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Automation of Aluminium Smelting Pot Cover Handling

Early Stage Development of a Customised
Gripper Tool and a Manipulator Concept
Review for Automation of a Primary
Aluminum Potroom Process

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Master of Science in Mechanical Engineering
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Preface

This master thesis has been written throughout the spring of 2017 as part of the Department of Mechanical and Industrial Engineering (MTP) master's programme at the Norwegian University of Science and Technology (NTNU). The paper is written for Alcoa Mosjøen in collaboration with the multi-disciplinary research group TrollLABS at NTNU.

The master thesis is a continuation of a project thesis written together with Jardar Winjum in the fall of 2016. The project thesis addressed research of automation potentials in the primary aluminium industry and is the foundation for this paper.

Abstract

Redistribution of cover mass is an aluminium potroom operation which is straining upon the workers at Alcoa Mosjøen. Though it is unpopular to perform, it is very much required for the production of top quality primary aluminium. A future goal for Alcoa is to substitute the current manual process with an automated guided vehicle (AGV), capable of performing the operation semi or completely autonomously. This thesis describes the early stage development of a subsystem for this vehicle.

The thesis objective is set to automate inside access to the smelting pots. This is acquired through gripping, handling and storing of removable hatches. To provide task automation, a system consisting of a robotic manipulator and a specialised gripper tool has been developed.

From the gripper development, a high-resolution aluminium prototype has been created. The prototype is capable of gripping, handling and storing of pot hatches securely through a mechanical self-clamping mechanism. With a purely mechanical gripper concept, Alcoa is provided with a robust, easily maintainable and energy independent gripping solution.

Through robot research, the possibility of exploiting the AGV propulsion along the pot has been identified. This has led to a 2-axis articulated robot concept, stationary placed on the AGV platform. Through scaled down testing of the robot and gripper system, dual simultaneous cover handling has been achieved. Further research has confirmed that "off-the-shelf" robot solutions exist, fulfilling the specific attributes required for AGV implementation. Feedback from Alcoa states conviction of system feasibility, and a kick-start of the automation project has been initiated as a result.

Norwegian Abstract

Anodedekking er en anstrengende oppgave som operatørene ved Alcoas smelteverk i Mosjøen daglig må gjennomføre. Selv om operasjonen er lite populær, er den en vital del av produksjonsløpet for utvinning av høykvalitets primæraluminium. Et fremtidig mål for Alcoa er å erstatte den nåværende manuelle anodedekkingen med en mobil dekkerobot som kan utføre operasjonen halv eller helt autonomt. Denne masteroppgaven beskriver tidligfase-utvikling av et delsystem til dette kjøretøyet.

Delsystemets hovedoppgave er å automatisere innvendig tilgang til smelteovnene. Dette kan oppnås ved å gripe, løfte og lagre avtakbare luker. Til å automatisere denne oppgaven har et robotsystem blitt utviklet, bestående av et griperverktøy og en robotenhet.

Fra griperutviklingen er det blitt designet og bygget en spesialtilpasset fullskala griperprototype i aluminium. Denne er i stand til å gripe, håndtere og lagre ovnsdeklser ved hjelp av en mekanisk klemmemekanisme. Med et fullmekanisk griperdesign kan verktøyet tilby Alcoa en robust, vedlikeholdsvennlig og energi-uavhengig griperløsning.

Gjennom robotutviklingen ble det identifisert en mulighet for å utnytte AGV-ens framdrift langs smelteovnene. Dette førte til et 2-akse robotkonsept som er plassert stasjonært på AGV-plattformen. Gjennom et nedskalert forsøk ble robot- og griperkonseptet testet. Her ble det oppnådd vellykkede resultater, hvor håndtering av to ovnsdeksler ble gjennomført samtidig. Ytterligere undersøkelser viser at fullskala robotløsninger eksisterer, med spesifikasjoner som støtter konseptet og bruk av det på en AGV-plattform. Alcoa har ytret begeistring for oppgaveresultatet og robotkonseptets grad av gjennomførbarhet. Som følge av samarbeidet har en initiering av automatiseringsprosjektet nå startet i Mosjøen.

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To the thesis business partner, Alcoa Mosjøen, I would like to express a special appreciation for providing thesis task, equipment, and be willing to give students the chance to confront the industry challenges of tomorrow. My contact person at Alcoa Mosjøen, Project Engineer Live Spurkland, has been remarkably helpful and has provided excellent guidance throughout the past year. I would, therefore, like to direct special gratitude to her. I also want to thank Head of Production Ellen Myrvold and Process Engineer Candidate Kim Ronny Elstad for facilitation and aid during the summer internship and thesis period.

Lastly, I would like to thank the remaining PhD candidates and master students at TrollLABS for contributing to a genuinely enjoyable, creative and motivating work environment at NTNU.

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List of Abbreviations

AGV	Automated Guided Vehicle
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Modelling
CE	Concurrent Engineering
DFR	Design for Reliability
DFX	Design for X
DOF	Degrees of Freedom
EOT	End-of-arm-tooling
FEA	Finite Element Analysis
HSE	Health, Safety and Environment
LIDAR	Light Detection and Ranging
MDF	Medium-Density Fibreboard
MTP	Department of Mechanical and Industrial Engineering
NTNU	Norwegian University of Science and Technology
PD	Product Development
PLA	Polylactic Acid (bioplastic)
QR	Quick Response code
R&D	Research and Development
SD	Software Development
TIG	Tungsten Inert Gas welding

List of Expressions

Several of the gathered expressions are collected from the ISO (ISO 2012) and OSHA Technical Manual vocabulary (OSHA 2017).

Actuator

A power mechanism used to provide motion. Also, a device that converts electrical, hydraulic, or pneumatic energy into robot motion.

Articulated robot

A robot with rotary joints, commonly known as an industrial robot, ranging from simple two joint systems to numerous jointing structures.

Anode

Anode refers to the carbon anodes utilised in the electrolysis process of aluminium production at Alcoa Mosjøen.

Anode covering

The process of redistributing cover mass on top of the carbon anodes used in aluminium electrolysis.

Autonomy

The ability to perform tasks based on current state and sensing, without human intervention.

Axis

The line of which a body rotates.

Clamping

The physical retaining/prehension performed on an object by a robot gripper.

Degrees of freedom (DOF)

The number of robot operating axes.

End-effector

An accessory device or tool specifically designed for attachment to a robot wrist or tool mounting plate to enable a robot to perform its intended task.

Grabbing vehicle

Vehicle used at Alcoa Mosjøen to cleanse the cryolite bath after used up anodes has been extracted from the pot. The bath cleansing is performed by hydraulically actuated grab.

Gripper

A robot arm end tool capable of gripping and restraining objects during handling.

Industrial robot

Automatically controlled, reprogrammable, multipurpose manipulator, which can be either fixed in place or mobile for use in industrial automation applications.

Joints/Links

The connection of different manipulator joints is known as robot links, and the integration of two or more links is known as robot joints.

Kinematics

The arrangement of rigid members and joints in the robot, deciding which motions can be performed.

Manipulator

A machine in which the mechanism usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several degrees of freedom.

Mechanism

Rigid bodies which are connected by joints in order to achieve force and/or motion transmission.

Mock-up

A scaled or full-size model of a design or device, used for teaching, demonstration, design evaluation with a variety of prototype resolutions.

Off-the-shelf product

Available for purchase products.

Palletizing robot

A subtype of the industrial robots which is designed to perform pick and place stacking operations for palletizing of goods.

Payload

The maximum object mass or carrying capacity of a robot.

Pick-and-place robot

A subtype of industrial robots specialised for picking and placing operations.

Potroom

The facilities of where production of aluminium is performed.

Potroom operator

Alcoa Mosjøen employees performing the operations required to produce primary aluminium. Also known as potroom workers.

Repeatability

The degree of accuracy to which a robot can return to a previous position.

Rendering

A term within data graphics used for the automatic process of generating photorealistic images from 2D or 3D models.

Robot

Actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks.

Robotics

Science and practice of designing, manufacturing, and applying robots.

Sensor

A device that responds to physical stimuli (such as heat, light, sound, pressure, magnetism, motion, etc.) and transmits the resulting signal or data for providing a measurement, operating a control, or both.

Working envelope

The region of space reachable by a robotic manipulator.

1 Introduction

Redistribution of cover mass is a potroom operation which is performed as part of the aluminium production process at Alcoa Mosjøen. A future goal for Alcoa is to substitute the current manual process with an autonomous guided vehicle (AGV), capable of performing anode covering. This thesis describes the early stage development of a subsystem for this vehicle. Frequently used expressions are actuation, autonomous, clamping, gripper, manipulator and potroom. Please see the list of expressions if term explanation is desirable.

The thesis objective is set to automate inside access to the smelting pots. This is acquired through gripping, handling and storing of removable hatches. These hatches are referred to as pot covers. To provide task automation, a system consisting of a manipulator and a specialised gripper tool has been developed.

From the gripper development, a high-resolution aluminium prototype has been created. The prototype is capable of gripping, handling and storing of pot covers securely through a self-clamping mechanism. With a purely mechanical gripper design, Alcoa is provided with a robust, easily maintainable and energy independent gripping solution. Through robot research, the possibility of exploiting AGV propulsion along the pot has been identified. This led to a 2-axis articulated robot concept, stationary placed on the AGV platform. Through scaled down testing of the robot and gripper system, dual simultaneous cover handling has been successfully achieved. Further research has confirmed that off-the-shelf robot solutions exist, fulfilling the attributes required for AGV usage. This is a summary of the thesis results and findings.

Starting the report, an introduction to the thesis partner, Alcoa Mosjøen, is presented. Following is a brief of the previous project thesis. Here, the main findings from the research which has relevance to the master thesis will be highlighted. Chapter 1 is concluded with a task description of the thesis objective, creating the fundament for the selected development methodology. The thesis methodology follows in second chapter 2.

1.1 Business partner Alcoa Mosjøen

Alcoa is a world leading producer of primary and wrought aluminium. With one of their cornerstone facilities in Mosjøen, they wish to increase their competition advantage with higher turnover per employee, while also increasing their standards of HES. Operations in their primary aluminium production facilities have workers engaged in an extreme environment of high temperature, extensive magnetic fields, gas and dust. Their strategy for realising increased turnover per employee is through production expansion and automation of repetitive tasks.

A promise has been made between Alcoa and the potroom operators concerning automation of the facilities in Mosjøen. This states that none of the employees is in danger of discharge as a result of successful process automation. With this agreement, the entire Alcoa organisation supports the development of cost and production beneficial automation projects.

Figure 1.1: The smelting pot environment at Alcoa Mosjøen.

This thesis project has been a pilot for Alcoa, where they for the first time have engaged NTNU students for execution of automation research and development. Having already contractors working on automation projects, what they have sought to achieve is an unbiased and 'outside the box' evaluation to how their future automation challenges can be solved. Based on feedback from Alcoa, the thesis collaboration has been a large source of inspiration, yielding realistic and implementable solutions to their now initiated anode covering automation project. Thesis contact person at Alcoa Mosjøen has throughout the year been Project Engineer Live Spurkland. There has also been contact with Ellen Myrvold, Head of Process, and Kim Ronny Elstad, Process Engineer Candidate.

1.2 Project thesis

The thesis is a continuation of a project thesis concluded in the end of fall 2016. The project thesis was written in collaboration with Jardar Winjum and explored automation potentials for a primary aluminium production process involving the inside environment of the smelting pots. The intention behind the paper was to form a thorough understanding of the automation project proposed by Alcoa Mosjøen. It was also concentrated on the challenges related to the potroom environment and to benchmark relevant technology. The thesis challenge presented by Alcoa is briefly described in the following subchapter, as it is the basis for the subsystem developed through the master thesis. If it is desired to acquire additional background information, the project thesis can be viewed in Appendix J.

1.2.1 Anode covering

As Alcoa are striving towards optimisation of their processes in Mosjøen, they have made up a list of possible automation projects for future execution. One of the prosperous, though not initiated projects, is the process of anode cover mass redistribution.

Anode cover mass redistribution, from now on mentioned as anode covering, can be described as a maintenance operation in the primary aluminium production. The goal of anode covering is to protect the carbon anodes from oxidation with air inside the smelting pots. When new anodes are inserted into the pots, a gravel-like cover mass is dispersed over the carbon, creating a barrier between the anode and the air. During the anode lifetime (approximately 28 days), the carbon is gradually lowered into the bath as it is consumed in the electrolysis process. During this process, the protecting cover mass will solidify, move or dissolve into the bath. The anodes will therefore over time become exposed if the cover mass is not attended to. Should anode oxidation occur without immediate attending, undesired effects will follow. This includes inefficient usage of raw materials, increased power consumption, increased CO_2 emissions, smelting bath heat loss and ultimately less aluminium produced.

To prevent air burn from occurring, the operators at Alcoa Mosjøen manually perform anode covering. Approximately twice a week, the workers inspect all of the 404 pots for signs of cover mass absence. To inspect the status of the anodes, the covers closing of the pot needs to be tilted out to allow inspection. If there are signs of exposure, the pot hatch must be moved out of the way, often placed on top a nearby cover. Then, anode covering can be performed (figure 1.2) with an aluminium rake-like tool. This is a brief explanation to why and how anode covering is performed AS-IS.

Figure 1.2: The manual operation of anode covering being performed at Alcoa Mosjøen.

1.2.2 Project thesis summary

The main topics reviewed in the project thesis concerned:

- Knowledge capture of Alcoa Mosjøen's potroom facilities and primary aluminium production
- Analytically breaking down the process of anode covering
- Identification of potroom environment related challenges
- Exploration of applicable sensory and actuation principles
- A division of future work

Within these topics, some of the insights and findings will prove valuable for the further thesis work. Through a summer internship at Alcoa in 2016, tacit knowledge of the aluminium production was acquired. Combined with the knowledge collected in the project thesis, a broad understanding of the master thesis challenge is already assimilated. During the summer internship, digital models of the most essential smelting pot components were also created (figure 1.3). As these models were constructed from Alcoa's own machine drawings, this will allow for computer-aided engineering (CAE) of the actual pot environment. The extreme potroom environment will also have to be taken into account, as it restricts the thesis development space. The knowledge captured concerning the environment will, therefore, be important for the further development.

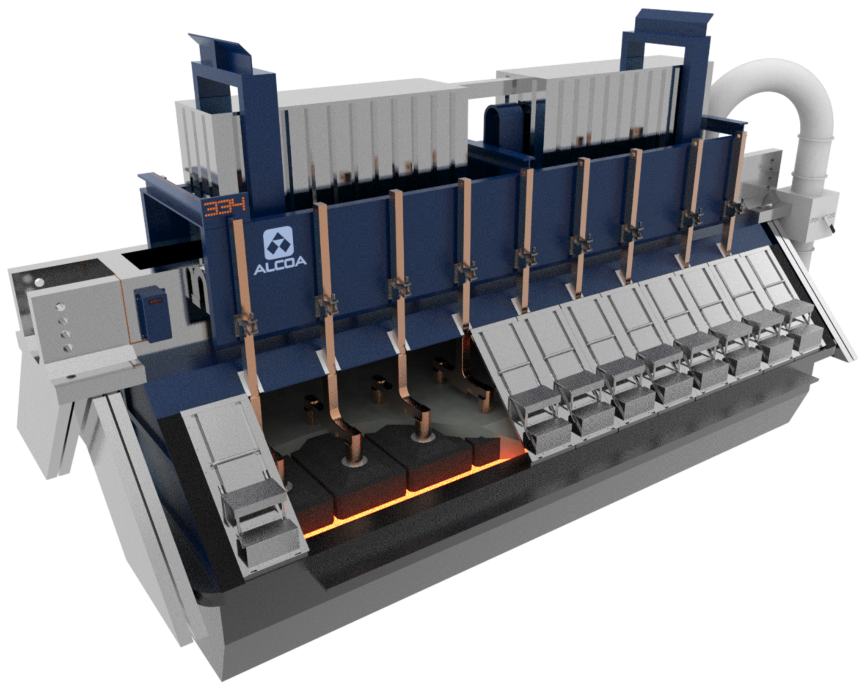


Figure 1.3: CAD model of the Alcoa smelting pot with accurate measurements, made during the project thesis.

Though the master thesis will mostly focus on mechanical design, the research performed concerning sensory and actuation principles will serve as a solid foundation for the further development.

Lastly, it was proposed that the continuation of the project could have a two-split division of the task. It was chosen to split the anode covering task into pot interior and pot exterior challenges. While Jardar Winjum will continue the development of pot interior operations, this thesis will emphasise how to automate pot exterior challenges.

1.3 Master thesis

Ending the project thesis, three master thesis topic proposals were suggested. To decide which of the topics to pursuit, Alcoa was engaged for consultation. The three topics provided were:

1. Development of an improved cover design

- For automation handling
- For operator handling

2. Development of a lifting mechanism for cover handling

- How the cover handling can be actuated
- How should the lifting mechanism grab the cover
- Where and how will the cover be stored during pot operation

3. Development of the cover handling automation process

- Identification of cover location, distance, etc.
- Measures needed to perform the process autonomously

The first of the proposed topics, development of an improved pot cover design, proved to be of less interest to Alcoa. Alcoa Mosjøen wishes to keep their present pot cover design, as they are satisfied with their current functionality. The design is customised to fit the ventilation of the pots, rendering the existing pot design with little room for improvement. Changing the design would also include additional expenses for Alcoa. The development of an improved cover design will therefore not be prioritised in the thesis.

The third topic concerning exploration of the automation process also seemed less attractive to the corporate partner. Alcoa stated that their primary interest is related to how pot cover handling physically can be performed, not the sensory and programming behind it. If a feasible handling concept could be presented, the processing behind it would be the subsequent step of the development. Based on this statement, the topic selection naturally became topic number two: The design development of a mechanical concept solution for pot cover handling.

The thesis task details and objectives will thoroughly be described in chapter three. Before the task specification, chapter two will address the development methodology and strategy selected for the thesis development.

2 Development strategy and methodology

This chapter address the development plan and the methodology foundation applied for the thesis. Based on the essential characteristics of the task at hand, a selection of tools has been chosen to aid and structure the development process.

2.1 Pahl and Beitz development structure

For structuring of the thesis process, a four-step product development approach has been selected. The four design and planning steps utilised are based on the Engineering Design (Pahl and Beitz 2007) product development book. Here, Pahl and Beitz proposes a division of the development process, involving four main phases:

1) Planning and Task Clarification
2) Conceptual Design
3) Embodiment Design
4) Detail Design

The first stage, planning and task clarification, was initiated in the prior project thesis, where a collection of information concerning requirements and existing constraints was performed. This step will be concluded in chapter three, where the project specification and requirement list will be defined before initiation of the conceptual design phase. During the conceptual design phase, ideation and iterative concept design generation will be performed. The primary goal of the conceptual design stage will be to develop principle solutions. To achieve this, Pahl and Beitz propose the following checklist:

- Identify essential problems
- Establish function structures
- Search for working principles
- Combine into concept variants
- Compare against criteria's

The conceptual design checklist will be used to propel the development forward to the following stage, embodiment design. In the embodiment phase, the preliminary concepts will be elaborated and refined. Measures increasing the concept resolution will be performed, with the end objective to present a layout proposition for the task solution. As this thesis will address the early stages of development, the embodiment stage will be initiated, but not completed. The last step, detail design, will therefore not be discussed in this thesis.

2.2 SCRUM

As a framework for managing the development process, and ensure progression throughout the master thesis, an SCRUM-inspired project planning style will be applied.

SCRUM (Cohn 2016) originated as a tool from Agile Software Development (Fowler and Highsmith 2001), which is a software development (SD) movement consisting of principles that emphasise on SD through collaborative cross-functional teams. SCRUM was initially formalised for SD projects but has later been proven applicable for all sorts of innovative and complex project work (Scrum Alliance 2017). It is a flexible and straightforward framework which sympathise on empirical feedback from short cycles of iterative work (CollabNet 2008). The traditional format of organising project work with SCRUM is by dividing participant roles into Product Owner, Team and Scrum Master. As this thesis is written by a single individual and not a team, SCRUM cannot be used as it originally is intended. It is, therefore, more accurate to describe the thesis structuring as inspired by SCRUM.

The aspects of SCUM which will be utilised for this thesis is the system of how work is organised during a project's lifetime. A prioritised set of goals is gathered in a list called Product Backlog. Starting each time defined iterative work cycle, called a Sprint, a chunk of selected objectives from the Product Backlog is placed into a Sprint Backlog. These are the desired goals or tasks to complete during the given period. At the end of a Sprint, a review is performed to determine the status of the tasks in the Sprint Backlog. The Sprint goals can either be marked as completed, be kept in the log for the next iteration, or be placed back into the Product Backlog for later consideration. As the project evolves, new targets might arise, and additional items will need to be enlisted into the Backlog. This management flexibility works both ways, allowing for removal of items which renders out of interest for the project. A figure describing the SCRUM management applied for the thesis can be viewed in figure 2.1.

In this fashion, the tasks and objectives will be listed, moved around, and iteratively be handled. From the primary objective of the thesis, enabling milestone deliveries will be proposed for the development. These milestones will again be divided into sub-tasks, facilitating the completion of the milestones. As the development evolves, new items can be put in the backlog or existing items removed, all according to the thesis progression.

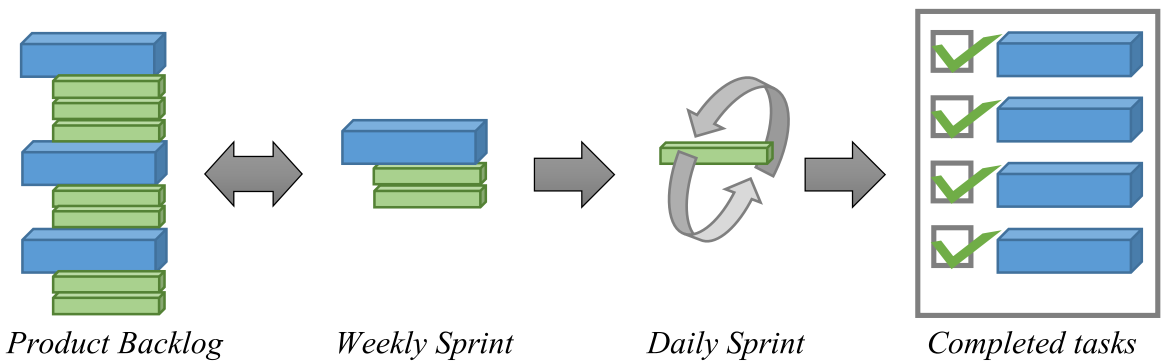


Figure 2.1: Simplified overview of the SCRUM management used throughout the thesis. Large blocks symbolise milestone achievements, smaller blocks represent milestone sub-deliveries.

2.3 Empathy and Design Thinking

The majority of the insights gathered from Alcoa Mosjøen's production was conceived during a summer internship in 2016. The knowledge captured then as well as for the master thesis period is based on the innovation methodology of Design Thinking (Rowe 1991). In particular, the d.Schools bootcamp bootleg toolkit (Both and Baggereor 2017) has been used for capturing knowledge through empathy. Design Thinking (DT) features human-centred design process, where the product development is divided into five stages:

1) Empathize
2) Define
3) Ideate
4) Prototype
5) Test

Design thinking is a PD methodology suitable for structuring ambiguous and radical innovative projects. With a well-defined task at hand, the Pahl and Beitz PD structuring was selected instead. It is therefore not desirable to fully base the thesis work on DT, but rather choose the tools which are considered profitable. Concerning this thesis, it is the Empathy stage of DT which are of most interest. d.School describes empathy as a combination of observing, engaging and immersing. Observing is associated with viewing the users and stakeholders in a relevant context. Engaging is linked to interviewing and talking to people closest to the problem you are trying to solve. Immersing is to experience the user's problems for yourself. To properly understand the needs at Alcoa Mosjøen, observation, engagement and immersion have been used to find the pain points of the potroom operators. The thought behind the thesis empathy focus was to harness the potroom operator's tacit knowledge. By doing so, less obvious solutions might occur, which hopefully leads to innovative and feasible concepts.

2.4 Design for Reliability

Design for "Excellence", commonly known as DFX (Stephenson, Wallace, and Eastman 2012), is a collection of concurrent engineering imperatives for product design development. The "X" in the DFX acronym is a placeholder for a term describing the project's head objective. Common attributes for DFX are such as Design for Assembly, Quality, Manufacturability, with much more.

It has been chosen that the Alcoa cover handling thesis will practise Design for Reliability (DFR). DFR was selected to aid the creation of qualified design decisions, enhancing the reliability of the concepts developed. Design for Reliability, or DFR, is a method for assessing which design configuration has the greatest potential for reliability at the early stages of the design process (Stephenson, Wallace, and Eastman 2012). Reliability, in the case of DFR, is the ability to perform a task under defined conditions given a set period of time. The sense of applying DFR is to implement the aim for reliability already in the conceptual design phase when the influence has the greatest impact on the end product. Some of the benefits provided through DFR is reduced product maintainability costs and increased solution HSE. Other profits of applying DFR early in the development is associated with prevention of costly redesign when reliability demands of products appear not to be met.

The reasoning for selecting DFR as a method for the thesis development is correlated to wishes of Alcoa Mosjøen. Throughout the project thesis period, it was expressed a desire for robust, functional and reliable solutions. Usage of DFR will ensure that their interest for reliable solutions is kept. For this particular project, the DFR toolset offers a method for selecting mechanisms based upon reliability as the key metric. Exploring robots and gripper solutions, the project will heavily depend on variations of mechanisms. DFR, therefore, stand out as especially favourable to utilise for the project. The DFX mechanism method (Aguirre 1992) evaluate three aspects by the mechanism design. These are categorised as Simplicity, Clarity and Unity.

Simplicity is defined by Aguirre (1990) as “the number of elements in a technical system should be the minimum necessary for its correct operation”. Simplicity can therefore straightforwardly be evaluated by comparing mechanism number of components and active interfaces.

One description of Clarity is provided by Pahl and Beitz (1984) as “the lack of ambiguity of a design (and) facilitates reliable prediction of the end product”. This concern the behaviour transparency of the mechanisms chosen or how easy it is to predict mechanism behaviour during usage. Aguirre states that clarity is the furthermost critical aspect of the mechanism when a selection between alternatives are performed. Mechanism clarity assessment is based on a ranking system which indicates the clarity between interfaces in a system.

The DFR interpretation of Unity is that a mechanism should aim towards a design where all components have an equal chance of failure. As unity is related to the chance of mechanism failure, is therefore often evaluated in the later embodiment stages of the PD process. Methods for evaluating unity can be engineering tools for strength and stress modelling, such as Finite Element Analysis (FEA). These three aspects of mechanism design will be used to evaluate which concepts should be selected for further development.

2.5 Prototyping and corporate collaboration

Understanding the main intent behind a prototype is of greater interest for this thesis. Many prototypes will be made, serving various purposes. Being able to identify the desired purpose as well as the required resolution of each prototype will be substantial for the thesis. These factors will have a great impact on the project efficiency and overall progression of the development.

There are numerous definitions to what a prototype is and the purpose of prototyping. One description is presented in the research article The Anatomy of Prototypes (Lim, Stolterman, and Tenenberg 2008). Here, it is stated that prototypes are the means by which designers organically and evolutionarily learn, discover, generate, and refine designs. In the 4th edition of Product Design and Development, it is suggested that the purpose of prototyping (Ulrich and Eppinger 2007) can be divided into four categories:

- Learning – Prototypes meant for knowledge capture
- Communication – Prototypes made for communicating ideas and intent
- Integration – Prototypes testing component and subsystem interaction
- Milestones – Prototypes displaying progress and functions based upon set goals

Figure 2.2: Communicative prototype of a smelting pot with detachable anodes.

In figure 2.2, a smelting pot prototype is depicted, made prior to the master thesis. This prototype was built to learn about smelting pots, communicate task and environment to externals and to see how the smelting pot subcomponents interact. Though Ulich and Eppinger divide prototyping into four defined categories, this indicates how category overlapping occurs.

Bryan-Kinns and Hamilton (Bryan-Kinns and Hamilton 2002) divide prototype usage into three dimensions; Fidelity, target audience and stage of development (figure 2.3). They propose that understanding the placement of a prototype within the three dimensions can help deciding what form a prototype should take. Bryan-Kinns and Hamilton's three dimensions will be used to structure the prototyping in this thesis.

When the goal is to efficiently and quickly build, test and learn, the prototype fidelity should be kept to a minimum. These prototypes can be made out of cardboard and materials which support rapid assembly and testing. This is typically situations where structural strength and aesthetics is not evaluated. For critical function testing, fidelity levels are to be elevated sufficiently to gain valid results. In these scenarios, laser cutting and 3D-printing of parts can be usable alternatives. These prototypes, where key concept functions are to be validated, can also be addressed as proof-of-concept prototypes (Ullman 2002). As proof-of-concept prototypes are finalised, the joint result can be developed into milestone prototypes for Alcoa delivery. These high-resolution milestone prototypes will in the thesis context serve as proof-of-product prototypes (Ullman 2002).

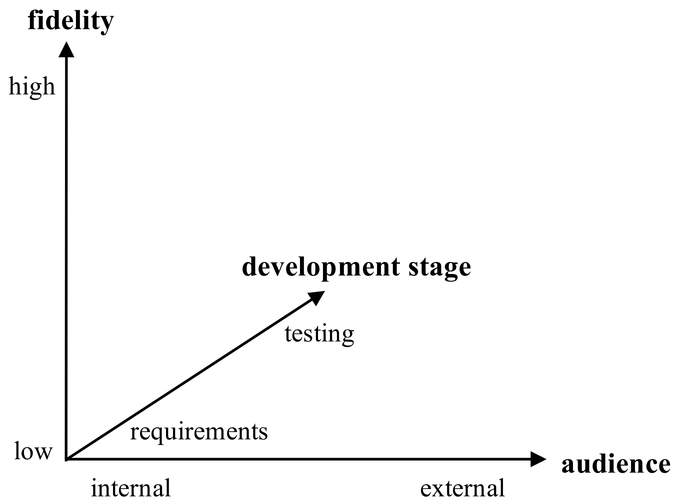


Figure 2.3: Bryan-Kinns and Hamilton's three dimensions of prototype usage impact. Source: (Bryan-Kinns and Hamilton 2002)

When the objective is to communicate ideas and design intent to the different stakeholders of this project, prototype fidelity needs consideration. For evaluation of concept intent with students and professors, low fidelity levels can be maintained in the form of sketches and CAD models. Concepts presented to the business partner, however, should be more refined, ensuring that the intent is correctly conveyed. Communicative external prototypes will, therefore, be either high-end aesthetic, physical prototypes or rendered CAD models. To convey the results to Alcoa, the prototypes will be recorded and sent either as slide shows or video. This will be continuously performed as new milestone deliveries are accomplished. With this, the goal is to generate business partner buy-in as well as acquiring regular feedback from the main thesis stakeholder throughout the project. These will be the prototyping guidelines for the thesis. A visualisation of the proposed prototyping structure can be seen in the Bryan-Kinns and Hamilton graph presented in figure 2.3.

