
- **Automotive safety** – used to detect obstacles or pedestrians on the streets to avoid accidents.
- **Retail** – used to recognize items during checkout at a store.

2.2.2 **Bin Picking**

The concept of Bin Picking emerged as a robotics challenge that heavily relies on computer vision. The task lies in picking loose items from a bin using a robotic manipulator. Though it may sound simple, finding a robust system that works for all items has yet to be found. The need for fast and efficient Bin Picking is high, as it is a common production step in the industry. The organization of products in cluttered bins is however, to a large extent, done manually today. (Truebenbach, 2019)

Bin Picking can be summarized in three important concepts: 3D/2D Scanning methods, pose estimation and trajectory planning. They can be concisely named Perception, Cognition and Action. In this subchapter, an overview of the concepts will be explained.

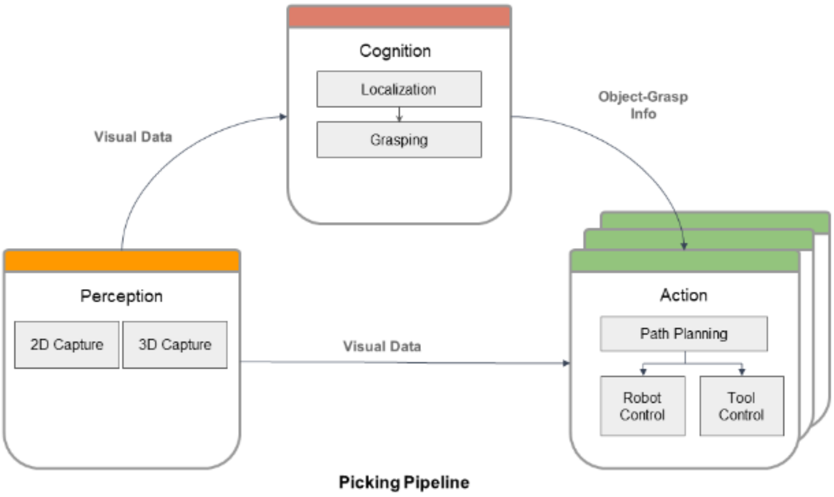


Figure 2.3 The three most important steps in Bin Picking. From: (Ojer, Li, Tammaro, & Sanchez, 2022)

2.2.2.1 Visual Data Collection (Perception)

Early Bin Picking solutions known as "blind bin picking" did not use sensors or cameras. This is not the case for modern implementations where the use of visual data from 3D scanners or cameras are standard. This is a brief description of some of the most common 2D- and 3D data capture methods (Haleem, Javaid, Pratap, & Rab, 2022, p. 162):

- **LASER triangulation 3D scanning.** This method involves projecting a single infrared-laser point that moves across the geometry. Using the reflected IR laser and trigonometric calculations, the depth of the measured point can be calculated. 3D laser scanning finds its use in the construction industry to digitize buildings and collecting geospatial data.
- **Structured light 3D scanning.** This method involves casting coloured stripe patterns onto objects using a video projector. The distortion of the patterns is measured using one or two cameras, enabling depth of each point to be calculated. This method is used in many sectors it's good price-to-performance ratio and high accuracy.
- **Photogrammetry.** Photogrammetry creates 3D environments through the interpretation of 2D images. Like the other techniques, this method uses triangulation using images recorded from multiple angles to calculate distances. Due to its accessibility its use can be seen in many applications such as augmented reality, topographic mapping, and worksite recording.

Alongside a scanning method, a format for the recorded data is also chosen. Three common data formats are based on 3D point clouds, depth maps and normal maps. Figure 2.4 depicts each of the formats. (Dirk, 2016, pp. 17-111)

a. **3D point cloud based**, which registers points of the recorded scene in a three-dimensional space. For this a 3D scanner is used directed at the scene from one or multiple angles.
b. **Depth map based**, which uses a 2D image of the scene with a depth value assigned to each pixel. The depth values can either be extracted using a 3D scanner or estimated from a 2D image.
c. **Normal map based**, which generates a map of surface normals from a 2D image. This type does not need a 3D scanner to perform pose estimation. The image below depicts the scene in different colours depending on the normal direction.

Since the 3D point cloud-based type will be used for the project, the following concepts in 2.2.2.2 and 2.2.2.3 will be described with regards to this data type.

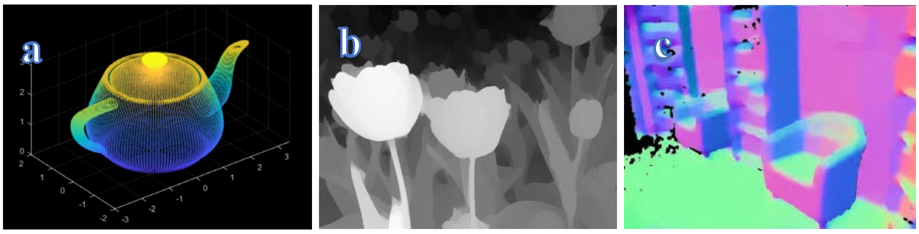


Figure 2.4 a) 3D point cloud model. From: (Revopoint, 2020) b): Depth map representation. From: (Looking Glass Factory, 2019) c): Normal map representation. From: (Wang, Fouhey, & Gupta, 2014)

2.2.2.2 Pose Estimation (Cognition)

After a 3D point model has been generated, the next step is the so-called pose estimation.

Pose estimation focuses on finding the position and orientation of an object with a known shape. The purpose of this is to depict the real-world objects in a virtual environment. For this project, the pose estimation for 3D point cloud models will be used.

Today, a wide variety of algorithms are used for this. There are simple, feature-based ones that use geometric elements such as planes, cylinders etc to help to align the models with the point cloud. The limitation here is that many objects often don’t contain these simple elements. An alternative solution is to convert the 3D model mesh to a point cloud model, giving us the same format as the scanner provided data. The points can now be aligned with each other. The RANSAC (Random Sample Consensus) is a commonly used algorithm that iteratively aligns the two point clouds point-by-point. (Dirk, 2016, pp. 18-20) This method is fundamental and is often combined with other algorithms to make it more robust.

2.2.2.3 Trajectory Planning & Collision Avoidance (Action)

In the case of Bin-Picking, the next natural step is to grasp the located object. The trajectory path that the robot takes follows determined waypoints that are calculated based on the target object pose. Waypoints are points in 3D space that mark the end-effector positions between trajectories. The difficulty lies in designing a robust collision avoidance algorithm. An effective algorithm should find the shortest possible path at an acceptable computational time. As the object, scene and gripper are available as meshes, checking for collisions is simple: any intersecting mesh surfaces between them count as collisions. As every position along the trajectory must be tested for this, the computational time can get high, especially with a high-resolution gripper model. Additional measures also need to be taken to ignore collision detections from scanner noise. (Dirk, 2016, pp. 28-29)

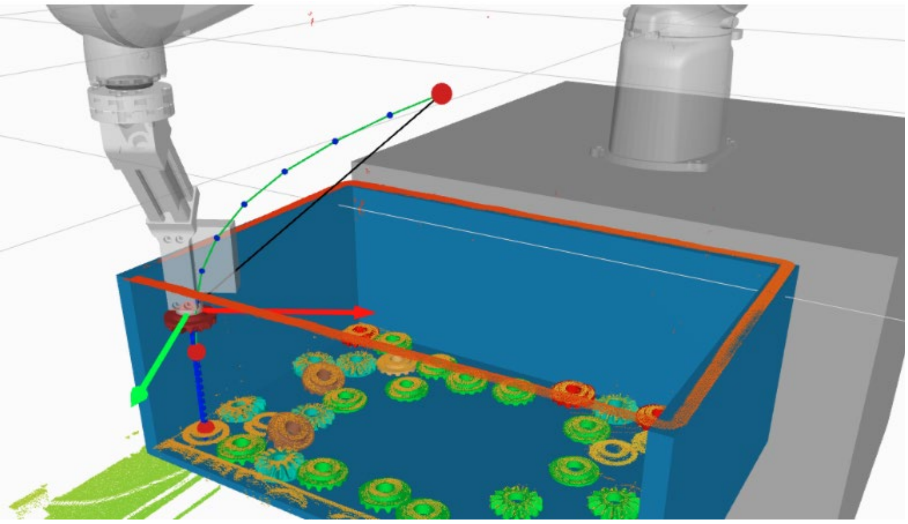


Figure 2.5 Image depicting a generated picking trajectory between 2 waypoints. The path is chosen not to collide with the bin walls. The image was found in the BPS documentation.

When selecting waypoints, *gripping points* must be defined beforehand. These points determine where the waypoints for the grasping action should be placed. The *Tool Centre Point* (TCP) usually determines the point of the tool where it will grasp the object. Additionally, object and gripper *invariances* must be defined. Invariances determine the possible directions they can be rotated around certain axes and still be picked. Figure 2.6 below illustrates invariances of the dumbbell. The dumbbell can be picked in the middle regardless of its axial rotation. Each angle of rotation in its axis is an invariance. The Two-clamp gripper itself does, on the other hand, not have any invariances on that gripping point.

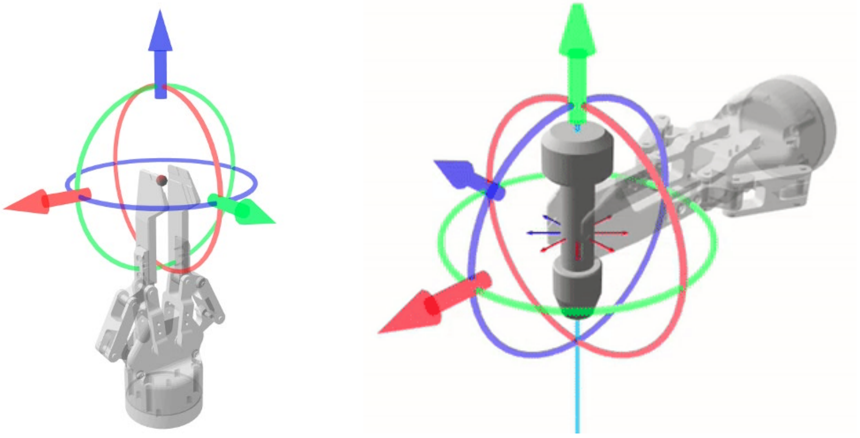


Figure 2.6 (Left) Location of the TCP of a Two-clamp gripper. (Right) gripper picking a dumbell with invariance in its axial direction. The image was found in the BPS documentation.

3 Gripper Design

In this chapter, the end-effector for the robot arm is designed. After some theory around gripper types and gripping methods, the development begins. The full process is described; from setting the target specifications and the initial concept drafts to a physical, usable prototype. The selected gripper is lastly tested and refined.

3.1 Approach

For the creation of the gripper of the robotic system, Ulrich & Eppinger's methodology (Ulrich, T., & Eppinger, 2012) is applied and adjusted. Certain steps are omitted, such as the e.g. market analysis. As this project is not consumer-oriented, the needs are not gathered from customer data.

Firstly, the target specifications were set. This was followed by a concept generation phase, in which several concepts for gripper designs are made. The promising ideas were then filtered out in a concept scoring and concept selection phase and subsequently tested in chosen test scenarios. From the tests a suitable candidate was chosen and finalized in the detail design chapter. These steps were visualized in Figure 3.1 below.

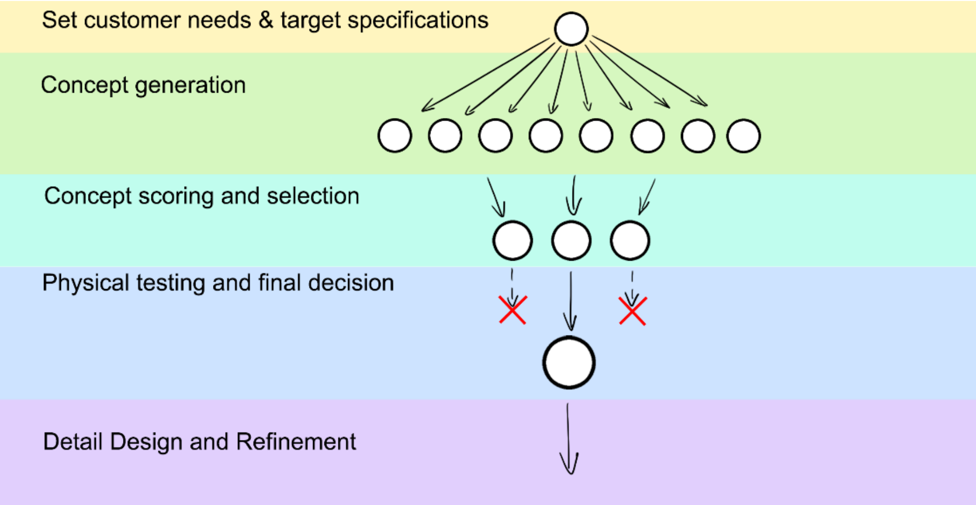


Figure 3.1 chart showing the steps of the development process for the gripper (based of the Ulrich & Eppinger Product Design Methodology (Ulrich, T., & Eppinger, 2012))

3.2 Customer needs and target specifications

The customer needs and target specifications for the gripper were established by gathering outside data and inside data at Odigo. The research was done to detect desired qualities of a gripper for foam cylinders while applying to general purpose grippers. A list of needs was firstly set up. The needs were selected based on online information surrounding general gripper design practices, discussion with Odigo and observations made at COG's factory. Experimentation with Odigo's equipment additionally affected the selection.

- **Ability to grasp** – the gripper can grasp the cylinder under ideal conditions on all required gripping points.
- **Reliability** – the ability for the gripper to perform the grasping motion repeatedly even with orientational and positional deviations of itself or the cylinder.
- **Lightweight** – The gripper is total weight is low.
- **Non-intrusive grasping** – the gripper isn't obstructed by other cylinders or obstacles while grasping.
- **Safe during operation** – the gripper doesn't endanger nearby humans.
- **Constructible** – the gripper is possible to fabricate given the time and workshop resources.

According to the Ulrich and Eppinger's model (Ulrich, T., & Eppinger, 2012), the next step is to translate the needs into measurable specifications. As some needs, such as *ability to grasp* or *reliability,* were too complex to be described by a single metric, the needs were taken directly as specifications. This can make the concept scoring less explicit but allows for a fair comparison between all gripper types.

The next step is to formulate ideas in a concept generation phase.

3.3 Gripper Theory

Grippers are a type of end-effector, referring to the attachment to tool flange of the robot arm. They are used to grasp objects. The *tool-centre-point* (TCP) defines the centre point of the gripper frame and is usually defined as by the picked objects middle point. For single-point grippers, such as a vacuum gripper using a single suction cup, the TCP is placed at the tip of the cup, where the picked object makes first contact.

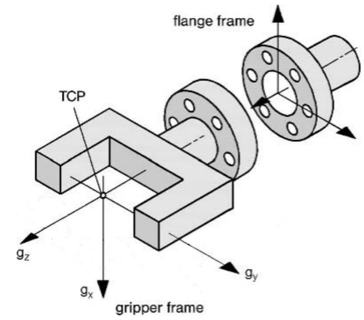


Figure 3.2 Image depicting an end-effector, it's TCP and the coordinate system of the Gripper frame. From: (Monkman, Hesse, Steinmann, & Schunk, 2007)

3.3.1 **Gripper Classification**

There are different ways in categorizing grippers. Two useful ways of distinguishing them is based on grasping method and on the mechanical actuation method.

3.3.1.1 Gripper classification based on grasping methods

Impactive gripper – gripping by force from at least two directions. Depending on the object's geometry and rigidity, different mechanical actuation methods are preferred. This also goes for the common, finger designs. Rigid objects can be grasped using a friction with high force, while delicate objects prefer to be grasped with encompassing grippers with less force.

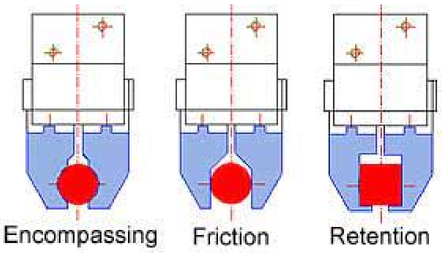


Table 3.1 Different finger design considerations. From: https://t.ly/KfwfK

A higher number of fingers increase the mechanisms complexity but allows for a more stable grip. Three-finger grippers make it possible to grasp spherical objects or irregularly shaped objects, like a claw machine in arcade machines. Other mechanical grippers, actuated by e.g., compressed air can be used to inflate bellows to grip objects, rather than using linear actuation. (Samadikhoshkho, Zareinia, & Janabi-Sharifi, 2019, pp. 1-2)

Ingressive gripper – Ingressive grippers attach themselves to objects by permeating the material, often using sharp needles. These gripper types have found their use in the textile industry as the porosity of textiles prevents lifting using vacuum suction. Wool, fabrics and carbon or glass fibre mats are often handled using needle grippers, as other types of grippers often struggle with the task.

Astrictive gripper – These gripper types use physical principles such as vacuum suction and electromagnetism to adhere to an object. Astrictive grippers are useful for delicate objects or objects with complex or varying geometry. Vacuum gripping is one of the most common methods used to handle packaging and boxes due to their ability to pick large objects. Electromagnetism requires materials that are ferrous, making their application slightly more niche. (Tuff Automation, 2020)

Contiguity gripper – gripping through adhesion, either by thermal or chemical adhesive contact. A primitive example can be achieved by sticking two-sided tape to the tool flange. This gripping type is advantageous when picking objects with complex geometry, much like the astrictive type. A new type is Gecko Pads, which use a material that was invented by engineers at NASA (Greicius, 2012). This material mimics the feet of gecko lizards, achieving superb adhesive properties. (Tuff Automation, 2020)

3.3.1.2 Gripper Classification Cased on Cechanical Actuation

The actuation methods used today are Vacuum driver, Pneumatic, Hydraulic and Servo-Electric. (Samadikhoshkho, Zareinia, & Janabi-Sharifi, 2019, pp. 2-3)

- **Vacuum Actuation**: Rather than moving a cylinder or mechanism, vacuum can be used to attract an object. Different suction cups can be selected to have a strong grip on the target object. Its main strength is its simple implementation and flexibility.
- **Pneumatic Actuation**: Pneumatic actuation use pressurized air which is space efficient and simple to incorporate. It’s ideal for motion that requires less accuracy in its control and high force.
- **Hydraulic Actuation**: Hydraulics are used for high strength applications. These require expensive equipment which are not available at Odigo Consulting.
- **Servo-Electric Actuation:** Actuation using electromotors are ideal for applications where control is important. Electric actuators can make us of force-feedback where pressure must be applied in a controlled manner.

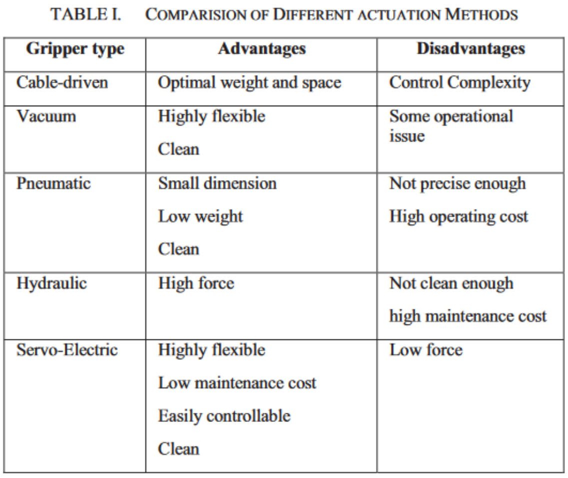


TABLE I. COMPARISION OF DIFFERENT ACTUATION METHODS

Gripper type	Advantages	Disadvantages
Cable-driven	Optimal weight and space	Control Complexity
Vacuum	Highly flexible Clean	Some operational issue
Pneumatic	Small dimension Low weight Clean	Not precise enough High operating cost
Hydraulic	High force	Not clean enough high maintenance cost
Servo-Electric	Highly flexible Low maintenance cost Easily controllable Clean	Low force

Figure 3.3 Different Actuation methods and their respective advantages and disadvantages. From: (Samadikhoshkho, Zareinia, & Janabi-Sharifi, 2019)

3.3.2 **Cylinders and Bin Characteristics**

The cylinders used for the task are made from polyurethane (PU) foam. Each cylinder comes with the dimensions 195 mm in diameter and 185 mm in height and a weight of 140 grams. By dividing the cylinder volume with its mass, a density of $25.36\,\frac{kg}{m^3}$ could be calculated, classifying it as low-density PU foam.

The cylinders are stored in cardboard boxes that are illustrated in Figure 10. While most of them lie loosely with random orientations, the bottom-most will be exposed to more pressured from the weight from above. The height to which the bin is filled is not guaranteed to be the same at the start of the bin-picking routine.

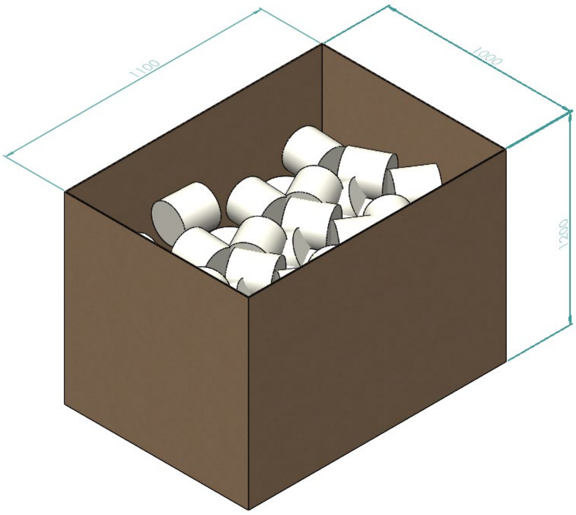


Figure 3.4 Image of a reconstruction of the cylinder-filled bin with its main dimensions

3.4 Gripping points

The shape of the picked object is important to consider when designing grippers. Most objects benefit from being able to be picked from multiple directions. One such direction can be referred to as the *angle of approach.* As cylinders are symmetrical along all the axes, three different *gripping points* can be identified: one on each of the circular faces, and one in the middle of the curved surface. The curved surface has a multitude of gripping point invariances as it’s symmetrical along a whole axis. This means that there is theoretically an infinite number of possible approach angles. More information around gripping points and invariances can be found in the theory chapter 2.2.2.3.

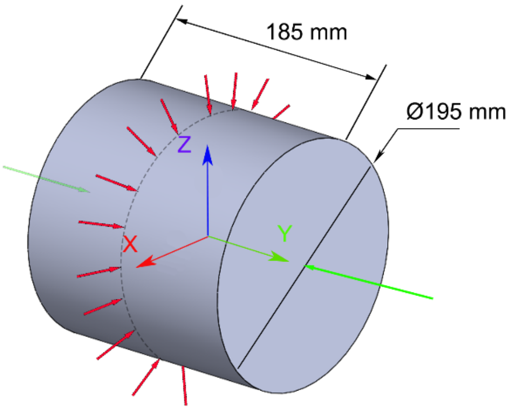


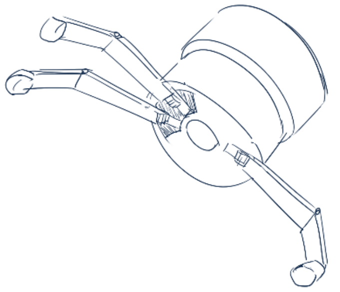
Figure 3.5 Image showing the possible the 3 unique gripping points defined by the arrows.

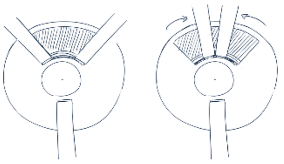
3.5 Concept Generation

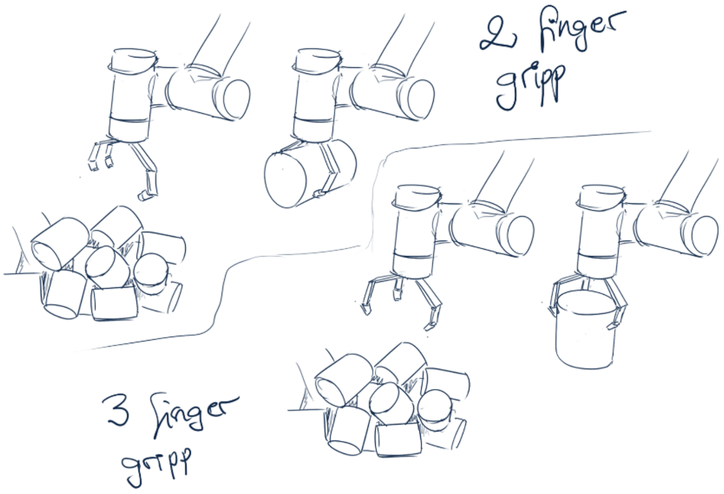
The concept generation stage was mainly expressed through sketches. Odigo's office space offers, apart from the workshop itself, a variety of pneumatic components and electric actuators to perform tests on. The concept generation was performed over the course of two weeks using rough sketches and simple prototypes. At this stage, no ideas were discarded as many of them can be further refined later. Some mechanical principles, such as vacuum suction, were tested to gain understanding of the equipment's capabilities. When enough ideas had been collected, refined sketches were drawn of the most promising concepts. To meet the specifications, attempts were made to cover a diverse range of specifications, grasping methods and actuation types. In the end there were a total of five impactive type grippers, two ingressive and one astrictive type.

I. 2/3-Finger gripper

A Mechanical gripper using three fingers. Two of the fingers can rotate around the circumference of the end-effector. This results in a gripper with two modes of operation: one for grasping the cylinders along its z-axis and one for gripping radially (square profile). The concept is based on being able to switch between a three-jaw gripper and a parallel motion dual-jaw gripper based on the approach angle.

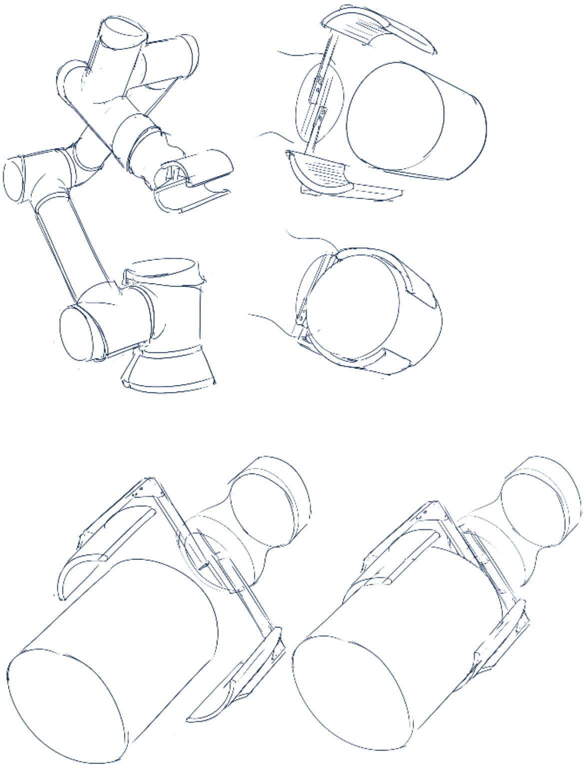






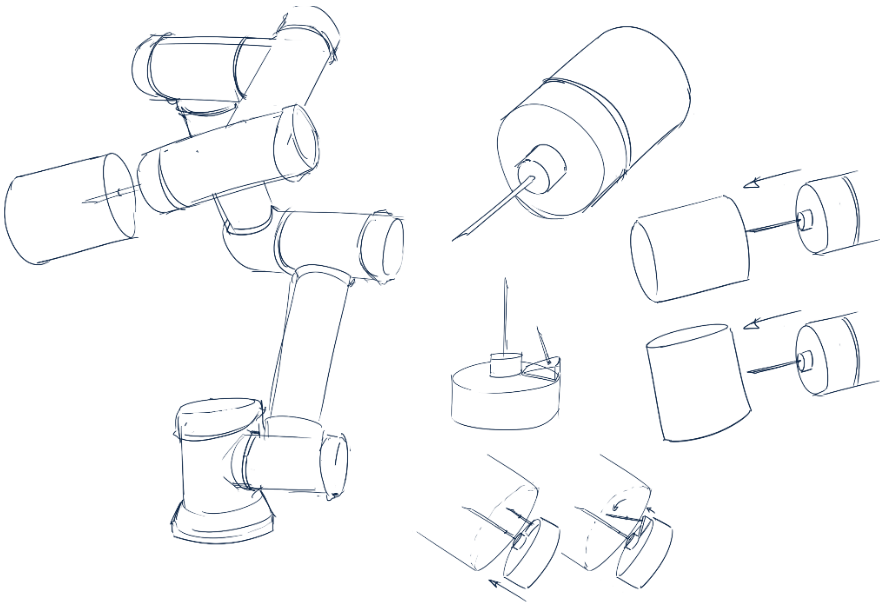
II. Simple Clamp Gripper

This concept consists of two variations of a simple parallel motion gripper. The two jaws move towards each other to grip the object. Each of the gripper types are specialized in one gripping direction only but may be able to grasp other gripping points with enough clamping force. The simple design makes the construction straightforward.



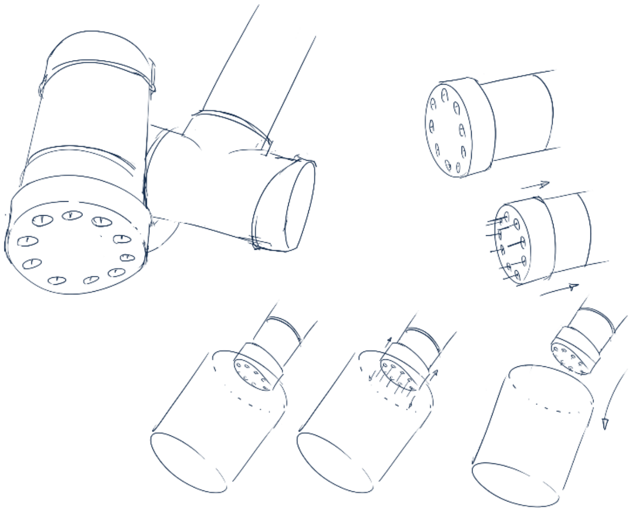
III. Marlin Gripper

This gripper uses a single needle with an optional supportive needle for a pinching effect. This ingressive gripper takes advantage of the PU foams porosity to pierce the material rather than to grasp it. The simplicity of the design makes the construction easy. Safety and control is a limiting factor.



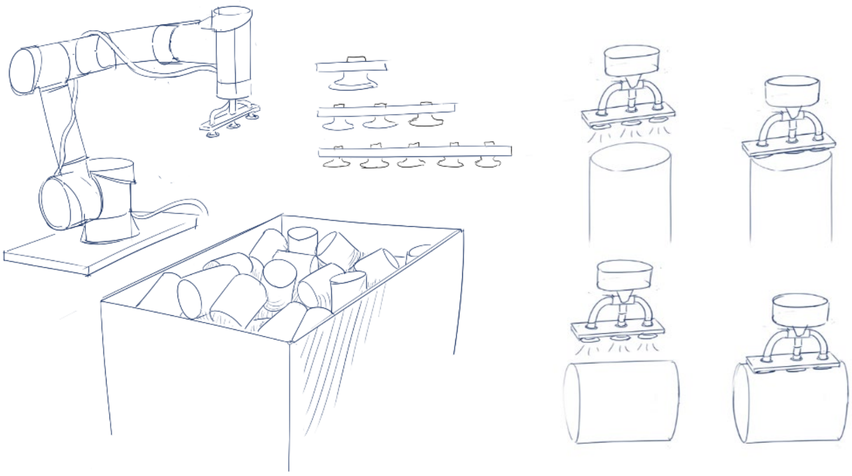
IV. Needle Gripper

Needle gripper using multiple retractable needles for a secure grasp. This concept relies on multiple, shorter needles to pierce and adhere to the cylinders instead of a singular, long needle. This way, the needles can be covered with the help of a movable cover. The cover can retract when the gripper needs to pick a cylinder and extend when the arm isn't carrying a payload. Such a feature can also protect humans from getting injured by the sharp needles.



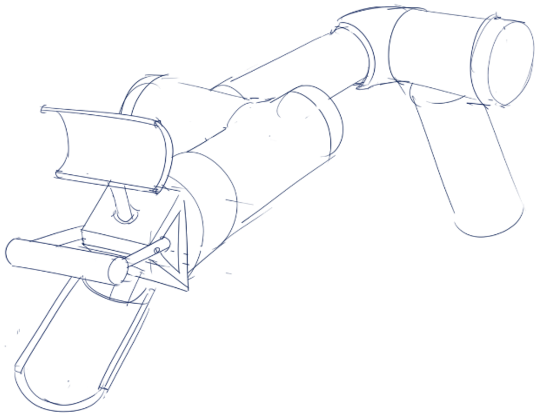
V. Vacuum Suction Gripper

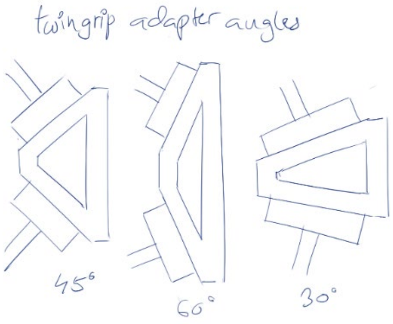
A simple vacuum gripper with three suction cups. To compensate for the materials porosity, that results in air leakage, multiple suction cups are used. The suction cups are spaced to fit on both sides of the cylinder with even flat contact with to the cylinder surface. The construction is simple due to the availability of pneumatic equipment at Odigo.

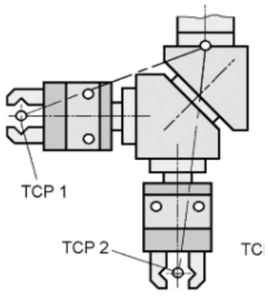


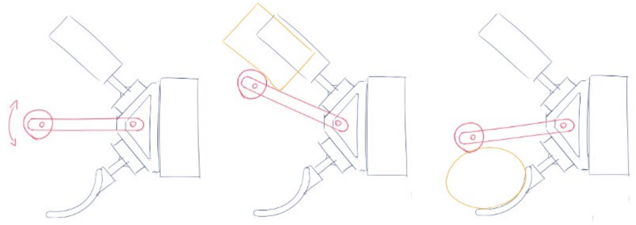
VI. Dual Gripper

The Dual Gripper stands out from the other grippers by having two separate tool centre points mounted on the rotating faceplate. This means that it can switch between two unique grippers depending on the grasping point of the cylinder. In this case, the two simple clamp grippers are used with a single, rotating lever used to exert clamping force on both sides. The gripper has a complex design and demands a large operating space.



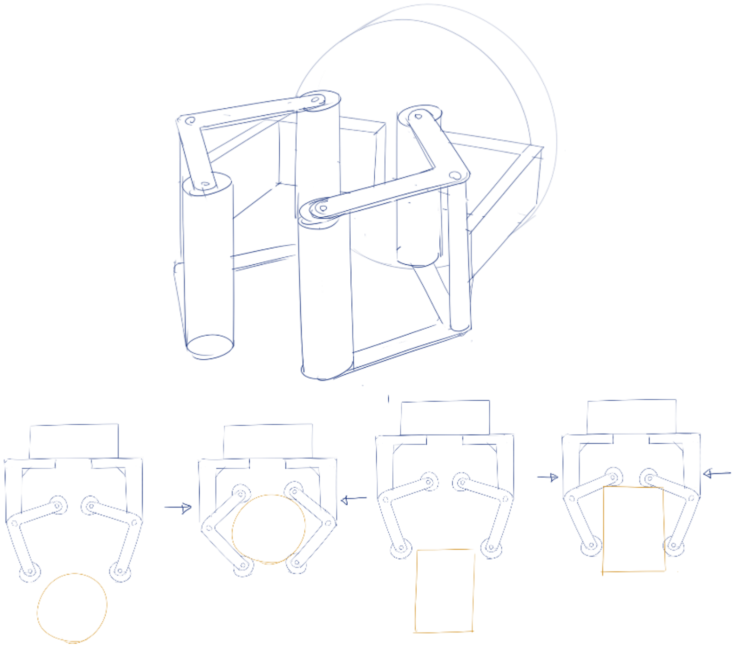






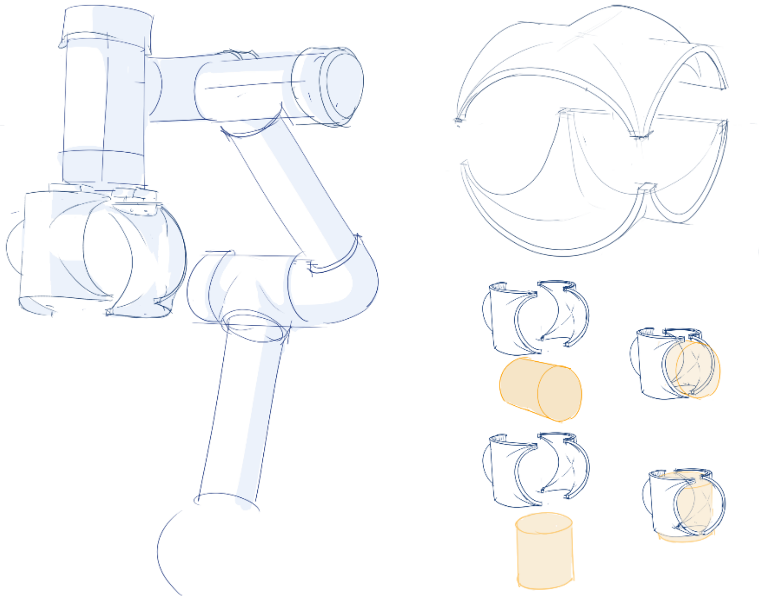
VII. Flip-Grip

This gripper is a clamp-style gripper that can adapt its method of grasping to either cylinder approach angle. The two mirrored L-shaped pieces carry TPE rollers on their ends and can move to conform to the cylinders shape. When the cylinder is in place, the parallel clamps close to tighten the grip. The working principle may need testing to confirm its performance.



VIII. Adaptive Simple Gripper

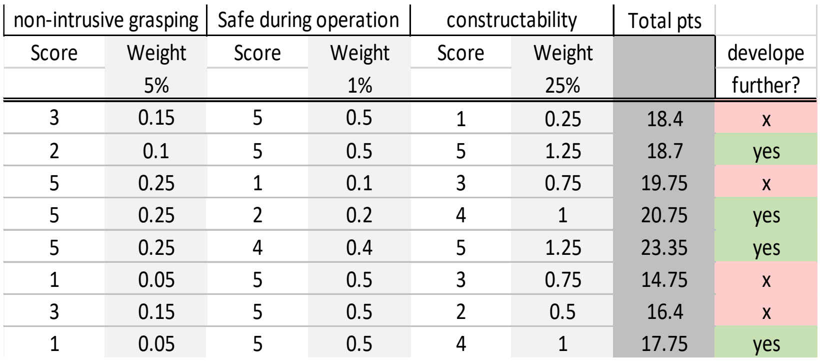
The Adaptive Gripper uses two concave, encompassing grippers to clamp the cylinders in two orientations. Like the simple gripper, its only moveable parts are the clamps, which alleviates the design from complexity.