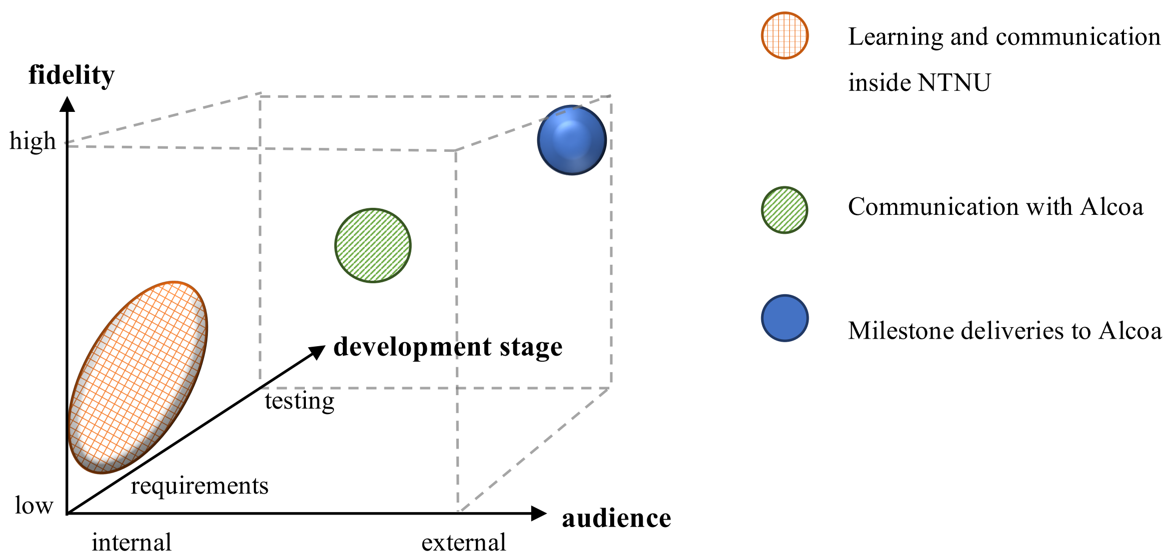


Figure 2.4: A visualisation of the thesis prototyping strategy, described through Bryan-Kinn and Hamilton's three prototype dimensions. Source: (Bryan-Kinns and Hamilton 2002)

3 Planning and task clarification

The planning and task clarification chapter will have the aim of thoroughly describing the details of the thesis challenge. This relates to questions such as:

- What is a pot cover?
- What is pot cover handling?
- What are the challenges related to automation of pot cover handling?
- What is the aim with cover handling automation?
- Which requirements are set by Alcoa?
- Which specifications should be set to provide Alcoa with their desired product?
- What is the main objective of the thesis?
- Which will be the milestone deliveries ensuring objective realisation?

These questions will all be answered throughout chapter three. Ending the planning and task clarification, a definite description of the project goals and outcome will be submitted before the conceptual design phase will be initiated. Starting off the task clarification will be an introduction to the pot cover.

3.1 The pot cover

To perform activities inside the smelting pots, exterior enablers are needed. The main enabler is pot cover handling; the removal and relocation of the pot hatches. Each individual smelting pot at Alcoa Mosjøen is equipped with 26 pot covers, closing the pot off from the surrounding environment. At Alcoa Mosjøen they have 404 smelting pots. This equals to roughly 10 500 pot covers in the potroom at all times. With a 24/7 production cycle, the current pot cover turnover period is four years. It is therefore required a steady flow of new pot covers at Alcoa. The covers are located on both long sides of the smelting pots. Each flank has 13 covers placed tightly in succession, fulfilling multiple purposes in the primary aluminium smelting process:

- Physical guard – Guarding the operators working in the potroom from falling into the bath
- Closing off the pots - reducing the escape of hazardous gas to the potroom
- Closing off the pots - maintaining the heat inside the smelting pots
- Providing the operators with steps for aid when inspecting anode rods

Figure 3.1: Render of a standard pot cover used at Alcoa Mosjøen.

Figure 3.2: Render of a side pot cover used at Alcoa Mosjøen.

The primary structure of the pot cover has dimensions roughly equal to 1,5 x 0,6 m. The pot covers are made out of aluminium, weighing approximately 13 kg when they are brand new. During potroom usage, the weight can increase up to 5 kg. This occurs as layers of fine dust gets stuck to the back of the covers.

All pots at Alcoa Mosjøen are equipped with two different types of pot covers: The standard (figure 3.1) and the side pot cover (figure 3.2). Of the 26 covers, there are only four side covers per pot, located at the pot end sides. The difference between the standard and side pot cover is an additional anti-flammable cloth patch, fastened to the cover long side. Besides the added feature, the pot covers are identical, consisting of five separate parts assembled with welds or screws:

- The main cover profile
- The hanger profile
- The handlebar
- The first step
- The second step

The main cover profile is made out of a single sheet of aluminium plate, providing stiffness and strength to the pot cover. The hanger profile is located on the top of the structure, providing a hook which rests on the smelting pot ledge (figure 3.3). This profile ensures that the cover rests securely on the pot, while also providing easy removal. The handlebar is either bolted or welded to the cover, yielding the operators with a grip for handling. The cover steps allow the workers to climb the smelting pot to perform measurements.

To describe pot cover orientation, the reference coordinate system provided in figure 3.3 will be used throughout the thesis. The pot covers are not attached to the pot but rest freely at a 45-degree angle on top of an angled ledge (figure 3.4) located right above the smelting pot opening. The covers are in theory capable of sliding along the ledge. They are, however, tightly positioned beside each outer, restraining most of the movement along the ledge x-axis. The ledge angle on the pots is designed in a manner restricting the covers from horizontal sliding tangentially out from the pot (y-axis). To remove covers from the pot, it requires tilting and/or lifting of the covers for further handling. This relates to freedom of movement in the vz-plane.

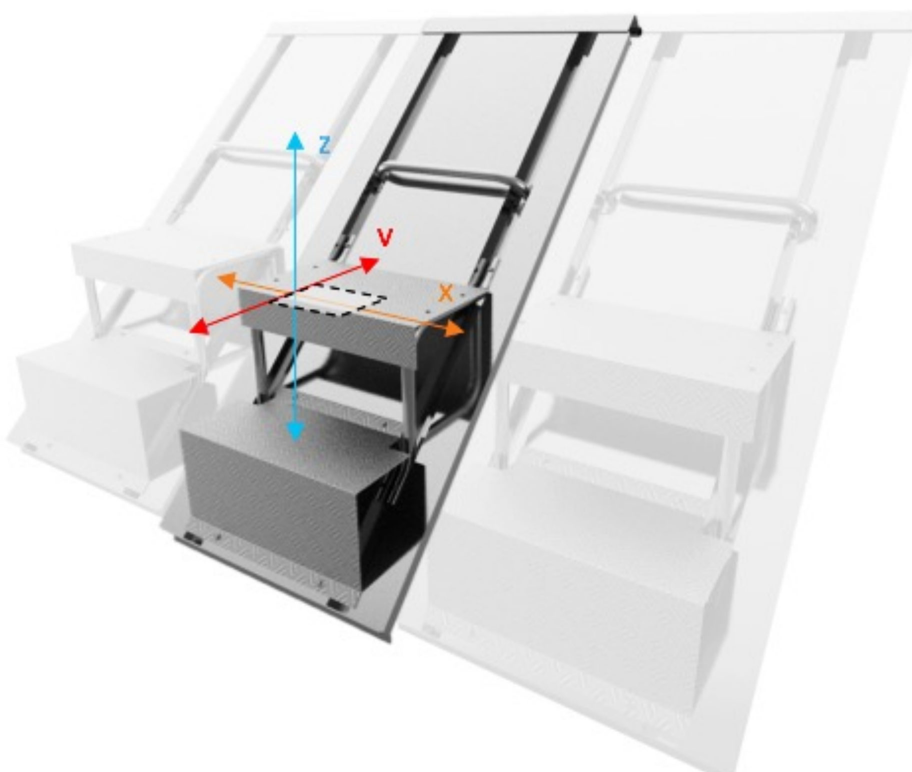


Figure 3.3: Figure displaying the reference coordinate system which will be used for cover orientation throughout the thesis

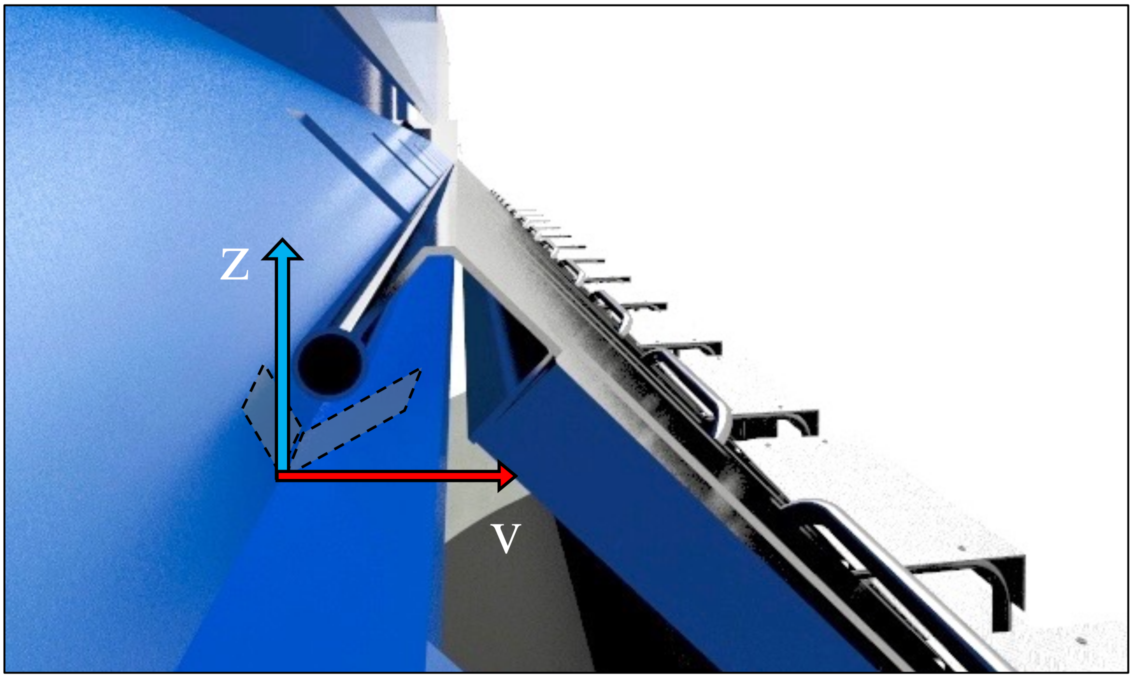


Figure 3.4: Close up of the smelting pot ledge, showing how the covers rest on the pot compared to the coordinate system.

3.2 Pot cover handling

During the summer internship at Alcoa, one month of observation, engaging and immersing was performed in the potroom environment. Multiple operations at Alcoa require cover handling, such as anode covering, probing and anode replacement. Through the month, a generous amount of pot cover handling was both observed and performed by the thesis author.

As of today, all handling of covers is performed manually. This is mainly done by the potroom operators and the process engineers. The three pictures displayed in figure 3.5 demonstrates how a process engineer, and former operator at Alcoa, perform cover handling. In this example, the sequential steps of handling are first grabbing the second cover step, followed up by hoisting the cover up. This is performed with an extended arm using the back muscles, stabilising the cover against the leg. The stabilisation is needed as the gripping is performed out of the cover centre of gravity. Storing of the cover is achieved by carefully placing it on top of a close by pot cover. Replacement of the cover is performed in the same manner, just reversing the process steps.

Figure 3.5: A process engineer at Alcoa Mosjøen performing typical handling of pot covers.

An observation to be made in figure 3.5 is the fact that the handlebar is not being used during the lift. There are multiple reasons for this, directly linked to the design of the pot cover. As shown in figure 3.6, the approximate pot cover centre of gravity is located at the root of the second step. Attempting to lift the cover by the handlebar will, therefore, lead to rotation around the handlebar axis. This results in tilting rather than lifting. If the cover is tilted to a standing position, it becomes awkward to lift from the handlebar due to the size of the pot cover.

To the far left picture of figure 3.5, the engineer has to lean in to reach the second cover step. To be able to reach the handlebar, he will need to reach even further in. The increased distance makes it straining to perform a lift from the handlebar. This ultimately leads to operators lifting covers from the step as shown in the figure. Cover lifting performed by both gripping the handlebar and the step is also feasible. This is also recommended by Alcoa according to ergonomics. After immersion and testing of the different techniques, handling from the second cover step occurred as the least straining and most ergonomic compared to the alternatives.

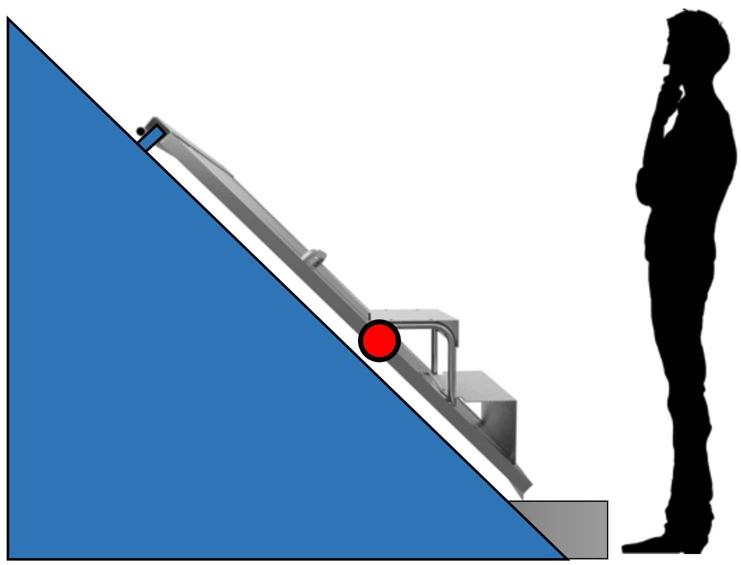


Figure 3.6: A section view of the smelting pot showing how the covers are positioned. The cover approximate centre of gravity at 45-degree placement is displayed with a red dot.

3.3 Pot cover handling challenges

This subchapter address potential physical challenges related to the automation of cover handling. These were identified during the internship at Alcoa and during the project thesis period. The environmental challenges related to heat and varying magnetic fields were addressed in the project thesis (Appendix J, Section 3) and is excluded from this thesis. The heat outside the pots is not a noteworthy problem factor and can be solved by cooling at summer time and heating during winter if required. The magnetic fields can be countered by application of compatible technology and magnetic shielding.

3.3.1 Pot cover damages

Producing primary aluminium require heavy tooling and machinery. Due to reckless handling of the equipment, damages frequently occur. It is common to see pot covers with smaller dents and scratches in the potroom. This is expected and will have to be assessed as a part of the automation challenge. Some covers, however, has severe damages, such as the ones displayed in figure 3.7, 3.8 and 3.9. Covers sustaining this type of damage needs replacement or repairing. Damages at this level would be hard for an automated robot to handle. Identification of such covers will be vital to prevent damages to the robot and pot.

Figure 3.7: Pot cover with the handlebar torn off.

Figure 3.8: Pot cover with a severe tear.

Figure 3.9: Damaged pot cover, missing the entire second step.

3.3.2 Dirt and dust

Another complication for cover handling automation is the contaminations of dirt and dust in the potroom environment. There are multiple sources and types, varying in both shape and size. The more commonly appearing varieties are:

- Alumina residue, fine powder-like texture
- Anode cover mass residue, coarse gravel-like texture
- Drifting by-products from the smelting process, very fine dust texture
- A hardened cover mass residue, similar to ceramic stone roughness

The dirt and dust introduce challenges related to several aspects of the handling operation. First of is the gripping. If the cover surfaces are covered with dust (figure 3.10), accurate gripping can be difficult to achieve. Robotic mechanisms might also be vulnerable to jamming related issues. Another hindrance is situations like figure 3.11 and 3.12, where dust and stone are located on top of the pot covers. If the cover is removed, these contaminations can fall on the ledge, blocking the cover from being placed back to the exact position.

Figure 3.10: Dirt and dust covering the pot cover step surfaces.

Figure 3.11: Dirt and dust are resting on top of the smelting pot cover rack.

Figure 3.12: Chunks of solidified cover mass rest on top of the smelting pot cover rack.

3.3.3 Operational standards

Automation of other processes is under current development at Alcoa Mosjøen. In the transition between the AS-IS situation and to the new TO-BE, operational standards would need to adapt to increase automation implementation feasibility. As previous stated, all of the current cover handling at Mosjøen is performed manually. Sometimes the covers can be stacked a bit too tightly, making it difficult to remove or place back the covers. Extra force might, therefore, be needed or a directional kick to the row of covers to create the required space. This can result in unaligned covers. Opposite of this is the situation where there is too much space between the covers. If not placed back warily, the covers can become unaligned on the pot (figure 3.13). For automation success, it is important that the overall handling standard and cover placement is kept high. Another standard that needs to be attended to is the cover production and assembly quality. As shown in figure 3.14, there is a noticeable height difference between the two handlebars. Large object differences can become a source of reduced automation reliability.

Figure 3.13: Misplaced pot cover, resulting in crookedness and a gap between covers.

Figure 3.14: Differences between pot cover handlebar height.

3.4 Thesis objectives and milestones

With the process objects and steps defined, this chapter will specify the exact expected outcome from the thesis. The principal expected product of the thesis is a robot concept capable of performing cover handling. To develop a manipulator system solution capable of replacing the current manual cover handling process, three key objectives will be carried out:

1) Develop a robot gripper concept specialised for pot cover handling at Alcoa Mosjøen
2) Develop a robot concept suited for pot cover handling from an AGV platform
3) Develop a concept for pot cover storage during pot operations

These are the three main elements needed to physically perform automatic or semi-automatic pot cover handling.

Should Alcoa wish to use parts of the provided concept, it is important that the sub-components of the system are not too dependent on each other. The gripper and manipulator development will, therefore, be handled in succession, separating the conceptual design phase of the two into bulk (figure 3.15). In that way, the two concepts can serve as separate solutions, not being too devoted to each other. By following this bulk procedure, the conceptual design process of the two will be clearly divided and transparent as well. To provide a joint cover handling system, the two concepts will be merged together in the subsequent embodiment stage. The third objective, pot cover storage, will be assessed concurrently during the conceptual design development of both the gripper and robot.

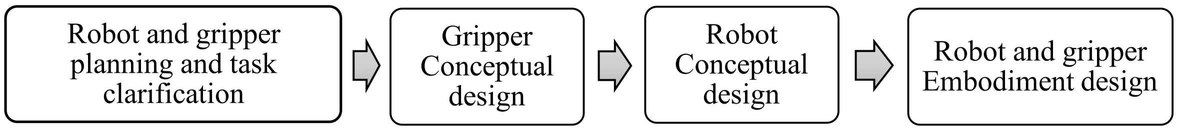


Figure 3.15: Thesis progression plan.

From the Pahl and Beitz development structure presented in chapter 2, a sub-delivery plan for the three primary objectives has been made. These are also broken down into sub-deliveries for storage in the SCRUM Backlog and iterative completion. This is the milestone plan which will be used to accomplish the three objectives:

Robot and gripper planning and task clarification

- Definition of system specifications and constraints

Robot and gripper conceptual design

- Ideation and creation of multiple low-resolution principle solutions
- Selection of the most promising preliminary concepts
- Development of preliminary concepts for concept testing
- Perform critical function testing and perform concept comparison and selection
- Create high-resolution prototype(s) of most feasible concept

These are the proposed milestones for achieving the desired results within the conceptual design phase. Finalising the conceptual design stage, high-resolution prototypes of the most viable concept(s) are to be delivered to Alcoa. In the gripper case, this will be a full-scale functional prototype. The final conceptual design manipulator concept(s), on the other hand, will be prototyped on a scaled-down level. It is considered too premature and resource expensive to perform full-scale building of robot concepts this early in the development process. The manipulator prototype(s) should, however, be a fully functional, capable of performing scaled down pot cover handling.

As the conceptual design goals are reached, the development can move over to the embodiment design phase. Here, the milestone delivery plan for both concepts are:

Robot and gripper embodiment design

- Joining of robot and gripper
- Refine and improve concept layouts
- Provide a final concept proposal for AGV implementation

These are the milestones and sub deliveries planned for completion throughout the thesis.

3.5 Task specification and constraints

Having clarified the project objectives and milestones, the planning and clarification stage of the process is near its completion. Left for finalising is the definition of the product specifications and constraints. Locking these down will aid the process in the manner of reducing the ambiguity level of the task. The product specifications are presented in the format of two requirement lists. The listed specifications are based upon company requirements, environment constraints, and operational demands for the final concept. The first requirement list (table 3.1) address the overall system demands, stating the functions required for the final solution from a must/should/wish perspective. The second table, table 3.2, state the requirements related to specific values.

The redesign of pot covers was early turned down by Alcoa, as stated in chapter 1.3. The current cover shape and functions are desired to be kept. Keeping the existing pot cover design will impact the thesis, as the robot gripper tool will be restricted to fit with the current cover design. It is also required that the robot solution is capable of handling both types of covers present at Alcoa.

Also impacting the development is where the manipulator system is to be installed. It is intended to be placed together with the anode covering robot, together solving the complete operation of anode cover mass maintenance. The two most feasible platform alternatives, identified together with Alcoa, is unit installation on the potroom overhead crane or an autonomous vehicle (AGV). As the potroom overhead crane is already operating anode replacement, AGV installation became the preferred choice. This also implicates that the system needs to be tailored for battery power drive.

SYSTEM DEMAND SPECIFICATION				
Description		Must	Should	Wish
1	No alteration on current pot cover design	**X**	**(X)**	
2	Fit AGV implementation	**X**		
3	Be battery powered	**X**		
4	Be able to store two pot covers	**X**		
5	Store the covers securely and fixed for motion	**X**		
6	Be able to perform handling of both types of covers	**X**		
7	Be able to lift two covers simultaneously			**X**
8	Be a reliable and robust solution		**X**	
9	High degree of system clarity		**X**	
10	High degree of system unity		**X**	

Table 3.1: System Demand Specification table.

A demand set by Alcoa is the number of storable covers during pot operation. To provide the anode covering robot with a sizable operation space, two pot covers should be possible to store at the same time. The storage should be practical and convenient, not obstructing the anode covering robot. Storage should also be safe, ensuring that the covers are fixed during operation according to HSE. With the additional focus on Design for Reliability, the solution should be robust, satisfying the factors of simplicity, unity and clarity. It is obligatory that the solution is capable of handling single covers. It would, however, be an additional bonus if it could handle two covers simultaneously, reducing the operational lead time.

There are some values which are definite and can be underlined. These include the numbers of covers for gripping, handling and storing. Others are at this point unspecified but can be addressed with threshold values. As two covers are wished to be lifted at the same time, minimal payload should succeed the weight of two pot covers combined. This yields 13kg x 2, combined with the unknown weight of the gripper tool concept. The reach of the manipulator should exceed the distance between the pot and AGV, plus the horizontal distance to the desired gripping area on the pot cover (3.16). Having not decided the designated gripping area, a minimum reach of 1.0 m is set. Alcoa is currently realising a project utilising AGV's in Mosjøen. Their AGV platform area has the approximate dimensions of 6.2x2m. This will be used as a reference size, being the upper boundary size of the AGV base. These are the defined product specifications and constraints which will serve as a framework for the following development process.

PRODUCT DEMAND SPECIFICATION		
1	Covers to be removed before anode covering	= 2
2	Covers to be gripped simultaneously	>=1 or =2
3	Covers to be stored simultaneously	= 2
4	Manipulator payload capability	> 13 kg x 2 + tool mass
5	Manipulator reach	> 1.0 m
6	Maximum AGV size	> 6.2 x 2.0 m

Table 3.2: Product Demand Specification table.

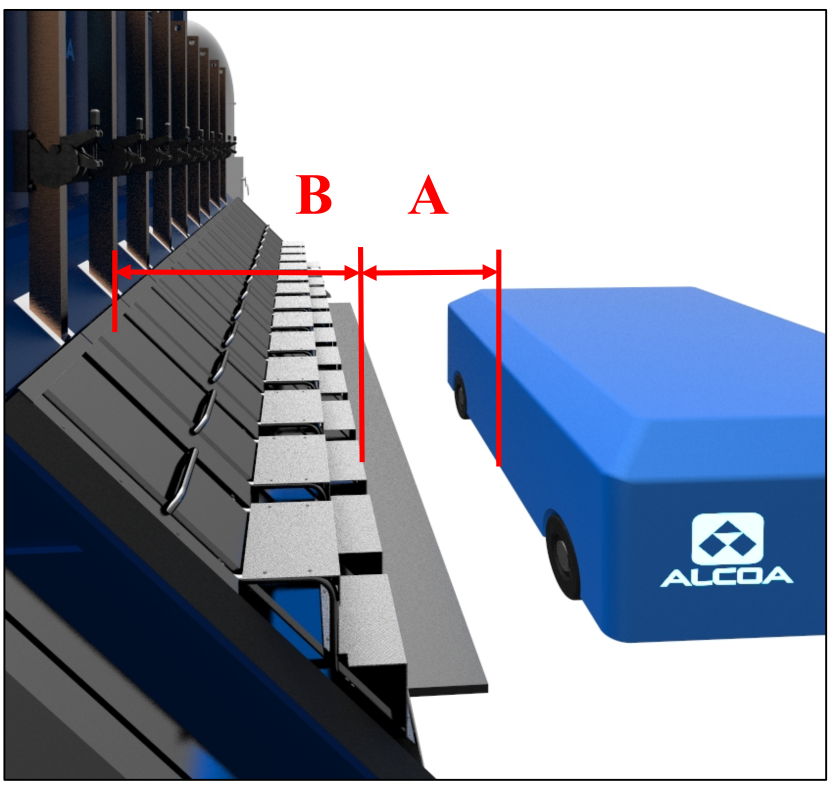


Figure 3.16: Max working distance between pot and AGV (A), combined with the unknown distance to the cover gripping location (B), decides the minimum reach for the cover handling robot.

4 Conceptual design: Robot gripper

First out is the conceptual design of the robot gripper. Ideation and preliminary concept generation will be performed to go wide and find a large pool of possible gripping solutions. By rapid prototyping and testing, these concepts will be evaluated. From the evaluation, the most promising concept will be brought further into development. End milestone selected for the gripper conceptual design stage is to have a full-scale prototype capable of reliably lifting a 1:1 sized pot cover. The conceptual design phase is initiated with a literature study on robotic grippers, filling in knowledge gaps related to the topic.

4.1 Literature study: Robot grippers

There exist multiple terms for the tools operated and handled by robots. In addition to gripper, commonly used terms are end effectors or end-of-arm-tooling (EOT). In the book Robotic Grippers (Monkman 2007), robotic grippers are divided into four categories describing their interaction with objects:

- Impactive
- Ingressive
- Astrictive
- Contigutive

Briefly describing the differences, the impactive grippers relies on physical and direct connection with objects, such as jaws or claws. Ingressive grippers penetrate the desired object to gain control, for example pins or hackles. Astrictive grippers depend on suction forces to lift objects, such as magnetism and vacuum. Contigutive grippers utilise direct contact for connection, for example glue or surface tension. Based upon information provided in Robot Grippers, a technology analysis table have been created. The technology analysis is used to identify which of the methods are most applicable for our task. The results can be viewed in table 4.1.

With basis in book recommendations, cross referenced with the pot cover gripping task, ingressive and contigutive grippers can removed as alternatives. These gripper methods are not suited for large rigid objects and therefore disqualifies as options. On the other hand, both impactive and astrictive grippers shows promise for implementation. The various impactive gripping methods can be explored as they are meant for solid object gripping. Of the astrictive gripping methods, vacuum is the most feasible option. This is due to the pot cover size and its material being non-ferrous.

TECHNOLOGY ANALYSIS: ROBOT GRIPPERS				
	Impactive	Ingressive	Astrictive	Contigutive
Forms of gripping	- Jaw - Inverted jaw - Claw - Pincers - Pinch mechanisms	- Brush elements - Hooks - Velcro - Needles - Pins - Hackles	- Magnetic adhesion - Electrostatic adhesion - Vacuum adhesion	- Surface tension - Thermal adhesion - Chemical adhesion (glue)
How	Physical and direct connection with object.	Penetrate the desired object to gain control.	Continuous holding forces to lift objects through adhesion	Direct contact for connection.
Typical application	Rigid objects.	Flexible objects, such as textiles and glass fibre.	Non-porous rigid materials, ferrous materials and micro-components.	Flexible and small, light objects.
Task advantages	- Fits task profile - Highly applicable		- Adaptable to gripping surface - Strong and rigid	
Task disadvantages	- Demand custom design to acquire retention of pot covers		- Power consuming - Increased system complexity - Weight - Surface requirements	
Summary	Traditional choice, various impactive grippers can be utilised	Not an appropriate method for pot cover gripping	Vacuum shows promise, other principles not applicable	Not an appropriate method for pot cover gripping

Table 4.1: Gripper Technology Analysis table.

Also provided in Robot Grippers is a checklist of properties hallmarking high quality robot grippers. As the pot cover gripper is meant for a repetitive and specific object handling, characteristic 2) is not of relevance. Besides this, the rest of the list sums up what to aim towards when designing a gripper tool. This list can be applied for benchmarking of preliminary gripper concepts:

1) Optimum adjustment of the gripper structure to the operations performed
2) Large adjustments range and options to prehend parts of different shape and size
3) Reliability with respect to dislocations of the object (stability of the object position and orientation)
4) Optimum gripping force path characteristics
5) Low number of links and joints (where applicable)
6) Small installation space and mass, robustness
7) High reliability combined with easy service
8) Avoidance of damage and deformation to the object during prehension
9) Sufficiently high object positional accuracy
10) Good wear resistance
11) Simple control and short action times

The book also presents the most widely and commonly implemented kinematic systems used for robotic manipulators and ingressive gripper designs. These mechanisms will be relevant for the development of the gripper as well as the manipulator, as actuation will be needed for properly securing the covers during handling. The kinematic systems presented are:

- Jointed mechanisms (lever gears)
- Screw gear
- Wedge gear
- Cam gear
- Wheel gear, rack wheel and rack and pinion gear
- Pull and pressurizing medium gear

In the manipulator case, actuation is relevant for acquiring motion in the different axes. The system providing robot actuation is known as the manipulator's drive system. In Robot Grippers, a table addressing the strength and weaknesses of the most commonly applied robot gripper drive systems (table 4.2) is provided. Similar to the list of mechanisms, these criteria's can be of utilised when deciding drive system for both gripper and robot.

Drive system / Evaluation criteria	Mechanical	Pneumatic	Hydraulic	Magnetic	Electric motor
High gripping force	◐	○	●	◐	○
Controllability	○	○	◐	●	●
Energy transmission	●	◐	○	●	●
Insensitivity to dirt	●	◐	●	○	◐
Maintenance	●	◐	◐	○	◐
Emergency stop behaviour	●	◐	◐	○	○
Constructional size	○	○	●	◐	◐
Environmental influences	●	◐	○	●	●
Costs	●	●	◐	◐	○

Table 4.2: Drive systems and their strength and weaknesses in relation to robot gripper tooling. Black symbolises advantageous properties, while white is unfavourable. Source: Robot Grippers (Monkman 2007).

In the subsection of impactive grippers, the book presents a specific type of impactive robot gripper termed self-sustaining grippers. These grippers can retain objects by force matching alone, securing through object mass. In other words, prehension can be performed without any sort of motor actuation. If proven plausible, this can be especially interesting for gripper clamping. With no motor drive systems required, the tool would be independent of the robot unit. Such a solution would be able to present reliability through high degree of simplicity and maintenance. A collection of self-sustaining drive systems can be viewed in figure 4.1.

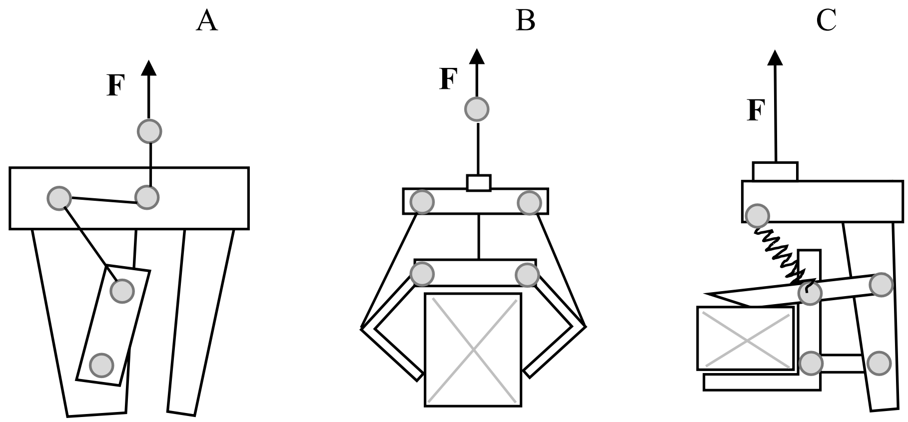


Figure 4.1: A collection of self-sustaining gripper mechanisms. Source: Robot Grippers (Monkman 2007).

4.2 Ideation and rapid concept generation

Starting the robot gripper ideation, some facilitation was performed to aid the idea generation session. To assist creativity, and to have physical objects to interact with during the session, two scaled down pot covers was 3D-printed (figure 4.2). These were made from the original pot cover CAD-files made during the project thesis, altered with a simplified geometry to enable printing with a Ultimaker 2+. Despite the geometry simplification, important factors such as centre of gravity and correct scaling was kept as part of the design.

Figure 4.2: Simplified pot covers 3D-printed in PLA, made for ideation session.

4.2.1 Pot cover gripping areas

With the two miniature covers at hand, the first brainstorming session aimed toward identifying areas available for gripping. The brainstorming was divided into the two gripping methods identified during the literature study; impactive and astrictive gripping. For the impactive grippers, this would implicate all areas providing something to grab hold of or areas capable of creating a physical connection with the EOT. Most relevant here is the areas surrounding the steps and handlebar, where there are many edges creating opportunities for impactive gripping (figure 4.3). The step plates and the pipe supports of the second step have a nicely defined symmetrical geometry, creating multiple possibilities of gripping. For astrictive gripping, it is the planar surfaces which is most suited for gripping. These areas are emphasised in figure 4.4. To ensure an unrestricted and agile ideation on gripping solutions, no screening of the gripping locations was performed at this point. This was postponed to after the rapid preliminary concept generation.

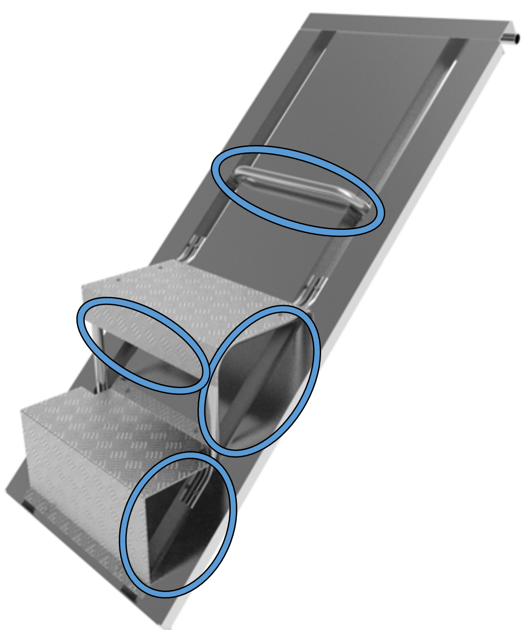


Figure 4.3: Pot cover areas identified as possible for impactive robot grippers.

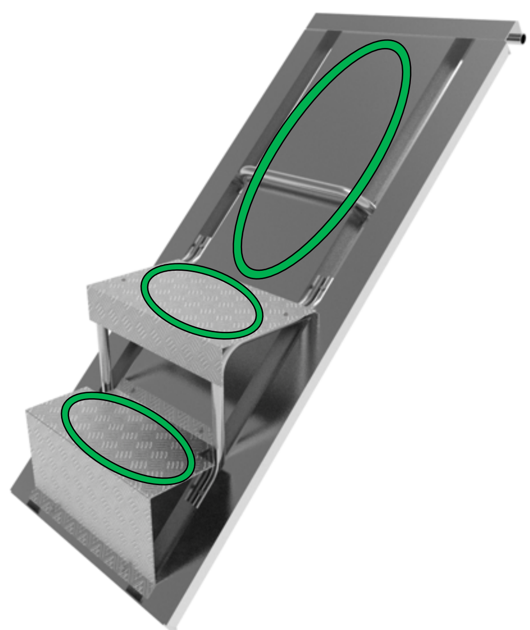


Figure 4.4: Pot cover areas identified as possible for astrictive robot grippers.

4.2.2 Cardboard and sketching ideation

With a clear vision of where gripping can be performed, a rapid ideation session was engaged. Equipped with cardboard as tooling material and a glue gun, low-resolution grippers were quickly built and tested on the scaled down covers (figure 4.5). The grippers were essentially crafted with function in mind, not aesthetics. Numerous impactive gripper prototypes was able to perform lifting based on the cardboard stiffness and design alone. To simulate astrictive gripping, the glue gun was used to glue the prototypes directly to the cover surfaces. Ending the session, some newfound knowledge was captured:

- Gripping principle and angle of the EOT greatly affects the tooling arm momentum and pot cover balance during handling
- Lifting balance was best acquired with the tools intersecting near the second step of the cover
- Though numerous of the concepts managed to handle one pot cover, not all of them would be successful at handling two covers simultaneously

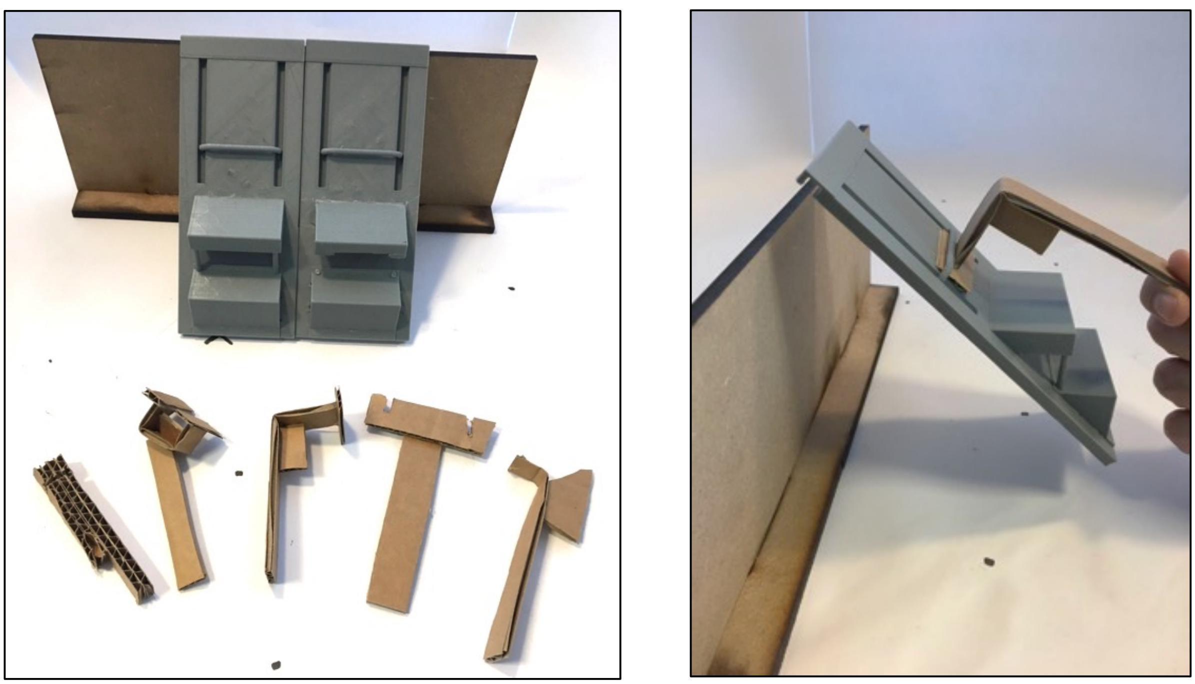


Figure 4.5: Two pictures taken from the cardboard EOT ideation session. The pictures show the test rig and some of the gripper prototypes which were tested.

After the session, the most feasible of the gripper prototypes were sketched down and their principles of retaining described. The five most promising gripper alternatives will be described in the following subchapter before an evaluation of the selected preliminary concepts are performed.

4.2.3 Preliminary concept 1: Vacuum gripper

The vacuum gripper concept is an astrictive gripping proposal applying pressurised air to create suction between the pot cover and the lifting tool. Traditional vacuum gripping is performed with suction cups made out of rubber, creating an air tight seal between object and tool (figure 4.6). Surfaces most preferable for gripping are the planar areas near the cover centre of gravity, illustrated in the far right picture in figure 4.6. Gripping from multiple surfaces for increased prehension can be a possibility.

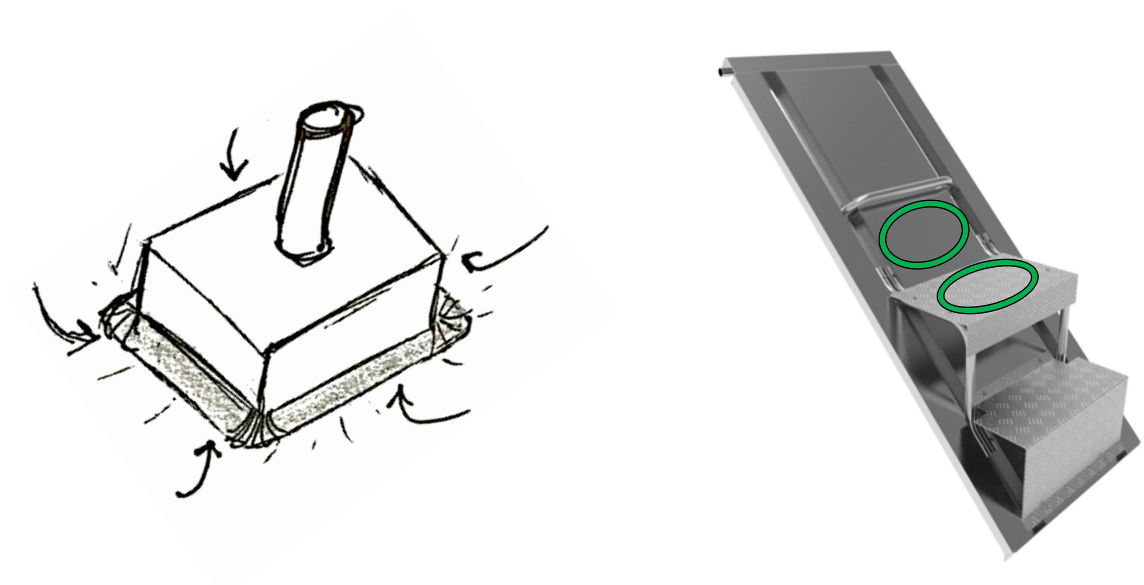


Figure 4.6: Vacuum gripper concept. The sketch to the left show the gripper concept, while areas of proposed usage is highlighted to the right.

4.2.4 Preliminary concept 2: Top step and bar gripper

The top step and bar gripping concept is based on symmetrical prehension from both sides of the cover second step plate. With some sort of clamping between two special fitted gripper tools, a firm grip can be acquired of the cover. The proposed areas for impact is on top of the upper step plate or direct contact with support bars holding the step, as shown in figure 4.7.

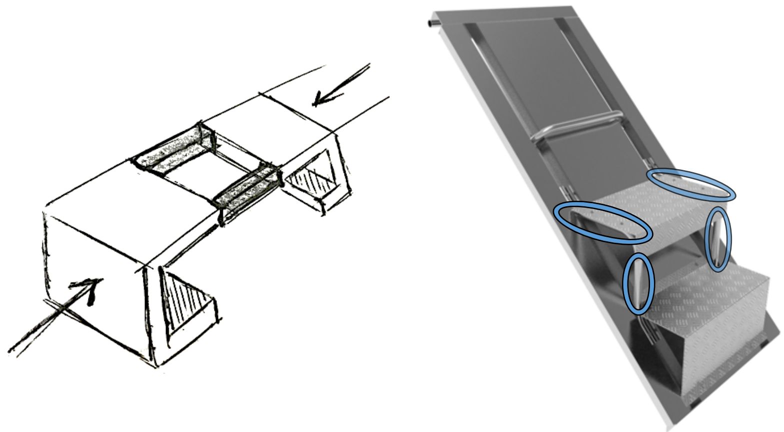


Figure 4.7: The top step and the bar gripper concept. Blue circles indicate the proposed gripping location.

4.2.5 Preliminary concept 3: Operator gripper

This concept is similar to the prior concept targeting the top step of the pot cover. Inspired by how pot operators at Alcoa Mosjøen handle the pot covers, this tool grabs the cover from underneath the second step plate. Similar to how the pot operators shape their hand for gripping, the EOT has a slot where the step plate brim can be inserted (figure 4.8). The concept restricts the most vital degrees of freedom, enabling lifting of the cover. For restricted movement in all directions, additional clamping would be required for secure execution of cover handling.

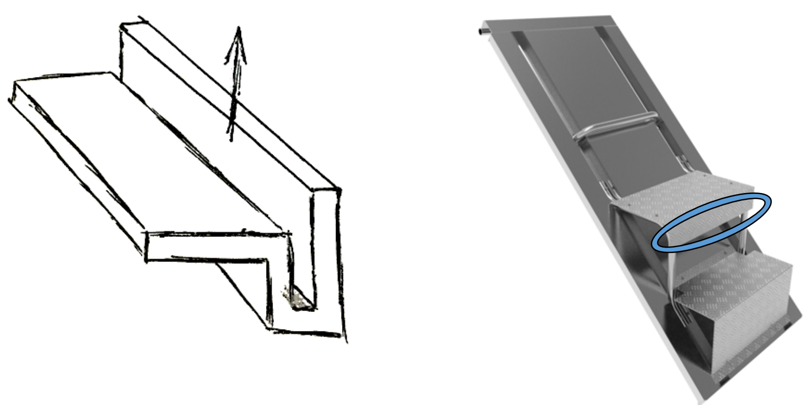


Figure 4.8: The operator gripper concept. The tool is inserted underneath the second step, then lifted upwards, confining the step plate in the tool slot. Blue circle indicate gripping location.

4.2.6 Preliminary concept 4: Bottom step gripper

Fitted for the perpendicular corner of the bottom step, this tool is based on the same principle as concept 2. With a symmetrical clamping motion, the pot cover is grabbed by gripping the first stepping plate with a specially fitted slot in the gripper. Concept sketch is visualised in figure 4.9.

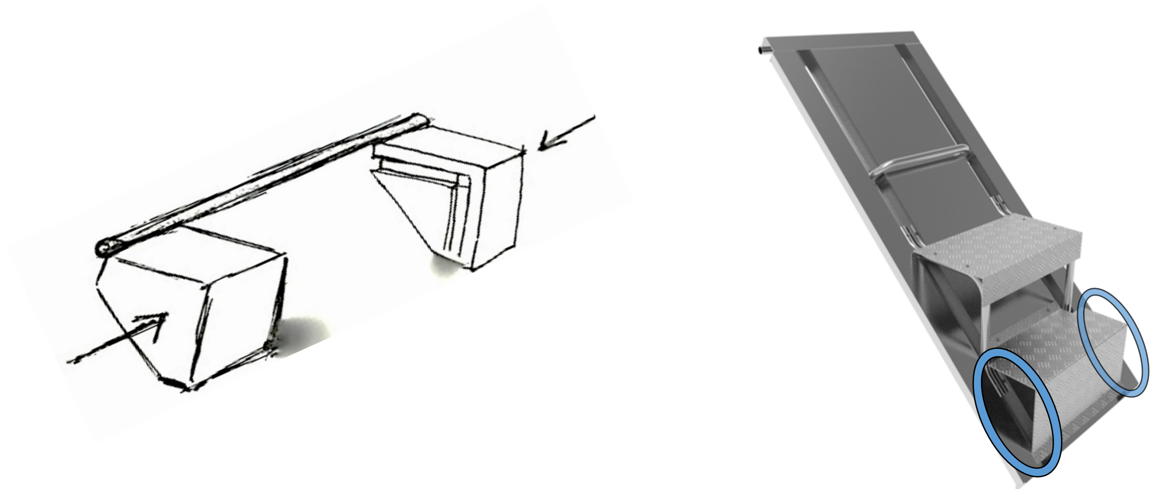


Figure 4.9: The bottom step gripper concept. With a slot fitting the bottom step plate, it restrains the cover for handling. Blue circles indicate gripping location.

4.2.7 Preliminary concept 5: Handlebar gripper

The handlebar gripper concept depicted in figure 4.10 is one of many possible designs of a gripper utilising the pot cover handling bar for impactive gripping. The sketch demonstrates a two-split tool which can grip the handle bar by using the planar surface of the cover for guidance. Once parallel with the surface, the gripper clamps the handlebar and confines it. The surface of the tool impacting the pot cover surface has an increased area of contact. This is chosen to distribute the forces better, as the cover sheet is quite thin (1.5mm) and can possibly buckle.

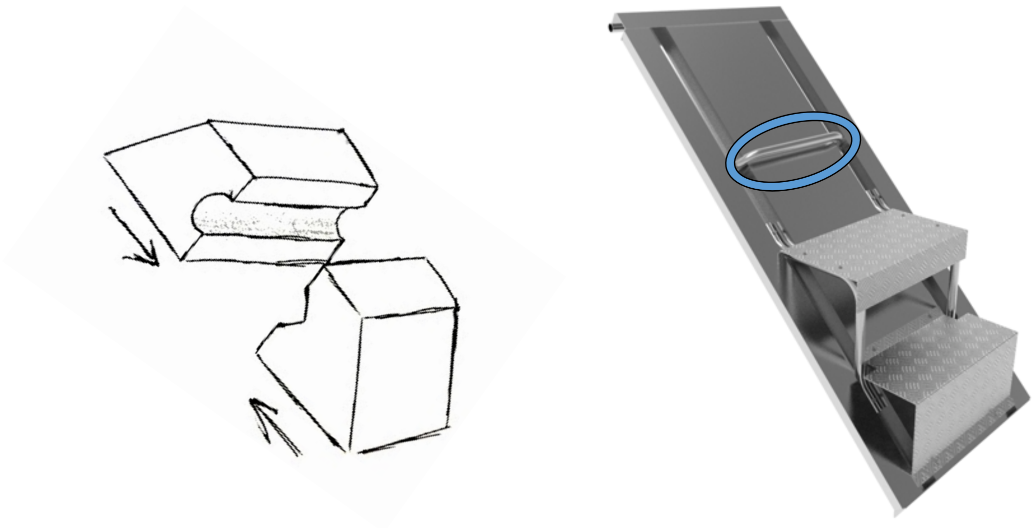


Figure 4.10: The handlebar gripper concept. Gripping location marked with a blue circle.

4.3 Preliminary concept review

The five concept proposals, though simplistically described and presented, appear feasible for pot cover handling. To reduce the number of preliminary concepts, a qualified evaluation will be performed.

The assessment can be based on multiple parameters. We have Design for Reliability, signifying the importance of simplicity. We also have the product specification table from chapter three, stating what is expected from the gripper. Ultimately, we have the list from Robot Grippers, hallmarking high quality grippers. Various of these attributes are collected and combined into a preliminary concept comparison matrix, presented in table 4.3. Through this matrix, the most promising concept will be selected. By evaluating the concepts against the matrix parameters in the matrix, insurance of product requirements being fulfilled is also obtained.

The vacuum gripper concept seemed applicable at first and was a favourite before conducting further research. It has its benefits of being the most adaptable gripper choice, being able to pick up covers with damages and even misalignments. There is, however, incriminating factors rendering vacuum gripping less attractive for usage. First of is the constant swirl of dust and dirt in the potroom environment. Most vacuum gripper systems are sensitive to dust, though dust can be handled by filtration systems or surfaces cleaning. Having to solve this, however, would reduce the simplicity of the final gripper design.

Part of the pot environment is also heat. The surfaces of the cover which is in direct contact with the internal pot environment has an increased surface temperature compared with the ambient potroom temperature. A thermal imagery investigation has been conducted at Alcoa, performed with a FlukeTi27 camera. The results unveiling temperatures ranging from approximately 50 degrees Celsius to 200 degrees under normal operation conditions (Appendix H). Industrial vacuum grippers withstanding heat up to 600 degrees Celsius ("Suction Cups for High-Temperature Applications | Schmalz" 2017) can be acquired, rendering this less problematic. High temperature lifting pads, however, require frequent maintenance and changing. There is also the issue of flames spiking up from the bath, applying additional heat to the cover surface. This can lead to heat levels exceeding the smelting point of the cover sheets, visualized in figure 4.11. With the possibility of these occurring temperatures, the reliability of vacuum gripping decreases.

Figure 4.11: Picture displaying a pot cover which has smelted.

To facilitate vacuum gripping, a pneumatic compressor would be required on the AGV platform. As the literature study revealed, the astrictive lifting methods require continuous holding forces. In other words, creating and maintaining prehension requires additional power usage. This is not beneficial on a platform utilising battery power. Combining these factors together, the vacuum gripping concept occur as a less obvious choice for pot cover handling.

The top step and bar gripper concept would grab the covers almost at centre of gravity, providing a nice, even lift from a large area of impact. One of the drawbacks with this concept is the required tool size. With the step plate measuring 490 mm across, a prehension mechanism performing gripping at this distance will be large and less simplistic. Large EOT's also provide additional weight to the robot arm, increasing the required payload.

When the cardboard test session was performed, only single pot covers were tested for handling. Evaluating the concept in light of simultaneous cover handling introduces concern. When the covers are placed in succession, the ideal distance between the stepping plates of two covers are only 103mm (figure 4.12). This is quite a tight fit for reliable gripping of two covers. The same can be said of **the bottom plate gripper concept**, which encounters the same distance. The bottom plate concept also has the disadvantage of being far from centre of gravity, generating bending momentum in the gripper.

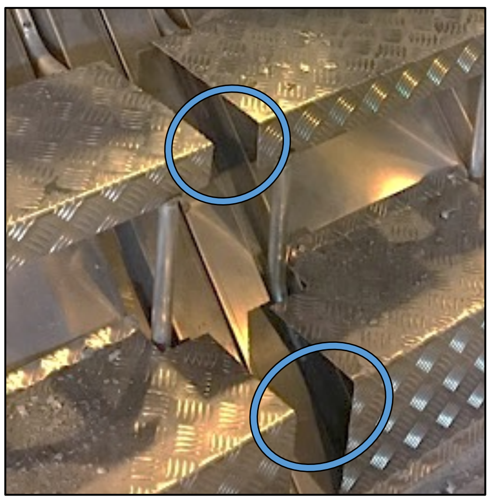


Figure 4.12: Picture illustrate the tight gap between the pot cover steps. When two covers touch and is aligned, the distance between the steps should be 103 mm.

The operator concept has some viability already confirmed, as lifting in this manner is already performed by the operators at Alcoa Mosjøen. The gripper concept can distribute the prehension force across the area of the stepping plate, yielding a nicely balanced lift. It also impacts the cover near the centre of gravity. The supporting step bars can ensure guidance of the tool, centralising it. Not having to impact the cover from its sides, the concept show promise for simultaneous cover handling as well.

As the concept is presented at this stage, it is the only of the presented solution not applying some sort of cover retention. With a fitted tool from this concept, careful handling of two pot covers could be possible to achieve. To provide consistency, reliability and HSE, however, some sort of clamping should be included in the gripper design. There are good chances for achieving this, should the concept be chosen for further development.

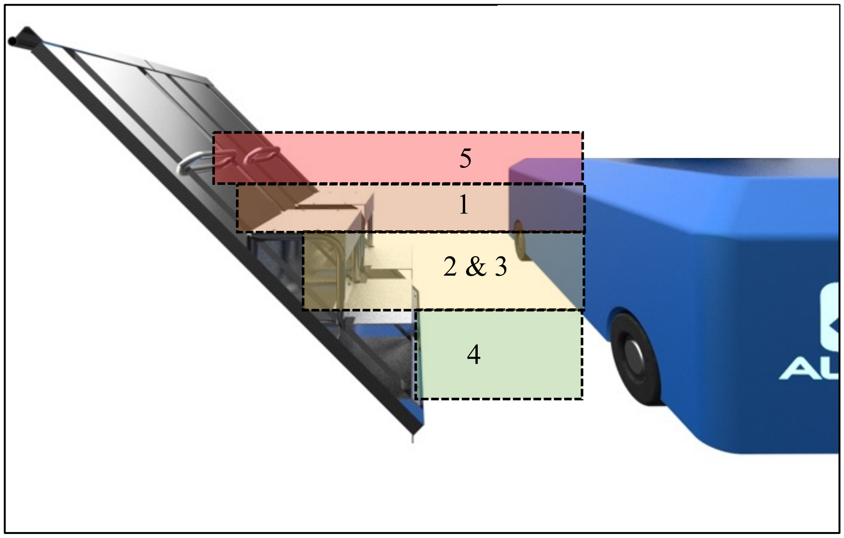


Figure 4.13: Figure showcasing the robot reach required for each of the preliminary concepts, presented with the concept numbering from 1-5.

The handlebar concept, similar to the operator concept, show few weaknesses for further development. The handlebar has a simple, graspable geometry where the object geometry can also aid with centralisation of the tool. Creating a lifting tool capable of lifting the cover from the handlebar seems quite feasible. A drawback from lifting covers from the handlebar is the bar placement on the cover, spanning far from the centre of gravity as well as the AGV. This increased distance might introduce gripper and robot implications. With the handlebar concept, the gripping force absorption will occur in the handling bar fastening area. This area is not especially large, and the bar is fastened to a 1,5 mm thin aluminium sheet. The strain generated in this area during robot handling can possibly succeed the sheet plate yield stress. This unknown factor implies risks with further development of the handlebar concept.

Engineering Design (Pahl and Beitz 2007) offers multiple evaluation tools for concept comparison. To summarize the concept review and to converge on the choice of concepts, a concept comparison matrix will be used. A list of parameters for each of the concepts are evaluated, where each parameter is weighted at equal scoring. The scoring for each parameter is set to 0-4 points, where 4 represents optimal attribute conditions. 0 indicates that the evaluated feature is not met at all. To converge towards the most promising designs, the points for each concept is summarized in the bottom of the matrix. The sum is divided by max achievable points to find the percentage of concept feasibility. Based on the concepts' percentage of feasibility, a comparison and verdict can be performed. According to Engineering Design, a viable concept should at least score 80% of the maximum possible score. The scoring presented in the matrix is based on the reflections presented in the concept evaluation.

PRELIMINARY CONCEPT COMPARISON MATRIX: GRIPPER					
Concepts / **Attributes**	Vacuum gripper	Top step and bar gripper	Operator gripper	Bottom step gripper	Handlebar gripper
Reliability with dust and dirt	1	2	4	2	4
Reliability with dislocated and damaged objects	3	1	2	1	1
Gripper interaction near gravity centre	3	4	4	1	1
Estimated tool size	3	1	4	1	4
Mechanism simplicity	4	2	4	2	4
Wear resistance	1	4	4	4	4
Supporting dual lifting	4	0	4	0	4
Manipulator reach	2	3	3	4	1
Self-centralizing features	4	2	4	2	4
Easy maintenance	1	3	4	3	4
Power consumption estimate	1	4	4	4	4
Points summarised	27	26	**41**	24	35
Percentage of attributes fulfilled	61%	59%	**93%**	55%	80%

Table 4.3: Preliminary Concept Comparison matrix.

The results from the matrix clearly discards concept 1,2 and 4 as interesting for further investigation. Both the handlebar and the operator concepts are within Engineering Design's 80% design screening limit and can therefore be considered for further development. The supreme winner of the concept comparison is the operator concept, which has a 13% lead on the second concept. The scoring of the operator concept relies on the possibility of applying a prehension mechanism to the design. With its strong lead, the operator concept is chosen for further development, with the handlebar concept as a reserve. From here on, the operator concept will only be addressed as the gripper concept.

4.4 Concept development

For the concept development, Alcoa provided the thesis with a new, full-scale smelting pot cover, enabling a low threshold for real-life testing of concept ideas. With cardboard and a glue gun at hand, first iteration of low-resolution prototyping and knowledge capture could be initiated.

4.4.1 First iteration

The starting goal of concept development was set to validate if the concept would be able to lift a pot cover without aid from a clamping mechanism. The challenge of clamping and simultaneous handling was postponed, based on the mentality of learning to walking before running. Quickly taping together something barely looking like a cover stepping plate, a test object was made. With this as a gripping object, a first iteration gripper tool was prototyped out of cardboard. Though not looking very much like a robot gripper, insights were made after brief two minutes of prototyping:

- To avoid horizontal movement or rotation in the v-axis, the gripper step plate slot should be as tight as possible, fitting the thickness of the stepping plate
- Increasing the step plate support area of the tool in vx-plane will increase the stability of handling as well as improve the distribution the gripping impact force
- Applying an abutment plate at the base of the tool can aid guidance of the stepping plate into the gripper slot

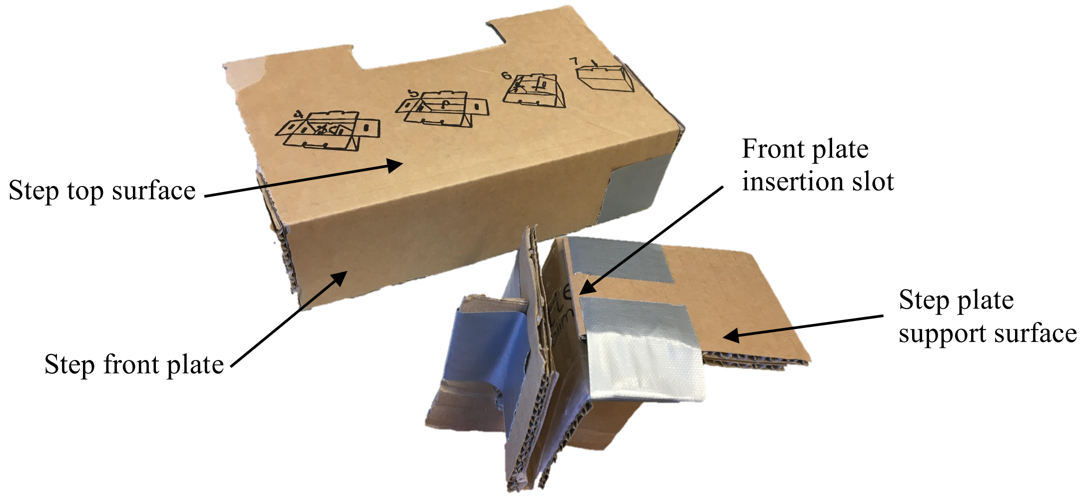


Figure 4.14: First iteration prototype of the gripper concept. Object top left represents the second stepping plate while the lower right object is the first iteration of the EOT.

4.4.2 Second iteration

For the next iteration, the full size pot cover provided by Alcoa Mosjøen was brought into the development process. Instead of looking at pot cover machine drawings, the second prototype was built to fit the physical pot cover step, known as prototype driven design specification. The cardboard which was used for the second prototype was hot glued together in double layers. This was performed to get increased gripper tool stiffness.

Applying the learning gathered from the first iteration, the step plate slot was made as narrow as possible. With a narrow fit and cardboard being quite flexible, the second prototype were able to latch on to the step plate by a tolerance fit (4.15). An abutment was added to the design, guiding the front step plate into the tooling slot. Also added was two support brackets, stiffening the tool. The size of the step plate support was also increased to better distribute the handling forces.

Prototyping directly on the pot cover was a positive experience, yielding a relationship to how big the tool actually needed to be. The second design iteration showed positive indications towards the prototype tool being able to lift a pot cover independently. With the narrow and stiff fit, the gripper felt strong and rigid though made out of cardboard. To be able to confirm the assumptions, the next prototype iteration should be made out of something stiffer and stronger than. It was therefore decided that the next prototype would be constructed from laser cut medium-density fibreboard (MDF).