3.6 Concept Selection

In the concept selection step, each candidate was entered in a concept scoring matrix. This served to evaluate the concepts based on the chosen criteria. Each concept was rated on each criterion with a value from 1 to 5 and then multiplied by its weight. The weight was chosen based on discussions with the supervisor at Odigo, online literature and problem specific observations made. The concept's score is calculated by taking the sum of each of its weighted criteria scores.

		Ability to grasp		Reliability		Lightweight		non-intrusi
		Score	Weight	Score	Weight	Score	Weight	Score
Nbr	Name		35%		20%		5%	
1	2-3-Finger gripper	4	1.4	4	0.8	4	0.2	3
2	Simple Clamp Gripper	2	0.7	3	0.6	3	0.15	2
3	Marlin Gripper	5	1.75	4	0.8	5	0.25	5
4	Needle Gripper	5	1.75	3	0.6	5	0.25	5
5	Vacuum Suction Gripper	1	0.35	4	0.8	5	0.25	5
6	Dual Gripper	5	1.75	2	0.4	2	0.1	1
7	FlipGrip	4	1.4	2	0.4	3	0.15	3
8	Adaptive Gripper	5	1.75	4	0.8	2	0.1	1



non-intrusive grasping		Safe during operation		constructability		Total pts	
Score	Weight	Score	Weight	Score	Weight		develope
	5%		1%		25%		further?
3	0.15	5	0.5	1	0.25	18.4	x
2	0.1	5	0.5	5	1.25	18.7	yes
5	0.25	1	0.1	3	0.75	19.75	x
5	0.25	2	0.2	4	1	20.75	yes
5	0.25	4	0.4	5	1.25	23.35	yes
1	0.05	5	0.5	3	0.75	14.75	x
3	0.15	5	0.5	2	0.5	16.4	x
1	0.05	5	0.5	4	1	17.75	yes

Figur 1 The concept scoring matrix featuring each need along with its weight percentage. The gripper names' colour indicates what type of gripper it is. Impactive (blue), Ingressive (green) and Astrictive (yellow).

The concept scoring results showed a wide spread of scores, ranging from 14.75 to 23.35. The concepts that scored the highest are typically selected to be developed further. The three highest scoring ones were the Marlin gripper, and the Needle grippers and the Vacuum Suction gripper. To gain some diversity in the gripper types, the Simple Clamp gripper was selected instead of the Marlin gripper. Even though the Adaptive gripper had a relatively low score of 17.75, it was selected for further development as it is relatively simple to construct (as opposed to the other mechanical grippers). With the 4 gripper concepts selected, the next stage in the gripper development could begin.

3.7 Prototyping

In this development stage, working prototypes were constructed and tested. The purpose is to confirm that the grippers function the way they were intended before further refinements are made. First, a digital version was designed to determine the correct dimensions. This was done to avoid time-consuming mistakes during construction and to create the 3D printable parts. The prototypes were constructed using a variety of materials and methods. The most common fabrication method was done using the available 3D printers from Prusa. The versatility of 3D printing allowed for quick production of prototypes, that could easily be revised with alterations in the digital CAD models. The majority of parts were printed in Polyethylene terephthalate glycol (PETG).

Simple Clamp Gripper

The Simple gripper was constructed first, as it has a straightforward design. The components were made from various materials found around the workshop. Using the *Hand-E gripper* by Robotiq, which uses two parallel linear actuators, the gripper can be opened and closed directly from the UR interface. The rest of the gripper was built using flat aluminum profiles with cardboard gripper hands, which were attached using the 3D printed connectors in red.

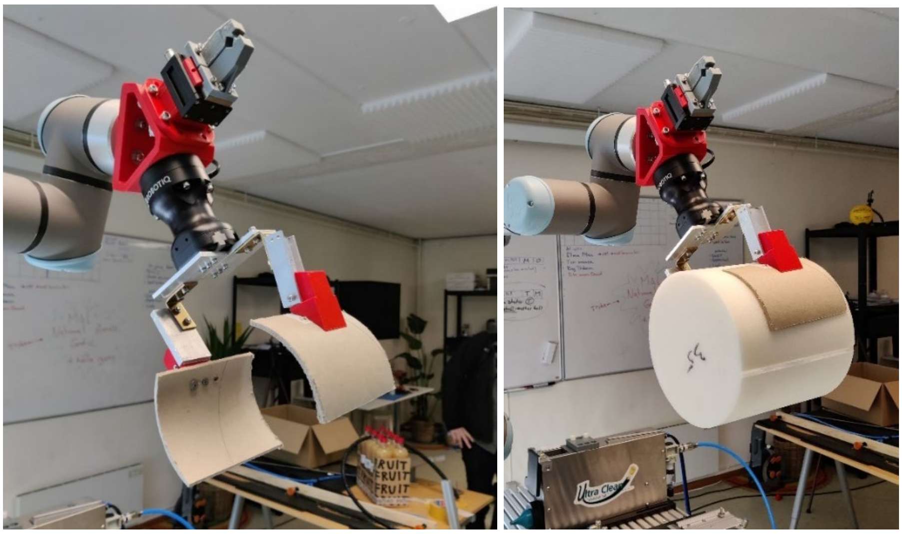


Figure 3.6 Image of the Simple Gripper, with- and without a cylinder

Adaptive Gripper

The second prototype is the Adaptive Gripper, which also makes use of Robotiq's linear servos. The Adaptive gripper can grasp cylinders lying perpendicular and parallel to the tool mounting plate using circular, encompassing clamps. The gripper was constructed using rolled sheet metal to make the gripper as light as possible, while retaining some rigidity. The plates are kept in place by a 3D printed connector that was then attached to the aluminium arms. The gripper requires a large space to open extend full, especially for cylinders that lie perpendicularly. To minimize this issue, the sheet metal clamps can be trimmed along the clamps to decrease the clamp span when the gripper is open.

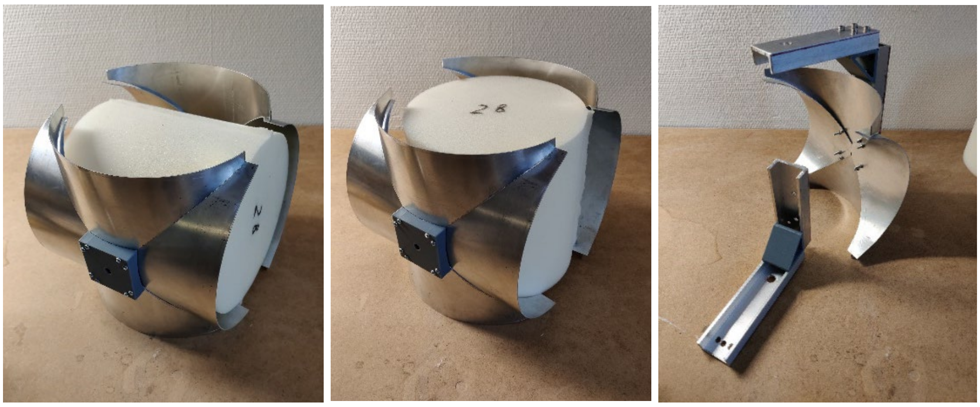


Figure 3.7 Images of the Adaptive Gripper, holding a cylinder in in two orientations.

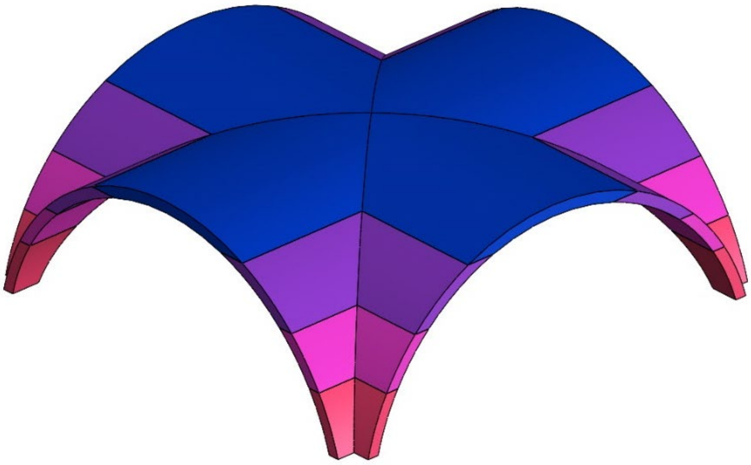


Figure 3.8 Examples of possible clamp depths to trim the prototype at.

Needle Gripper

To explore alternative picking methods, a prototype of the needle gripper was selected. To control the movement of the cover, a Pressurized air was used. Pneumatic cylinders offer accessible linear motion with the help of a controllable valve to open and close the airflow. The pneumatic cylinder is a spring-loaded single acting type of cylinder, meaning that the cylinder extends when air is supplied and retracts when it isn't. Inspiration was gained from a needle pad gripper, that was designed for foams (Zoller, Zentay, Meggyes, & Arz, 1999, pp. 234-237). While linear control using electronic motors offer more accurate control, it also requires complex driver boards and mechanical systems, making it more expensive. This tool only requires enough force to push the foam cylinders off the tool, making pneumatic cylinders adequate for the task. The airflow is controlled by a valve that can be controlled directly from the UR Control unit. For the piercing tool, 30mm long pin-needles where used. The rest of the parts were 3D printed in PETG.

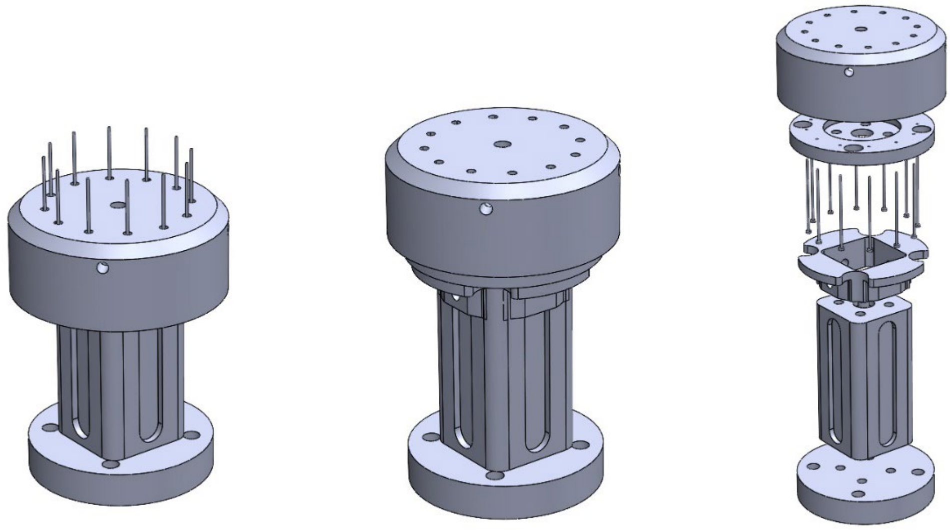


Figure 3.9 CAD model of the needle-gripper in its retracted state (left), it's extended state (middle) and exploded view (right)

The bottom collar can be removed whenever needles need to be replaced. This function is helpful when using affordable pin-needles since they are frequently undergoing plastic deformation during tests.

Vacuum Gripper

Vacuum suction cups are advantageous when grasping larger objects with multiple unique gripping points as they can conform to curved surfaces. Much like the needle-gripper its required volume for gripping is also small. Pneumatic grippers struggle to pick up foam-based objects because of their porosity. This can, however, be compensated for with enough air-flow.

A simple calculation was made (see Appendix B.5), which was based on the approach by A. K. Jaiswal1 and B. Kumar in an article (Jaiswal & Kumar, 2017). However, the result of said calculations could not be considered viable as they did not account for large amounts of air-leakage due to the foams porosity. Instead, a simple version of the vacuum gripper was constructed out of 3D printed parts to be tested. The suction cup type is of the bellow type, which is ideal for concave and rough surfaces. (Jaiswal & Kumar, 2017)

Figure 3.10 Image of the vacuum suction gripper

3.8 Physical Tests on Prototypes

Tests were conducted to evaluate the grippers based on the criteria, ability to grasp and reliability as they influenced the choice of concept the most.

After connecting the gripper prototypes to the robotic arm, the cylinders were to be picked up under 3 different conditions:

- **Case 1**: Ideal conditions: the cylinders lie on a flat surface in line with the gripper. The cylinders will be tested standing up and lying down.
- **Case 2**: Angle and Position deviation: The cylinders are picked with a deviation in the x-, y- and z-axis and in the Euler angles denoted as α, β, γ.
- **Case 3**: Tightly packed bin: Multiple cylinders share a confined space. The reason is to test the grippers ability to grasp cylinders that are occluded and its ability to lift objects that may be stuck. To lift a cylinder, extra force is required to overcome the interfacial friction between 2 cylinders or between a cylinder and the bin’s surface. For this test, a small bin is used with three tightly squeezed cylinders inside.

Each of the test cases were performed with the cylinders lying down sideways and standing on its bottom surface.

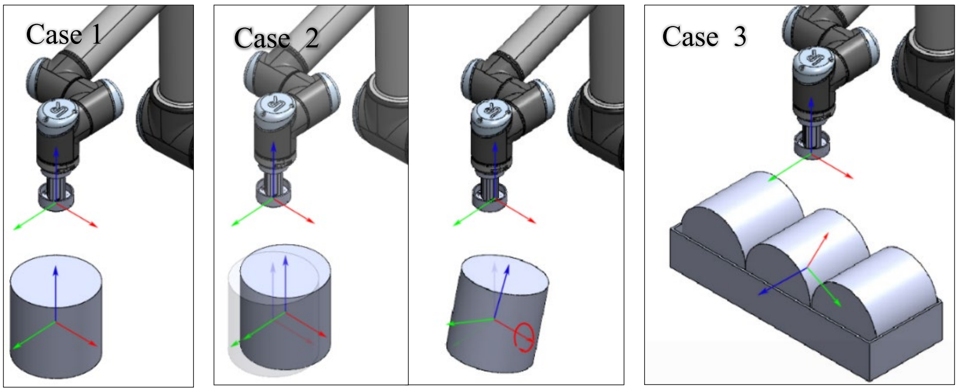


Figure 3.11 Possible picking offsets. Case 2 shows cases for positional and orientational deviations. The images were made in Solidworks.

Depending on each case, a test-rig had to be implemented. Case 2 required the cylinders to be tilted and displaced in various directions. To handle the possibilities, an adjustable rig was built (images and explanations can be found in Appendix B.2). The rig was constructed out of various materials found at the workshop. It is able to rotate the cylinder in all three axes. Due to the rig's inaccuracy, it was replaced by simple 3D printed blocks that were placed under the cylinders to angle them. For the x, y and z displacements, the robot arm is jogged linearly in each of the directions.

Test results

The tests were conducted on each of the grippers. Case 1 showed a consistent behaviour on all grippers except the vacuum suction type. The gripper was not able to generate enough lift to pick up a cylinder, even with multiple suction cups and larger tubes. For this reason, the gripper was discarded. The Simple gripper was able to lift the standing cylinder, despite its lower traction.

Case 2 showed promising results as the grippers were able to grasp even larger deviations in both rotation and translation. The adaptive gripper was able to handle large rotations along the z-axis. The needle-gripper outperformed the mechanical grippers and was able to handle rotational deviations for all rotational orientations and large positional deviations of the cylinders.

Lastly, case 3 revealed a severe flaw for the mechanical clamp grippers. Both the Simple and Adaptive grippers were unable to grasp a cylinder from the box due to the width needed of the gripper to reach around the cylinders. The density and friction of the cylinders cause the grippers to deflect, transferring a large amount of bending-torque on the linear actuators. The adaptive gripper clamps were trimmed by 65mm. This resulted in smaller, less obtrusive clamps, in hopes to reduce the probability of collisions. The problem persisted, as the clamp arms remain common collision points. For this reason, both the Simple and the Adaptive gripper had to be discarded. The needle gripper, being a single point gripper, was unaffected by the surrounding cylinders and could perform the lifting operation repeatedly.

3.9 The Chosen Concept

3.9.1 **Intent**

Due to the needle gripper’s superior picking ability, it was selected to be the final concept. The advantages and disadvantages are firstly discussed in the subchapter 3.9.2. Subchapter 3.9.3 and 3.9.4 discuss aspects of the gripper that required extra considerations. Section 3.9.3 section is about needle dimensioning and was included as it highly influences the grippers grasping ability. In 3.9.4 the needs, safety and reliability are discussed that the tests could not reveal by themselves.

3.9.2 **Advantages and Disadvantages**

Due to the needle gripper’s superior picking ability, it was selected to be the final concept. The advantages that come with it are as follows:

Pros

Invariance in the z-axis	The gripper is invariant in the z-axis, which will simplify the grasping process.
Robust gripping with low risk of fail	The gripper can attach itself to the cylinder even if the deviations are high.
Space-efficient	The gripper uses a minimal amount of space.
Detachment mechanism	The gripper features a mechanism to detach the cylinder from the needles mechanically.

Cons

Safety	The gripper uses sharp needles that pose a safety risk

Table 3.2 Pros and Cons of the needle gripper concept

Contrary to e.g., a 2-jaw gripper, the gripper is symmetrical along the z-axis of the tool. This reduces the computational complexity (see chapter. 4.2.3) and minimizes possible collisions with other cylinders. The small form factor is also an advantage in picking hard-to-reach cylinder. The cylinders are detached from the gripper by extending the cover and thereby pushing it off the needles. This cylinder actuation slides instantaneously but can be adjusted to release in a more controlled manner if necessary.

Figure 3.12 Image depicting the complete needle gripper while the cover is retracted.

3.9.3 **Needle Dimensions**

The test cases revealed that the needles dimensions are a significant factor for the gripper's performance. Parameters such as number of needles, needle length and diameter determine the gripper's ability to penetrate the cylinders and hold them in place. Though material specifications are influential too, they are more difficult to control due to the lack of material data on store-bought needles and the PU foam. Zoltán Zoller (Zoller, Zentay, Meggyes, & Arz, 1999, pp. 231-233) shows a possible way to calculate pull-out and intrusion force for specific needles for PU foams.

For this gripper, 12 pin needles with 40 mm length and 2 mm diameter were selected based on empirical tests. With these dimensions, the needles can be fully driven into the material with little force. The holding force is high enough that they will not fall off, even when subjected to high accelerations.

3.9.4 **Reliability & Safety**

Even though the tests showed satisfactory results, long term effects are a potential concern for the current gripper. As the gripper was only made up of 3D printed parts, possible improvements should be made to increase its longevity and make its gripping operation more robust.

- Stronger & stiffer needles (e.g. leather needles)

- More Robust structure
- Machined metal parts for less friction and longer lifespan

Odigo offered to purchase commercial needle grippers from Gimatic to conduct tests. Two different grippers were selected to be tested from which a new gripper was designed and constructed. The grippers work by extending multiple small needles in 45 degrees to the tool flange. This way, the picked object is held in place due to the holding force of the crossing needles rather than friction.