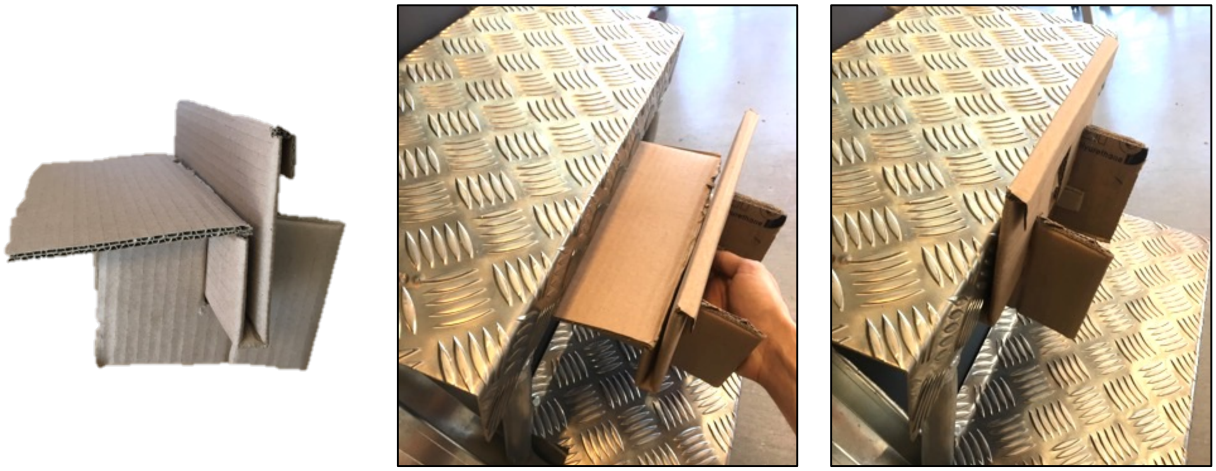


Figure 4.15: Pictures of the second iteration robot gripper tool results. Most left picture showing an isometric picture of the tool, while the two other pictures show testing of tool.

To summarize the second iteration, the following insights in relation to design improvements were collected:

- The abutment was a positive add-on to the first design, though could benefit from being even higher for increased guidance
- The support brackets collided with the first step and need improved design
- The gripper size can be increased, especially in the x-axis

4.4.3 Third iteration

Moving away from cardboard and increasing the prototype resolution leads to an increased amount of effort required to reach the next delivery. The third iteration goal was to make a prototype stiff and precise enough to perform an assisted pot cover lift. Ensuring high progression speed and low costs in case of design failure, laser cutting was selected as prototype production method. To provide stiffness and toughness, 6mm plates of MDF was selected as prototype build material. With material and dimensions in mind, 2D drawings of the tool parts were drawn in Siemens NX9 CAD software (figure 4.16 and 4.17).

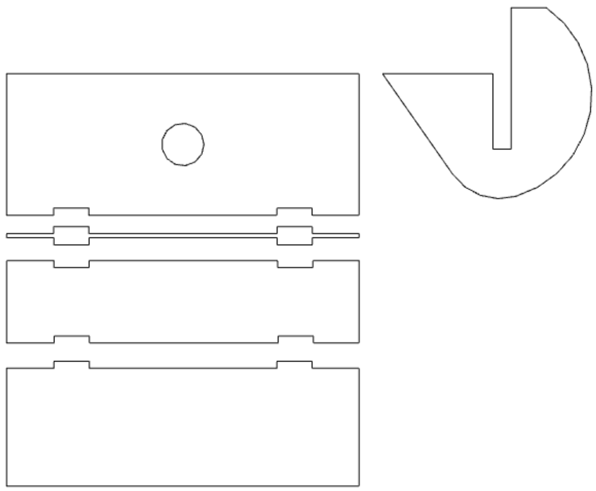


Figure 4.16: Third iteration gripper prototype components drawn in 2D, utilised for laser cutting of the parts.

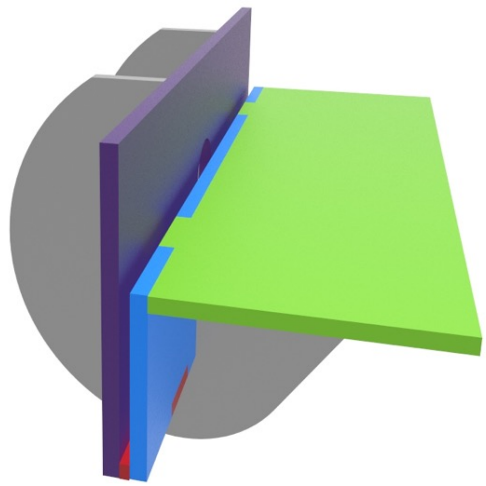


Figure 4.17: Render of the third iteration gripper tool, displaying with colour the separate laser cut components.

Learning from the bracket failure in the previous iteration, the new bracket design was created more compact and organic. Also altered was the height of the abutment, now increased with a couple of centimetres. The second prototype had a tolerance fit for the stepping plate insertion gap. With laser cutter as tooling, all measurements set for the third prototype would come out with high precision. A measurement of the stepping plate thickness was therefore performed, recording a max thickness of 3.4mm.

Having successfully assembled the laser cut parts with a glue gun, the critical function test could be performed. Despite the efforts of measuring the step plate thickness, the third prototype also clenched to the stepping plate through a tolerance fit. When inserted, however, the prototype felt sturdy and well balanced. Testing of the gripper was conducted by the author using his hand as a manipulator substitution (figure 4.18), holding the tool in his hand. By doing so, successful pot cover handling was performed as a careful vertical lift. The stepping plate showed no signs of buckling during the lift. This validates that the concept itself, without a prehension mechanism, is able to lift covers vertically. This completes the goal for the third development iteration.

With the wish to explore the extent of the prototype's ability to handle covers, accelerated movement in different directions was actuated. Accelerating the cover up and down did not result in any displacement in the z-axis. This result can be deemed unreliable as a robot could exert much greater acceleration on the cover. If displacement in the z-axis should occur, the cover could jump out of the tool. This cannot happen. With some rough handling of the cover sideways (x-axis), the cover started to slide inside the gripper slot, gliding sideways between the step plate support bars. This could be solved by increasing the tool width to fit exactly between the step plate support bars. Not having any excess room for the tool, however, would decrease the adaptability of the tool, making it harder to insert. The importance of the gripper support brackets was revealed during the test. Being the component keeping all other the parts together, it would need to be properly dimensioned for the next prototype.

Figure 4.18: Pictures captured during the critical function testing of the third iteration gripper prototype. The pictures depict insertion and cover lifting with the concept.

Summarizing the test results, the present concept can perform lifting, but will require a clamping mechanism to be able to precisely, efficiently and safely handle covers. The goal for the fourth design iteration therefore became to find a suitable retention mechanism, implementable on the current design. The newfound knowledge captured during the third concept development iteration were:

- A 4 mm (0,6 mm tolerance) slot fit is not realistic and needs to be enlarged
- The support brackets need to be robustly dimensioned for the next prototype
- The abutment plate still has possibilities for an additional height increase
- Blending of the insertion plate edges can aid the gripper with self-centring between the step plate support bars

4.4.4 Fourth iteration

Having proven that the current design would be able to lift independent covers, the fourth development iteration concentrated on providing the tool with cover clamping. To evaluate which features would be needed, such as prehension principle and drive system, the areas available of clamping first were assessed. The most areas identified as most pertinent is visualised in figure 4.19. As clamping on top of the step plate appeared most accessible with the gripper concept design, it was selected among the two alternatives.

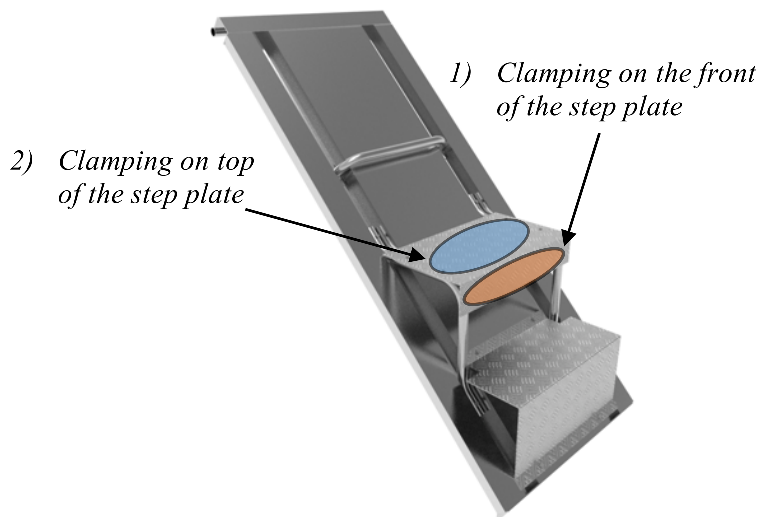


Figure 4.19: Illustration showing the two areas identified as most pertinent for impactive clamping.

To assess how the clamping of pot covers can be performed, knowledge from the Robot Gripper literature study was exploited. To assist the selection of the cover retention mechanism, all applicable principles and methods from the literature study has been gathered in a morphology analysis (table 4.4). The morphology table aim is to visually connect the different features needed for cover prehension into one or multiple concepts.

Evaluating drive systems, the magnetic drive system is seen as less suitable for the potroom, with high danger of being influenced by the highly magnetic environment. Electric drive systems can also be affected by the magnetic environment, as well as the increasing heat close to the pot. Looking at table 4.2, pneumatic drive systems offer less gripping force compared with mechanical and hydraulic systems. Both mechanical and hydraulic drive systems have high resilience towards dust and dirt, which is here beneficial. Information from Alcoa states that they have vehicles working in and around the pots operating with hydraulic drive systems, validating this alternative. A drawback with hydraulic actuation is the need for a hydraulic pump system installed on the AGV. If a purely mechanical solution can be applied it would be preferable, as the drive system would not be in danger of being affected by either the heat or magnetism. It would additionally not require electricity, nor power in form of pumps and compressors.

MORPHOLOGY ANALYSIS: GRIPPER TOOL CLAMPING						
Area of clamping	Top of the stepping plate			Front of the stepping plate		
Impactive gripping principles	Jaw	Self-sustaining	Pincers	Pinch mechanisms	Claw	
Drive systems	Mechanical	Pneumatic	Hydraulic	Magnetic	Electric	
Kinematic systems	Wedge gear mechanisms	Screw gear mechanisms	Jointed mechanism	Cam gear mechanisms	Wheel, rack wheel and rack & pinion	Pull and/or pressurizing medium

Table 4.4: Morphology Analysis Table, visualising gripper tool clamping combinations. The two most promising concepts are drawn in the matrix, checking of the selected attributes with dots.

Moving over to kinematic systems, all kinematic mechanisms presented in the morphology analysis are applicable for creating impactive gripping motion. Combined with the drive systems, however, some of the systems are more applicable than others. In the case of hydraulic drive, pistons for pulling and pressurising are commonly used. These are robust, dust resilient and already in used on the potroom grabbing trucks. This kinematic system is therefore a viable choice for hydraulic clamping. For a purely mechanical solution, linkages and jointed mechanisms would ensure simplicity and robustness. Gears, screws, wheels or cams would be applicable, but would also decrease the simplicity of the solution. With this review in mind, two competing concepts for cover prehension materialised.

4.4.4.1 Self-sustaining clamping concept

Inspired by Robot Grippers' subchapter concerning impactive grippers, the self-sustaining clamping concept exploits the mass of the pot cover and utilises it to clench the cover during handling. A few working principles of self-sustaining grippers was presented in chapter 4.1 (figure 4.1). In figure 4.20, a sketch shows how mechanism C of the presented self-sustaining mechanisms can be adapted to fit the current gripper design.

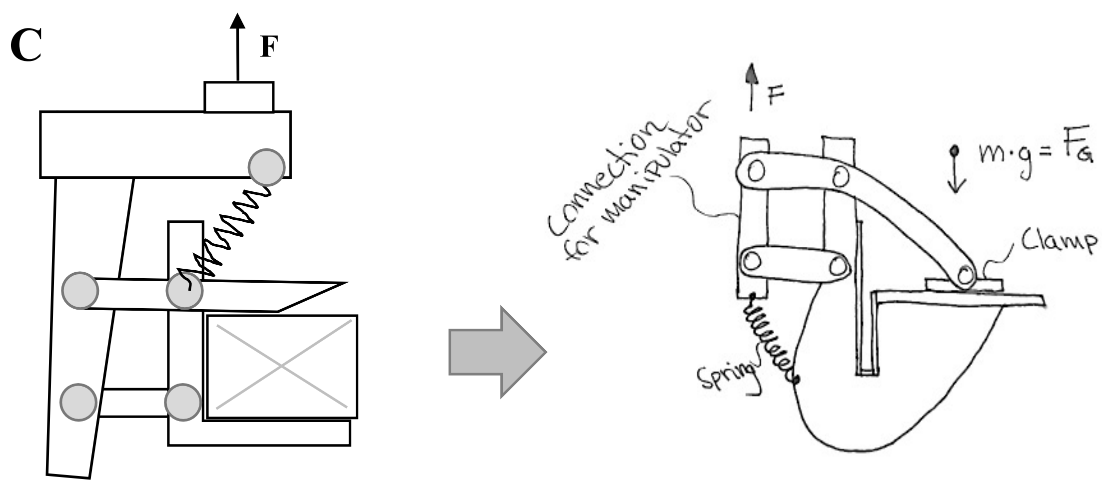


Figure 4.20: A sketch outlining how a self-sustaining clamping mechanism can be applied to the current gripper concept.

This retention mechanism is consisting of a four-bar linkage, where a jaw is naturally open by spring force. When the gripper starts to apply lifting force on a pot cover kinematic movement in the linkage occurs. When the manipulator arm force become great enough, the clamp reaches the stepping plate and starts to apply pressure on it. It is first when force equilibrium occurs that the cover is lifted from the ground and handling can be performed. That is the outline of how the self-sustaining prehension concept would work.

4.4.4.2 Hydraulic clamping system

A hydraulic prehension system for the gripper concept could be drafted in a vast variety of designs. One design example is sketched in figure 4.21, where a hydraulic piston is placed perpendicular to the stepping plate. With an extension connecting the piston with a clamping plate to the existing design, you have a robotic gripper with a prehension mechanism securing the pot covers during handling.

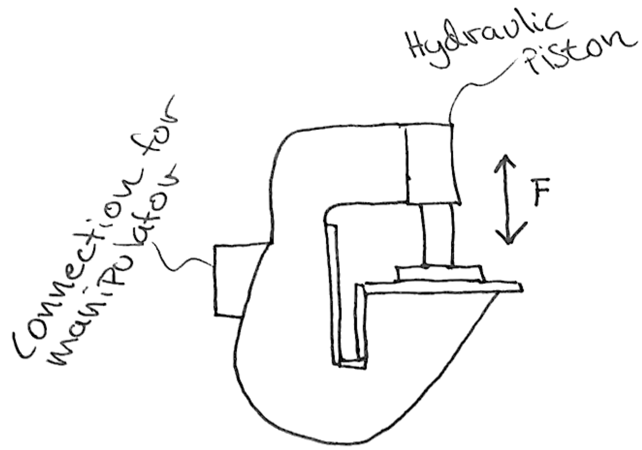


Figure 4.21: A draft of how a hydraulic piston can be implemented on the robot gripper to restrain pot covers during handling

4.4.4.3 Selection of clamping system

From the morphology analysis we have obtained two viable concepts for implementation of clamping. Both of them have their advantages and shortcomings. From table 4.2 we have that the hydraulic concept can provide a compact solution with high gripping force and a low sensitivity to environment contaminations. The energy consumption of a hydraulic drive system, on the other hand, is high. Controllability, maintenance and costs is ranked to average. A purely mechanical prehension solution provides medium gripping force, but marks high on low environment sensitivity, maintenance, environmental influences, cost and last but not least, zero power usage. The controllability of a mechanical system is however low, and requires more space than a hydraulic solution.

To be able to select one of these clamping solutions, evaluation through priory set specifications should be used. As the gripper tool and robot unit has separate conceptual design phases, it would be beneficial if the gripper could act as an independent solution. This points towards the mechanical solution, which also could be put on a traverse crane, truck or be operator handled, etc. Selecting the hydraulic system would lead to a simple tool with few movable parts, but require a hydraulic drive system on the AGV. As power is a scarce resource on a AGV, the increased consumption has an impact on the operational time in light of battery capacity. This points in favour for the mechanical solution. But comparing mechanical and hydraulic prehension, the mechanical solution has a higher linkage complexity and has less degree of controllability than the hydraulic tool has. In the case of pot cover handling, the need for tool controllability is small, as there is only one object desired for handling. In regard of simplicity, the need for a hydraulic drive system decrease the simplicity of the hydraulic alternative as well. To conclude the review, both concept show promise for implementation. It does, however, tip in the mechanical clamping mechanism's favour. The self-sustaining prehension concept was therefore selected for further development and to be integrated on the operator gripper concept.

4.4.4.4 Prototyping the clamping system

Decided to continue with the mechanical concept, the first development iteration of the clamping mechanism could be initiated. Instead of constructing a fourth prototype to test the linkage mechanism, the third gripper prototype was utilised as a test platform.

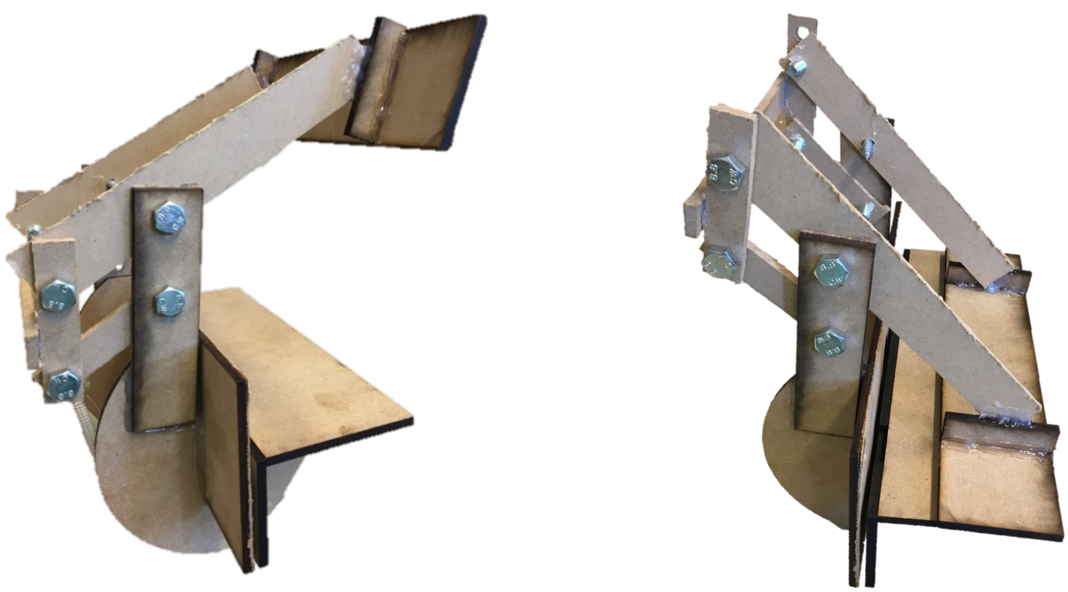


Figure 4.22: The combined product of the third iteration gripper prototype and a self-sustaining clamping mechanism prototype.

Crafting with the concept sketch as inspiration, a retention mechanism was assembled ad-hock on the gripper prototype with hot glue (figure 4.22). To provide the linkages with rotating joints, machine and wood screws was used as bearings. Despite the low accuracy and resolution of the clamping prototype, the mechanism work surprisingly well. The tool was now able to create the desired motions typifying self-sustaining grippers. When the linkage was exerted a force upon and an object of significant mass was placed on the tool, the jaw closed and prehended the object until the mass force was matched. To provide the linkage with a naturally open state, two ball pen springs was hot glued between the mechanism and the gripper tool. These two springs proved to be weak, not able of keeping the jaw naturally open. This issue combined with multiple accuracy and design improvements is to be brought further to the next iteration. Looking beyond the minor details, a functional proof-of-concept prototype was actually created.

Having acquired working solutions to the most critical aspects of pot cover gripping, the fifth and final iteration could be initiated. With a high-resolution milestone prototype in mind, the learnings gathered for the last development iteration was:

- All assembly parts need accurate measurements to ensure smooth linkage motion
- The pinching plate was glued stiffly to the linkage mechanism. Applying a rotary joint can enable a more adaptable fit, ensuring perpendicular force distribution
- Correct spring dimensioning will be important to ensure that the retention mechanism is naturally open when not interacting with pot covers
- A rubber layer between the pinching plate and the pot plate can increase the friction between cover and tool, preventing movement in the x-axis

4.4.5 Fifth iteration

Having successfully built a proof-of-concept prototype, the preparations for the proof-of-product prototype could be started. All failures and learnings from the previous four iterations were now to be joint into a high-resolution prototype. During planning, the milestone gripper prototype was set be fully capable of performing full-scale pot cover handling. Therefore, a stronger, more durable material was decided to be applied. Important for consideration is the strong magnetic fields present in the potroom environment. Non-ferrous material is preferable, as they are not affected by the magnetic fields. As the gripper also adds mass to the manipulator, the weight of the tool would preferably be low as well. The degree of quality and reliability feel of the prototype should also be high. Being also a prototype for communicating results to Alcoa, it should radiate product integrity and implementation likelihood. Taking these parameters into account, the choice for prototype material lead to the use of aluminium.

Having selected aluminium as material, research was conducted regarding plate and rod thickness availability for aluminium, enabling tailoring of design for manufacturing. With 5, 10 and 20mm aluminium plate and 16mm aluminium rod available, these sizes were selected for the prototype build. While the aluminium plates would be used for the all static and moving parts, the 16 mm rods were to be used as bearings for the linkages.

Figure 4.23: Pictures depicting the approach for the linkage design. First, the rigid part of the tool was modelled, with holes for the bearing rods. Secondly, placement of the clamping plate and manipulator connection bracket was inserted. From the restricting dimensions created from the two first steps, links joining the prehension mechanism components was made.

Until now, most of the product development had been performed from hand drawn sketching, applying some 2D CAD to perform laser cutting. In the fifth iteration of the design development, a focus-shift toward computer aided engineering (CAE) was made. Starting out, a digital model of the gripper concept without the retention mechanism were made in 3D. Secondly, the clamping plate and a manipulator attachment was designed and placed according to the gripper model. Having all parts located with accurate placement, a linkage assembly could be made, connecting the gripper assembly. The results from this design iteration is shown in figure 4.23. Joints and constraints was applied in the software, enabling the possibility to manipulate the 3D gripper concept. With this model available, iterative design improvements could be performed during the computer testing, improving the linkage design. Finalising the simulations, holes for spring assembly were added. A couple of new design edits was made, based on insights from the third and fourth design iteration:

- The step plate slot was increased from 4 to 10 mm, providing the possibility to test various gap dimensions with the finished prototype
- Additional brackets added to the design, designed for positioning of bearing rods
- Edge blends on the step support plate were added for additional tool guidance

Having finalised the digital model of the cover gripper, preparations for the tool construction could be performed. From 2D drawings of the model parts, machine drawings were created with all necessary measurements (Appendix C). A beneficial production method for creation of the sheet metal parts would be water or laser cutting, yielding high accuracy components. Due to lack of access to such equipment, other production methods had to be considered. For all parts made out of 5 mm aluminium, a sheet metal cutting machine was utilised to divide the large aluminium sheets into pieces. With a metal bandsaw, the aluminium sheets were cut into the desired shapes. All of the bearing rod holes were marked up and drilled using a pillar drill. Due to exact tolerance precision in CAD versus real life construction, the holes were drilled with a 0,5 mm slack. The mechanism linkages, made out of 10 mm plate, were CNC-milled for precise hole placement accuracy. The bearing rods were cut in suitable lengths by a metal bandsaw, followed by pillar drilling of locking pin holes. The robot connection bracket was made to fit with a 32mm steel pipe, suitable for usage as a mock-up robot arm. The manipulator attachment was made out of a solid aluminium cylinder, drilled and turned to fit outside the steel pipe.

When all the components were readily produced (4.24), they were ridden of sharp edges through grinding and chamfer drilling. Having cleaned all necessary surfaces, welded could commence. After welding, some parts were deformed due to heat retraction. Corrections were performed with a rubber hammer before the bearing pins could be inserted and a suitable spring be connected. Now, the gripper assembly was finalised and the final prototype was ready for feasibility testing.

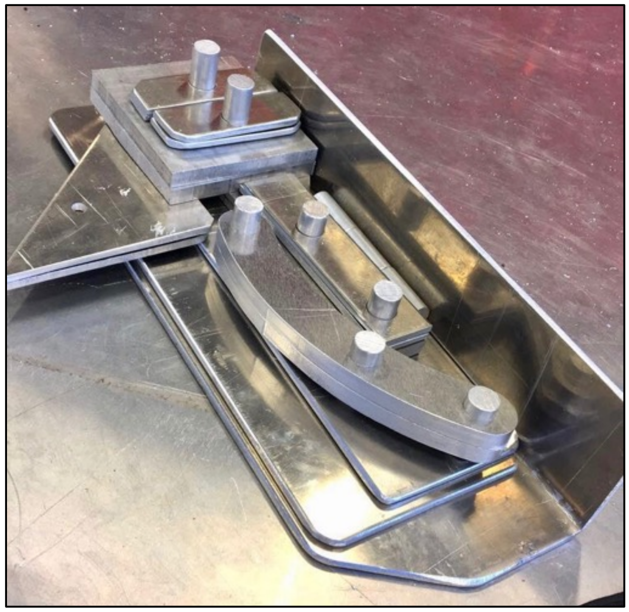


Figure 4.24: All subcomponents of the final gripper prototype gathered before welding assembly.

4.5 Conceptual design gripper result

Figure 4.25-4.27 show the finally assembled result from the fifth and final concept development iteration. The prototype presented is the embodiment of the accumulated knowledge throughout the process, being the result of numerous design choices. A critical function test was now performed to authenticate the proof-of-product prototype.

Figure 4.25: Isometric view of the proof-of-product prototype. An F-clamp is used to hold the clamping mechanism shut, as it is normally open due to the spring.

Figure 4.26: Side view of the final gripper prototype. Detailed viewing of the step plate slot, support bracket and step plate support surface.

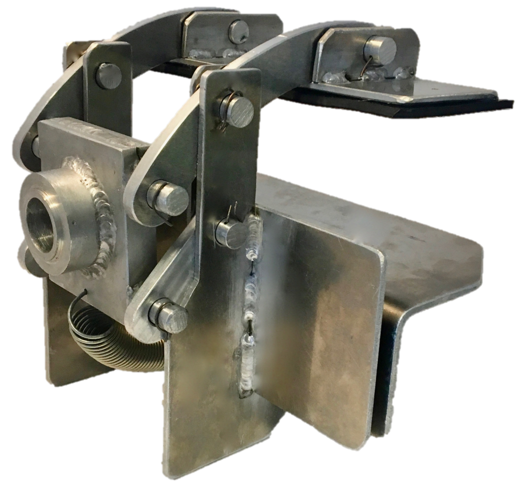


Figure 4.27: Isometric tool view from behind displaying linkage, spring, clamp and manipulator connection.

4.5.1 Pot cover gripper critical function test

For testing of the high-resolution prototype, the pot cover provided by Alcoa was positioned at 45 degrees. With the prototype EOT mounted on a mock-up robot arm, the prototype was manually tested as depicted in figures 4.28-4.31. Starting the test, insertion and prehension of the cover was effortlessly achieved. Lifting the cover up from the ground felt secure and stable, with no signs of tool or cover yielding or deforming. To challenge the gripper, shaking and rough handling was exerted with the cover retained in the prototype. This did not affect the pot cover, still firmly grasped by the self-sustaining gripper mechanism.

The figures describe the four sequential steps identified for achieving impactive gripping, where handling of the covers can be performed once all steps has been completed. Once the handling is performed, reversing the step order will release the pot cover from the gripper. A video recording of the critical testing, combined with summary of the conceptual design phase was put together and sent to Alcoa for milestone delivery. Link to the video of the gripper test can accessed in Appendix A.

Figure 4.28: First step of gripping: The gripper is centralised and aligned for insertion underneath the second step.

Figure 4.29: Second step of gripping: The tool is inserted until it reaches the gripper abutment

Figure 4.30: Third step of gripping: The EOT is raised vertically, achieving front plate slot insertion and tool contact with the step plate surface.

Figure 4.31: Fourth step of gripping: Raising the robot arm, the clamping mechanism activates. Gradually, the cover becomes increasingly restrained until force match occurs and the cover can be handled.

4.5.2 Evaluation of the gripper conceptual design phase

The proof-of-product prototype yielded affirming results during the testing. There is left no doubt regarding the concepts ability to grip and sustain pot covers for handling in a test environment setting. To ensure that the expectations and demands from Alcoa are met before moving the development further, a specification comparison with table 3.1 can be performed. First off, no alterations on the existing pot cover has been performed. The concept is fitted for implementation on a AGV platform as it does not require any power from the battery system to actuate gripping. Through testing, it has also been proven as a reliable and robust concept for performing impactive gripping of covers. The gripper concept design provides handling of side or standard covers just the same. The current design should also be able to be joint into a double gripper version, enabling simultaneous lifting of covers. This, however, depends on the manipulator concept as well.

Alcoa was concurrently included and informed with the progress of the gripper conceptual design development. Having received and viewed the video results from the gripper test, Alcoa responded positively to the product provided. Knowing that Alcoa's aspirations also was met, the gripper conceptual design phase could be concluded and the manipulator development be started.

5 Conceptual design: Robotic Manipulator

Having created a fully functional robot gripper concept for cover handling, the next step in the development plan was to perform conceptual design on gripper manipulation. Following the specifications in table 3.1 and 3.2, the system should first and foremost be able to be installed on a AGV platform. It should at least be able to handle the payload from one pot cover and facilitate storage of two covers during pot operations. It should also be robust and simplistic solution, tailored with the exact degrees of freedom needed to perform successful pot cover handling. The end goal for the conceptual design phase is to have a viable manipulator concept for implementation on the AGV. To validate concept feasibility, a test setup should be built for testing at a scaled down level. Concluding the phase, the concepts tested will be compared and evaluated, yielding the most prosperous concept for joining with the gripper tool in the following embodiment phase.

5.1 Literature study: Industrial robots

Specialised robotic handling for picking and placing of objects is commonly performed in the automated industry. Today, the industry standard of automating operations is through utilisation of industrial robots. The ISO vocabulary for robots and robotic devices (ISO 2012) has defined industrial robots as automatically controlled, reprogrammable, multipurpose manipulators, programmable in three or more axes, which can either be fixed in place or mobile for use in industrial automation applications. To gain a knowledge foundation on the topic before beginning the manipulator ideation, a study was performed on industrial robot technology. Starting the study, some research was conducted related to industrial robotic terminology for improved topic understanding. Most relevant industrial robot parameters identified with their corresponding definition are:

Degrees of freedom

Number of robot operating axes. Two axes freedom are required to reach any point in a plane, while three axes are required to reach any point in space. To be able to have full controllability of EOT as well, three additional axes are required. These three additional axes are known as yaw, pitch and roll.

Drive system

The actuation principles which are used to provide the robot with motion, such as hydraulic, pneumatic, electric or mechanical.

Payload

The maximum object mass or carrying capacity of a robot.

Robot kinematics

The arrangement of rigid members and joints in a robot, deciding which and how motions can be performed.

Repeatability

How well a robot can return to a previous position or state.

Working envelope

The region of space which is reachable by the robot EOT.

Industrial robots can be divided into categories based on their means of movement. The most commonly known are the Cartesian robots, Scara robots, Articulated robots, Redundant robots and Dual-arm robots (Robotiq 2014). Among these, the most task relatable robot types are the Cartesian, Scara and Articulated robots. The Cartesian robots usually perform movement in three axes by performing linear motion. The traditional Scara robots perform motion through three rotating translations, with an additional rotation around the EOT axis. Being perhaps the most relevant robot category is the Articulated robot category. These are equipped with rotary joints, ranging from simple two joint systems to numerous jointing structures. The traditional 6-axis robot has three body translations and additional three EOT 3 orientations, able to position the tool freely within the work envelope. A figure displaying a 6-axis articulated industrial robot layout can be viewed in figure 5.1.

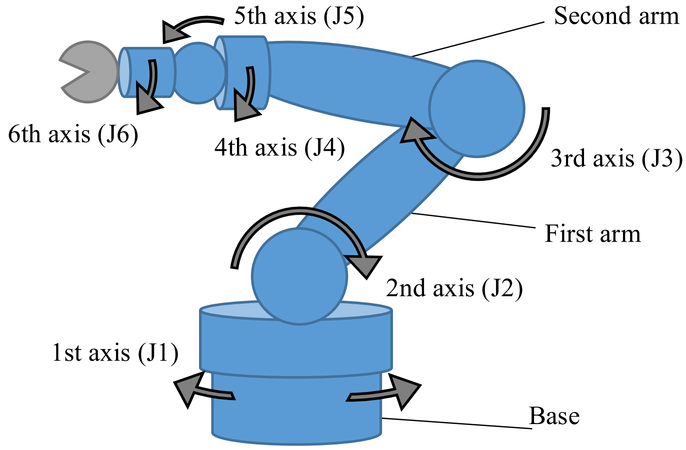


Figure 5.1: Figure showing the traditional layout of a 6-axis industrial robot. The axes and components are named, while the "J" of each axis refers to the joint number.

Typical industrial robot usage applications can be material handling, palletizing, painting, pick and placing, assembly and welding. Within the 6-axis segment, it is the palletizing and pick/placing robots which coincides best with the task of cover handling. While the objective of pick and placing robots are obvious, the palletizing industrial robots are originally designed for handling of goods and stacking them onto pallets. The palletizing robots can be used for pick and placing purposes as well. Looking up industrial robots online, frequently occurring brand names could be Yaskawa Motoman, Kawasaki, ABB, KUKA, FANUC, with more. Checking out KUKA's webpage, they have divided their robots into the categories of low, medium and heavy payload. The low payload category stretches from 6 to 20 kg, the medium category between 30 to 60 kg, while the heavy segment robots can handle loads from 360 to 1000 kg. These three categories are used to benchmark which segment our cover handling robot will fall in under.

To identify which product segment for our cover handling robot falls in under, a payload approximation has been performed. The AGV robot payload requirement depend on pot cover and gripper mass itself. As each cover weighs at least 13 kg each, and it is desirable to be able to lift two covers simultaneously, 26kg is minimal cover payload weight. The aluminium made gripper prototype weighs approximately 5kg. When including the capability of doubled gripping and the structure needed to unify the tooling, a rough estimate for the tool is 14 kg. This yields an approximated payload of 40kg, putting our desired robot solution in the medium payload category.

Having an increased understanding of industrial robot technology, the manipulator ideation stage can commerce.

5.2 Ideation and rapid concept generation

Starting the manipulator ideation session, the prototype rig utilised during the gripper development was reused. With the two 3D-printed pot covers lined up, and cardboard yet again used for modelling, the goal was to identify which motions would be needed to perform handling. The desire was to learn the minimal required degrees of freedom. By knowing this, customised and simplistic robot units could be conceptualised. Using hot glue to fix rigid parts and straws to crate rotating joints, a mock-up manipulator with three axis freedom was created (figure 5.2). By manual steering of the manipulator to perform pot cover handling, insights arose. Through various motion patterns, 2-axis movement in the vz-plane rendered as the fewest DOFs possible to achieve pot access. It would, however, not grant access to the anode covering manipulator. By adding a third DOF in the x-axis, a 3D space work envelope is available, introducing numerous additional options for solving cover handling. For a reliable cover handling system, x-axis motion was considered unavoidable. More DOFs can be included if desired, but from the test results, 3-axis motion yielded the minimum DOFs.

Figure 5.2: The low-resolution test setup used for manipulator DOF ideation.

Obtaining 3-axis motion can be achieved through linear or rotational translation. In the next subchapter, the most viable concepts from the ideation session will be presented and reviewed against each other.

5.2.1 Pot cover storage

Multiple aspects impact the development direction of the cover handling concepts. One of the factors which heavily impact the design of the manipulator as well as the AGV is how the pot covers are to be stored during pot operations. Having developed a gripper tool capable of prehending covers based on gravity, two principal manipulator categories can be evaluated:

1) Manipulator concepts which stores covers on a storage unit
2) Manipulator concepts storing covers statically in the robot gripper tool

The first alternative describes concepts where the covers are handled, then then placed on a storage unit, such as a rack, as anode covering is performed. By having the possibility of intermediate storage, it could be possible to utilise the anode covering robot for both operations. The second alternative, where covers are stored statically in the gripper, can be achieved by having a dedicated manipulator unit for cover handling. This option is supported by the developed gripper concept, needing no clamping power during handling or storing. From these two categories, numerous concepts were generated. Following are the four concepts evaluated as the most plausible of them.

5.2.2 Preliminary concept 1: Multi-tooled manipulator

This concept proposes to implement an end effector configuration where the anode covering robot can change between EOTs, visualised in figure 5.3. By having the capability to change between tools, one robot can perform both cover handling and anode covering. To be able to perform both processes, the covers need intermediate storage when pot maintenance is performed. This could be accomplished by having a storing rack placed on the AGV platform. This configuration would require more than 3-axis movement.

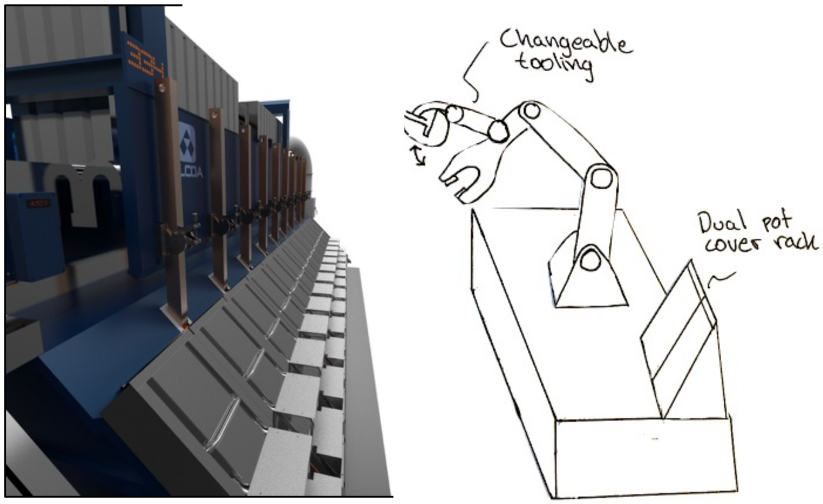


Figure 5.3: The multi-tooled manipulator concept.

5.2.3 Preliminary concept 2: Sliding manipulator

The sliding manipulator concept propose movement in both v,x and z-axis while the AGV is stationary. By utilising a robot capable of actuation in the vz-plane, the concept lifts the covers away from the pot. By a rail system along the AGV front, the covers can be moved to the side, enabling anode covering. This concept suggests static cover storage in the gripper. This concept requires an independent cover manipulator in addition to the anode covering robot. It also requires linear motion along the AGV railing.

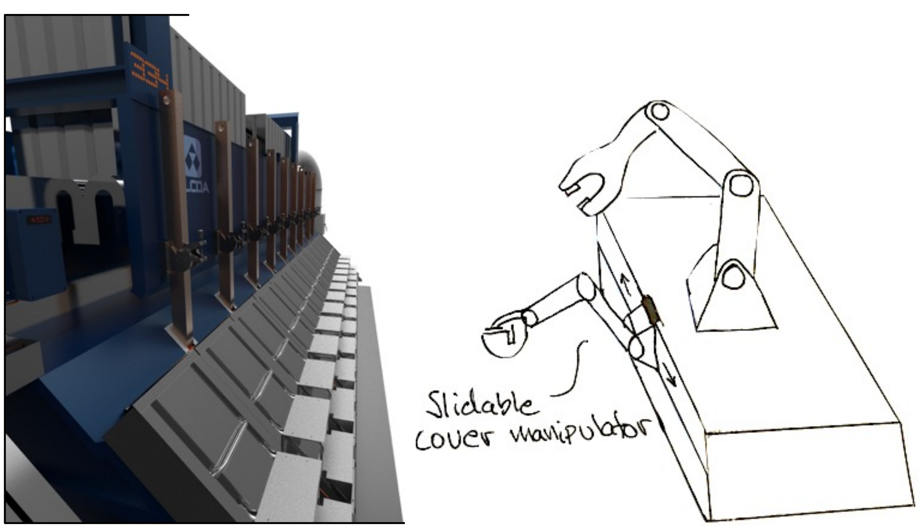


Figure 5.4: The sliding manipulator concept.

5.2.4 Preliminary concept 3: Stationary manipulator

Taking advantage of the AGVs linear motion along the x-axis, a specialised 2-axis manipulator with movement limited to the vz-plane can fulfil the requirements for actuating pot cover handling. The concept proposes a AGV layout which consist of the anode covering manipulator on one end of the AGV platform, and a dedicated cover handling robot on the opposite end. First step of concept cover handling is aligning the AGV parallel with pot. With motion in the vz-plane, the cover handling concept can remove the covers away from the pot. Now, the AGV can propel itself forward or backwards, positioning for the anode covering robot. This simultaneously moves the covers out of the operational space. Similar to the previous concept, storing can now be performed in the gripper due to the self-sustaining mechanism. By backtracking the robot sequence, the covers can be placed back at the same location on the pot.

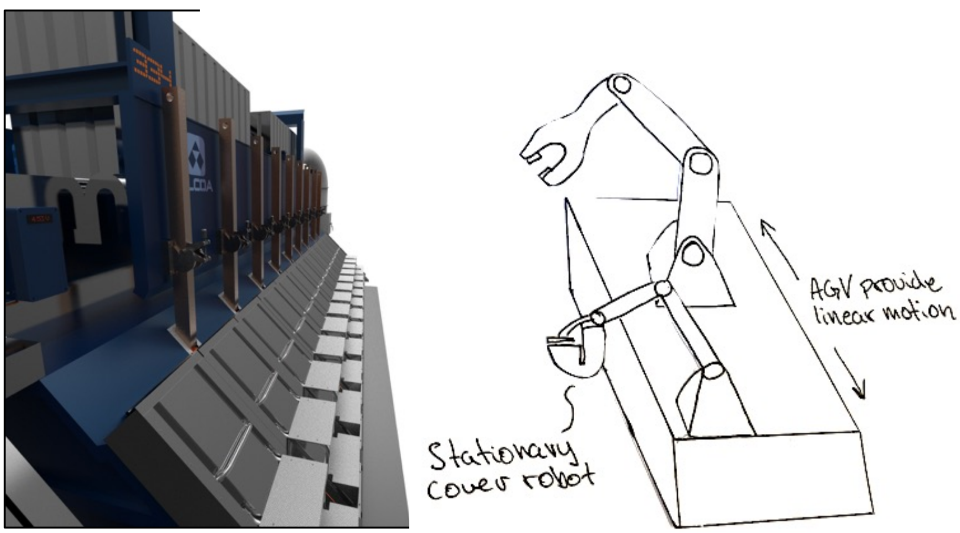


Figure 5.5: The stationary manipulator concept.

5.2.5 Preliminary concept 4: Cover tilting manipulator

This concept attempt to solve the cover handling by only operating in the vz-plane. This is proposed through elevation of the covers above the anode covering robot. By using a robot arm capable of raising the covers above the pot entrance, the maintenance robot will gain access to the inside of the pot. This can be solved through, for example, a rotating mechanism at the base and a telescopic boom arm. This concept is also based on covers being stored in the gripper during pot operations, identical to the two previous concepts.

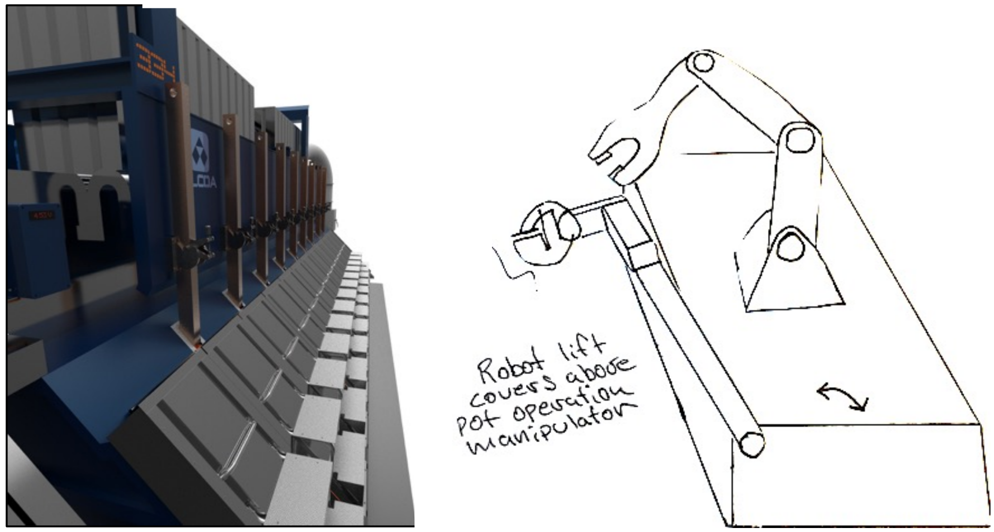


Figure 5.6: The cover tilting manipulator concept.

5.2.6 Preliminary concept review

All four concept proposals should somewhat be able to perform pot cover handling. To find the most suiting manipulator concept for the cover handling, this review will use elimination through ability of meeting specifications and requirements earlier set. Also used as a metric for evaluation is Design for Reliability and simplicity related to the number of actuating mechanisms needed to perform cover handling. The equally graded attributes will be gathered in a concept comparison matrix (table 5.1), where the most viable concept will be selected based on the same scoring principle used for the gripper preliminary concept review.

What differentiate **the multi-tooled manipulator concept** from the other proposals is the need for two manipulators. This is advantageous, with power consumption in mind. The intermediate storage, however, is troublesome. Intermediate storage reduces handling simplicity and increase the chance of error as the covers need to be gripped and placed twice as many times as the competing concepts. This also affects the HSE, as chance of accidents doubles as well. The multi-tooled robot unit would need to work both outside and inside the pot, yielding low scores on maintenance. This fact renders dual cover handling awkward, due to the required EOT size. Multi-tooled robots are expensive, and is evaluated as the most expensive alternative amongst the four concepts. Scoring low on most of the desired attributes, this concept appears to be of low relevance.

The sliding manipulator concept scores well on factors considering HSE, estimated power consumption and support for dual lifting. High HSE scoring is related to the AGV being stationary during cover handling and that all handling occurs between the pot and the vehicle. Compared to the other concepts, the estimated power consumption is the most beneficial. Dual cover lifting should also be feasible. Good scoring is given on principle simplicity, mechanical robustness, estimated cycle time and concept price. There is, however, challenges related to the dirty potroom environment. This will impact the need for maintenance as accurate sliding is an important aspect of the concept. But overall impression of the concept is decent and show implementation feasibility.

Best exploiting the AGV platform's degrees of freedom is **the stationary AGV utilising concept**. Being stationary placed on the platform introduce concept simplicity and robustness. As the AGV will need high accuracy when positioning itself in the potroom anyhow, it yields high operational reliability. Great possibilities of dual cover handling. The manipulator concept is considered as the most affordable option as well, since it only requires movement in the vz-plane by a stationary robot unit. The drawbacks identified to the concept is the AGVs need for driving back and forth. This affects the HSE, cycle time and power consumption undesirably. It is worth mentioning that the HSE aspect is possible to resolve by safety sensory. The summarised impression of the concept, however, show high applicability.

The last remaining concept, **the cover tilting concept** is mechanically less elegant matched to its competitors. Requiring long reach and high elevation of handling, this concept seems awkward compared to the other concepts at hand. Due to the wish of exploring possibilities of manipulation only in the vz-plane, this concept was brought further to concept evaluation. It seems, however, to score low on important attributes such as HSE, manipulator size and mechanical robustness. Powerful actuation drive systems would be required due to the great reach and height required, producing a need for excessive dimensioning and power usage. This will only increase with the wish for simultaneous dual cover lifting. Though it scores fairly good on the principle simplicity, maintenance and cycle time attributes, it seems like a less obvious choice before evaluating the four concepts in the attribute comparison matrix.

PRELIMINARY CONCEPT COMPARISON MATRIX: MANIPULATOR				
Concepts / **Attributes**	Multi-tooled Manipulator	Sliding Manipulator	Stationary Manipulator	Flipping Manipulator
Handling principle simplicity	1	3	4	4
Mechanical reliability and robustness	2	3	4	2
Manipulator maintenance	2	2	4	3
Operational HES	2	4	3	2
Concept size requirement	2	2	4	2
Support of dual simultaneous cover handling	1	4	4	2
Estimated power consumption	3	4	3	2
Estimated handling time	3	3	3	4
Estimated price	1	3	4	2
Point summarised	17	28	**33**	23
Percentage of attributes fulfilled	44%	78%	**92%**	64%

Table 5.1: Manipulator Preliminary Concept Comparison matrix.

From the table we have that the multi-tooled concept and the cover flipping concept both are far beyond the 80% attribute fulfilment score, thus eliminating them from further exploration. The sliding rail concept is placed just underneath the acceptance bar and can be considered as viable but not optimal option. Coming out on top, with a decent margin of 14%, is the stationary AGV utilising concept. The concept has minor drawbacks but multiple attractive attributes, leaving it the most favourable of the concepts. The stationary manipulator concept is therefore selected for the further concept development.

5.3 Manipulator concept development

With a preliminary manipulator concept chosen for cover handling, there are various possibilities of designing the manipulator unit in concern to kinematic arrangement and drive systems.

Compared to the preliminary gripper concept, which was structured in development iterations, the manipulator development progression will benefit from diving the concept development into sub deliveries. Within these sub deliveries, iterative work will be performed to reach the divided task milestones. To reach the final manipulator conceptual design milestone of testing and identifying most viable manipulator concept, the following sub delivery list is proposed:

- Creation of a scaled down feasibility test setup consisting:
    - A simplified section of a smelting pot with covers for handling
    - A simplified AGV platform providing linear motion along the pot (x-axis)
    - Simplified robot tooling mimicking the prototype gripper tool
- Develop and build two scaled down kinematic robot systems for testing
    - Cartesian manipulator
    - Articulated manipulator

The scaled down feasibility test setup should consist of a pot subsection, simplified gripper tooling and an AGV platform. The intention behind creating the setup is to:

- Provide the information necessary to select the proof-of-concept manipulator
- Provide Author with robot cover handling knowledge
- Reveal possibilities and/or challenges connected with execution of the desired operation
- Communicate concept reliability to Alcoa in a format they are familiar with and get feedback

The two manipulator arrangements chosen for development is one purely linear and one purely rotational actuation system. Both are based on standard actuation principles and systems utilised in robotic industry. The creation of the these will be performed with mechatronics, enabling full robotic control of scaled down cover handling. Selection of drive system will be postponed until the embodiment design as this is for evaluation of kinematic arrangements. Through testing of the two concepts in the feasibility test setup, the information necessary for concept comparison and selection should be provided. The test will also serve communicational purposes, delivering concept intent and results to Alcoa. By communicating the test results to Alcoa, the intention is to collect feedback before further development through embodiment design. Test aesthetics is considered essential, setting a high-resolution requirement for the mock-up cover handling test.

5.3.1 Feasibility test setup

With the intent of testing and displaying the kinematic arrangement of the manipulator concepts, some additional facilitation was considered useful for providing context and increased information gain. The desire was to create a concept test environment imitating the potroom at Alcoa Mosjøen. The components identified as compulsory were briefly mentioned in the previous chapter, but will be elaborated here with a description of the development of each individual delivery. The final feasibility setup can be viewed in figure 5.7.

Figure 5.7: Picture of the ready-for-use feasibility test setup, containing a pot section with four pot covers and a mobile AGV platform. A 3D-printed mock-up robot is added to the AGV, representing the anode covering robot.

5.3.1.1 The AGV

There are two main demands from the mock-up AGV. It should provide a slot for robotic manipulator insertion, allowing for testing of both kinematic concepts. Secondly, it should provide propulsion along the x-axis. In addition to these factors, it was wished that it would be identified as a vehicle from a bystander's perspective.

The AGV platform was designed with the max AGV measurements presented by Alcoa in mind. Therefore, a rectangular base with the ratio of 1:2 (4.0 x 2.0 metres) was selected. Similar to the construction of the early gripper prototypes, it was drawn digitally in 2D and parts were laser cut out into pieces of 3mm MDF. Included in the design was a hole in the top lid, providing space for internal manipulator integration. To provide the robot with space for mechatronic integration, the AGV was designed as a hollow prism. The AGV bottom assembly was fastened with hot glue, while the top plate was left as a lid for easy inside access. The top lid was provided with glued on corner centring blocks, ensuring that the lid would keep its place during testing. Having the constructed the AGV platform, holes were drilled for wheel installation and for computer wiring to the microcontroller. Finalising the AGV exterior, coloured paper and logos were glued on the platform to provide an appealing look.

From the online community of CAD sharing, GrabCAD, a model of an industrial robot (Dgn 2017) was collected and 3D-printed for usage as a placeholder for the anode covering manipulator. This was included on the AGV for visual and communicational purposes as well as providing some size comparison to the cover handling manipulator unit. The linear propulsion along the pot side was created with a DG02S Mini DC Gear Motor ("Gearmotor - 65 RPM" 2017) controlled by an Arduino Genuino microcontroller ("ArduinoBoardUno" 2017). Connected to a computer, the AGV could now be propelled back and forth by pressing explicitly assigned keys. The motor wiring diagram as well as the Arduino code for AGV control can be viewed in Appendix D and E.

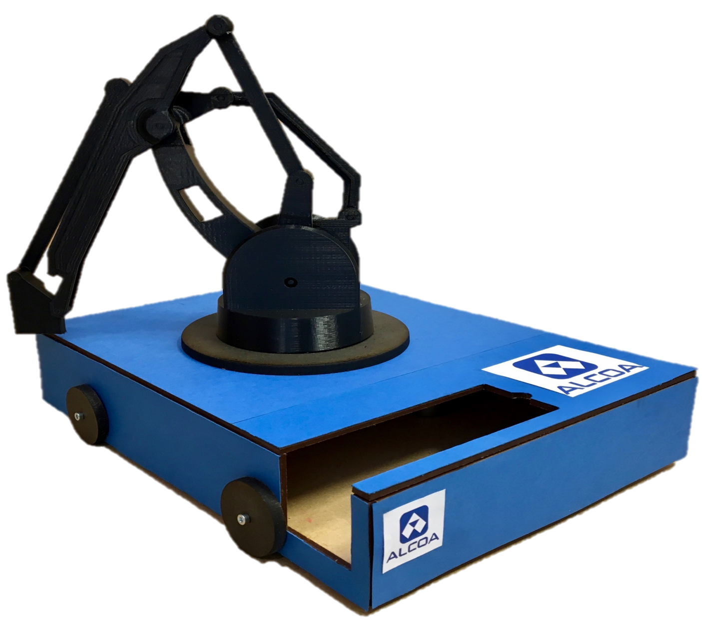


Figure 5.8: The finished mock-up AGV.

5.3.1.2 Mock-up pot section

Applying the same digital as well as physical tools used for AGV creation, 3mm MDF parts were drawn, laser cut and assembled, creating the mock-up pot section for cover placement (figure 5.9). The most critical functionality of the mock-up pot design is the rack, ensuring that the covers are placed alike smelting pots in Mosjøen. The design of the pot section frame was created intentionally simplistic, with few details, to not draw attention from the cover handling. Reusing the cover CAD model, used for 3D-printing during the gripper ideation, four new covers were printed. A piece of fine grey sand paper was left inside the frame, mimicking the mass used for anode covering.

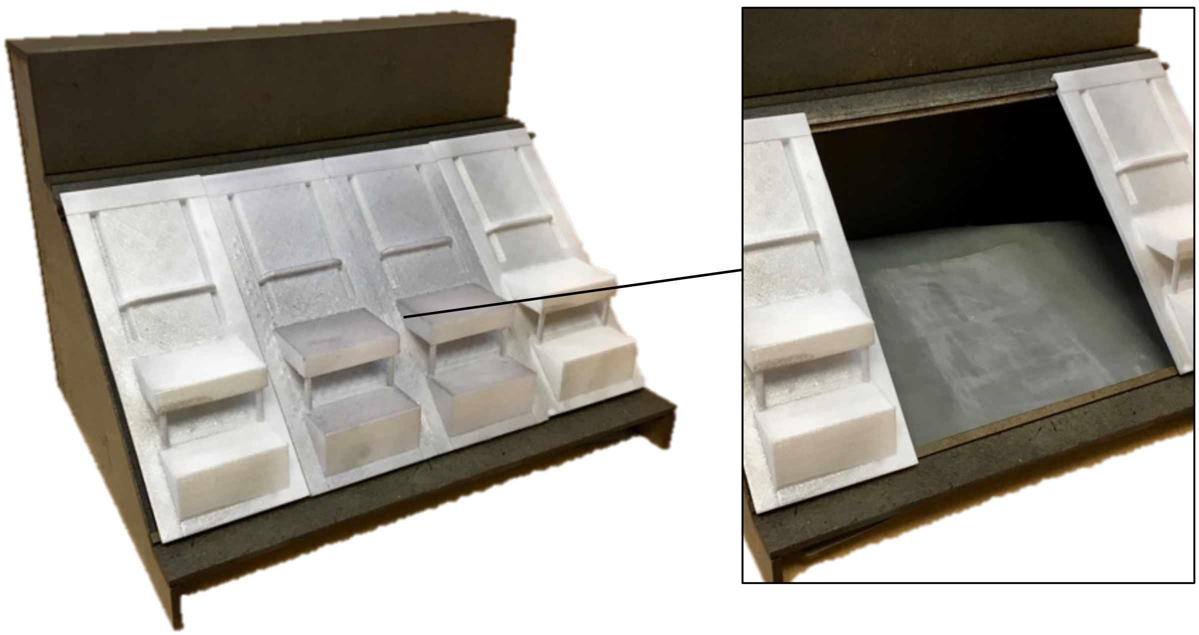


Figure 5.9: The finished mock-up smelting pot section with four detachable pot covers.

5.3.1.3 Simplified gripper tooling

For handling of the 3D-printed pot cover geometry, simplified gripper tooling was designed for end-of-arm implementation on the kinematic concepts. An important aspect of the tool design is to uphold the four handling steps identified in figures 4.28-4.31, maintaining the most important gripper characteristics. This implicates horizontal tool insertion followed by a vertical lifting pattern. Instead of spending time designing a miniature prehension mechanism on the simplified tooling, a tight tolerance fit was employed to mimic the clamping behaviour. The idea was that the simplified tool could fit around and enclose the 3D-printed cover step, which is in the shape of a rectangular prism. This should be enough to retain the cover during handling in all directions, accept negative linear movement in the insertion plane (v-axis). With this as the initial idea, CAD sketching and designing was initiated.

To not waste printing time and material, the first design iterations and prints was single gripper models. Due to low printing quality settings and CAD model flaws, various misprints were created (5.10). The design and printing trial and error provided rapid learning, which ultimately lead to a functioning single gripper. Due to later end-of-arm differences between the two manipulator concepts, the EOT connection had to be fitted to their individual design.

Figure 5.10: Picture of various iterations of the simplified gripper tooling for manipulator testing.

5.3.2 Kinematic system concepts

The two kinematic systems chosen for exploration was a purely linear actuated manipulator concept and a purely rotary actuated manipulator concept operating in two axes. When picking out the mechanisms for providing motion, a minimal amount of drive units was prioritised. This was performed with kinematic simplicity and robustness in mind, providing only the most necessary movements to successfully perform cover handling. With a wish for high-resolution look and performance, the robots should also have full functionality and controllability in the defined work envelope. With the intent of integrating the manipulators in the AGV platform, concept compactness was also prioritised during the design development.

The Cartesian manipulator concept had its origin from the final gripper tool prototype, which requires linear horizontal and vertical tool insertion to provide gripping. This can be achieved simply by combining one actuation unit providing linear horizontal movement with another unit creating the vertical. By relying only on linear motion, a sequential operation of the individual actuation units of robot can be performed. By simultaneous actuation, curved movement patterns can be achieved, providing the exact same movement patterns as the concept in comparison. The Articulated concept is based on the traditional excavator design, providing motion similar to what an industrial robot would provide if restricted to two axes. The development of the two concepts now follows.

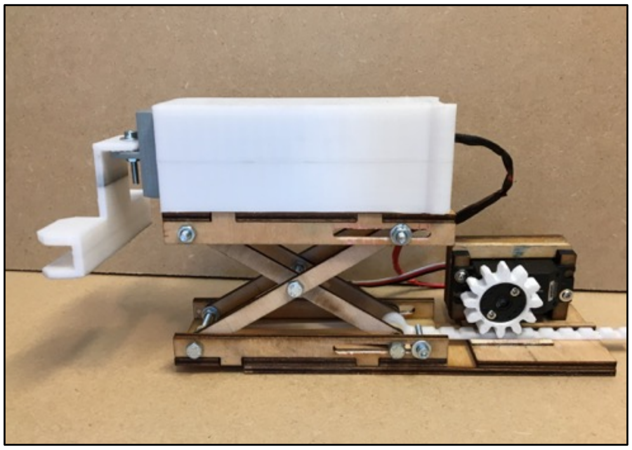


Figure 5.11: The finished 2-axis Cartesian manipulator prototype before testing.

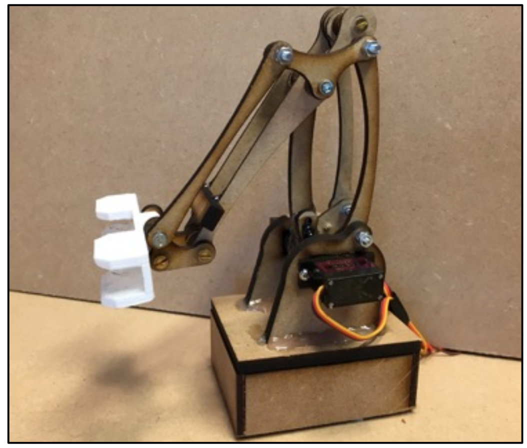


Figure 5.12: The finished 2-axis articulated manipulator prototype before testing.

5.3.3 Cartesian manipulator concept development

To break down the task of creating a robotic manipulator consisting of linear actuators, each of the units was developed independently. Though developed separately, the integration of the units was kept in mind during design. Using the list of commonly used kinematic systems from chapter 4.1, the mechanisms for horizontal and vertical movement was selected. To provide the vertical movement, a scissor lift mechanism was chosen. Scissor mechanism, also known as a pantograph mechanism, are commonly used to provide sturdy, linear motion. The mechanism consists of "X"-formed foldable linkages, extending itself by applying external force upon one of the mechanism ends. Being somewhat simple to create, control and integrate on the AGV, this was selected for the vertical motion. The horizontal motion of the manipulator was selected to be performed by a telescopic boom. With these two kinematic systems selected, the design development of a compact and accurately performing Cartesian manipulator was started.