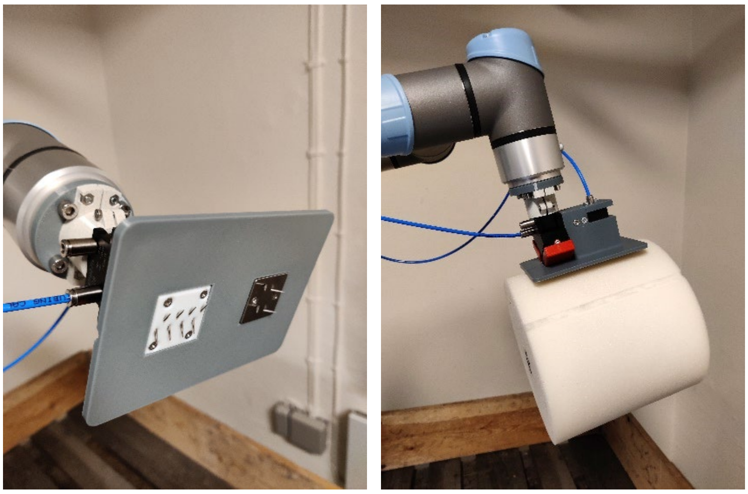


Figure 3.13 Image depicting the commercial gripper with extended needles (left) and while holding a cylinder (right). The needles point 45 degrees away from the plate.

This design was abandoned after performing the testcases from chapter 3.8. The tests showed that neither of the grippers were able to lift cylinders reliably due to their limited stroke length. The short distance of the needles and the fragility of the foam caused the cylinders to frequently break loose from the needles' grip, particularly on the gripping point 3, showed in Figure 3.14 to the right.

To improve the original needle grippers' robustness, four machined metal guiding pins were used for the sliding cover mechanism. Although more could be done to improve the mechanisms rigidity, this was an effective measure given the available development time.

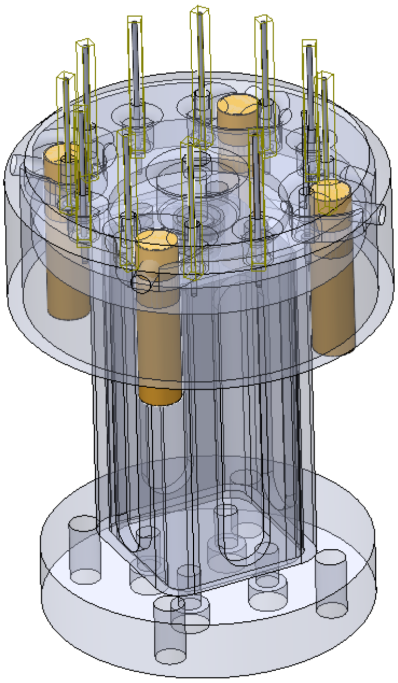


Figure 3.14 Image of the needle gripper. The orange cylinders are the machined guiding pins.

Safety is a factor to consider when using ingression-type grippers. As the gripper is part of the robotic system, it plays a role when confirming whether the robot is collaborative. For this gripper design, the retractable cap acts as a protective measure to shield humans from the needles. It retracts only whenever the gripper is in use and extends to detach the cylinder from the gripper. This way, the needles are only exposed a fraction of the cycle time. This feature helps but cannot keep the robot's collaborative status by itself. Proposals for more safety features will be covered in chapter 4.4.

3.10 Reflection

Some reflections were made on the approach of the gripper development.

The gripper was developed entirely using Ulrich & Eppinger's model for product development. This methodology allowed for an exploration of a diverse range of ideas, which converged into a final concept. The Double Diamond Model was also considered as it uses a more holistic approach. For instance, exploring the grippers in relation to the fixture and the filled bin may have helped to understand the root problem better. Nonetheless, the chosen development model allowed a diverse range of ideas to be explored systematically.

The market analysis was skipped in the beginning to bring new ideas to the problem. Many gripper types were not known about until the search for the commercial gripper had started. This partly kept the concept generation open minded but could at times limit its divergence. Future development could benefit from researching competitor's products more and to incorporate elements into the concept generation.

The concept testing was a necessary step in the process to prove each grippers capability. The choice of testcases and execution of them were based on observations made on the cylinders and the bin picking station. A more thorough analysis of the cylinder configuration inside the bin could have confirmed the relevance of each case.

Due to the structure of the project, the gripper was developed before the Vision Software could be tested. Certain issues related to the Vision System were discovered during the Bin Picking Station implementation. An alternate structure of the thesis could consist of a parallel development of the gripper and the Bin Picking software. In the end, this structure was acceptable due to the 3D vision equipment only being available much later in the project (see Appendix A).

3.11 Conclusion

The development of the gripper was concluded. A foundation for the development process was set by establishing the product specifications and discussing both task-specific and general background around grippers and the cylinders. The concept generation phase allowed for free creation of ideas. After the selection of ideal concept candidates was made, prototypes were constructed and tested using three different test cases. In the end, the needle gripper stood out as the most suitable gripper and was selected. Correct needle dimensioning and small guiding rails served to further refine its design.

The gripper was complete and ready to be included in the bin picking solution. This ingressive gripper takes advantage of the foams porous characteristics while also remaining mostly unaffected by the materials elasticity. It is a single-point gripper, giving it large flexibility and high success-rate while picking.

Even if this partial objective is completed can the solution's validity only be confirmed once the rest of the bin picking system is set in place.

4 Bin Picking

With the completed end-effector design, the computer vision system side of the project can now take place. This chapter breaks down each of the steps taken to create the complete Bin-Picking system from start to finish.

4.1 Approach

4.1.1 **Flowchart**

The necessary steps needed to complete the Bin Picking routine are numerous and influence each other. The flowchart below (see Figure 4.1) serves to illustrate the approximate order of steps taken, even though frequent backtracking was unavoidable.

- **Test station build** – The first step is to construct a virtual station in the Bin Picking Studio (BPS) software and a physical test station.
- **Scanner Configurations** – The Photoneo Scanner is set up using PhoXi Control to gain high quality cloud point data.
- **Gripping Points Selection** – After having designed and loaded all Cad models to the vision controller, decisions on gripping points and invariance were made. This concept is described in Chapter 2.2.2.3.
- **Object Localization** – To ensure accurate matching of object models and their real-life correspondence, the localization must be tested. Chapter 2.2.2.2 explains the concept of Pose Estimation.
- **Waypoint & Trajectory Calculation** – Measures for improving the waypoint and trajectory calculations are taken. Like mentioned in chapter

2.2.2.3, efficient path planning ensures low cycle times and low risk of collisions.

- **Fixture Design & Placement** – The fixture for object placement needs to be designed and constructed. The fixtures' purpose is to position the cylinders for the subsequent production step.
- **Testing** – The station is tested, and its cycle time is calculated.

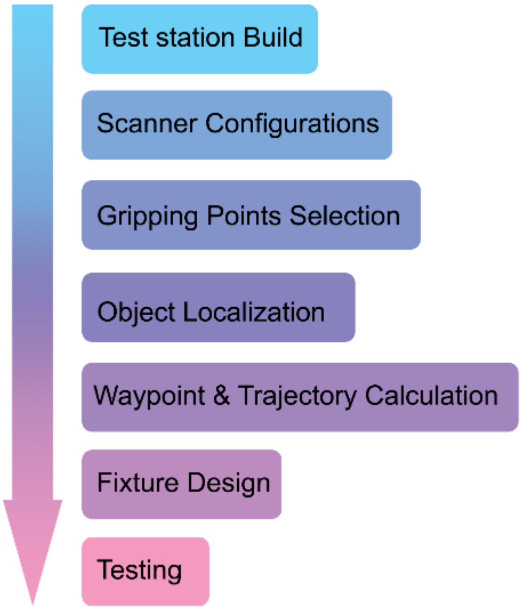


Figure 4.1 Flowchart showing the steps taken to design the Bin Picking System.

4.1.2 Firmware Structure

An explanation on the firmware structure and its key components is necessary.

The structure was chosen based on what equipment Odigo had at their disposal. Besides the UR10e robot (and its Robot Controller unit), a Photoneo PhoXi 3D scanner was used. This scanner sends the data it collects to the vision controller unit, whose job it is to host the Bin Picking Server. The vision controller (Bin Picking Server) uses the collected point cloud data to output desired robot arm trajectories to the Robot Controller, which then executes them on the robot.

The Bin Picking Server and the Robot Controller form the core of the firmware hierarchy as they together locate, pick, and place the target objects through a series of commands.

The desktop monitor is only used to access BPS that’s installed on the vision controller.

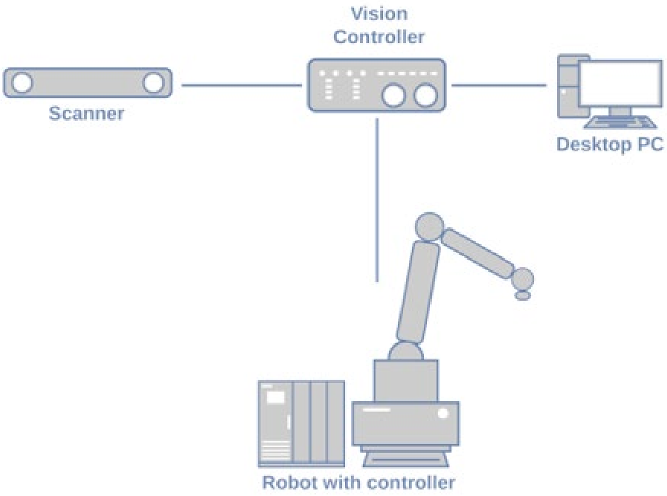


Figure 4.2 The proposed structure of the vision system

4.1.3 **Bin Picking Studio (BPS)**

BPS is the software that was used to complete most of the steps to develop the Bin Picking routine. It hosts a virtual representation of the bin picking station in which the robot is simulated. The browser hosted software contains the necessary functions to create and simulate Bin Picking applications. Certain functions such as the command for the gripper and the placing operations must be implemented on the Robot controller using UR code.

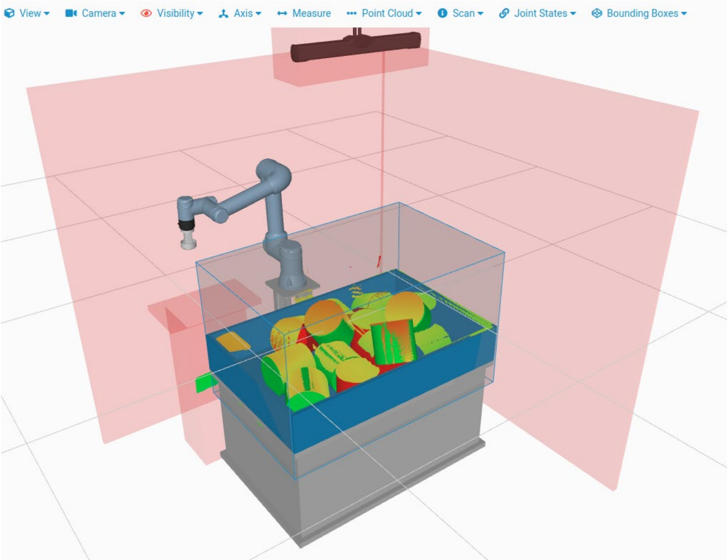


Figure 4.3 The Robot station environment. BPS provides a user-interface containing a simulation of the robot and its environment that updates in real time.

4.1.4 Photoneo Camera & PhoXi Control

PhoXi Control is an application that acts as driver for the Photoneo 3D Scanner. Its GUI is used to configure the Scanners settings. The camera can be triggered to test the quality of the point cloud. A good point cloud should capture the target geometry well and be free of noise. Depending on the result, the camera position may also need to be adjusted. The Scanner settings can be saved as a Vision profile, which is then used to set up the localization profile in BPS.

4.2 Implementation

4.2.1 Test station build

A real and a virtual test station were created.

The real station's main parts are the robot arm, the bin and the fixture table and the Photoneo Camera. The robot arm was securely mounted on a support structure to hold it in place. The bin was constructed out of stacked Euro-pallets and a pallet collar which acts as the bin walls. To place the cylinders, a simple cardboard box was used as a table. The table receives its fixtures at a later stage in the process.

Lastly, the Photoneo Camera was mounted above the bin with the help of extruded aluminium profiles.

The station was also constructed virtually in BPS. Besides serving as a visual representation for the user, the virtual model is used by the Vision System to detect surrounding obstacles and generate appropriate robot trajectories. Joint constraints could still be incorporated as an additional security measure to prevent collisions.

Figure 4.4 Image depicting the real-world test station (fixture table not yet added)

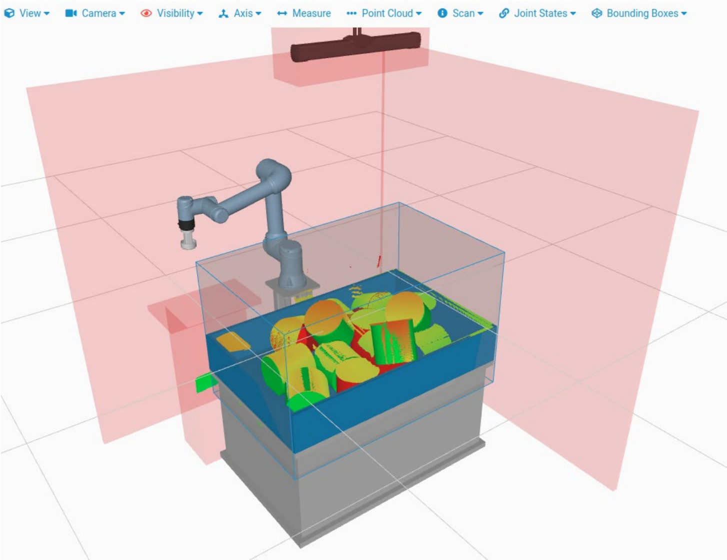


Figure 4.5 Image showing the virtual station. The blue, see-through boundary box indicates the space the robot uses to perform bin-picking.

4.2.2 Scanner Configurations

The 3D scanner must be configured to get reliable point cloud data. This is done using the PhoXi Control application included in BPS. For this picking application, many settings can be left untouched. The foam has a rough surface texture with low reflectivity allowing it to absorb the projected light. Though the images show a high-quality 3D point map, a small amount of noise is visible. Though it will not affect the object-matching algorithm, it can be registered as an obstacle for the path generation algorithm. The source of the noise is unknown, and for this reason data-cutting is introduced in the z-axis. This means, that the algorithm deliberately ignores recorded points at a certain height. This solution was viable as the amount of noise was reduced significantly.

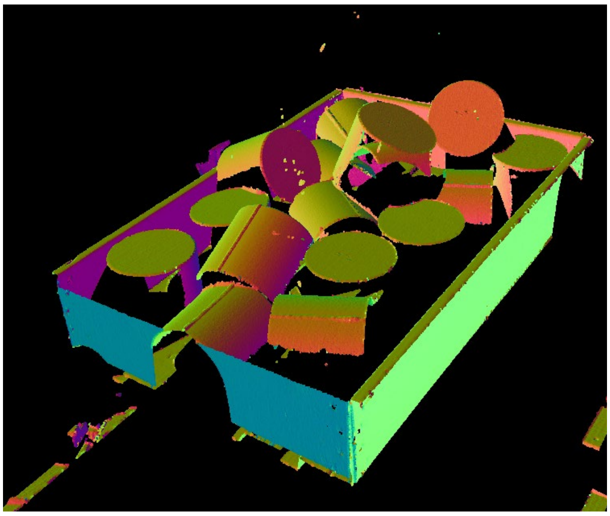


Figure 4.6 Image showing the point cloud map of the scene in PhoXi Control. The Surfaces are coloured according to the direction of the surface normals.

4.2.3 Gripping points and Invariance Selection

Three unique gripping points where already previously determined in chapter 3.4. For a cylindrical object, these are located on the top and bottom side and radially. The radial position is invariant in the z-direction, meaning that the cylinders can be gripped around the circumference. The tool is in this case also positionally invariant in the z-direction.

In the end three different gripping points are registered in the program. Priority levels can be assigned to each point in case a certain point is preferable to pick from. This was left untouched to instead give picking priority to cylinders that are higher up.

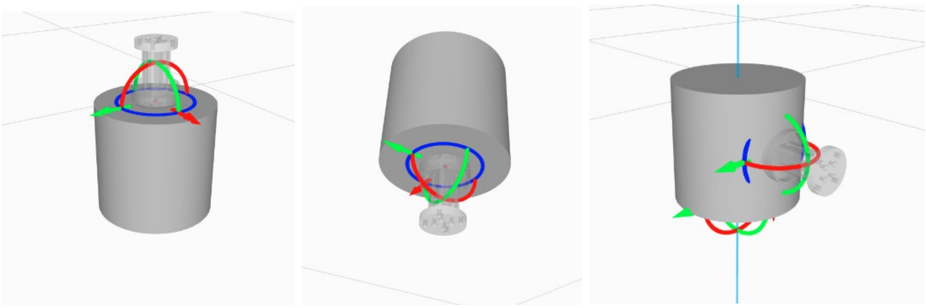


Figure 4.7 . Images of the three gripping points. The blue, translucent line in the third image depicts the z-axis around which the invariance points are placed around,

The invariance settings are very important as they directly impact the optimization of the program. The amount of invariance points determines the number of points the gripper can attach to. Too few points limit the possible joint configurations of the robot, while too many can make the calculation of the possible join angles computationally demanding. The computational time should be kept low to not slow down the detection routine. For this task, 12 invariance positions enabled the robot to approach the cylinders from an acceptable number of angles.

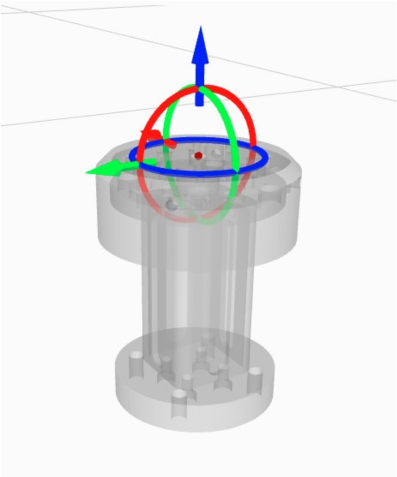


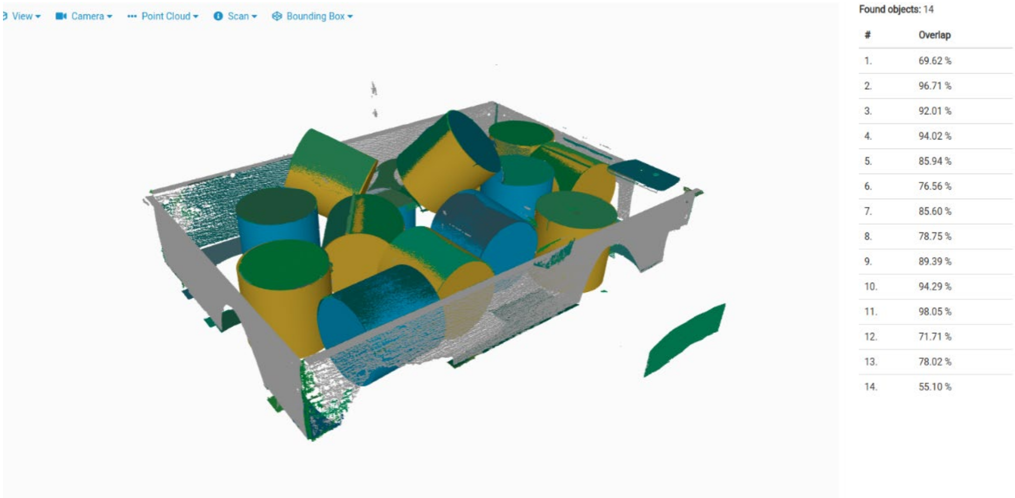
Figure 4.8 Virtual gripper tool with its TCP. Invariance in the z-axis (blue) is turned off.