The telescopic beam was identified as the size restricting element of the Cartesian manipulator build. The idea was to integrate a standard Arduino DC motor inside the inner beam element, serving as the drive system. To provide beam extension, a rack and pinion drive system was to be designed from scratch. With wheels attached to the motor drive shafts, and the outer beam equipped with a rack, motion would be acquired (figure 5.13). The telescopic beam was first roughly sketched with a DC-motor at hand for prototype-driven measurement specification. It was afterwards modelled digitally, ensuring accurate fit between the parts. After animating the mechanism movement in the software, ensuring that the parts fit well together, the individual components were 3D-printed for assembly. 3D-printing was selected as manufacturing method as it would provide the prototype with smooth, low friction surfaces as well as enabling the rack to be integrated in the outer beam structure. A script for DC-motor control was created (Appendix E) before part assembly enabling testing of the motor assembly. Having all components ready, the telescopic boom was assembled and greased up in the areas where friction might occur.

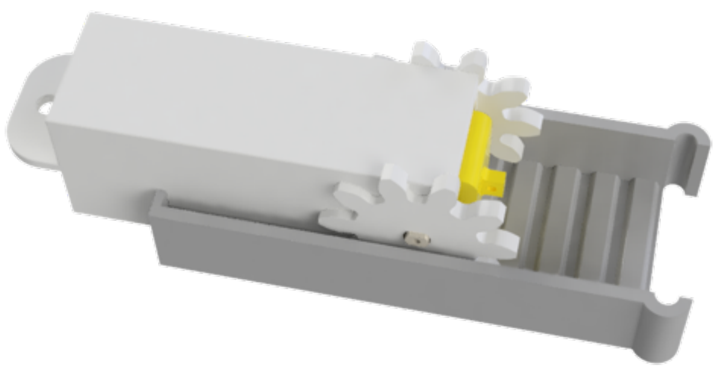


Figure 5.13: Section view render of the rack and pinon driven telescopic boom, providing horizontal movement for the Cartesian manipulator concept.

The development of the scissor mechanism was divided into the creation of the pantograph system and the creation of the drive system. Creating a lift system small enough to fit on the AGV would prove challenging, consisting of small linkages and joints. By trial and error, a design was created digitally (figure 5.14). Deciding to apply laser cutter for manufacturing, each individual subcomponent was designed with pattern locking features. Having finalised and successfully assembled the CAD model, all rigid parts were cut out in 3mm MDF and joint. The linkages were assembled using machine bolts, nuts and washers as mechanism joints.

Figure 5.14: Rendered detailed view of the scissor mechanism CAD assembly. Exerting force on the bottom link bar will result in elevation of length x of the lift table.

To provide drive system propulsion, a strong 360-servo ("Generic High Torque Servo" 2017) was selected. Having selected the motor in beforehand, the mechanism design could be tailored to fit the motor. Wishing to reuse previous work, the rack from the telescopic beam was altered to fit the base of the scissor mechanism. The cogwheel design was altered to fit the provided mounting of the servo motor. Through this, motor driven actuation of the lift was accomplished.

Having designed both actuation units for assembly, the boom could be installed on top of the lift with ease. A quick test was performed to ensure that the manipulator concept performed as it should, tweaking code parameters for smooth operation. The pictures shown in figure 5.15 and 5.16 depicts the finished Cartesian manipulator concept, with the individual actuation elements performing movement in their respective axes.

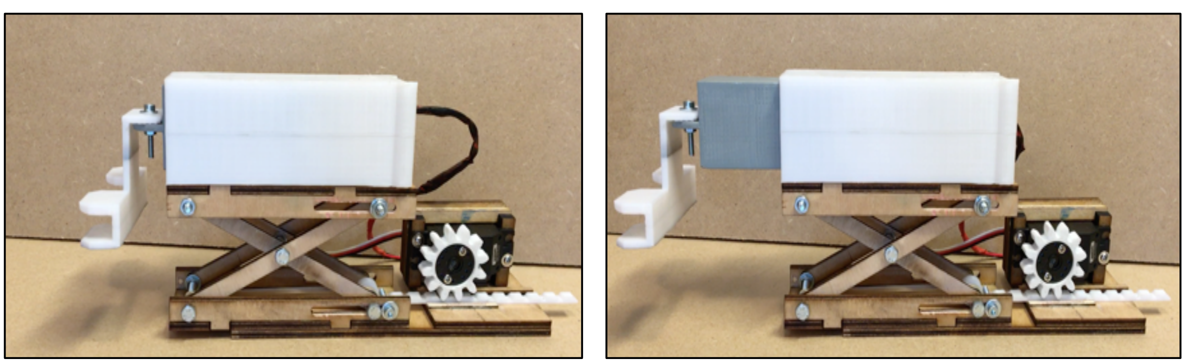


Figure 5.15: Figure showing the Cartesian manipulator concept performing extension of the telescopic boom element, providing motion in the horizontal axis.

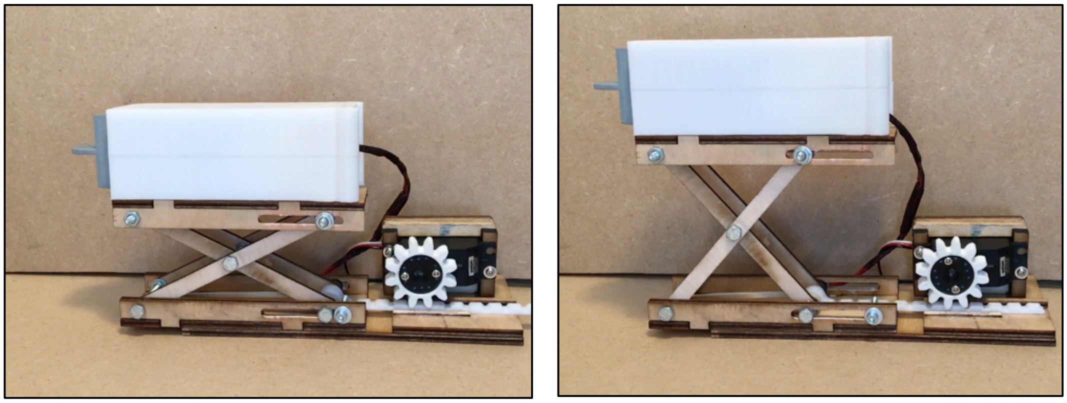


Figure 5.16: Figure showing the Cartesian manipulator concept performing extension of the scissor lift element, providing movement in the vertical axis.

5.3.4 Articulated manipulator concept development

With the desire to create a manipulator utilising the same mechanisms as excavators, a search for design inspiration was performed. Being a popular kinematic design for hobby robot makers, many existing CAD models is shared and available on CAD community sites like GrabCAD. Crucial for the robot design would be maintaining a planar tool placement at all times during operation. This is due to the concept gripper tool design, which is in need for strict linear motion when the front step plate is inserted into the tool slot. Most excavator designs fulfil this need by having three actuating units operating in the two axes. While two of the actuators generate arm positioning in the working envelope, the third actuator controls the angle of the tool itself. This would work for the pot cover handling robot as well, though full tool control is not a requirement, only for the tool to stay at a constant angle when grabbing of the cover is performed.

An alternative manipulator design is available, exploiting linkage elements to provide the EOT with a constant angle. This kind of linkage mechanism can be found on tractor backhoes, where EOT control is not of importance but horizontal alignment is. By implementing this design in the articulated manipulator concept, one actuation unit can be eliminated. This is depicted in figure 5.17 and 5.18. Having the desire of making the robot as robust and mechanical as possible, while keeping the design reliable, the latter design was chosen for the rotary manipulator concept.

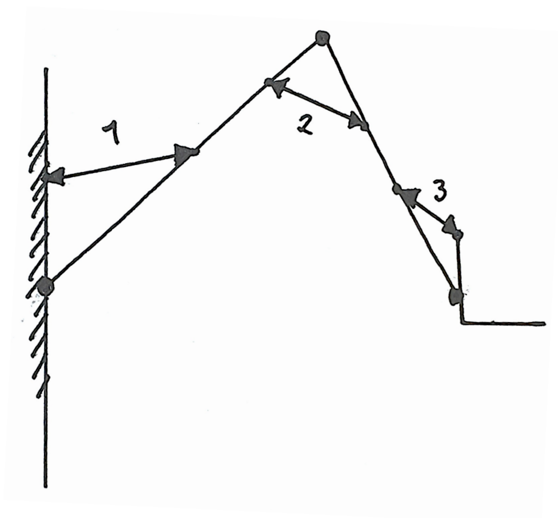


Figure 5.17: The layout of a traditional excavator mechanism. Two linked members is controlled by the three numbered actuating units, providing positioning of the robot arm and the EOT.

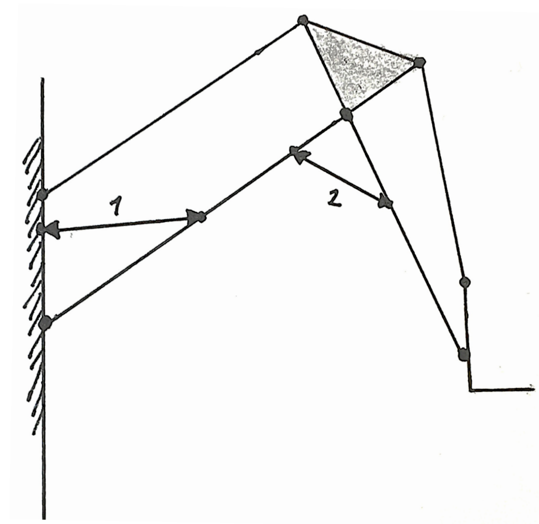


Figure 5.18: The alternative backhoe mechanisms design. The two additional four-bar mechanisms substitute the third actuator from the design in figure 5.17.

Starting the development of such a articulated design, a similar robot layout was collected from GrabCAD (Suárez 2017), utilising two high-torque servo motors to provide motion. This existing manipulator could in theory perform the desired task, but was far too big to fit on the AGV platform. A design alteration was therefore required, scaling the model down to attain the desired manipulator size. The following side-effects from the scaling lead to the necessity for multiple design alterations. Deciding to redesign the robot for manufacturing, alterations of model component thickness was needed. As 3 and 6mm MDF was available for the laser cutter, all the parts were given one of the following thickness dimensions. By doing so, the initial manipulator base became unfitting, requiring total redesign. When the down scaling was performed, the original drive system would not fit the manipulator anymore. Therefore, two standard Arduino servo motors ("Generic Micro-Servo" 2017) were selected to fit the new manipulator design. Cutting out the final design, machine screws, nuts and washers was used for joint assembly and hot glue for all rigid parts. Having assembled the prototype, coding was performed to control the servo drive system (Appendix E). With two functioning kinematic manipulator concepts at hand, the feasibility test could be performed.

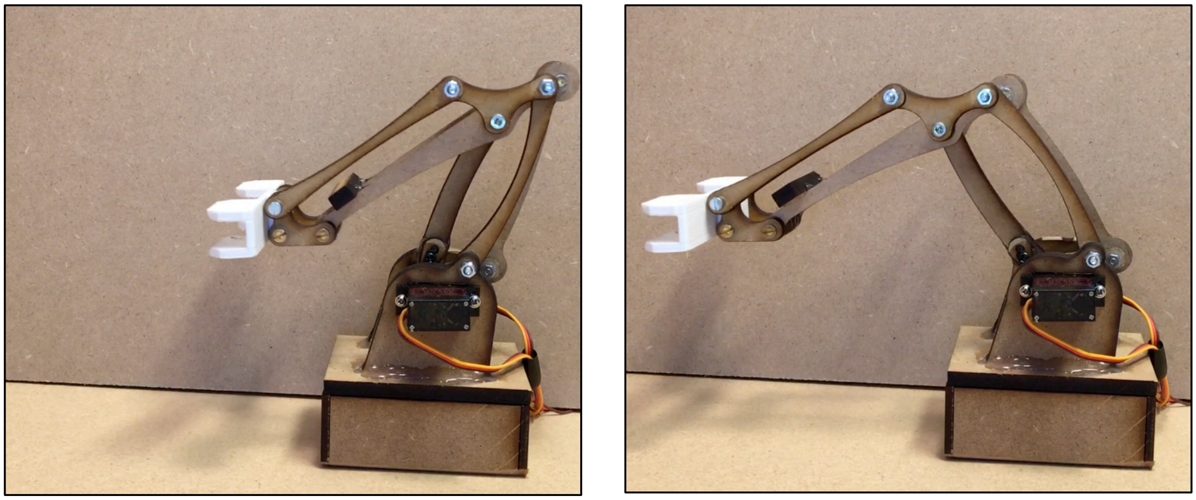


Figure 5.19: The Articulated robot concept being tested. Movement is acquired with two servos, while the additional linkage mechanism keeps the EOT at a constant angle.

5.4 Concept feasibility test

To provide a uniform test rig environment, boards of MDF was put together, creating a scene (figure 5.20). This was performed to remove the visual workshop background noise and to improve the recording of the test. These measures were performed as it was intended to share the results afterwards with Alcoa. The video results from this test session which can be viewed from the link in Appendix A.

Defining the test sequence, a scenario was planned out, identical for both of the concepts. First, the AGV should be positioned parallel with the pot, at a distance from the pot cover section. From that position, the AGV should drive to the location where the cover handling concepts should be aligned for dual cover gripping. Then, the manipulator unit should be able to handle the covers clear from the pot rack. With the covers removed and safely stored, the AGV should propel itself to enable the anode covering robot access to the open pot. When these steps are performed, the sequence should to be reversed, placing back the covers.

Figure 5.20: The stage created for the manipulator test recording.

Starting out, the Cartesian manipulator concept was integrated in the mock-up AGV. Having independent code and wiring for AGV propulsion and the manipulator actuation, a system integration was needed before the test could be initiated. The final Cartesian manipulator prototype with AGV propulsion wiring schematics can be viewed in Appendix D, while the test code is listed in Appendix E. The final code yielded control of the system through live computer interaction with the microcontroller. By hitting designated buttons, six different motions could be performed either sequentially or simultaneously. Each button push was given a specific operation time, yielding high controllability and precision during manipulation.

Following the predefined steps of the test, the AGV was aligned with the pot before the linear manipulator concept completed a clean removal of two pot covers simultaneously. Having the two covers hanging firmly in the simplified gripper tooling, the AGV was driven back and forth before the covers was carefully placed back on the rack. The test was carried out by live typing on the computer with sequential movements, only performing one linear movement at the time. Pictures taken during the handling can be viewed in figure 5.21. The kinematic concept carried out the process of cover handling flawlessly. After multiple trials to ensure robot repeatability, which also was successful, the concept was validated as a highly feasible cover handling concept.

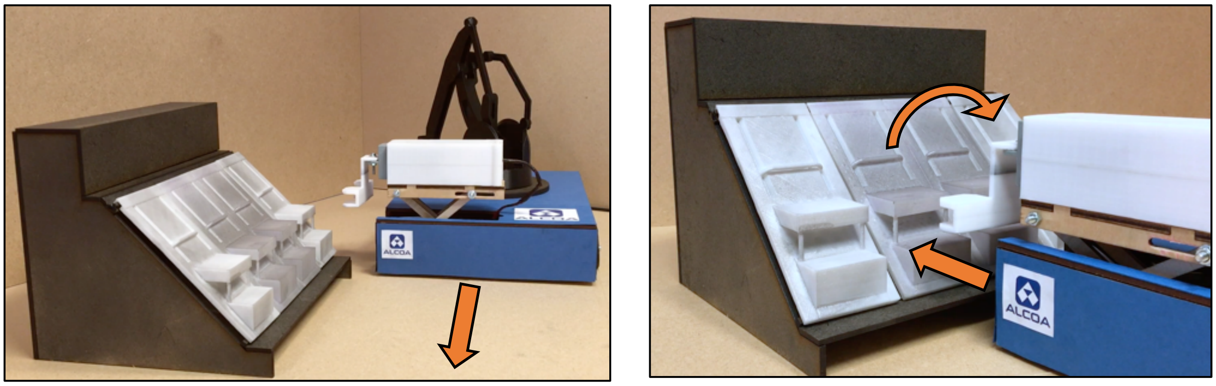
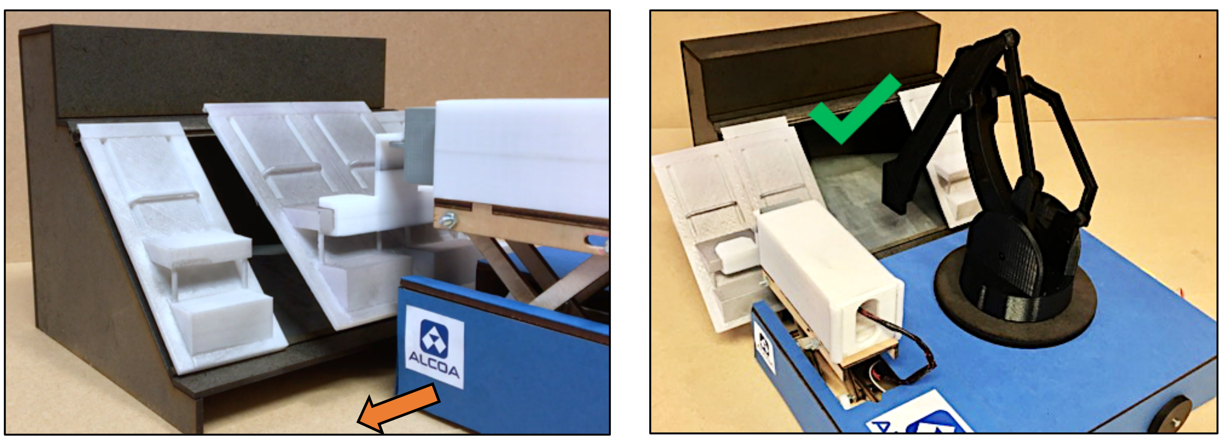


Figure 5.21: Pictures showing the successful testing of the linear manipulator concept. The top left shows the AGV at its initial position. In the top right picture, the AGV has aligned itself with two pot covers. The lower left picture shows the manipulator after accomplished cover handling. By moving the AGV along the pot, the anode covering robot has acquired access to the inside of the pot, depicted in the bottom right picture. Video link in appendix A.



With the AGV ribbed free from the Cartesian manipulator prototype, the articulated manipulator could be fitted into the AGV hull and connected with the microcontroller. With the AGV control code altered for the second concept (Appendix E), the test could be performed for the second concept. Going through the exact same sequence as the previous concept, the rotary concept performed just as well as its predecessor. Pictures taken from the second test can be viewed in figure 5.22. With two equally successful cover handling test results, both concepts yielded high degree of implementation feasibility.

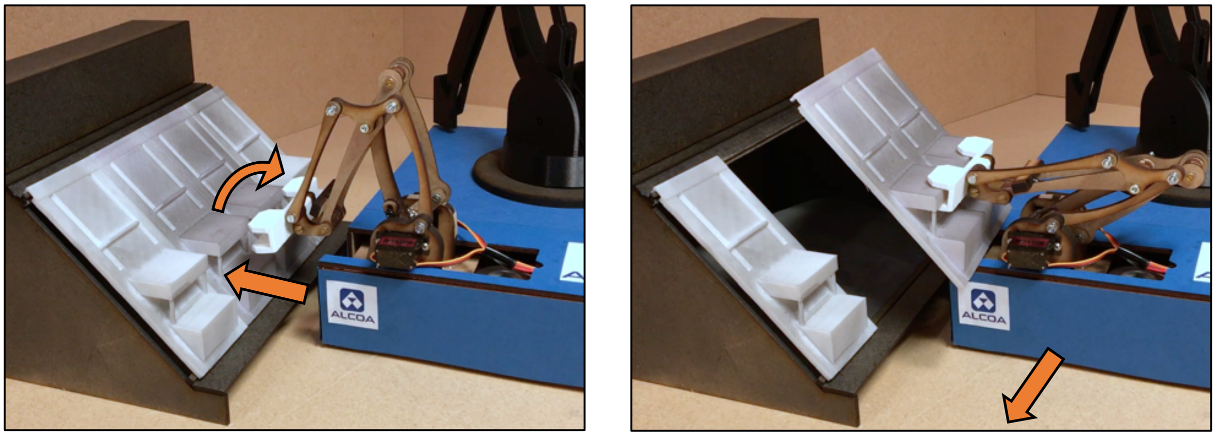
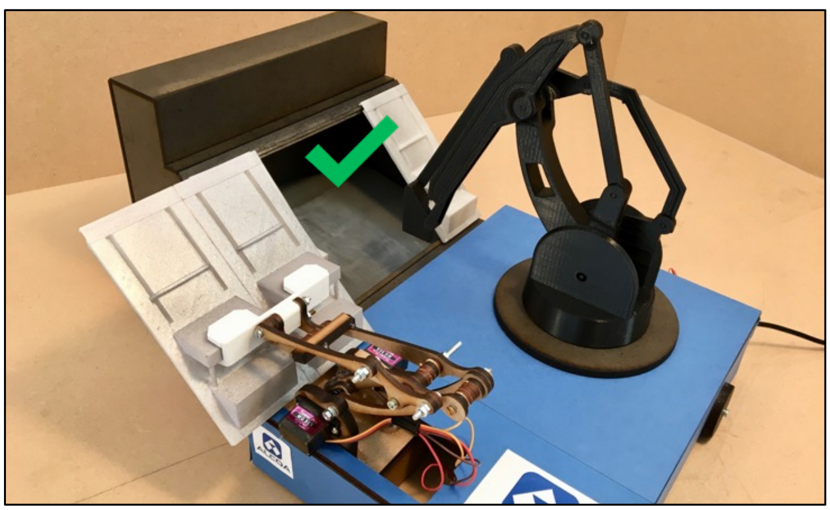


Figure 5.22: Pictures showing the successful testing of the Articulated manipulator concept. Having already aligned the AGV, the top left shows the AGV aligned and the manipulator ready for gripping of the two pot covers. The top right picture shows the manipulator after accomplished cover handling. By driving the AGV along the pot, the pot operation robot gains free access to the inside of the pot, depicted in the bottom picture. Video link in appendix A.



5.5 Conceptual design manipulator result

From the feasibility test, both of the concepts yielded positive results, perfectly capable of executing the task in the scaled down potroom environment. Now, a concept selection should be performed based on their capability to meet the set of requirements. Also being part of the evaluation is how the individual designs reliability is met, comparing concept attributes with each other. Perhaps the most important metric for this selection is the business partner feedback, provided after the manipulator feasibility test video had been presented (Appendix A).

5.5.1 Conceptual design concept review

The Cartesian manipulator concept offers two separable units, assembled to create the robot unit. This modularity yields improved maintainability, enabling simpler reparation if components should fail. All kinematic mechanisms utilised are common and well established solutions, ensuring concept integrity. The mechanisms selected are adaptable, providing possibilities of changing actuation principle solutions for more resilient alternatives. Drive systems can be strategically placed at a distance from the pot, away from heat and most intensive areas of the magnetic fields.

Telescopic boom designs can handle large loads effortlessly, which can be said for the scissor lift system as well. Combining the two modules, however, will create asymmetric stress concentrations in the scissor base due to the momentum created from covers are handling. This yields reduced design clarity, which is less beneficial according to Design for Reliability. Making assumptions based on the prototype design, this type of system would require a considerable installation space on the AGV platform. The extending beam element demands retraction space on the AGV, while the lift module would require a larger area of the platform to provide manipulator stability. Due to the specific combination of kinematic systems and our specific operational demands, off-the-shelf solutions for the linear robot concept was not found when research was conducted. Finalising such a concept for the AGV would therefore require a custom design, which could prove costly to develop.

The Articulated manipulator concept is compact and based on existing excavator and backhoe designs. Compared with the competing concept, it does not provide the same degree of modularity. It is, however, well known for pick and placing operations and with a kinematic system consisting of well know mechanical linkage principles, it provides high degree of reliability. Depending on only two drive units for tool manipulation, it is also a robust solution with high degree of maintainability. An additional benefit of the rotary manipulator concept is articulated robot designs are common, and comparable existing systems has been found available as off-the-shelf robot products. Not depending on customised development of the robot unit increase the concept feasibility and the degree of implementation realism. Having a compact design also improve the possibility of adding extra degrees of movement if desired if company partner would desire this. This could be, for example, a base providing 360-degrees rotation or tool angle manipulation.

Based on the concept review, the Articulated manipulator concept stands out as the most promising of the two. Without presenting the evaluation results, Alcoa was given the video results of the feasibility test and were asked to yield their opinion. One of the returning comments from Alcoa came from Kim Ronny, Process Engineer Candidate at Alcoa Mosjøen:

> *"I actually think both of the concepts looks very promising, and it is most definitely a good start on solving the cover handling challenge. It is positive that the system reliability has been considered, as the pot covers has a tendency of getting fairly stuck to each other. If I were to select the concept I have the most faith in, it would have to be the second concept (the articulated manipulator concept). In my opinion, it resembles the most how we handle pot covers today. At the same time, the mechanical principle used has similarities to the grabbing vehicles we use at the potroom. "*

This comment exemplifies the uniform feedback from Alcoa, clearly stating a preference towards the articulated concept. Combining the previous evaluation with Alcoa's conviction towards the rotary manipulator concept, a confident concept selection can be performed. Selecting the articulated manipulator concept for further development, the conceptual design phase can be finalised.

5.5.2 Manipulator conceptual design result

To close up the manipulator's conceptual design, a kinematic concept design proposal is provided. What has been confirmed through development and testing is that an articulated manipulator with only 2-axis motion is able to perform cover handling. Providing the manipulator concept with motion is two actuating units and a linkage mechanism providing constant EOT angle. Combined with the AGV, this enables all motions necessary for successful cover handling. What remains untouched, in need for consideration, is what drive system should be used for actuation. Also for consideration is how Alcoa should progress to acquire a suitable cover handling robot unit. These questions will be taken into further consideration during the embodiment stage of the development.

6 Embodiment design: Gripper and Manipulator

Entering the last development stage addressed in the thesis, the operator gripper and the articulated manipulator concept will be joined into a complete cover handling solution. The conceptual design phase was concluded with confirming results of concept feasibility for the two concepts. Now, in the embodiment phase, refinement and improvement potentials of the robot will be addressed. As far as it is sensible to optimise design this early development process, robot weak spots are to be eliminated. The development performed in this partial embodiment phase will be the last objective for completion on the milestone plan before concluding the thesis with a discussion and conclusion chapter.

6.1 Gripper embodiment design

Though five iterations of gripper concept development were performed in the conceptual design phase, the current gripper prototype has many improvement potentials. In the gripper embodiment design, gripper design flaws and areas for improvement will be addressed. Refining measures will either be taken or proposed for future development.

6.1.1 Dual gripper tool design

Though it was performed dual gripping during the manipulator feasibility test, a full-scale dual gripper tool is yet to be created. The final outcome of the gripper conceptual design was a fully functional aluminium robot gripper. Constructing and producing a second full-scale aluminium made dual gripper will not be prioritised for the thesis. For this design iteration, the development will be restricted to CAD. To provide dual gripping, it is needed to unite two of the existing gripper designs. It would also be desirable of the robot connection is aligned with the area of gripping. The unifying design should also not interfere or collide with the cover design. It should be sturdy, fitting with current unity of robot and tool, not creating a weak linkage in the current design.

To unifying two gripper tools, a measurement is needed. Vital for the design is the distance from one cover middle point to the other when placed tightly in succession. From machine drawings, the ideal distance is targeted to be 593 mm. The existing single tooling has a 20 mm margin in both directions between the step plate support pipes. By using exactly 593 mm for distancing between the two grippers, a decent fit is maintained, enabling some room for misalignment. The first design iteration (figure 6.1) unified the two tools by a 40x40 mm pipe, welded to the back of the robot connector brackets. Though functional, this design did not align robot connection and gripping area, generating unwanted momentum in the robot tool fastening area.

Figure 6.1: Isometric view of the first dual tool joining proposal.

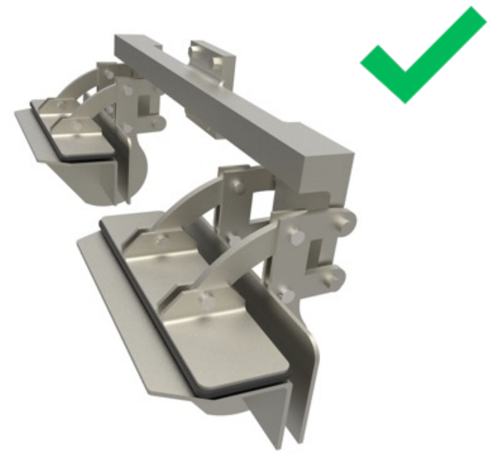


Figure 6.2: Isometric view of the second and final dual tool joining proposal.

It was therefore decided to perform a second iteration, moving the connecting bar above the gripper instead of behind the connection brackets (figure 6.2). By doing so, the robot mounting bracket becomes vertically aligned with the back hinge of the two grippers, generating less momentum in the tool connection. The unifying bar proposal is connected with a 40x40 mm pipe welded to extended hinge brackets. By simulating usage of the dual tool in CAD software, tool collision did not occur. This is the preliminary design proposal for the tool unifying.

6.1.2 Rigid gripper improvement potentials

In this subsection, embodiment design improvements will be evaluated for the rigid parts of the gripper tool. Towards the end of the thesis period, a presentation of the aluminium gripper prototype was performed at a thesis conference with production engineers at Alcoa Mosjøen. After the prototype presentation, a feedback session was conducted addressing both gripper tool and robot. The joint concept solution was well accepted among the crowd, but it was addressed minor concerns related to how the gripper can handle damaged covers. It is difficult to create sturdy and robust gripping solutions which also are adaptable enough to handle heavily deformed objects. Heavily deformed covers either way needs changing, being a risk to potroom HSE. But taking this feedback into consideration, this subsection will address design changes improving the tools reliability concerning covers with minor damages. Also included in the subsection is improvement proposals aiding additional robustness and reliability.

6.1.2.1 Cover front plate insertion slot

At this stage, the aluminium prototype has been equipped with an exaggerated large plate insertion slot. Though the plate is roughly 4 mm thick, the tool slot is currently 10 mm wide (figure 6.3). As some time passed between the gripper and robot conceptual design phases, some maturing of thoughts occurred. In figure 6.4, the new proposal for the slot design is depicted in orange. Going from a purely parallel slot shape to introducing a right-triangle shaped slot, followed by a shorter parallel track. The new design allows for easier step plate guidance into the slot. It also reduces the chance for dented stepping plates to get stuck when they are inserted, as it has only a tolerance fit at the bottom of the slot. This refining attribute is therefore added to the CAD model.

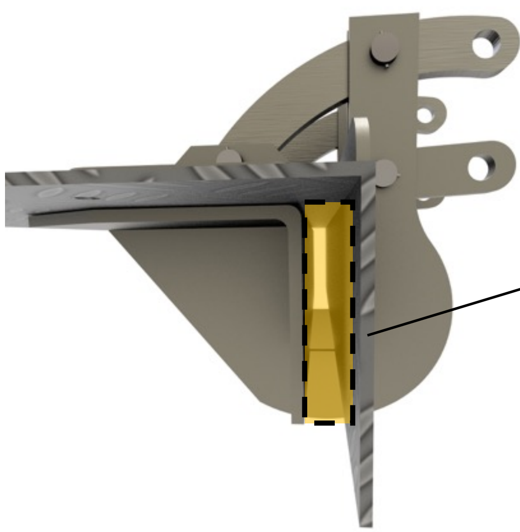


Figure 6.3: Side view of the current tool slot design with superficial spacing highlighted.

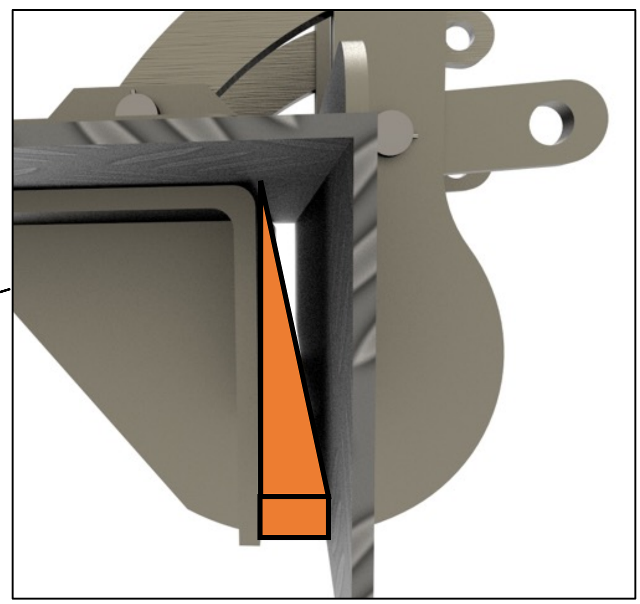


Figure 6.4: The proposal for a new tool slot design.