The attached tool also has options for invariance when determining its contact point. Whether invariance is turned on here doesn't affect the outcome. To mitigate any possibility for added computational complexity it is left off.

4.2.4 **Object Detection**

After testing three different cylinder placements, the localization of the cylinders was tested. The vision controller uses template matching to align the hull of the CAD model with the point cloud geometry. The *alignment* measures how much the two surfaces intersect with each other and is an indicator of how confident the program is in its cylinder registration.

It managed to align with all 14 of the cylinders with a minimum percentage of 55.1%. The localization program was performed on two other bin configurations to ensure consistent results. The overall lowest value was above 55 % and the mean percentage was 82.68 %. The algorithm manages to consistently detect less occluded cylinders but may experience failure with cylinders that are too close to the camera. This is logical as surface coverage is lost at proximity to the laser. The cut-off value was placed at 50% to eliminate any misplaced cylinders.



Found objects: 14

#	Overlap
1.	69.62 %
2.	96.71 %
3.	92.01 %
4.	94.02 %
5.	85.94 %
6.	76.56 %
7.	85.60 %
8.	78.75 %
9.	89.39 %
10.	94.29 %
11.	98.05 %
12.	71.71 %
13.	78.02 %
14.	55.10 %

Figure 4.9 Image of the localized cylinders inside the bin. The dark green texture represents the point cloud.

4.2.5 **Waypoint Calculation & Path Planning**

4.2.5.1 Waypoint calculation

To calculate a path for the robot end-effector to move along, the waypoints are firstly calculated for the key positions. For a normal bin picking operation, usually not more than 5 are required:

- **Start** – the starting position of the bin picking process defined in the initialization request
- **Approach** – a relative offset from the grasp position
- **Grasp** – the grasping position computed based on the gripping point and tool point definitions
- **Deapproach** – a relative offset from the grasp position
- **End** – the ending position of the bin picking process defined in the initialization request

The start-, the end-, and the home position are defined in the UR script while the rest are unique to every program cycle. Though they are dependent on the gripping point position, they can be configured to behave differently. For this task the deapproach point will be placed far into the z-direction to gain clearance from other cylinders.

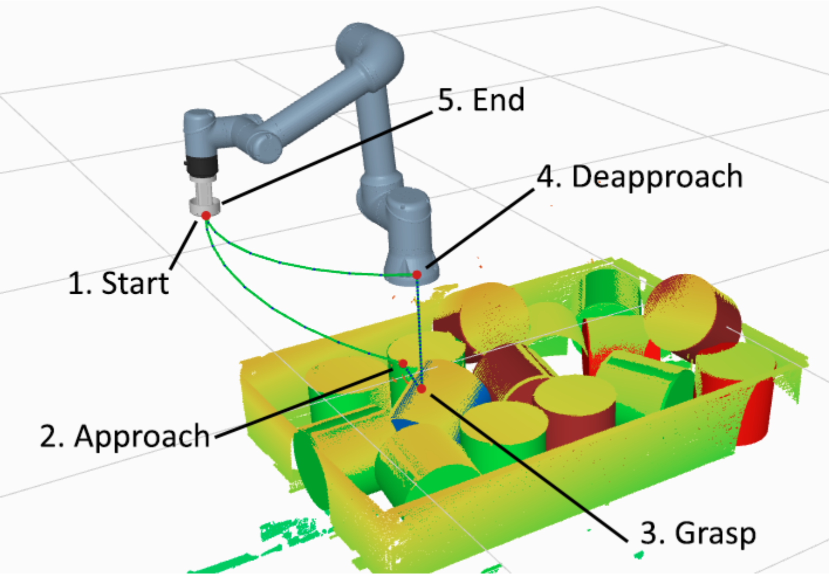
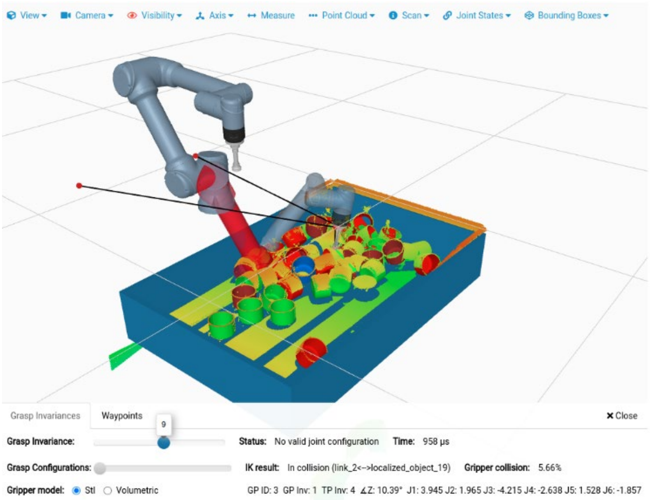


Figure 4.10 Image showing the names and location of the used waypoints which are connected by trajectories. The red cylinders are cylinders that were marked as unpickable due to path generation issues or waypoint placement issues.

The vision system initially struggled to calculate waypoints for most cylinders. Test-simulations revealed that the program detected collision results while calculating waypoints, which resulted in many of the pickable cylinders to be deemed non-pickable. The collisions happened mostly during the grasping stage. To get around these collisions, the distance of the TCP was slightly increased beyond the surface of the cover plate, resulting in an increase of pickable cylinders. Changing the collision sensitivity of the gripper can make the vision controller more lenient to collision detection. Although an increase in by 40% is sufficient, 60% yielded a higher number of pickable cylinders.

4.2.5.2 Path Planning

After suitable waypoints have been selected, the vision controller calculates a path along which the Robot arm end-effector moves. Though not as frequent, some of the unoccluded cylinders were deemed unpickable once again. Closer examination shows that the problem is largely due to incorrect inverse kinematics (IK) solutions (see chapter 2.1.2). An example of a false solution to the inverse kinematics of the robot is shown in Figure 4.11. Many settings can improve the IK solver but to remove the solutions that contain undesirable joint angles, the easiest solution is the implementation of joint angle constraints. This limits the robots working space but in return gives more predictable path planning.



Grasp Invariance:
Status: No valid joint configuration Time: 958 μs
Grasp Configurations:
IK result: In collision (link_2<-->localized_object_19) Gripper collision: 5.66%
Gripper model: ● Stl ○ Volumetric
GP ID: 3 GP Inv: 1 TP Inv: 4 ∡Z: 10.39° J1: 3.945 J2: 1.965 J3: -4.215 J4: -2.638 J5: 1.528 J6: -1.857

Figure 4.11 Image depicting an example of an incorrect inverse kinematics solution, causing the arm to collide with the bin.

The joint angles below (see Figure 4.12) were decided after careful testing by jogging the robot arm to the outer-most positions of the desired working space. A correctly tuned robot working space should have joint angle values that prevent unpredictable and poorly optimized paths that also do not restrict the path planning algorithm excessively. As the robot uses pressurized air joints such as joint 5 uses a restricted joint angle range to avoid pulling apart the externally mounted air tube.

Joint limits

● Degrees ○ Radians

Joint 1 range [°]: 0 – 269.8

Joint 2 range [°]: -179.9 – 0

Joint 3 range [°]: -179.9 – 89.9

Joint 4 range [°]: -219.4 – 89.9

Joint 5 range [°]: 0 – 179.9

Joint 6 range [°]: -359.9 – 359.9

Figure 4.12 Image depicting the final joint limit settings. Joint 1 refers to the joint of the base while joint 6 controls the rotation of the toolflange joint.

4.2.6 **Fixture & Placement**

4.2.6.1 Fixture

Before the fixture was constructed, brief placement tests were conducted with the existing cardboard table with a separate UR script. The results showed that the robot could repeatedly place the cylinder on the same position.

Despite this, a fixture is needed to align the cylinders more accurately for the preceding production step. A list of needs and corresponding specifications was created (see Table 4.1).

Nbr	Need	Specification	Unit of measurement	magnitude
1	The fixture is lenient towards cylinder misalignments.	Cylinder concentricity tolerance	mm	20
2	The fixture should allow the yaskawa robot to grip the cylinders.	Clearance from cylinder top	mm	110
3	The fixture should allow placement of required cylinder orientations.	Both cylinder orientations are supported	Binary	yes
4	The fixture should be quick to develope.	Development time	seconds	N/A

Table 4.1 The fixture's needs, their respective specifications, unit of measurement and magnitude.

The fixture can take various forms to meet the requirements. For this task, a simple fixture is desirable to minimize development time. Besides simplicity, the cylinder requires a modest positional accuracy to allow the Yaskawa gripper to encompass the cylinders.

The first design was a passive fixture with a bottom-locating bucket-like design. The side flaps are formed like a funnel to allow misoriented cylinders to shuffle towards the middle. The flap in the back also functions to cushion the force of the cylinders when detached from the gripper. The flap in the front is missing to give clearance for vertical placements of the cylinders.

The design was modelled in SolidWorks and printed out of PLA. The design was printed in one piece, omitting assembly and alignment time.

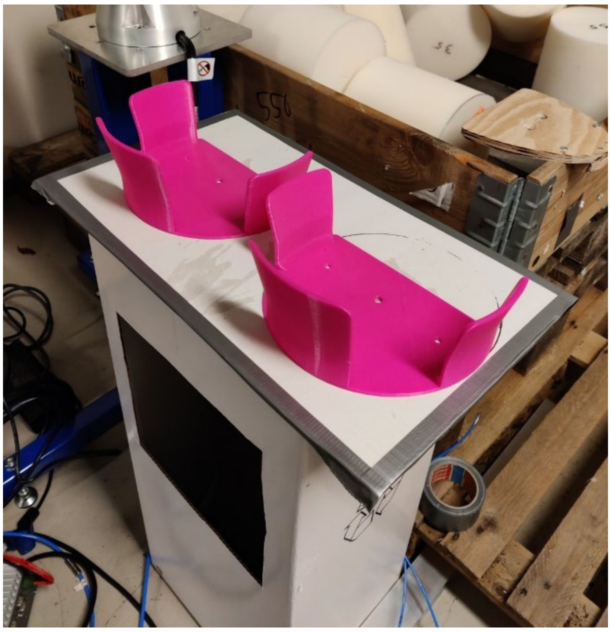


Figure 4.13 Table with fixtures for two cylinders

4.2.6.2 Placement

The cylinders were tested for the two placement orientations. The Bin-Picking program was run several times with different grasping positions. Positional misalignments up to 1 cm were handled well by the fixtures. Larger deviations caused the cylinders to stick to the inside of the flaps due to surface friction, rather than sliding along them. A simple preventive measure was to cover the inside surface of the fixtures with a smooth tape. The flap in the back can catch the cylinders as they are detached from the gripper during horizontal gripper placements, but the pressure caused by the piston causes the cardboard table to shake slightly. To prevent any displacement of the target placement positions, the table was reinforced with heavy steel sheets.

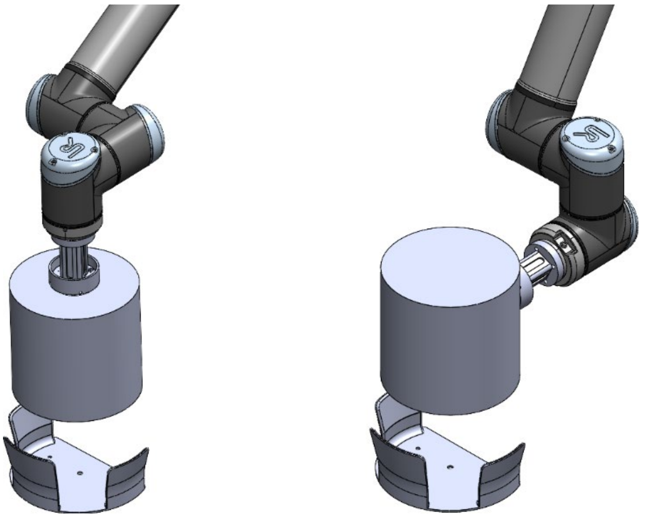


Figure 4.14 The two placement types. The cylinder is placed vertically downwards in both cases: vertical gripper placement (left) and horizontal gripper placement (right).

The UR code is programmed to switch between the two placement types depending on the Vision Controllers gripping point id.

4.2.7 **Testing & Cycle Time**

After the test station was constructed, the system was simulated to test reliability of the bin picking system. The purpose of the tests was to ensure that the system performs consistently on a multitude of cylinder arrangements in the bin.

The bin picking algorithm could consistently detect and pick the target cylinders with high precision. The program was configured to prioritize the top-most cylinders and cylinders that are unoccluded. Positional and orientational deviations affect the picking motion minimally, like the previous tests (chapter 3.8) have shown and could mostly be compensated for using the lenient fixture.

4.2.7.1 Fail cases

Despite the systems high pick-rate, it could fail to pick cylinders when certain conditions are met.

The gripper occasionally fails to impale the cylinders entirely when there is poor traction between the cylinder and other cylinders or the bin surface. While the needles are partly able to penetrate the material, the lack of traction may cause the cylinder to slide along with the robot end-effector, resulting in a poor connection.

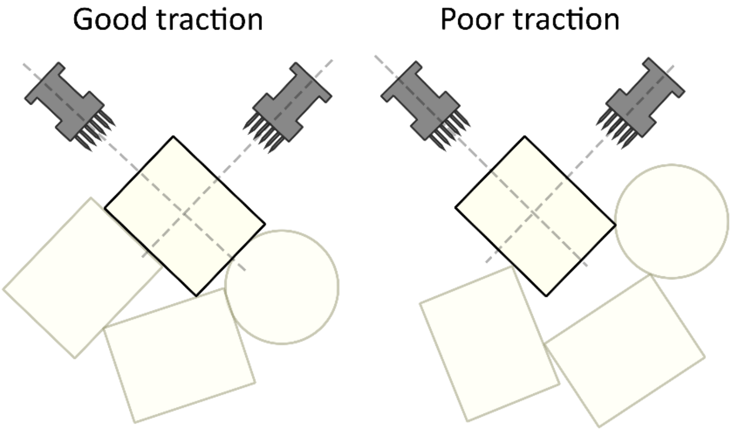


Figure 4.15 Graphical representations of two possible traction scenarios.

This problem results in 2 modes of failure. In the first mode, the cylinders slide off the needles during the penetrative motion. This means that the cover of the gripper stays retracted for the rest of the cycle, leaving the needles exposed to potentially cause harm. In the second failure mode, the cylinder stays loosely attached to the gripper. This may cause problems during placement, leading to pinched cylinders and plastic deformation of the needles. Issues such as these are unattractive as they often require maintenance of the station.

Possible solutions to decrease the fail-rate will be discussed in the Future Work section.

4.2.7.2 Calculation of Average Cycle Time

Data such as cycle time is interesting to better understand the systems capability to pick the cylinders. The BPS software keeps a record of the time it requires to complete each cycle.

From the initial settings, an average cycle time of 25.5 seconds was achieved. For the approach and deapproach operations 45% of all the robots maximum joint velocity and -accelerations were used. For the linear grasping and placement operations around 15% was used. These percentages were tested to produce the highest pick-rate-to-speed ratio.

Figure 4.16 Graph showing the cycle times using 45% of the robots' maximum speeds and accelerations (for the approach and deapproach steps).

Higher cycle time can be produced at increased joint speeds at the expense of a higher fail rate. As Figure 4.17 illustrates, an average cycle time of 15.7 seconds was produced with the motors running at maximum speeds. The fail-rate here is mostly caused by the transferred vibrations from the robot into the robot stand caused by the large accelerations. The real-world implementation with a more stable robot bench can be assumed to tolerate accelerations and speeds of this magnitude.

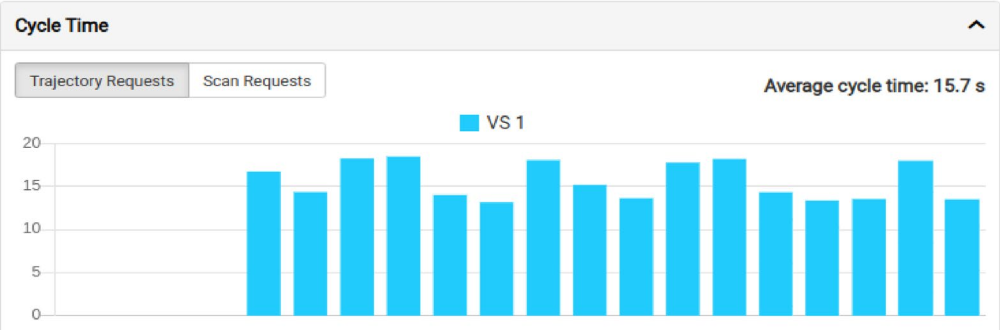


Figure 4.17 Graph showing the cycle times using the highest speeds and accelerations (for the approach and deapproach steps). Around half the picking attempts were unsuccessful.

4.3 Reflection

With the finished robot station design, the customer-oriented goal of the project had been completed. Developing the bin picking program and station setup was a complex task that required a multitude of decisions to be made within the given timeframe.

The time schedule may have influenced the final gripper design. The initial Gantt chart (see Appendix A) schedules a gripper to be developed parallel with the Bin Picking software. The equipment from Photoneo was provided the 18th of October. This schedule works as most work before that was dedicated to the gripper, early experimentation with the Vision System may have changed the outcome of the gripper design.

The Ulrich & Eppinger method (Ulrich, T., & Eppinger, 2012) was chosen to develop the gripper. This methodology works well when applied to the gripper but fails to take the system-level solution into consideration. For a multifaceted project such as this, other methodologies could have been considered. Although intentionally left out, a market analysis also could have enriched the variety of gripper designs.

The issue relating to cylinder traction (see chapter 4.2.7.1, fail cases) was an issue that was not tested during the prototype testing step. Further projects could benefit from a more in-depth study of the cylinders inside the bin to reveal all significant cases to test.

4.4 Conclusion

The bin picking implementation demonstrated, in the end, the objects suitability for this type of industrial task.

The bin picking routine can consistently move cylinders from the bin to the fixtures. To get a working bin picking routine, the BPS environment had to be set up by correctly tuning the variables. Though the PhoXi scanner provided an accurate point cloud, a noise reduction filter was introduced together with a point cloud limit to get better data quality. To get the waypoint calculation to work properly, the collision detection between the gripper and the cylinders had to be avoided. Setting up correct joint angle boundaries improved the path planning algorithm and made the path planning more predictable. The measurements made on the test station resulted in a high cycle time of 25.5 seconds. With a more reliable station and further optimized settings, this value is expected to go down significantly.

Although there is further work to be done, the bin picking routine proved to be suitable for this type of application due to the following reasons:

1. **Good surface texture of the foam cylinders**. The rough PU foam surface absorbs the projected light, leading to a point cloud with high accuracy.
2. **Large number of gripping points**. A combination of the single-point gripper and the invariance points of the cylinder enables the BPS to find and access many gripping points.

3. **Simple geometry of the picked object**. Simple shapes such as cylinders are ideal for template matching, making the virtual model accurate to that of the real world.
4. **Good gripper and object adherence**. The ingressive gripping method enables a reliable bond between the gripper and the cylinders.

4.5 Robot Station Design

To complete the bin picking station, a CAD model of the real-world implementation was drawn. The image below depicts the proposed station layout with all the necessary elements. The station includes all the necessary parts to complete the three bin picking steps described in the introduction 1.2.2.