6.1.2.2 Rigid tool adaption for moderately damaged covers

First being at the thesis conference in Mosjøen, a testing of final prototype in the potroom environment could be performed. The prototype yielded pleasing results with standard covers and covers with slightly damaged stepping plates, though was not capable of handling moderately damaged stepping plates. During the testing, a 5mm spacing plate was in the tool slot, yielding only 1 mm of slack.

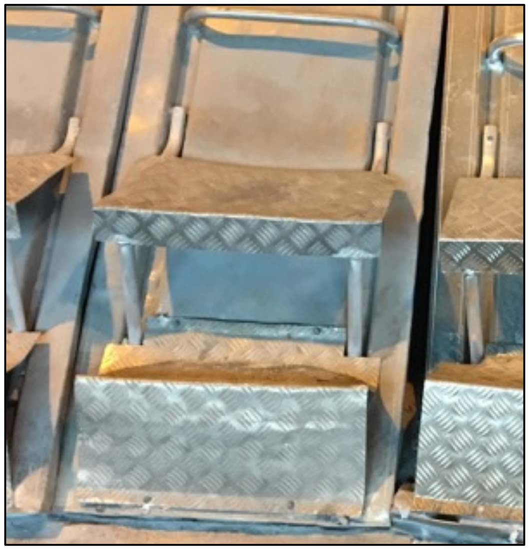


Figure 6.5: A pot cover with moderate denting damages on both lower and upper stepping plate.

The most typical stepping plate damages occurs as denting due to heavy machinery accidents. Two typically occurring situations of stepping plate denting is displayed in figure 6.6. What they both have in common is that the larges deformations occur on the step plate centre, while the denting is minimal close to the step plate support bars. This can have a correlation to the additional support the bar provides, as well as how the step plate is welded to the bar, yielding no displacement in this area.

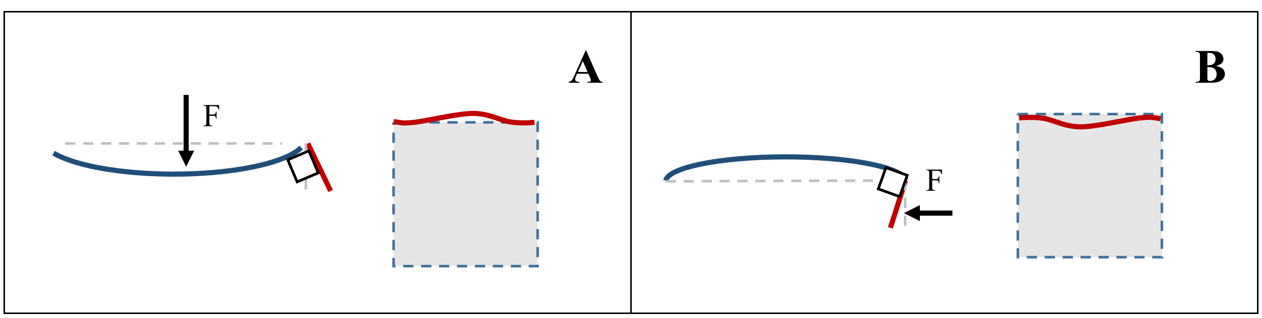


Figure 6.6: Deformation A describes the situation where a force has hit the top of the step plate, resulting in a dent on the step surface. Top left, a side view of the step plate deformation is visualised. The right figure shows the step plate from underneath, with the red line visualising the resulting unwanted deformation. Deformation B describes the situation where a load has hit the front of the stepping plate. The red line visualises the resulting unwanted deformation.

The current tool design has a continuous stepping plate support and plate slot. During the presentation at Alcoa, the challenge of buckled stepping plates was presented to the attending engineers. A question was raised, asking if the continuous step slot and abutment plate actually needs to be continuous. Reviewing the current design, this should be perfectly possible to modify. By removing parts of the support and abutment plate, dented front plates can obtain a greater chance for successful gripping, having additional space for deformation (figure 6.7). To facilitate the design changes, the tool support brackets will need to be relocated further out toward the edges. This will also affect the reliability of the tool, as both the abutment plate and the tool slot provides stiffness to the structure. It is therefore needed to add additional support elsewhere on the tool to balance out the reduced design unity.

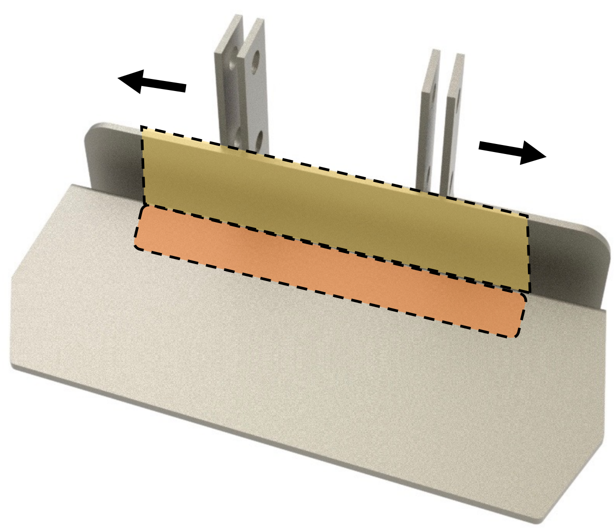


Figure 6.7: Picture showing areas for rigid tool structure removal, increasing compatibility with damaged stepping plates.

6.1.3 Refined rigid gripper results

Due to the actions requested in the two previous subchapters, the tool support brackets needs to be moved towards the tool edges. Due to the reduced design robustness occurring from the desired design alterations, some additional tool support would be beneficial. By exchanging the two pin holding brackets with two additional support brackets, the structural integrity of the gripper can be increased. With an increased distance between the support brackets, not having the continuous abutment plate confining them, the tool stiffness is now compromised. By implementing a pipe between the brackets, the required stiffness can be provided. This bar can also serve as a mount for the self-sustaining spring. Having combined all of the improvement potentials mentioned through chapter 6.1.2, a new design for the rigid part of the robot gripper can be created. The final model can be viewed in figure 6.8. Being just a model, the new design should be tested in a real potroom environment to ensure that the reduced front step plate contact area does not lead to buckling of the plate or other unforeseen effects.

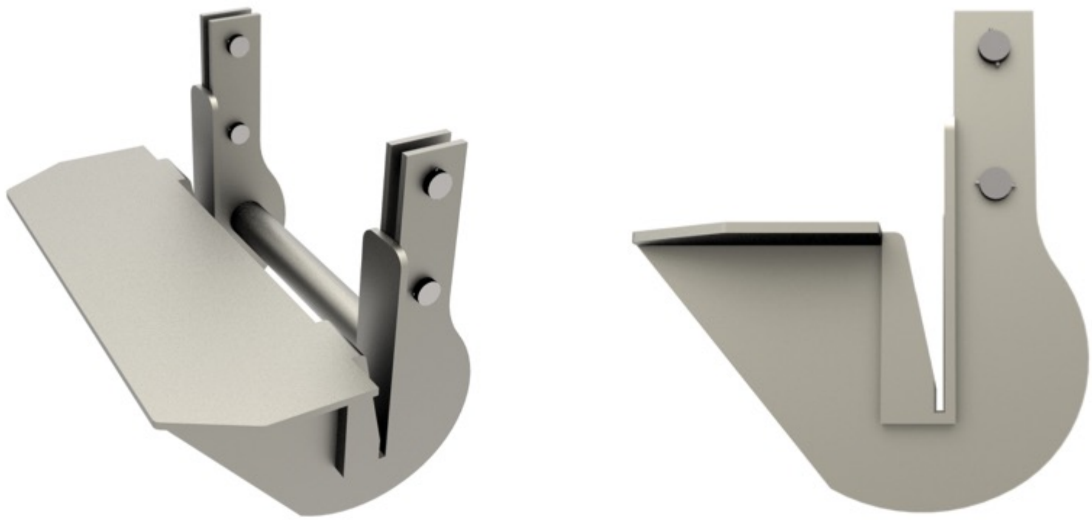


Figure 6.8: The refined rigid gripper design after the embodiment review.

6.1.4 Kinematic design improvement potentials

In this segment, the parts of the tool which are in motion will be evaluated. The goal is to perform a design review, presenting improvement potentials of the current kinematic design where it is deemed feasible.

6.1.4.1 Clamping mechanism

During the conceptual design phase, the creation of the clamping mechanism was heavily impacted by an ad-hock approach to create linkages fitting the existing gripper design. From the low-resolution physical prototype to the aluminium gripper, based on the CAD model, enhancements where made ensuring that the links would perform prehension as desired. It was, however, not evaluated how the linkage lengths would impact the resulting retention force on the stepping plate. Though the current clamping mechanism show no signs of providing insufficient retention, there are possibilities of increasing prehension force by altering the linkage design.

In figure 6.9, the current tool linkage design is depicted. To the far left in the figure, the connection points of the arm which applies the clamping forces is highlighted. The diagram to the right is a simplified representation of how the prehension forces are applied to the cover during lifting. The leverage point of the current link is quite close to the tool connection, as can be seen in the figure to the right. The tool force F_{tool} is generated by the pot covers' mass and will remain constant in this example. The size of the resulting clamp force N, however, will be impacted by the momentum created by the leverage arm of the tool force F.

$$\sum M = 0 = N_{Clamping\ plate}a - F_{Tool}b$$

From the equation above, we have that when the cover is prehended at maximum force, a moment equilibrium occurs and the covers are lifted. Due to the short leverage arm "b" and the longer leverage arm "a", the clamping force N will be considerably smaller compared to the tool force F. However, if the bearing point of the linkage is moved in direction "x", the leverage arm "b" will increase while "a" decreases. By doing so, the retention force N will increase, and higher clamping force can be obtained by linkage optimisation only. Worth mentioning is that by applying changes, the four-bar mechanism joining the gripper and the robot connection also needs adaption. By increasing the length "b", the other parts in the four-bar linkage should also being increased, preserving the linkage unity. By increasing "b", the clamping mechanism will increase in size and the overall tool design become less compact. Increasing the linkage length should therefore be considered if the additional force would be worth the trade-off.

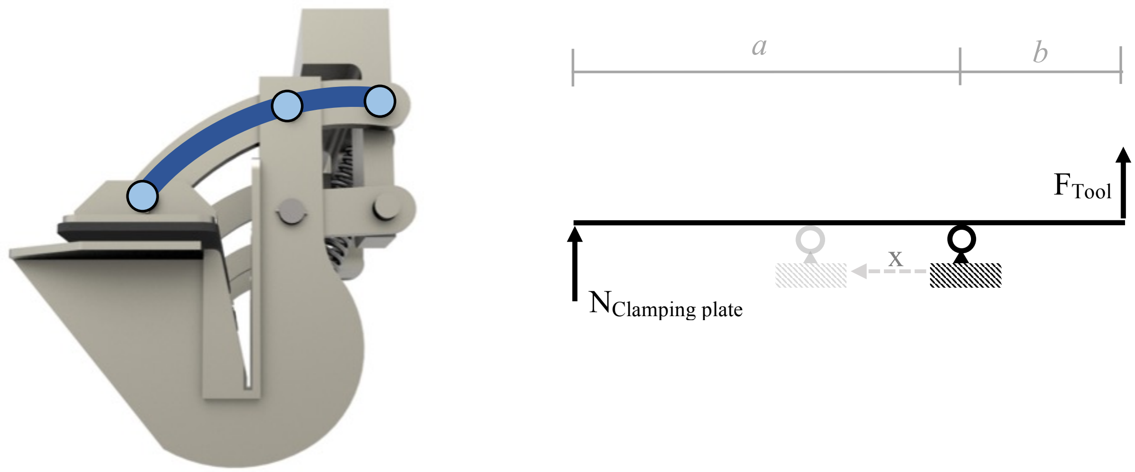


Figure 6.9: Figure showing how the link joint distances affects the clamping force N applied to the pot cover during lifting with the self-sustaining clamping mechanism.

Also created with the existing prototype tool design in mind was the clamping plate itself. The large area it delivers the prehension force over was made with the intention of decreasing the chance of buckling the top plate due to high pressure. At this point, retention is acquired without signs of stepping plate buckling. Another important task the clamping plate has to perform is to generate friction between the tool and the stepping plate. The tool having a total 40 mm clearance between the step plate support bars, it needs friction to prevent sideway slippage during handling. The current design has a rubber lining on the clamping plate and diamond patterning on the step plate. From the equation below, we have that with a constant prehension force N, the pressure applied on the stepping plate will increase by reducing the impact area of the clamping plate. This could be performed if there should be a need for increased reassurance towards sideways slippage.

$$P_{Clamping\ plate} = \frac{F}{A} = \frac{N_{Clamping\ Plate}}{lb}$$

6.1.4.2 Gripper spring mechanism

The spring used for the final prototype was selected from a range of different spring sizes available, ending with a spring keeping the clamping mechanism at an equilibrium when not interacting with a cover. With the spring only being at equilibrium, and not preloaded, the clamp shows tendencies to move when the tool experience acceleration. In addition, when the tool was tested in the hot potroom environment at Alcoa Mosjøen, the spring stiffness decreased and the undesired clamp movement worsened. It is therefore desirable to improve the current state of the self-sustaining mechanism spring.

Though the current spring is stiff and large enough, it is not being able to keep the mechanism steadily open due to low pretension. If the spring is overly preloaded, valuable clamping force can be lost due to the spring opposition. This could be solved empirically by adjusting the preloading of the spring to match with the desired behaviour. What also needs consideration is the varying ambient temperatures occurring in the potroom throughout the year, ranging from -20 degrees Celsius at winter time to 60 degrees during summer. Having the possibility to increase and decrease the spring tension throughout the year would therefore be a benefit. One solution to this is replacing the current spring with a mechanically adjustable spring, allowing for spring adaption as the environment change. Being a purely external and simply replaceable component, the spring could also be replaced during service to fit with the time of year.

6.1.4.3 Linkage joints and bearings

The current gripper prototype utilises 16mm 6061 aluminium round bars as linkage connection as well as plain bearings for the prehension mechanism. This is not an ideal solution for long time usage. This type of bearings presents noticeable surface friction, leading to bearing wear over time. The wear will ultimately result in joint slack, reducing linkage stiffness and accuracy. The way the link is designed today, it is also susceptible to the dusty environment. The 6061 aluminium round bar which was used for the prototype is workable and light, but not especially suitable for bearing usage. An evaluation of how the linkage joints could be improved for usage at Alcoa in a final product is therefore desired.

To find suitable bearing options for the gripper mechanism, the SKF rolling bearing catalogue (SKF 2016) has been utilised. In the catalogue, a list of factors is presented, aiding the selection of suitable bearing solutions. Most relevant factors in our case is bearing load, stiffness and environment contamination levels. The loading which the links will be experiencing is purely radial from the weight of tooling and covers. The expected speeds of the joints will be low, while the contamination levels are anticipated to be high. Lastly, the bearing stiffness is important for linkage precision. With a strictly radial loading, the SKF guide propose usage of roller or ball bearings. Due to the stiffness criteria, cylindrical roller bearings would be favourable compared to ball bearings. To accommodate the high potroom contamination factor, bearing seals should be included in the bearing selection. To provide additional stiffness and durability, the prior 16mm aluminium rods can be replaced with more suitable bearing steels. SKF offer multiple alternatives, one of them being high chromium content stainless steels like X65Cr13. By implementing the proposed bearing refinement, the linkage precision and lifetime will surely increase.

6.1.5 The final gripper design

Having now addressed and implemented refinement of the conceptual gripper design, an upgraded design proposal has been materialised. The improvements which has been engineered and included in the new design can be viewed in figure 6.10. This includes a redesign enabling dual cover lifting as well as altering of the previous rigid design to better cope with damaged covers. Alterations which has not been included in figure 6.10 are design changes related to the kinematic systems. This is the final concept iteration of the cover gripper tool in the thesis.

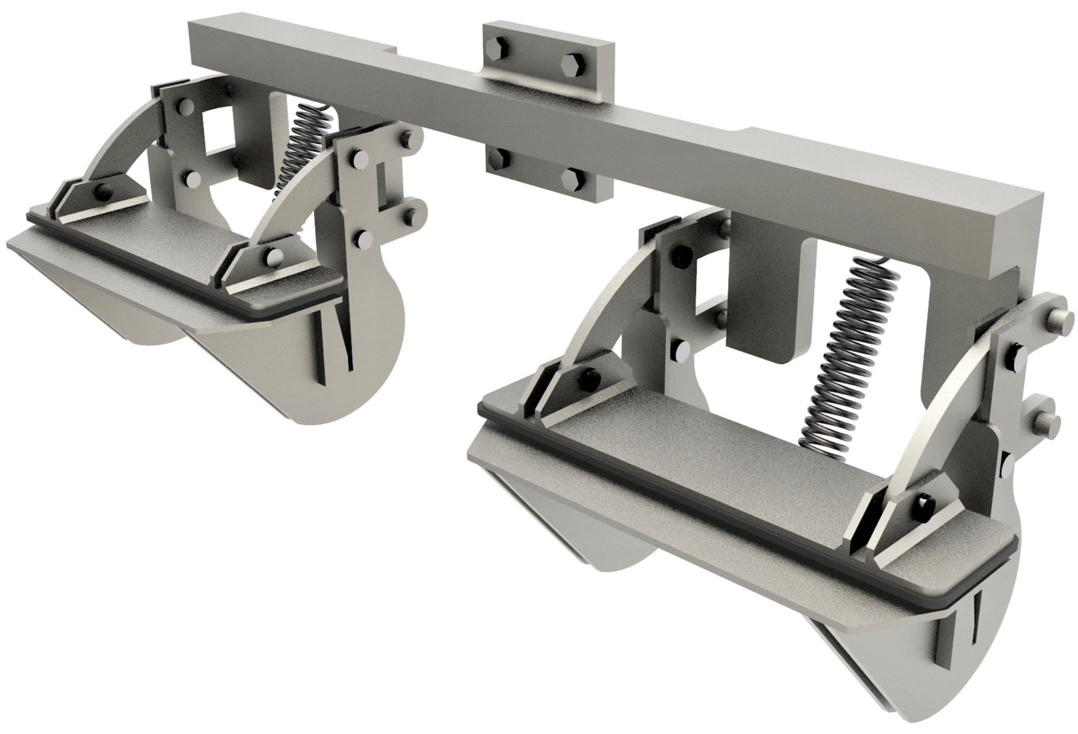


Figure 6.10: The final gripper design concluding the thesis, including dual tool connection and embodiment design refinement.

6.2 Manipulator embodiment design

In the manipulator embodiment design stage, a further specification and refinement of the proposed robot concept will be performed. This incorporate an evaluation of which drive systems can be utilised for the final robot solution. Based on the evaluation, research will be conducted regarding the possibility of finding existing off-the-shelf robots suiting the list of wishes. Also brought up in the embodiment design is sensory considerations. Though sensory has not been a focus area in the thesis, some findings from the prior project thesis can be of relevance. This will be the main objectives for assessment before concluding the embodiment design with the final joint robot and gripper proposal.

6.2.1 Robot drive system

Looking yet again back at the drive system table 4.2 in chapter 4.1, we can review which types of actuation principles suits our robot the best. Mechanical and magnetic drive can immediately be excluded, which does not fit our implementation context. This is due to the fact that mechanical principles will not be sufficient for automation of a robot unit, and that magnetic drive would be vulnerable in the magnetic potroom environment. Pneumatic drive could be utilised, but is not an obvious choice compared to electric and hydraulic drive, which both is more commonly used for larger robotic operations.

Following the trail of thoughts from selecting the gripper drive system, we can quickly identify hydraulic drive as a possible alternative for the robot. It is strong and durable, already tested and confirmed for usage in the potroom environment. Regarding electric drive, it has been confirmed by Alcoa that testing of industrial service robots using electric motoring have been conducted in the potroom environment. The results from the test yielded no signs of the robots being affected by the varying magnetic fields or heat surrounding the pots. Though no data is acquired, validating the test, there are no reasons to exclude electromotor drive as a viable option. Comparing electric and hydraulic drive, the hydraulic drive is slower and less accurate compared to electric drive. Hydraulic drive would additionally need a hydraulic pump installed on the AGV to provide actuation. Hydraulic drive can provide superior strength compared to electric drive, though extreme strength is not required in our case, where payload will be roughly 40 kg. Evaluating the two remaining drive options, the electric alternative should be the preferred option. Hydraulic drive, still being a feasible option, should also be considered if fitting robot alternatives can be provided.

6.2.2 Acquiring the robot

The Articulated manipulator concept proposed in the end of the conceptual design phase has a layout intending to be as reliable and simplistic possible. This includes as few degrees of freedom as feasible. Having validated the concepts ability to perform the desired task through scaled down testing, the next step would be to acquire a robot capable of performing the task at full-scale in the potroom environment. Seen from an Alcoa's company perspective, there are numerous factors which can affect this process. Existing subcontractor partners, already delivering automation solutions at Mosjøen, can be a preferred choice for acquiring such a robot system. This could be linked to factors such as good relations benefits related to maintenance. Using this as an example, there can be multiple unforeseen factors impacting how Alcoa would wish to proceed with the procurement of the robot unit. To be able to propose a tangible robot and gripper system, however, the author of the thesis has decided to conduct an investigation after existing robot solutions. As there are multiple approaches for procuring a robot, the search has been performed with three parameters in mind. These are listed in a sequence associated with their degree of desirability:

1. Acquire an off-the-shelf robot system specifically fulfilling task specifications
2. Acquire an off-the-shelf robot system exceeding task specifications
3. Contact robot supplier for customization of a robot solution

From the specifications determined throughout the conceptual design, the optimal robot solution would be restricted to movement in the vz-axis, only actuated by two drive units. If it could be possible to acquire this exact robot layout as an already existing product, development costs and risks can be eliminated. This would therefore be the most desirable procurement option. It would, however, need to be in the right payload segment, with a pleasing work envelope reach. This might yield difficult to acquire. If such a product does not exist, it is possible to find a robot system which resembles the task specifications. For this to be a viable option, the identified manipulator needs to exceed the desired properties. The third option, getting a supplier to customize a robot solution, could prove to be the most expensive and risk intensive alternative in this scenario. Therefore, the two first options are the ones focused on when the search for a fitting robot for cover handling was performed.

On KUKA's webpage, various 4-axis palletizing robots can be found, though all of them greatly succeed the cover handling payload segment. Researching the product portfolio of other brands names such as Kawasaki and ABB yielded similar results. Browsing through the Yaskawa Motoman product catalogue, however, lead to the MPK50 4-axis palletizing robot (Yaskawa 2017) (Appendix G). This articulated robot has a maximum capacity of 50 kg, fitting satisfactory with the payload requirements. It has the desired movement in the vz-plane, with an additional DOF at the robot base and in the tooling mount. With its two superfluous degrees of freedom, this robot falls in under the second priority category. It was therefore decided to perform additional research in hope of finding a more suitable option to the MPK50.

Looking through the FANUC portfolio, the M-420iA occurred (RobotWorx 2017). Similar to the MPK50, this is a 4-axis robot suited for machine loading, palletizing and assembly, but with a smaller payload capacity of 40 kg. Screening through the M-420iA brochure (Appendix F), an altered version of the M-420iA can be obtained, the M-421iA. While both the MPK50 and the M-420iA has 4-axis motion (J1-J4), the M-421iA is only equipped with two drive units, providing it with 2-axis motion in the vz-plane (J2-J3). It is correspondingly installed with the critical alignment mechanism, ensuring that the EOT is at a constant horizontal angle. The two drive units are placed at the robot base, matching the design for the articulated manipulator prototype. Compared to the M-420iA, the M-421iA has a reduced mechanical weight of 100kg and an increased payload capacity up to 50 kg. To provide an overview, a selection of the robot attributes has been gathered in a comparison table (table 6.1).

ROBOT COMPARISON MATRIX			
Robots / **Attribute**	Yaskawa MPK50	FANUC M-420iA	FANUC M-421iA
Number of axes	4	4	2
Payload capacity	50 kg	40 kg	50 kg
Reach	1893 mm	1855 mm	1855 mm
Repeatability	± 0,5 mm	± 0,5 mm	± 0,5 mm
Mechanical weight	670 kg	620 kg	520 kg

Table 6.1: Robot Comparison matrix.

From the research conducted, it has been proved that it is possible to acquire an existing robot product, matching the robot specifications which was identified though the manipulator conceptual design. The FANUC M-421iA, being a lightweight, task optimised, ideal payload capacity robot, would be pertinent for pot cover handling and AGV implementation. If increased adaptability were considered utterly favourable, scaling up to a 4-axis robot like the MPK50 could be considered as an alternative. What this research has confirmed is that there is no need for å bottom-up development of a cover handling robot.

6.2.3 Facilitating robot automation

In the prior project thesis, reviews of potroom applicable sensory was a considerable part of the research which was conducted. With a tough environment, consisting of varying temperatures, magnetic fields and dust, applicable sensory was regarded important to explore for automation enabling. A review of the project thesis results regarding sensory, facilitating automation of the gripper and manipulator has therefore been performed. Some of the identified scenarios in need for data collection and processing to facilitate automated cover handling are:

- Identification of cover location on pot
- Verification ensuring that the covers are properly prehended
- Verification ensuring that the covers are properly handled and stored
- Identify scenarios where the robot should not perform pot cover handling

In the project thesis, testing was conducted on how to identify placement and location of pot covers with 2D camera technology (Appendix J, Section 5.2.1.3). By usage of contour or corner detecting algorithms, the shape of the pot covers can be identified and located. Another viable 2D camera option is utilisation of Quick Response code technology, marking selected pot locations or the covers themselves with QR barcodes. From these barcodes, location and distance can be obtained with 2D camera vision systems. 3D camera systems might be implementable, able to record objects and their distance based on point cloud recording. Infrared 3D camera technology has, however, difficulties with reflective surfaces such as aluminium. Being also computational demanding, the 2D camera solutions showed the highest degree of implementation from the previous work. Also useful for location of covers is the AGVs potroom position tracking, yielding the system with a pot distance reference.

Verification regarding successful prehension, handling and storing can be performed with multiple sensory solutions. Previously mentioned vision systems can monitor the process, though simpler sensory might yield sufficient. Using load cells, the robot can identify if the covers is balanced properly in the gripper tool during gripping, handling and storing. When being handled or stored, distance measuring sensory such as LIDAR (Appendix X, Section 5.2.3), infrared or ultrasonic sensors can ensure that the covers does not translate in the tooling. LIDAR technology can also be used to ensure that the HSE aspect of utilising mobile industrial robots in a human-robot interacting environment is met. If unknown obstacles occur in the working envelope of the robot, such a system can scan and prevent accidents from occurring. In situations where pot covers are severely damaged, misplaced, or are blocked by stones and dirt, LIDAR and vision systems can be applied to obstruct the robot from performing cover handling. These are a few suggestions to how automation of the robot system can be facilitated.

6.3 Embodiment design summary

According to the Pahl and Beitz's development plan, the thesis project is still in the embodiment phase as it has reached its completion. There are additional refinement and improvement considerations left before detail design can commerce. Among the tasks are further calculations, design analysis, design refinement, weak spot elimination, part listing, definite layout detailing, with more. The details concerning the further work will be addressed in the following discussion chapter.

Summarizing the final product from the thesis embodiment design, we have a proposal for a gripper and manipulator combination. The gripper tool has undergone assorted refinement changes and reviews has been performed for further improvement potentials. The manipulator has undergone a drive system review, a search for existing products has been conducted and automation sensory has been proposed. A render of the AS-IS product result from the thesis can be viewed in figure 6.11 and 6.12, showing the combined solution of gripper and manipulator. Also included in the figure is a mock-up AGV with a substitute anode covering robot. Additional high quality renders of the final robot and gripper system can be viewed in Appendix B.

Figure 6.11: Visualisation of the proposed robot solution installed with the gripper tool concept. A small gripper design modification is performed to allow connection with the robot. The yellow robot is a model of the FANUC M-420iA robot acquired from GrabCAD (TheNicman 2017).

Figure 6.12: Visualisation of the proposed robot system on a mock-up AGV. The grey robot is a placeholder for the anode covering robot acquired from GrabCAD (Bejenaru 2017; TheNicman 2017).

7 Discussion

In the thesis discussion section, the key segments of the thesis will be reviewed and discussed. This include thesis results, thesis development method and methodology and business collaboration.

7.1 Gripper development

The goal for the gripper development was to generate a concept solution capable of securely and robustly acquire physical control of pot covers during handling. By combining company expectations with the environment and task specifications, ideation and preliminary concept development were completed in the conceptual design phase. Performing iterations of development over the preliminary concept, a full-scale feasibility test was performed on the fifth iteration prototype. Having validated the designs capability of gripping and handling covers reliably and safely, the concept was brought for further embodiment design refinement. The current status of the development is at an ongoing embodiment design state, as the thesis period has reached its completion.

With the fifth and final physical prototype, satisfactory results were obtained, meeting the specifications which were priorly set for the development. The results were communicated to Alcoa through video recordings and a thesis presentation at the end of May, yielding positive feedback from Alcoa. Alcoa employees stated that they liked the purely mechanical design of the gripper, judging the design as reliable. The fact that the tool does not depend on actuators for gripping was also mentioned. Since then, additional improvement measures have been applied to the digital model, increasing its compliance with dented covers. Meeting the product specifications as well as receiving affirmative feedback from Alcoa, the gripper development can be considered successful. The early stage development of the robot gripper tool has now been concluded, yielding key attributes which can offer Alcoa:

- Independence, providing the option for usage on any platform
- Reliability through a purely mechanical design with self-sustaining clamping
- Simplicity with no need for actuation drive
- Zero energy consumption
- Easy maintenance and high degree of repairability

With the current gripper tool concept, we can handle most of the trials met in the potroom environment. There is still, however, cover handling challenges that need consideration and solving. The main disadvantage with a purely mechanical gripper solution is the reduced control of the tooling. If covers are positioned to tightly next to each other, the clamping mechanism can be released before the covers are properly placed. Ensuring that this will not happen should, therefore, be a part of the further work.

The further work of the robot gripper can take multiple directions. If Alcoa would select to continue with the provided gripper concept, there are additional steps within embodiment and detail design left before the tooling is fully prepared for full-time potroom usage. Further work for completion is:

- FEA analysis and topology optimisation of tool components
- Refine and include the proposed linkage joint improvements
- Refine and include improvement suggestions concerning the mechanism spring
- Reduce the risk concerning stuck pot covers
- Design a robot connection bracket fitting the selected manipulator
- Creation of maintenance routines
- Perform miscellaneous potroom facility tests

Just one test session was performed with the gripper prototype at Alcoa. Possible design flaws and improvement potential can be revealed through long time testing at Alcoa, which is hard to identify early in the development. It is, therefore, recommendable to perform more facility testing of the EOT. FEA and topology analysis of the tool has not been prioritised in the thesis as it was considered less relevant to perform this early in the development process. Instead, the components which have been designed are all been dimensioned generously to ensure structural integrity. Due to this, it exists refinement potentials concerning the mass reduction of the tooling. Refinement suggestions for the link joining have been proposed and should be evaluated as part of the further development. The same yields for the mechanism spring.