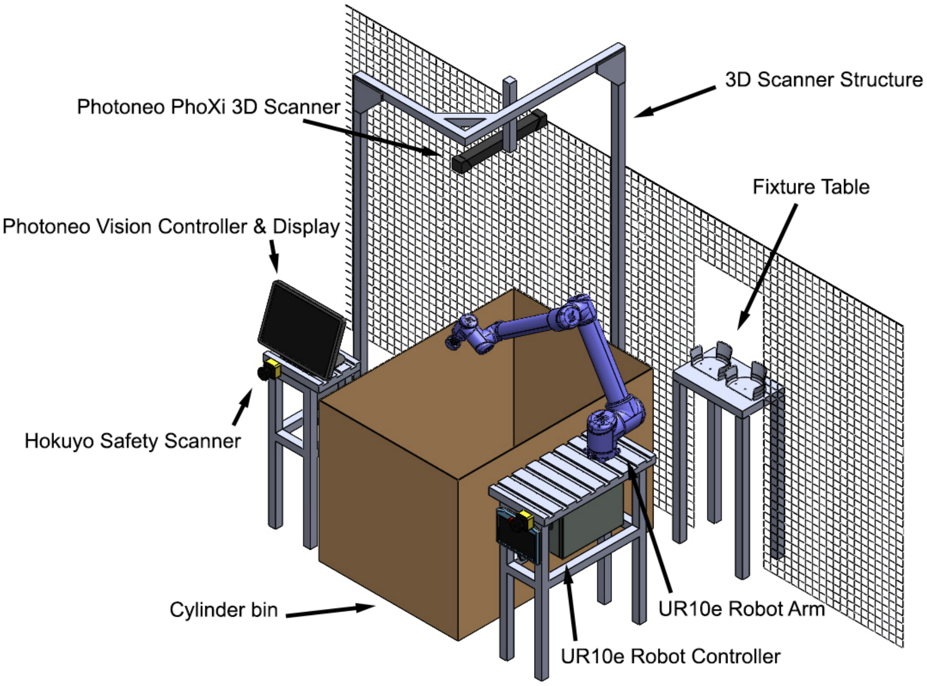


Figure 4.18 Schematic of the robot station.

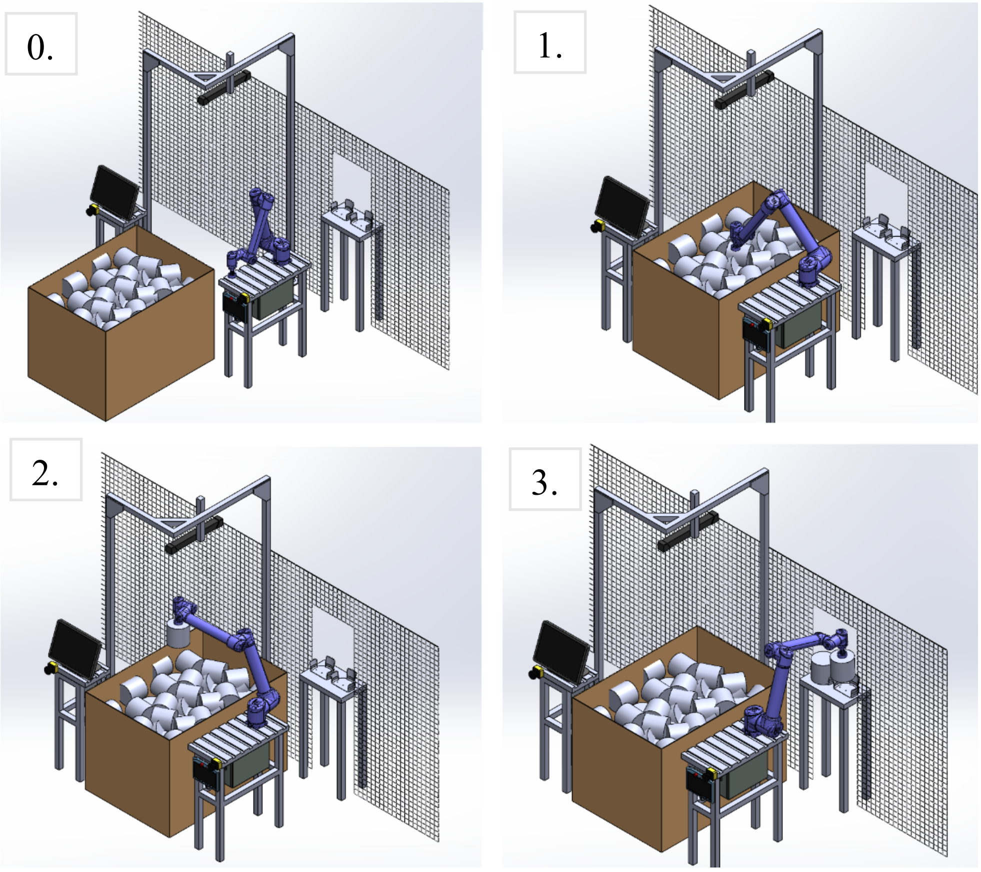


Figure 4.19 The initiation step and the three steps of a complete cycle the robot station.

4.5.1 **Program cycle**

With the box is placed in the picking workspace, the bin picking program can be activated on the vision controller display and on the robot control pad. The program will continue until the box is emptied. The program can be paused and resumed at any time during the program cycle.

1. Localization – pickable cylinders are identified and position/orientation is calculated.
2. Picking – The System selects a cylinder and grasps it using a suitable end-effector.
3. Placement – The Robot places the cylinder on a table or designated fixture.

4.5.2 **Safety**

This station layout functions without an enclosure, classifying its level of human-robot-collaboration as *coexistence* per definition by IFR (International Federation of Robotics (IFR), 2022). This means that the workers and the robots do not share a common workspace and the station does not need an enclosure. This type of solution necessitates the inclusion safety measures.

Precautions have been taken to ensure that the possibility of accident scenarios are mitigated. The retractable cover of the gripper ensures that the needles are only exposed during the grasping operation. The joint speeds and accelerations are configured to move slowly during the approach and deapproach steps.

Basic UR robot functions also contribute to the station's overall safety. All safety functions can be found in Universal Robots documentation (Universal Robots, 2022). Collision such as the triggering of the safeguard stop when the robot collides with an operator are included. Additionally, emergency stop buttons will be placed by the Vision- and the Robot controller.

Safety Laser Scanner can also be used to protect operators. For this, a high-end range finder from Hokuyo was selected. Its main benefits are its 270 degrees of coverage and high reliability. The BPS system can be configured to follow safety protocols when humans are detected within predefined distances of the station. A possible configuration is to slow down all robot movements by 50% should a worker enter the 3-meter radius and come to a halt if he/she enters the 1.5 m one. Multiple scanners grant the station coverage from all angles (see proposed scanner arrangement in Figure 4.20).

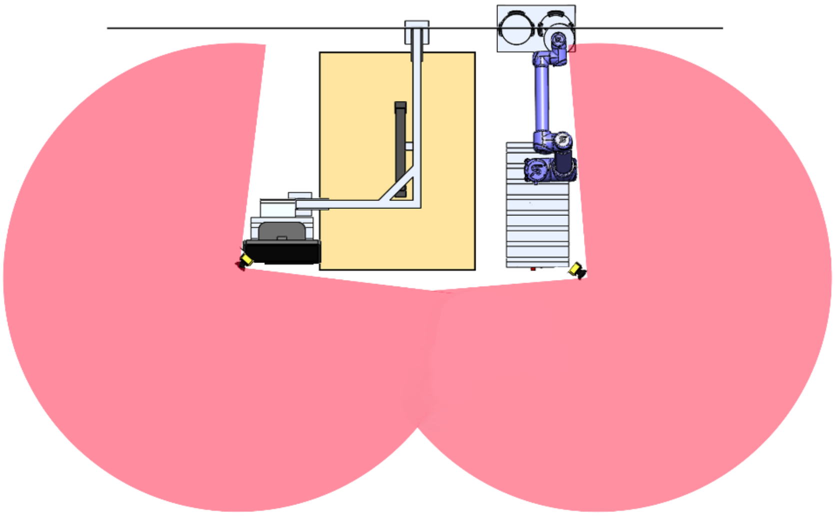


Figure 4.20 Image of the station viewed from above depicting a proposal for a safety scanner placement. The red area signifies the area covered by the scanners

5 Bin Picking, new case

The previous chapter concluded the development of the customer-driven project. This chapter aims to fulfill the secondary objective, (see chapter 1.3) to take a deeper look at bin picking, 3D vision and its challenges. It also serves to further test the capabilities of the Bin Picking Studio software.

5.1 Approach

For this project, a new object was selected to be picked. Odigo Consulting had prior plans to perform a bin picking task on plastic parts used as draining gutters in showers. These parts will be referred to as plastic cups in this chapter. These plastic cups have characteristics that makes bin picking more challenging and were therefore selected.

Changing the picking target is convenient as the transition uses parts of the existing software- and hardware setup. For this implementation, a new gripper, vision system and fixture were designed. Steps applied in the cylinder picking project are summarized and chapters such as the *Station Build* and *Cycle Time* are omitted to direct focus on the computer vision aspects.

5.2 Implementation

5.2.1 **Cup characteristics**

The plastic cups are 90 mm in diameter and weigh 50 grams each. As the parts are injection moulded, characteristic features such as parting lines, drafts angles and injection gate marks are present in the geometry.

The cylindrical shape of the cup makes it invariant in the radial direction, though care must be taken to avoid contact with the protruding lips that go in the axial direction. A CAD model of a cup was made to be used in BPS.

Since the material is a hard plastic (polypropylene), vacuum was selected as the most suitable gripping method. The simple implementation makes it ideal to perform this test.

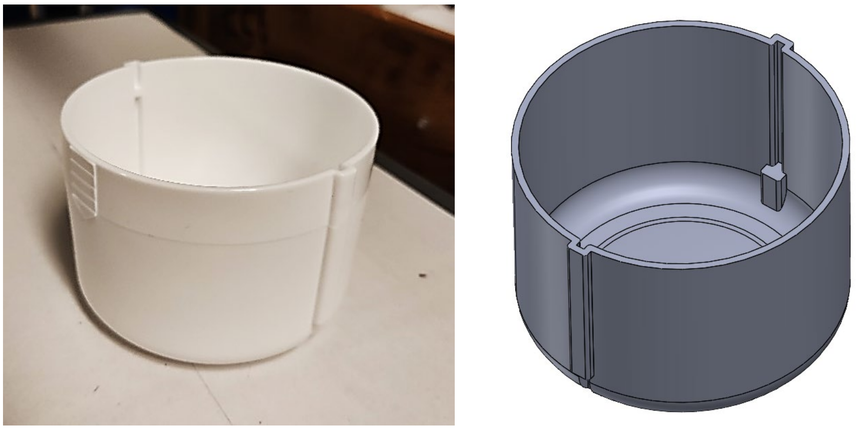


Figure 5.1 Images showing the plastic cup and its respective CAD model.

5.2.2 **Gripper Selection**

For this gripping task, a different gripper type needed to be used. The needle gripper demonstrated the advantage of a single-point gripper in bin picking. It provides invariance in the tool's z-axis and is non-intrusive, contributing to easier waypoint calculation. For these reasons, the previously constructed vacuum suction gripper (chapter 3.7) was selected. The gripper uses a single suction cup with a significant offset from the tool flange. This helps the tool reach cups that are obscured by obstacles such as the bin walls or other cups. Simple tests were performed to confirm its functionality with the plastic cups.

5.2.3 **Gripping Points**

Three unique gripping points were identified after inspecting the cup geometry. These points are located axially inside and outside the cup and radially on the cylindrical surface of the cups. Similar to the cylinder's case, the gripping point on the cylindrical surface is invariant in the cups z-direction (Figure 5.3: axis in blue). For the invariance number here, 12 was initially selected. The invariance gripping points on the protruding lips are special cases, as they prevent the suction cup from laying flush on the surface. For this reason, they were discarded, reducing the total number of invariances to 10. Like the needle gripper, the gripper is a single-point contact and so received no invariances along its z-axis (see Figure 5.4).

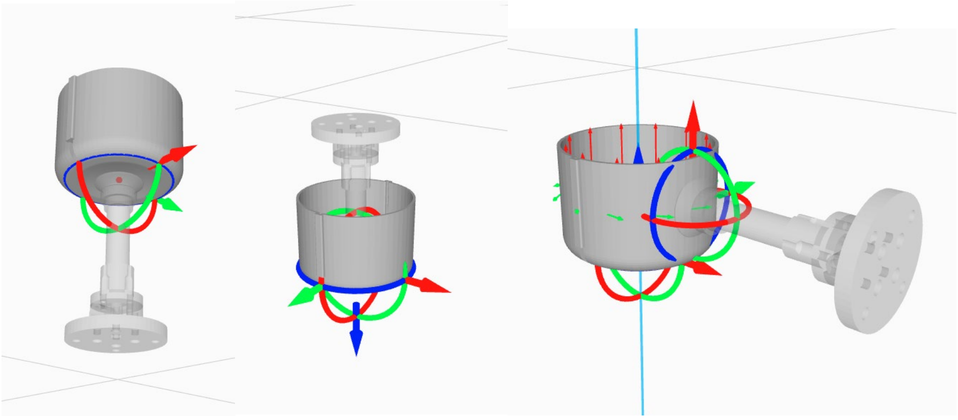


Figure 5.2 CAD models of the cups with all three gripping points.

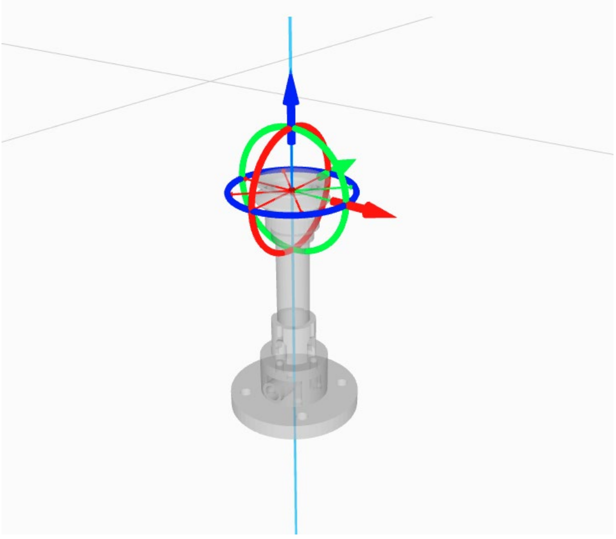


Figure 5.3 The TCP of the vacuum suction gripper.

5.2.4 Scanner Configurations

Difficulties in generating point clouds came along with the plastic surface of the cups. By observing the scanned point cloud, floating point cloud segments could be observed inside and above the bin. The problem shares similarities with research from Mohit Gupta et al. (Gupta, Agrawal, Veeraraghavan, & G., 2013, p. 2) where the floating point data can be attributed to reflections from the cups. Reflections are hard to avoid with even moderately glossy surfaces. The reason is likely due to long range reflections (interreflections) between surfaces that make it difficult for the camera to detect the geometry. The reason is that the generated stripe pattern from the Scanner gets overlaid with unwanted light. This is especially common for concave and rounded geometries such as these cups.

The image below shows the raw point cloud together with a 2D image overlay of the scene. From this image, many floating point segments can be observed above the bin. Similar images from Gupta (Gupta, Agrawal, Veeraraghavan, & G., 2013) can be found in Appendix C.2.These artifacts will be interpreted as obstacles from the vision controller and therefore must be removed.

Figure 5.4 Scan of a bin filled with cups. Above the bin, floating point artifacts can be seen.

Figure 5.5 Example of errors in point cloud reconstruction due to interreflections

Attempts at diminishing noise were made using different approaches:

- **Filters -** Attempts were made to reduce their influence using various settings. The resolution of the point cloud volumetric model was decreased (reducing the size of the point cloud voxels) and an interreflection filter was used. Even with these settings enabled, the noise did not change notably.
- **Lighting conditions** - Ambient lighting (often wavelengths contained in daylight) can contribute to errors in the quality of the point data. Different *Scanning schemes* can be employed to for the structured light projectors to increase the light beams intensity which are not supported by the BPS-software. (Gupta, Yin, & Nayar, Structured Light In Sunlight, 2013, p. 2) Attempts were made at scanning the scene with different light conditions in the room, with limited results.
- **Data-cutting** - Another option was to simply remove point segments from a distance from the camera. This method is effective at removing noise but can cause problems in later stages if the bin contents reach the set cut-off distance from the camera.

Despite its drawbacks, Data-cutting proved to be the most reliable solution and was therefore introduced.

5.2.5 **Object Detection**

Due to the accurate digital recreation of the cups in Solidworks, the matching algorithm was able to detect most of the cups with moderate accuracy. With a cut-off percentage at 60% matching, most of the cups were located and aligned inside the point cloud. However, the localization test was not problem-free:

- **Misalignments:** Some of the cups demonstrate the software's difficulty in orienting them correctly, especially in the z-axis. The protruding lips were often not aligned. The reason is likely its small size, reducing its influence on the object alignment decision. Only cups above 95% matching could be considered consistently accurate while cups bellow that percentage vary in quality. Settings related to *fine alignment* and *searching* were tested, but only with limited results.

- **Cup occlusion:** Another, lesser occurring problem is related to occlusion between cups that are in proximity. The localization algorithm struggled to place cylinders models that would intersect other models and therefore fails to place them. A solution was to this is change the occlusion handling settings, reducing its tolerance for placement. This helped reduce the number missed cup placements, but also reduced its accuracy.

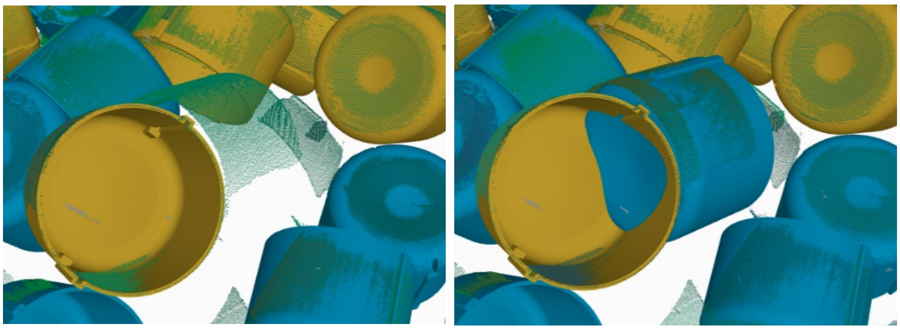


Figure 5.6 (Left) Localization with default occlusion handling tolerance. The cup was failed to be aligned. (Right) Localization with decreased occlusion handling tolerance. The previously missing cup points is erroneously mirrored in its relative z-axis' direction so that its bottom interesects another cup.

By tweaking the localization parameters, only moderate success was achieved in improving the object placement and alignment. Although many cups were either misaligned or missing, the result was considered tolerable to continue with the next steps.

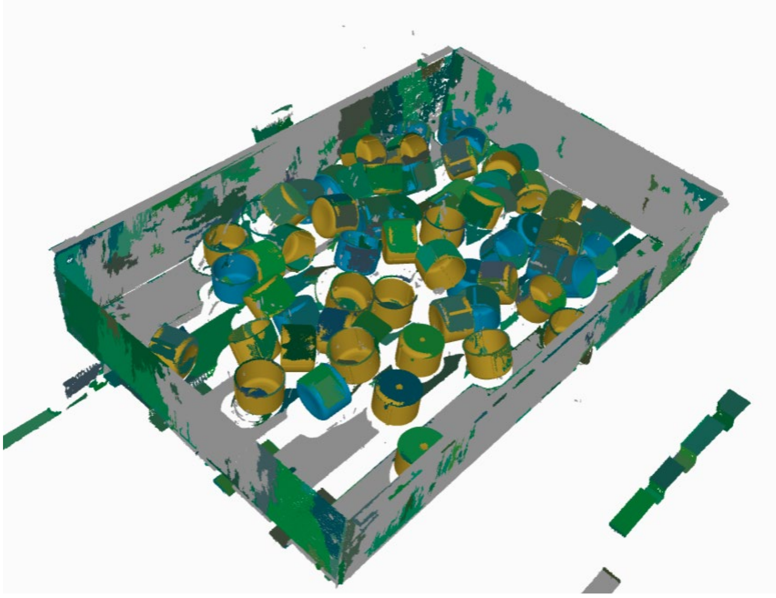


Figure 5.7 Image of the localized cups inside the bin.

5.2.6 **Waypoint Calculation & Path Planning**

The precautions taken to achieve good waypoint placement was comparable to those taken for cylinder picking, see Chapter 4.2.6. Due to frequent collision detections with the contact point of the gripper, the collision sensitivity was increased, once more to 70% to eliminate most erroneous collision detections. Additionally, the minimum size required for a point cloud model to be registered was increased to eliminate any remaining floating point segments.

Thanks to the previous implementations, such as the data-cutting and the limit on minimum cloud segment size, the path planning performed well. Joint angle constraints ensured efficient path planning generation and making sure the robot stays close to the bin. The same constraints were used as the ones for the cylinders in chapter 4.2.6.2.

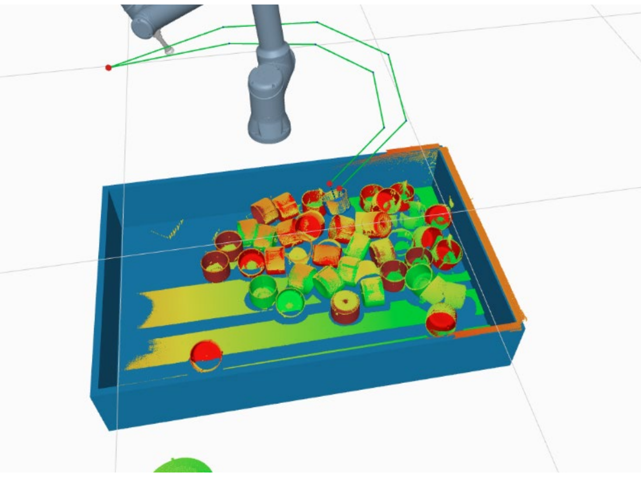


Figure 5.8 Example of unnecessarily long path planning due to noise and no joint angle constraints.

5.2.7 **Fixture & Placement**

The original objective for the cups (mentioned in 5.1) required the cups to be placed on a fixture with a determined angular orientation along its z-axis.

A simple placement fixture using 3D printed jaws was constructed for this purpose. The concept was designed to hold the cup in place and leave clearance for the gripper. Little development time was dedicated to this due to time-constraints.

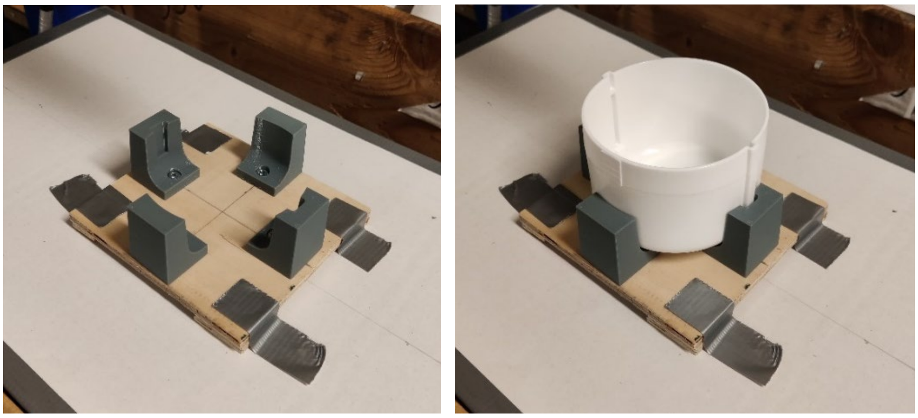


Figure 5.9 Images of the fixture with, and without a cup inside

5.2.8 **Testing & Fail Cases**

With a working gripper and configured BPS program, the system could once again be tested for consistency. The test simulations showed a mixed performance. Notable fail cases were documented.

Case 1: Although the vision system could detect the cups and perform path planning well, a large portion of the cups are deemed unpickable by BPS. A closer look revealed that leftover fragments of the cloud point model was the reason. The program was often unable to generate trajectories, leading to unnecessarily long computation times.

Case 2: Issues also occur when attempting to pick and place the cups. The picking action could be performed at times but suffers from a high fail rate. The placement action was executed with little to no success. Poor traction between cups results in cups on the top layer to lie loosely. The poor balance sometimes causes them to move when the tip of the gripper makes contact. This may result in the gripper sometimes picking the cup and sometimes not. When being picked, the cups show a tendency to attach themselves imprecisely such as in Figure 5.11. This problem is enhanced by the slight misalignments between the models and the point cloud.

The frequency of the fail consequently meant that the recorded cases cycle time could not be considered valid. The system is generally good at picking but struggles to place them correctly on the fixture.

Figure 5.10 Tilt as a result of the convex surface on the inside of the cup.

5.3 Reflection

The task was to explore 3D vision further. This was achieved through discovering difficulties that the cylinder picking did not have.

The characteristics of the cups was a large influence on the point cloud model and the localization step. Small details such as the protruding lips cause difficulties for the algorithm to align the cups correctly in the z-axis. Objects with simpler shapes and less details are therefore more suitable for 3D Scanning and Bin Picking. The reflectiveness of the glossy plastic was confirmed to be the source of the interreflections. Even with various settings, this problem persisted in all steps of the bin picking implementation. Decisions to cancel the implementations could have been made at an early stage.

Most of the time was dedicated to configuring the BPS application and the PhoXi Scanner. An alternative strategy would have been to focus more on improving the hardware to compensate for the cup alignment issues. Possible measures include making the gripper more robust or using a fixture that automatically corrects tilted cups.

5.4 Conclusion

A secondary Bin Picking application was created but with mixed results. Appropriate gripping points on the object were selected and a new gripper was chosen. For the scanner configurations, interreflection filters had to be introduced together with data-cutting to remove some of the cloud point noise. The object localization was improved with certain fine-alignment settings. A low collision sensitivity resulted in a better waypoint calculation and trajectory generation.

From the tests, it can still be concluded that this Bin Picking Implementation requires further experimentation. The problems that remained are as follows:

- **Floating point segment artifacts.** The waypoint calculation and trajectory generation suffer from the artifacts due to interreflections and other point cloud noise. Several cups that lie unoccluded, with accessible gripping points were deemed unpickable by BPS.
- **Picking/Placement inaccuracy.** The reason for the numerous failed picking attempts can either be attributed to the BPS configurations or the gripper/fixture combination. Cup alignment with the point cloud remained inaccurate even with many attempts to adjust the parameters. Fail case 2 demonstrates the grippers inability to accurately pick and place the objects in its fixture.

The resulting problems can be partly dealt with improved hardware, such as more precise grippers and more lenient placement fixtures. Further tweaking of the Scanner or BPS settings can improve the pose estimation and eliminate the remaining cloud point fragments. For this, more research is required to find the root cause of the problem.

In the end, the project served to highlight the capabilities of the vision system. Applying the technology on two different scenarios helped to understand what parameters influence each bin picking scenario the most. The discoveries here should be used as examples for what objects this technology should be applied for in the future.

6 Final Conclusion and Future Work

This chapter aims to briefly summarize the conclusions made in the report and discuss options to extend on this project in the Future Work section.

6.1 Final Conclusions

Having completed both the primary and the secondary objectives, the project can be concluded. The most important conclusions made from each part of the primary objective solution and the secondary solution can be summarized as such:

- **Gripper**: A functioning gripper was designed and constructed. For the task of picking large foam objects, the ingressive gripper type proved itself to be well-suited.
- **Bin Picking System**: A working station, suitable for an industrial setting, was created. The test simulations show the feasibility of a 15 second cycle time. The Foam cylinders are suitable objects for this bin picking system.
- **Computer Vision and 3D Scanning**: The secondary application showed the chosen object's material characteristics large influence on the Scanners performance. Problems relating to cloud point noise cause difficulties in later steps of the implementation.

6.2 Future Work

For Odigo to fully automate this production step, further work is necessary. This chapter presents recommendations on how they should proceed in the future. Suggestions were written for each of the solutions mentioned in 6.1.

6.2.1 **Gripper**

General directions for an improved needle gripper design were previously given in Chapter 3.9. Further research went into improving a self-built version.

Future developments on the gripper should introduce more sensors to the system. For example, an infrared distance sensor under the base of the fixtures can inform the UR robot controller (or the subsequent robot station) whether a bin picking cycle was executed successfully. Such sensors can be mounted on the gripper for similar purposes.

The previous tests using the constructed, industrial gripper (see Chapter 3.9) demonstrated problems related to its stroke length. Rather than developing further iterations on this design, it is advantageous to combine the Marlin gripper (see Chapter 3.5) with the current design to create a pierce-and-pinch gripper. The design shown in Figure 52 features four large needles that moves like a 4-finger lathe chuck. The principal functions similarly to the current needle gripper, but with a pinching mechanism to hold the cylinders in place. This grants the gripper more holding power but with fewer needles, resulting in less friction while piercing.

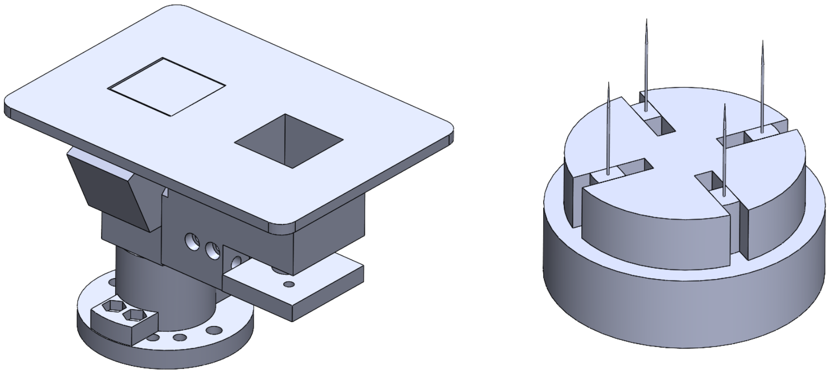


Figure 6.1 CAD models of the industrial gripper (left) and a simplified CAD model of the pierce-and-pinch gripper (right)

6.2.2 **Bin Picking System**

The bin picking station has been configured to perform the gripping action without fail. With a new gripper design, parameters and UR code needs to be adjusted. In the case that the gripper does not use a retractable cover, a new, improved fixture should be implemented. A more in-depth design development strategy can serve to boost its reliability.

Although a lot of point cloud noise was removed in the first project using data-cutting, a more reliable solution should be investigated as the bin will have varying degrees of filling.

For this project, safety features were implemented and discussed in chapter 4.4. However, for the safety features to abide to workplace safety standards a risk assessment must be performed. Depending on COG's needs, a CE marking may even be necessary. This is a time-consuming endeavour that is not included in this project and should be addressed during future developments.

The development of a more detailed robot station design is the next step in the development process of COG's order. Further investigations with COG should be undertaken to establish concrete specifications and boundaries for the project. The robot station proposal in Chapter 4.4 Robot Station Design serves as a visualization of what the implementation should look like.

6.2.3 **Computer Vision and 3D Scanning.**

Besides work related to the customer-driven project, more needs to be understood surrounding bin picking and computer vision. While multiple projects help to gather software-specific knowledge, a long-term approach is to understand the underlying theory on computer vision better. The PhoXi scanner and the BPS application are relatively quick to implement with basic functions, however, optimization requires a deeper level of understanding of the vision configurations.

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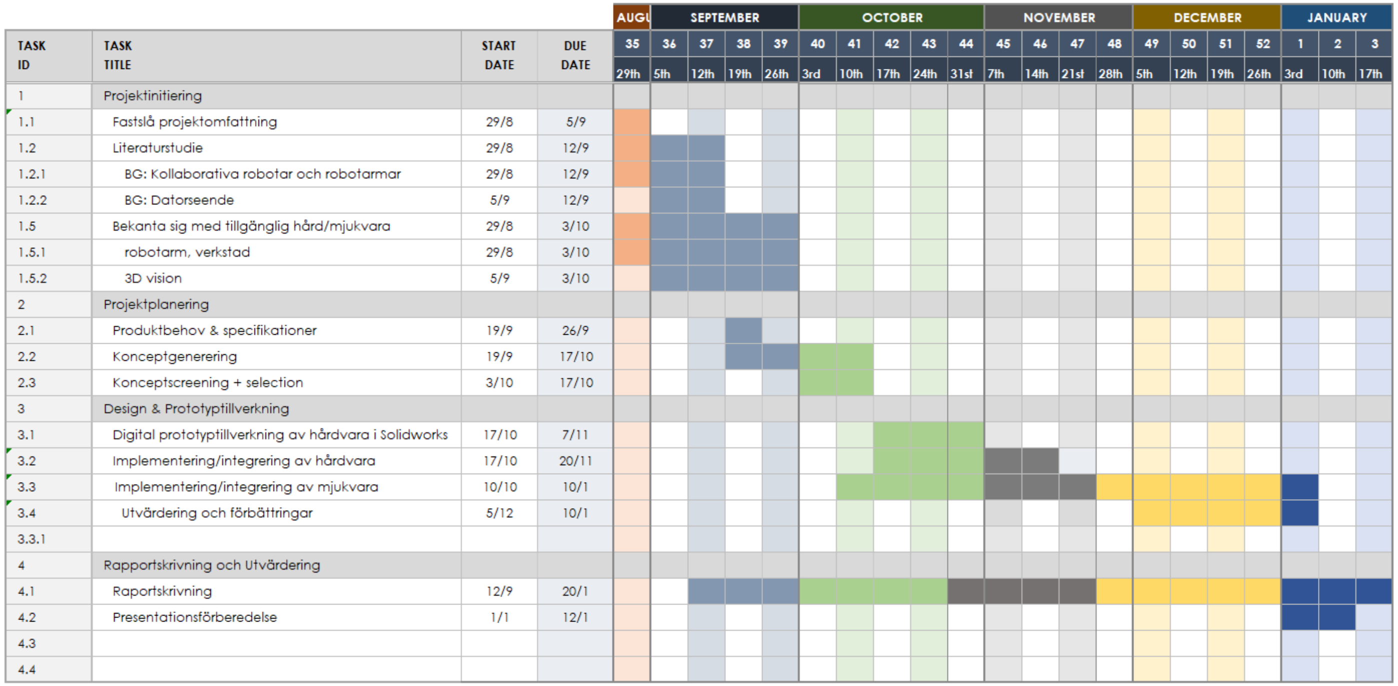
Appendix A Time plan

The scheduling for the project was represented by a Gantt chart. In this section, the initial and the actual project plans are presented and compared.

A.1 Project plan and outcome

Although the project proceeded with a relatively steady pace, the Gantt chart only roughly resembles the actual time plan. The familiarization of the 3D Vision equipment was done later than anticipated due to scheduling-related reasons. The equipment from Photoneo was available starting from the 18th of October rather than from the start. Another change in the timetable can be seen in the steps in developing and integrating the hardware. More time had to be invested into developing digital and physical prototypes than initially expected. CAD models of the fixtures, the virtual station and new gripper required more time to be allocated to said steps.



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				29th	5th	12th	19th	26th	3rd	10th	17th	24th	31st	7th	14th	21st	28th	5th	12th	19th	26th	3rd	10th	17th
1	Projektinitiering																							
1.1	Fastslå projektomfattning	29/8	5/9	■																				
1.2	Literaturstudie	29/8	12/9	■	■	■																		
1.2.1	BG: Kollaborativa robotar och robotarmar	29/8	12/9	■	■	■																		
1.2.2	BG: Datorseende	5/9	12/9		■	■																		
1.5	Bekanta sig med tillgänglig hård/mjukvara	29/8	3/10	■	■	■	■	■																
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1.5.2	3D vision	5/9	3/10		■	■	■	■																
2	Projektplanering																							
2.1	Produktbehov & specifikationer	19/9	26/9				■																	
2.2	Konceptgenerering	19/9	17/10				■	■	■	■														
2.3	Konceptscreening + selection	3/10	17/10						■	■														
3	Design & Prototyptillverkning																							
3.1	Digital prototyptillverkning av hårdvara i Solidworks	17/10	7/11								■	■	■											
3.2	Implementering/integrering av hårdvara	17/10	20/11								■	■	■	■	■									
3.3	Implementering/integrering av mjukvara	10/10	10/1							■	■	■	■	■	■	■	■	■	■	■	■	■		
3.4	Utvärdering och förbättringar	5/12	10/1															■	■	■	■	■		
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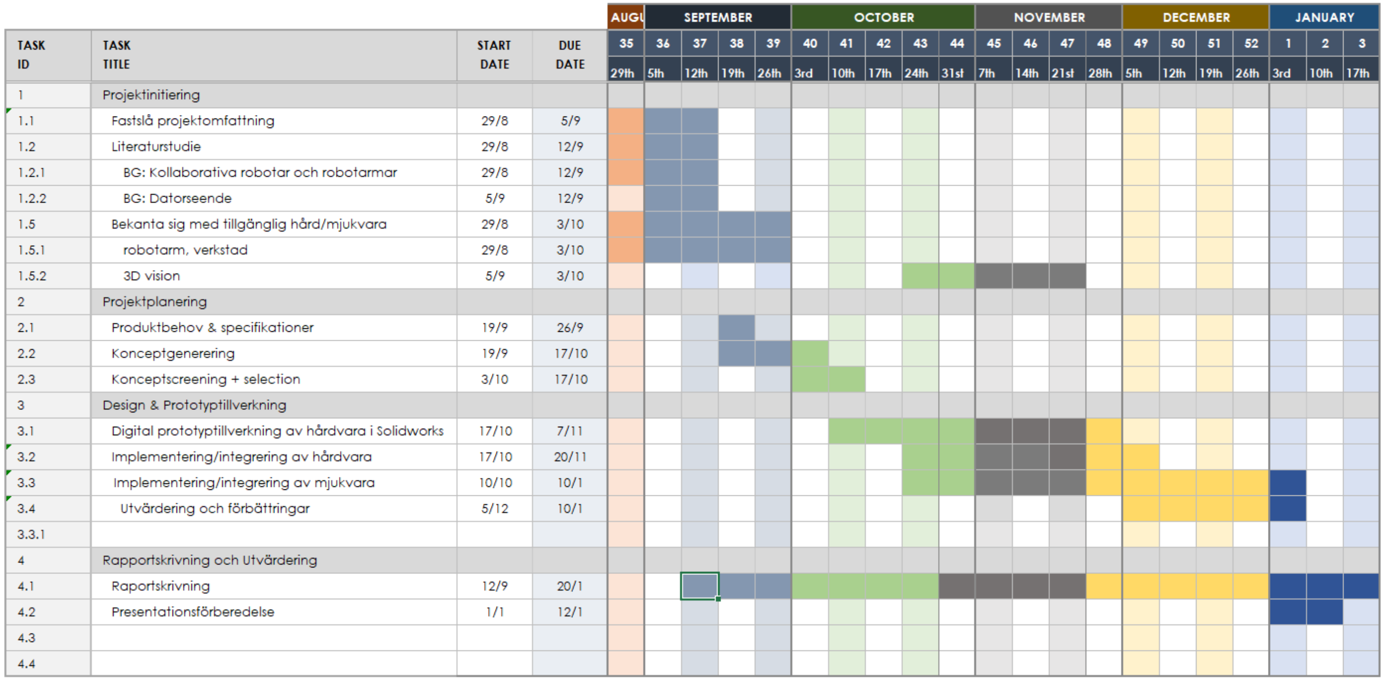
Figure A.4 Gantt chart of the planned time table.



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1.5	Bekanta sig med tillgänglig hård/mjukvara	29/8	3/10	■	■	■	■	■																
1.5.1	robotarm, verkstad	29/8	3/10	■	■	■	■	■																
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2.2	Konceptgenerering	19/9	17/10				■	■	■															
2.3	Konceptscreening + selection	3/10	17/10						■	■														
3	Design & Prototyptillverkning																							
3.1	Digital prototyptillverkning av hårdvara i Solidworks	17/10	7/11							■	■	■	■	■	■	■	■							
3.2	Implementering/integrering av hårdvara	17/10	20/11									■	■	■	■	■	■	■						
3.3	Implementering/integrering av mjukvara	10/10	10/1									■	■	■	■	■	■	■	■	■	■	■		
3.4	Utvärdering och förbättringar	5/12	10/1															■	■	■	■	■		
3.3.1																								
4	Rapportskrivning och Utvärdering																							
4.1	Raportskrivning	12/9	20/1			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.2	Presentationsförberedelse	1/1	12/1																			■	■	
4.3																								
4.4																								

Figure A.4 Gantt chart of the actual time table.

Appendix B Gripper

This section features additional material related to the development of the grippers.

B.1 Commercial Grippers from Gimatic

These grippers were purchased from Gimatic to create the commercial gripper. The PT28 features 8 needles and a longer stroke length while the smaller one, PT30N uses 4 needles with a short stroke length. Both are actuated using pressurized air.

Figure 7.1 The two gripper variants, PT28 (left) and PT30N (right)

B.2 Testing rig for cylinders

This device was constructed to precisely measure deviations for the prototype testing phase. It functions similarly to a gyroscope, allowing the cylinders to be rotated around all three of its axes. With this, orientations could be measured around. The rig was mostly made from 3D printed parts and bent sheet metal and steel rods.

Its function is to rotate cylinders in along all three of its axes. Due to the structural complexity of the design, the measurements were inaccurate.

Figure 7.2 Images of the test rig.

B.3 Needle Gripper Drawing

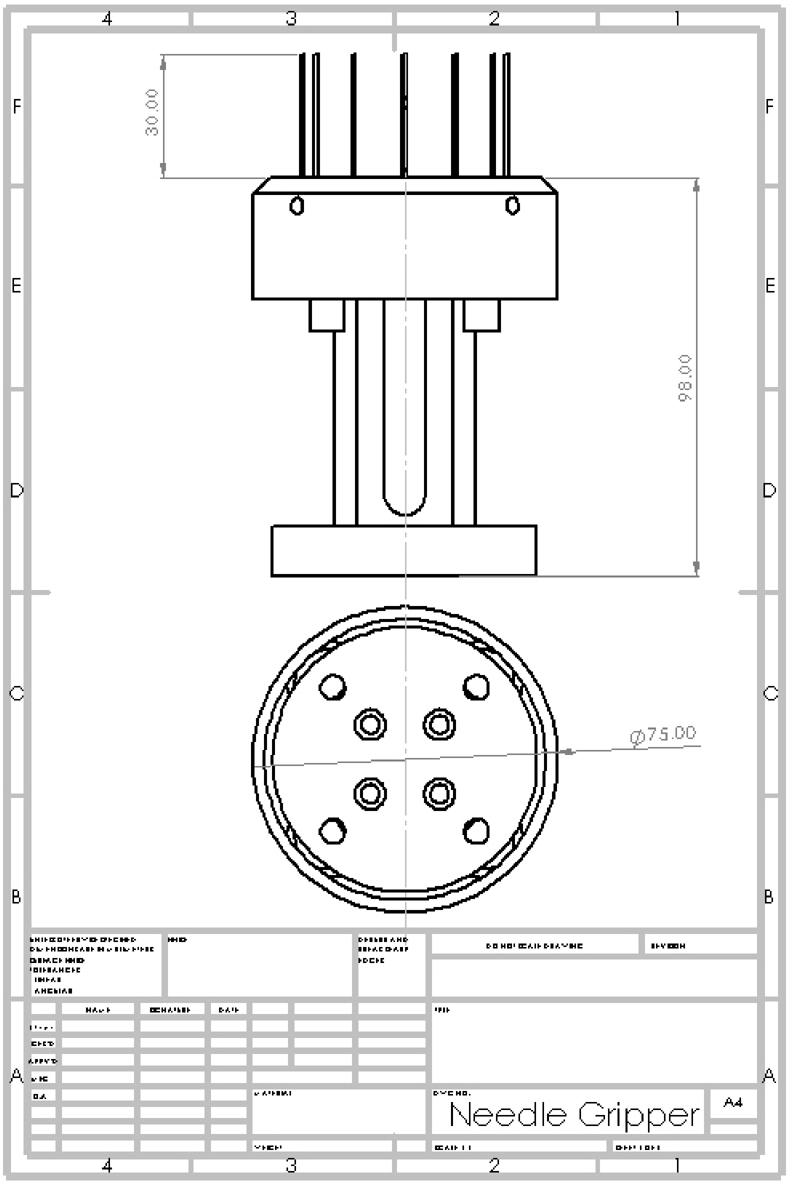


Figure 7.3 Drawing of the complete needle gripper with its main dimensions

B.4 Vacuum Gripper Drawing

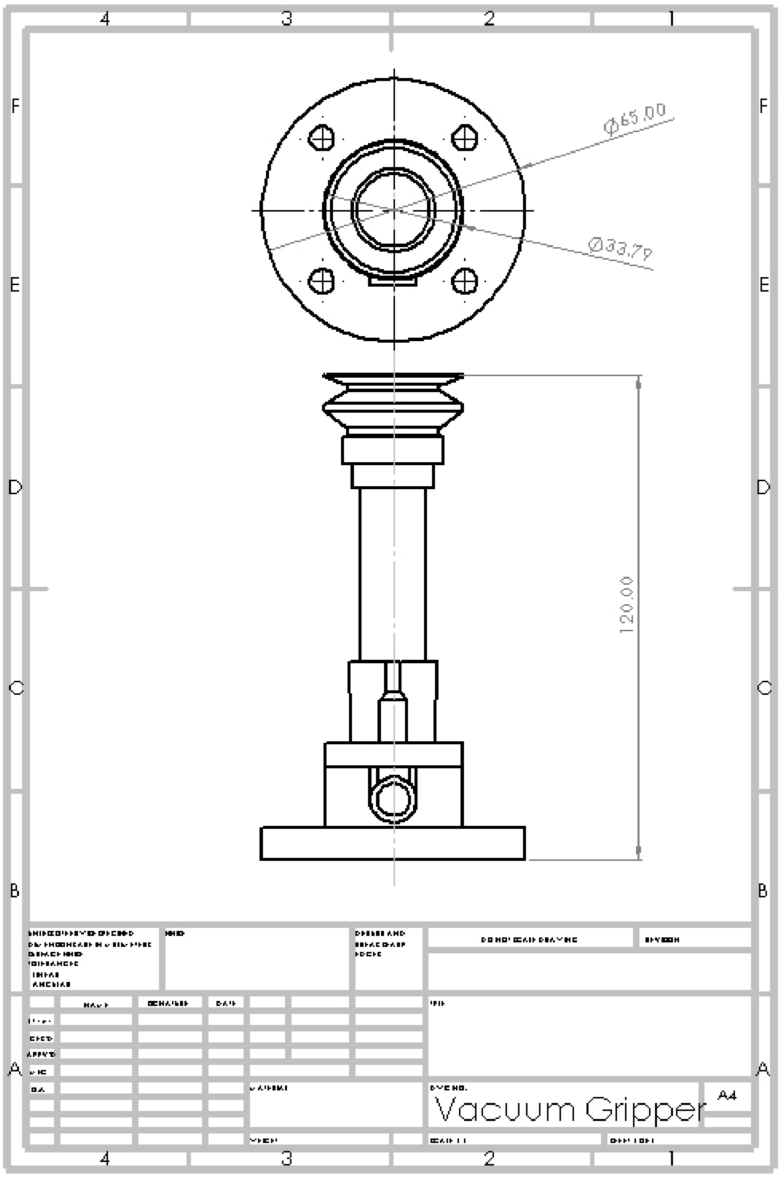


Figure 7.4 Drawing of the complete needle gripper with its main dimensions.

B.5 Suction calculation

Two cases can be identified with different load conditions. The cylinders are expected to handle a certain acceleration.

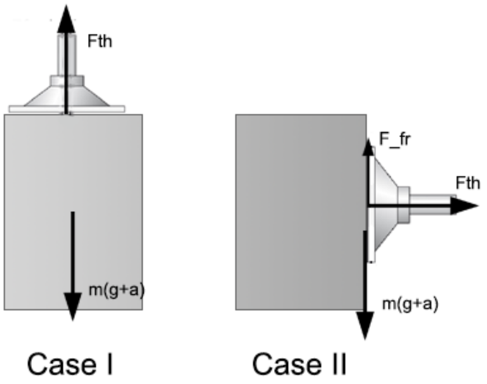


Figure 3.5 Freebody diagram of 2 different load cases. In case 1, the suction force comes vertically from above and in case 2 it comes horizontally

$a = 2.0 \frac{m}{s^2}$ minimum acceleration the system is expected to handle.

$A_{suck} = 0.00302 m^2$ cross-sectional area of a suction cup with a diameter 31mm.

$\mu = 0.6$ represents the surface friction between the suction cup and the cylinder.

$g = 9.81 \frac{m}{s^2}$ acceleration due to gravity.

$S = 2$ Safety factor for porous materials or rough surfaces.

The pressure required to be exerted by the suction cup can be expressed using the

$$P = \frac{F_{th}}{A_{suck}} \tag{1}$$

Case I:

$$F_{th} = m \cdot (g + a) \cdot S = 0.14 \cdot (9.81 + 2.0) \cdot 2 = 3.3\,N \tag{2}$$

Case II:

$$F_{th} = m \cdot \frac{g + a}{\mu} \cdot S = 0.14 \cdot \frac{9.81 + 2.0}{0.6} \cdot 2 = 5.5\,N \tag{3}$$

With the suction force F_{th} from (2) and (3) we can calculate the required minimum pressure P_{min} needed for to pick up the cylinders with (1).

$$P = \frac{F_{th}}{A_{suck}} = \frac{5.5\ N}{0.00302\ m^2} = 1821\ \text{Pa} \tag{4}$$

The value of 1821 Pa is easily managed for the compressor and vacuum pump as they typically operate in the range of 300-1500 kPa. Empirical evidence on real cylinders show that this is not the case. For this reason, the validity of the mathematical model should be viewed skeptically.

Appendix C Bin Picking & Computer Vision

This section contains extra material related to the Bin Picking implementation and computer vision.

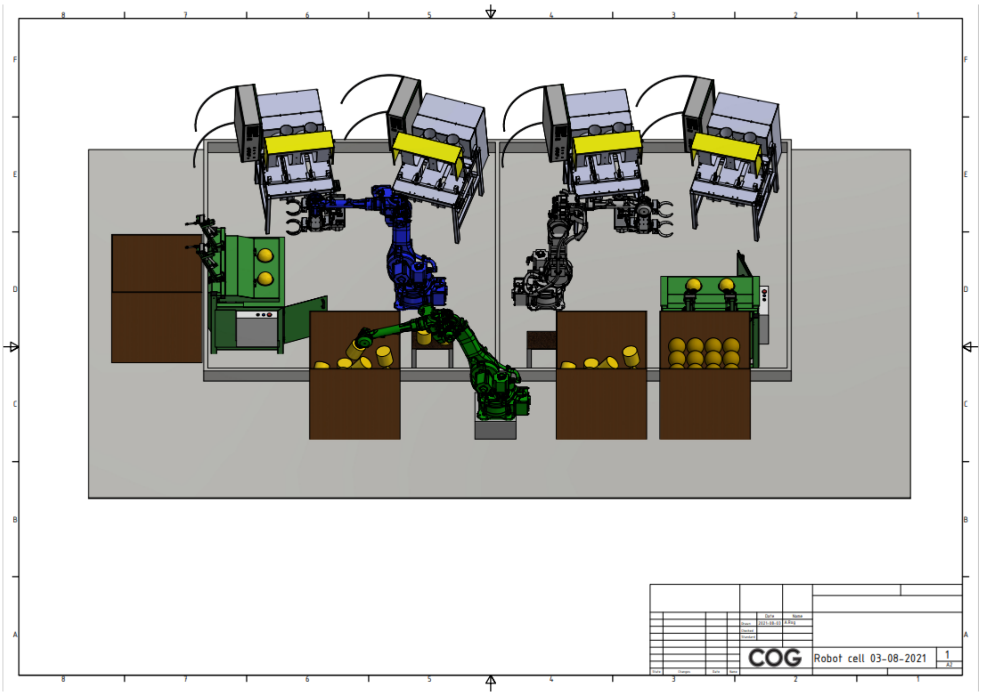
C.1 Images from COG

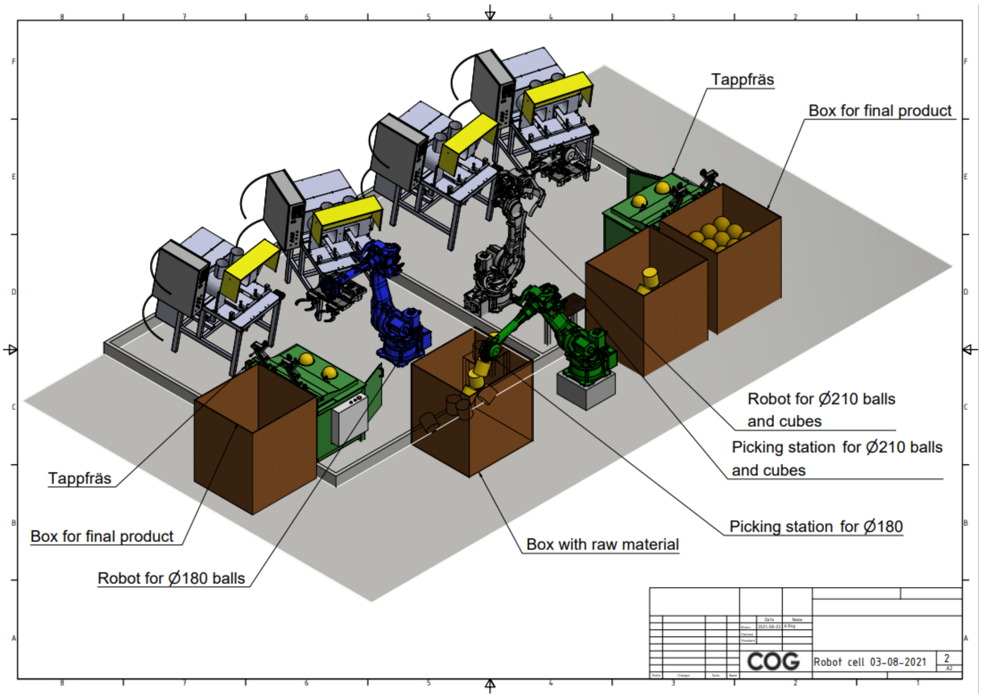
C.1.1 Cylinder Magazine

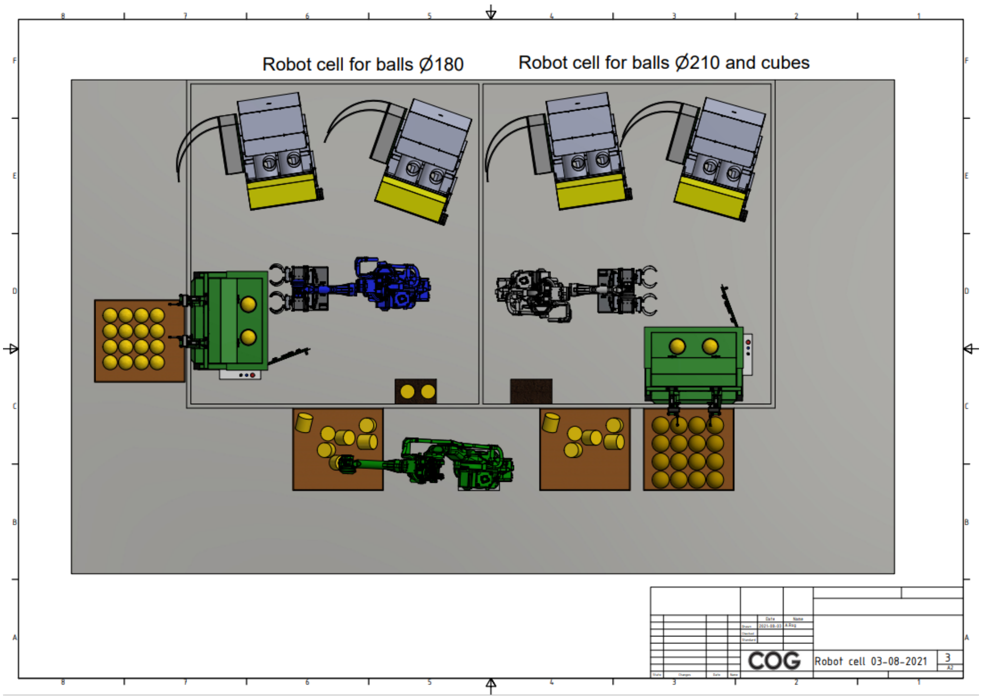
The previous solution uses a rollable magazine in which the cylinders are stacked on top of each other manually. The hard-coded grasping operation is executed inside the enclosure.

Figure 7.6 The Cylinder magazine inside the enclosure. The magazine can be pushed with the help of wheels underneath.

C.1.2 COGs Bin Picking station layout







C.2 Additional Computer Vision material

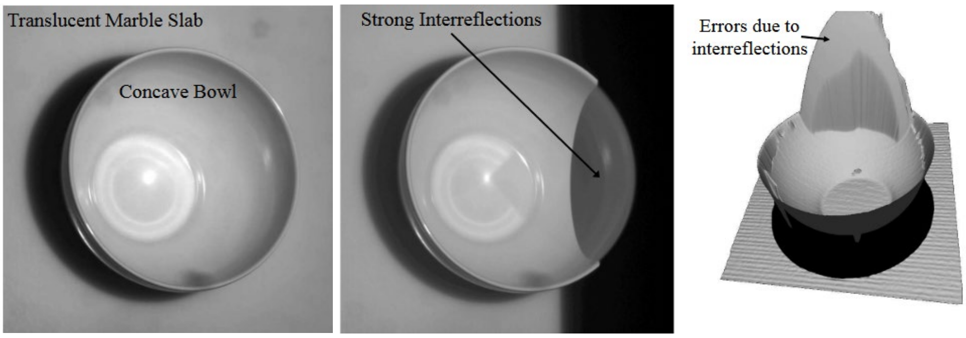


Figure 7.7. Example of Interreflections in reflective bowl-shaped objects. From: (Gupta, Agrawal, Veeraraghavan, & G., 2013)