The issue of stuck covers should be evaluated, and countermeasures should be included in the design. Some suggestions can be provided, such as creating permanent placement spots for each cover. This could be achieved by having locking pins on the pot, guiding the covers. Including an additional mechanical mechanism preventing the clamp to open too early is also an alternative. If it is rendered undesired to continue with a self-sustaining clamping mechanism, application of electric or hydraulic actuated prehension should be considered. In this case, the rigid gripper part of the tool could still be utilised, only modified to fit the alternative clamping system.

To ensure that the gripper will work at an ideal state at all times, future maintenance of the tool will be imperative. A part of the further work would, therefore, be the establishment of good maintenance routines. Due to its simplistic mechanical design, it would be possible to manufacture spare parts for all the main components of the tool. Continuous maintenance operations would include bearing lubrication, clamp plate rubber lining replacement, spring adjustment and replacement of damaged or consumption parts.

Heavily impacting the development of the gripper was the restriction stating that the pot covers should not be altered. If future cover design could be permitted, an independent gripping module could be added to the cover design. This could severely simplify the gripper tool design, leading to simpler, lighter and even more robust tooling solution. This, however, could be considered at a later stage, when the AGV system is up and running, as it will be possible to change the manipulator tooling later on.

7.2 Robotic manipulator development

The overall objective of the project development was to provide Alcoa with a viable proposal for a joint robot and gripper solution, enabling reliable pot cover handling. The progression plan for manipulator development was to identify the most significant motions needed for cover handling, continued by conceptualisation of simplistic and compact robot system solutions, with the desire to either provide a manipulator for further development or find fitting existing robot alternatives. Through industrial robot literature studies and DOF experimentation, the minimal amount of robot axis freedom was identified, leading to two viable kinematic systems for further testing and validation. After performing the planning, drafting and building of a scaled down test rig, the two kinematic systems were tested for feasibility and attribute comparison. The test was concluded with the continued development of the chosen articulated robot concept, utilising rotary joints and the AGV's propulsion for movement in three axes. In the embodiment stage of the development, robot drive systems and existing robot solutions were evaluated. This led to the 2-axis FANUC M-421iA, fulfilling all desired attributes, enabling dual simultaneous cover handling with the concept gripper tool.

Following the manipulator development process, it has been proven that robot solutions specialised for the pot cover handling operation exist, yielding the possibility to acquire off-the-shelf solutions. This can speed up and cost reduce the development process of the anode covering AGV platform. Depending only on two electric drive units, placed at the robot base, the proposed manipulator solution is both compact, lightweight, energy efficient and robust.

The final manipulator proposal is heavily dependent on the accuracy of the AGV. This can become a design weakness should the AGV prove to have insufficient accuracy. Scaling up to a manipulator with 4-axis control should, therefore, be taken into consideration as part of the further work. With a 4-axis articulated robot, additional degrees of freedom could yield adaptiveness for the future, reducing accuracy-related risks. It could also yield future possibilities, should cover redesign or additional tasks be desired for performance later on.

Future work for AGV manipulator implementation should include how to connect the robot to the AGV platform. This includes providing the right power supply from the AGV battery pack. It also includes system integration with the AGV control system, facilitating the autonomy of the operations. Sensory implementation, providing enough data for accurate and safe autonomous handling, must also be considered. Simulations and calculations concerning the manipulator weight and its influence on the AGV should also be addressed. Lastly, measures increasing the potroom standard of pot cover placement, contaminations and damage prevention needs to be assessed.

7.3 Development method

Through the Alcoa summer internship and project thesis period, a lot of knowledge concerning the thesis task was acquired before master thesis initiation. Due to the knowledge available, a bias towards planning formed, wishing to have a well thought through development structure before starting the early stage development. This led to a bit of a slow start of the physical development. It was, however, valuable as it ensured an analytical development process throughout the period. With a clear plan for the development, a steady progression was attained from the start till the end of the project.

Having a clear vision of the desired thesis outcome, with constraints and specifications set early, the thesis progression has been ensured through prototyping in many formats. To have a sound development foundation, literature studies was early conducted to fill in knowledge gaps. Throughout the thesis, the prototype resolution has been varying. From cardboard to working with aluminium, and from rough sketching to detailed CAD simulations. Mechanical design has therefore been a significant part of the thesis work. Through the gripper development and the construction of the two robot concepts, mechanism design has been a key factor. Electronics has also been included in the thesis work through automation of the kinematic systems, including mechatronics and programming to enable motion through motor actuation. For increased realism of digital models, there has been an emphasis on CAD rendering. Capturing and communicating the results has also been part of the development process, taking photos and clipping videos. With a pot cover present in Trondheim, gripper testing has been possible to test in full-scale. Building test rigs and perform testing of concepts has also been a vital part of the thesis. From the various results obtained during the thesis work, multiple evaluations and analyses have been performed to secure feasible development outcome.

Reviewing the development method at the end of the thesis period, it has been a structured and unexpectedly smooth process. There has not been major delays or major setbacks during the development, making it a linear and enduring process. This might be related to the flexible SCRUM planning style, allowing to shift between work tasks when the progress slowed down. The thorough pre-work may also have had its positive effect, making it possible to predict development pitfalls before they occurred. Based on the final results and the company feedback, the author deems the development method as successful.

7.4 Development methodology

In this section, a review of the applied methodology will be presented, evaluating what was useful and how implementation was performed during the project period.

7.4.1 Pahl and Beitz planning and design structuring

The application of Pahl and Beitz' planning and design division has been a worthwhile contribution to the development process. It was beneficial as it reduced the project ambiguity by providing clear development milestones and goals throughout the thesis period. By assessing the provided working steps of each phase, a development overview was provided, helping with the structuring and planning of the project. With the intention of ending up somewhere in the embodiment stage of development, it has also served as a project timeline, indicating if the development was ahead or behind schedule. Though it has not been followed slavishly, with a bit overlap between the conceptual and embodiment design tasks, it was a positive contribution to the project.

7.4.2 Design Thinking: Empathy

Though the Design Thinking mindset of empathy has not been a large part of the master thesis method, it was an important part of the prior summer internship and project thesis period. This period was important for the master project, as a lot of the knowledge utilised during the master thesis was amassed then. By just being aware of Design Thinking empathy as a product development tool, it has tacitly been a part of the development process. It was also a large contributor when identifying the pain points of the AS-IS cover handling, ultimately leading to the operator gripper concept. Summarised, the usage of empathy is rendered an important contributing factor to value creation in the project.

7.4.3 Design for Reliability

From the beginning to the very end of the development process, a bias towards reliability was imprinted in the thesis through Design for Reliability. Though Design for Reliability emphasis on reliability for mechanisms, the mindset of reliability has tacitly affected other design decisions as well. Simplicity and unity have been brought up frequently during the planning and conceptual design, while clarity has been evaluated in the later stages of the conceptual and embodiment design. What has been experienced is that when concentrating on fulfilling a specific design attribute, in this case, reliability, the other requirements has also been met along the way. Alcoa desires solutions with a high degree of robustness and simplicity. As the final concepts facilitate reliability in the potroom environment, DFR is considered one of the most principal contributing factors to the final thesis results.

7.4.4 SCRUM planning and structuring

Due to the previous usage of SCRUM in a product development associated contexts, SCRUM was selected for task overview and milestone management. Providing a flexible display of the various milestone sub-objectives, sprints has been engaged and executed, often in the shape of prototype iterations. The possibility of moving and changing priorities based on daily or weekly basis has together with the Pahl and Beitz design structuring provided the project with transparency and adaptability. Multiple situations during the project were aided by the SCRUM flexibility. In one of the sprints, the 3D-printer had to be taken out for maintenance halfway in the building process a prototype, and the build had to be put on hold. Having an adaptable schedule with multiple tasks readily in need for attention, the sprint objectives could be altered to the situation at hand, and the current build could be postponed to the next sprint. Though SCRUM carries a reputation for being advantageous in group management, the author considers it is highly implementable for personal project management as well.

7.4.5 Prototyping

It has been a produced numerous prototypes throughout the thesis. With a basis in the Bryan-Kinns and Hamilton chart, a prototyping plan was created to provide prototyping structure throughout the development. With this as a foundation, it has been well-defined which resolution the various prototypes should provide.

Though learning was obtained in every step of the process, the specific learning prototypes were mainly created in the first iterations were the prototype resolution was at its lowest. These were vital for the progression of the development, leading to the creation of the integrational and milestone prototypes. Through the gripper and manipulator testing in the conceptual design phase, integrational prototyping was conducted, looking at component and subsystem interaction. These prototypes also served as communicational prototypes. Being able to produce proof-of-concept prototypes, further development could be executed, yielding the final gripper and manipulator proof-of-product prototypes.

To sell in ideas to Alcoa and create buy-in from the company, there has been a substantial focus on delivering aesthetic and appealing prototypes for the milestone deliveries, ensuring that the desired message has been conveyed. Among the assortment of prototypes produced, these prototypes required the most work and time. Having the possibility of not meeting the firm's expectations, they also contained the highest degree of risk, as the project has a limited time resource. Risk mitigating measures, such as continuous business communication between the various builds, ensured that the prototypes which were built were also of interest to Alcoa.

The prototype planning has been an important factor to the project success, as a lot of time has been invested in prototyping. If the time resources had been spent on building unnecessary or wrong high-resolution prototypes, it could have an undesirable effect on the result of the thesis. The pre-work performed, facilitating the prototyping, has therefore been a vital aspect of the development process.

7.5 Business collaboration

Thesis contact and collaboration with the corporate partner was initiated the start of summer 2016. Since then, a one-month summer internship in 2016 and three trips to Mosjøen has been conducted during project and master thesis period. Between the trips, it has been important to have frequent contact with Alcoa to ensure that their requirements are met. To facilitate continuous communication, phone meetings were scheduled each another week. Between the conference calls, mailing has been used if any questions should occur or details be in need of clarification.

Writing the thesis for Alcoa Mosjøen, compared to a standard university master, has shaped the development process towards delivering tangible product concepts continuously throughout the thesis period. In accordance with the conference calls, biweekly milestone deliveries were practised to ensure the company of the thesis progression. In addition to communicating progress, it was intended to show concept ideas to gain feedback and engage Alcoa in the process, generating buy-in in the project results. With Alcoa providing continuous constructive feedback, this was fortunate for the advancement of the thesis. Confirmations from Alcoa concerning the provided concepts has also yielded disclosure before moving further in the development process, reassuring that their wishes have been met. For further Alcoa and NTNU collaboration, the author would recommend usage of video conferencing over the utilised phone meetings, as it enhances the collaboration experience drastically.

Collaborating with Alcoa throughout the thesis has been a valuable experience, yielding products where Alcoa has had the possibility to affect the direction of development continuously. Concluding the thesis and the following conclusion chapter is a citation from Alcoa, stating their experience from the thesis collaboration.

8 Conclusion

The thesis objective has been to provide Alcoa with a viable concept solution for an AGV-based robot and gripper cover handling system. By substantiating the project in the planning and task description phase, milestones have been created, and a task specification been provided for the development process.

Through iterative work in the conceptual design phase, a self-sustaining gripper prototype has been developed. From the gripper concept, a high-resolution proof-of-product prototype have been constructed out of aluminium. As tests has been performed, satisfactory results within gripping, handling and storing of pot covers has been obtained.

Ending the manipulator conceptual design phase, two viable kinematic systems have been developed and evaluated through scaled down testing. The test clouded with a 2-axis articulated robot concept, utilising AGV propulsion for movement in three axes. The scaled down manipulator, and gripper test also yielded validating results of dual simultaneous cover handling.

In the embodiment stage of the development, refinement measures concerning the gripper design have been performed and reviewed, increasing its reliability with moderately damaged covers. Drive system alternatives and sensory options have been explored for the manipulator embodiment phase. Further manipulator research has also confirmed that off-the-shelf robot solutions exist, fulfilling the concept system specifications. The final thesis product is a joint robot and gripper solution, showing a high degree of feasibility for AGV implementation.

Central for the further project progression will be the selection or development of the robot unit. Depending on the manipulator, the gripper tool will need an additional redesign before installation. The number of installed robot DOFs should also be thoroughly thought through. Two axes of freedom might render insufficient if additional tasks are desired performed by AGV. Sensory and manipulator AGV integration will also be important aspects of the further work. To facilitate automation operations in the potroom, a need for an elevated potroom standard of equipment handling and exterior pot maintenance will be essential. This will be necessary to eliminate issues related to stuck pot covers, various cover damages, and dust and rocks contaminations obstructing cover gripping. Also of importance will be to increase the quality requirements sent to the pot cover supplier, decreasing the varying dimensions between each produced pot cover.

The thesis development has been a linear process without significant setbacks or obstructions along the way. The authors review the thesis results as satisfactory, with affirming feedback from Alcoa. Concluding the thesis is a replay from Live Spurkland, Project Engineer at Alcoa, addressing the collaboration and the thesis results after a presentation in Mosjøen end of May 2017:

> *"The entire process, from the very start to the showcasing of the thesis results, has been a great inspiration to us at Alcoa Mosjøen. It has been advantageous to be aided with the kick-starting of a project which until now has only been a future dream. Alcoa Mosjøen can learn a lot regarding how it is possible to cultivate the wildest of ideas. At the same time, it is ensuring to us that the presented thesis results are down-to-earth, with realistic and implementable concepts. The demonstration of the final thesis results in Mosjøen, where large sections of corporate executives were present, served as an internal spark at Alcoa, initiating the project start negotiations."*

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10 Appendix

APPENDIX A: Media Links

Robot Gripper Results and Concept Demonstration

https://drive.google.com/file/d/0B7yncu0zXNbPQkpzc2xmTlpwa2M/view?usp=sharing

Robotic Manipulator and Concept Demonstration

https://drive.google.com/file/d/0B7yncu0zXNbPSDhEMXJfZ3BsZWc/view?usp=sharing

CAE files

https://drive.google.com/drive/folders/0B7yncu0zXNbPUjMwZ1k4b0JNeWc?usp=sharing

APPENDIX B: Assorted HQ Renders

Figure 10.1: Isometric HQ render of the final iteration dual robot gripper.

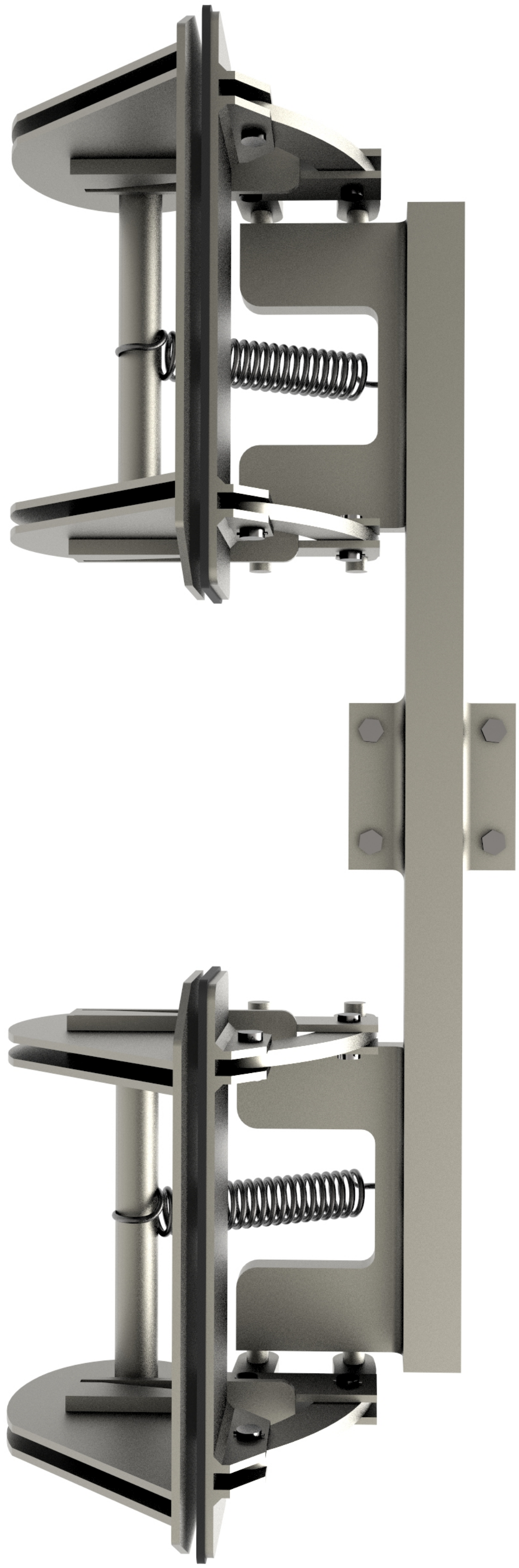
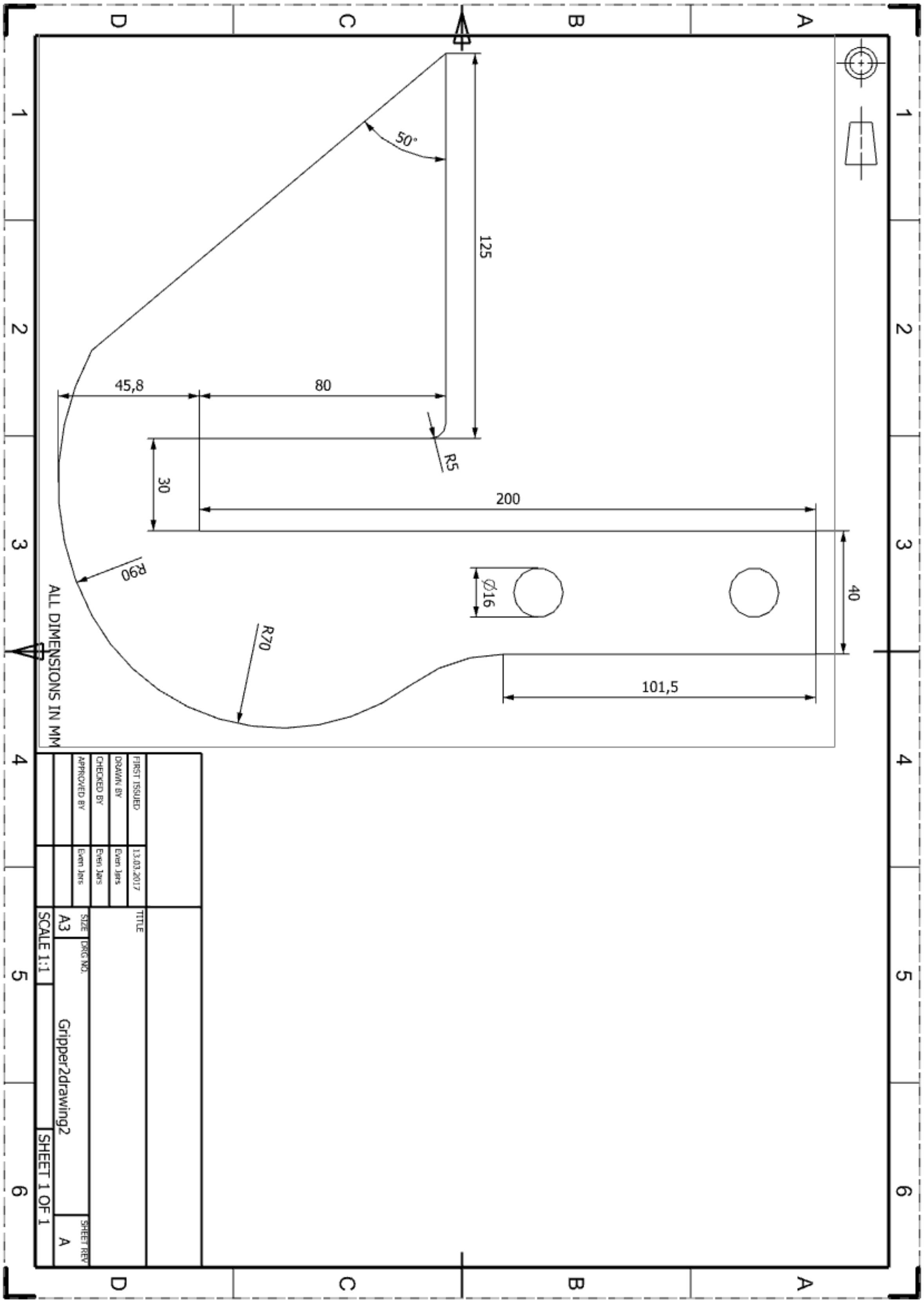


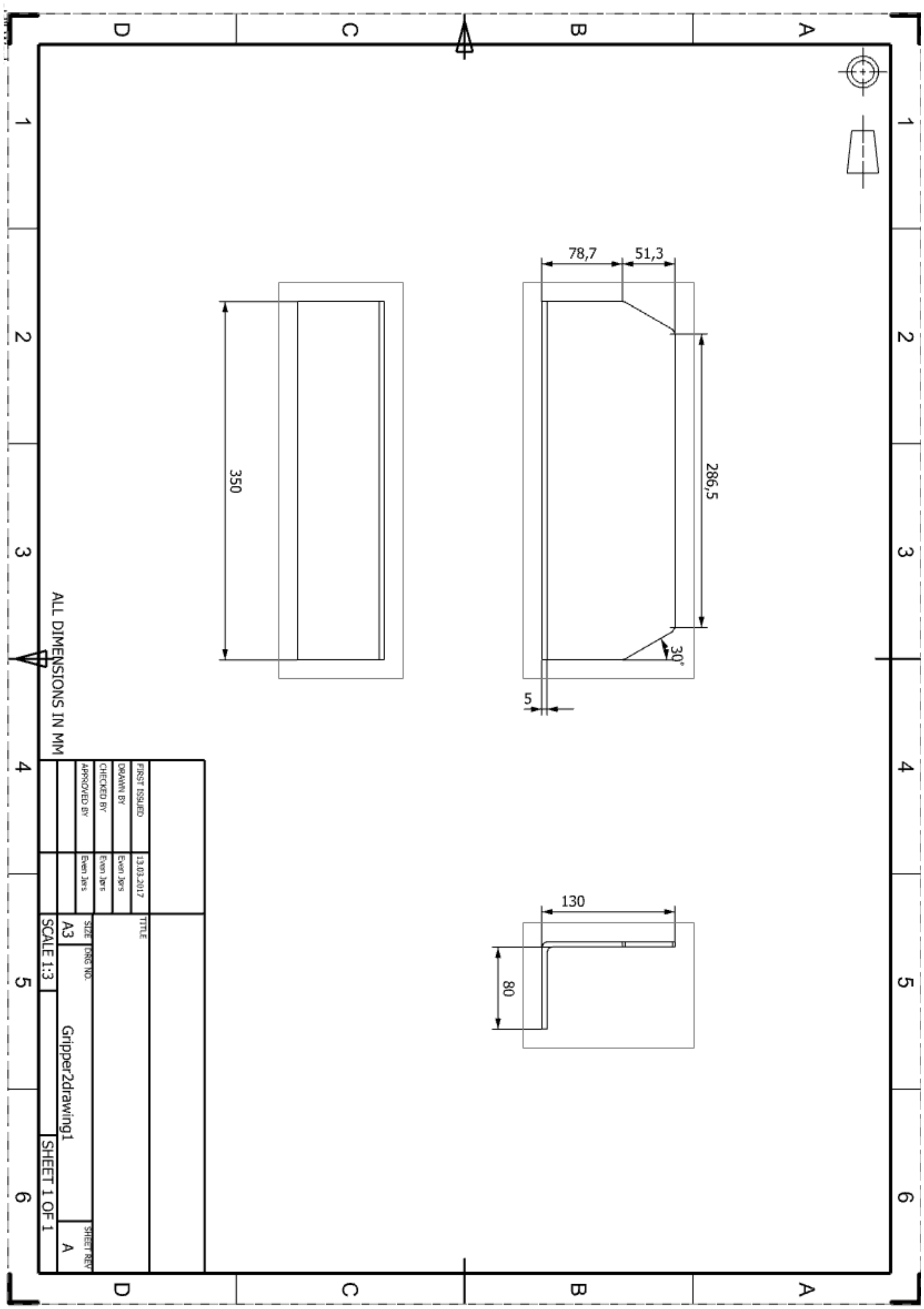
Figure 10.2: Front view HQ render of the final iteration dual robot gripper.

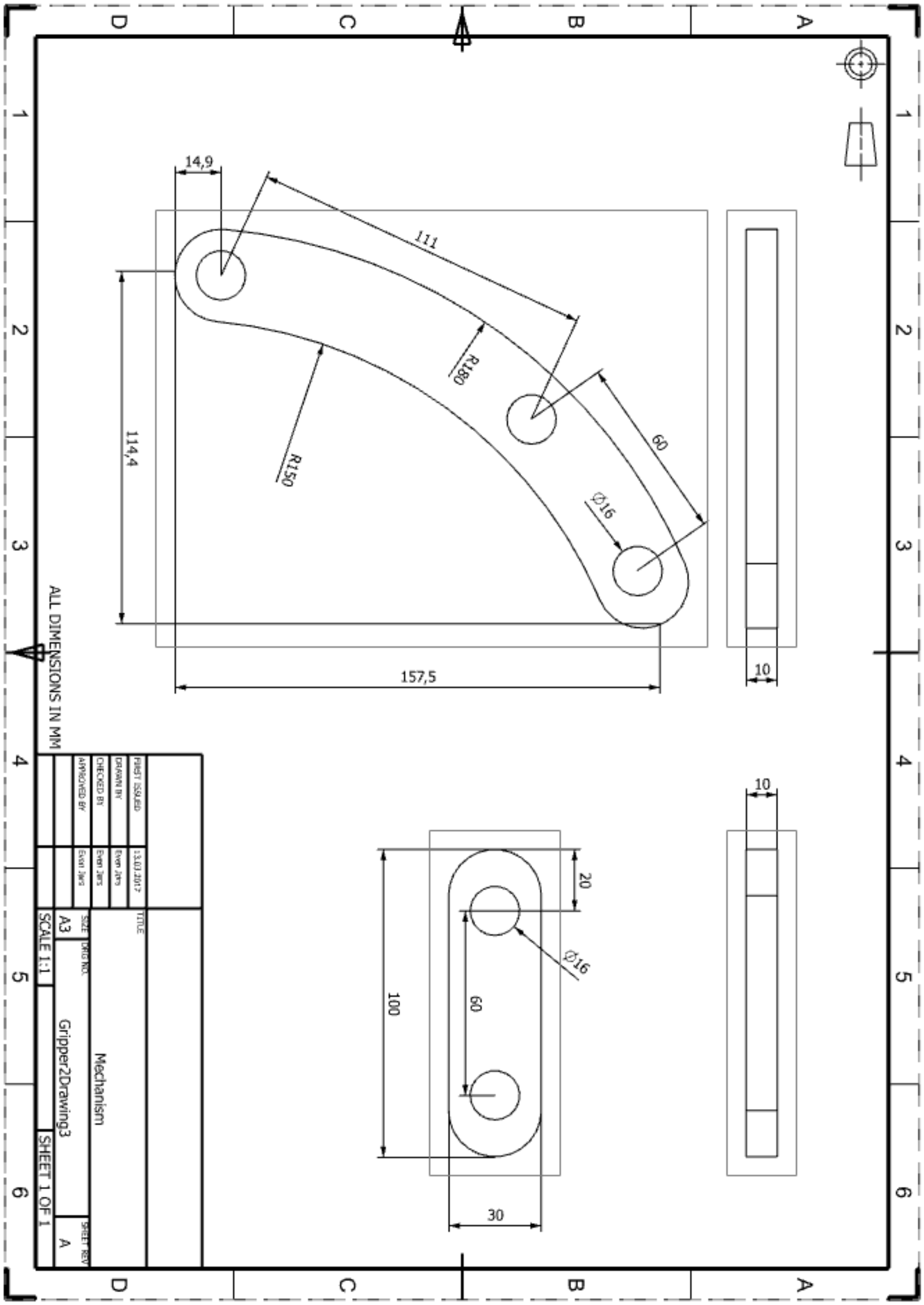
Figure 10.3: HQ render of the selected FANUC manipulator combined with the dual gripper concept.

Figure 10.4: HQ render of the manipulator and AGV concept, placed into a photo taken from the Alcoa potroom environment. Manipulator models gathered from GrabCAD (TheNicman 2017; Bejenaru 2017).

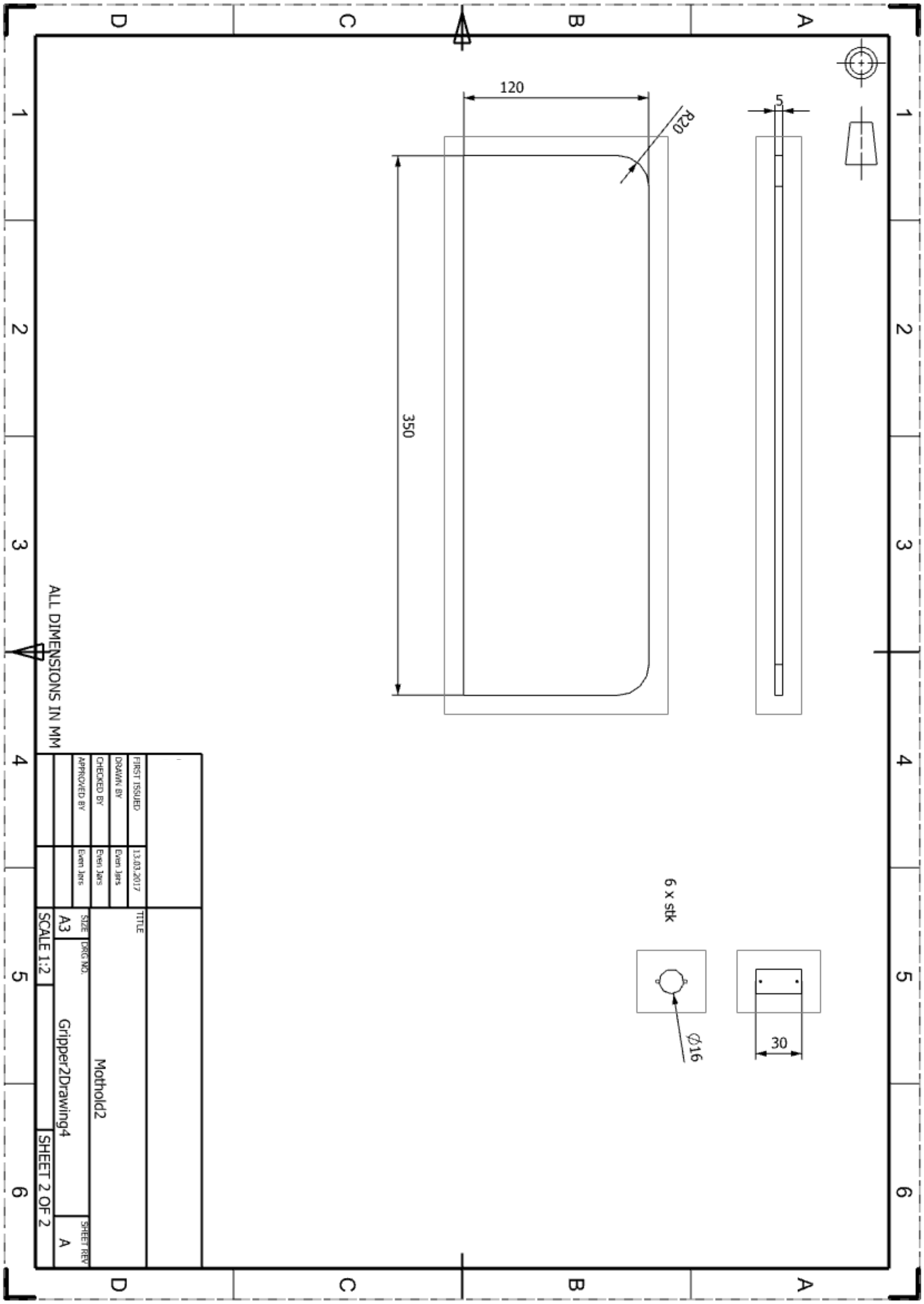
APPENDIX C: Aluminium Gripper Prototype Machine Drawings

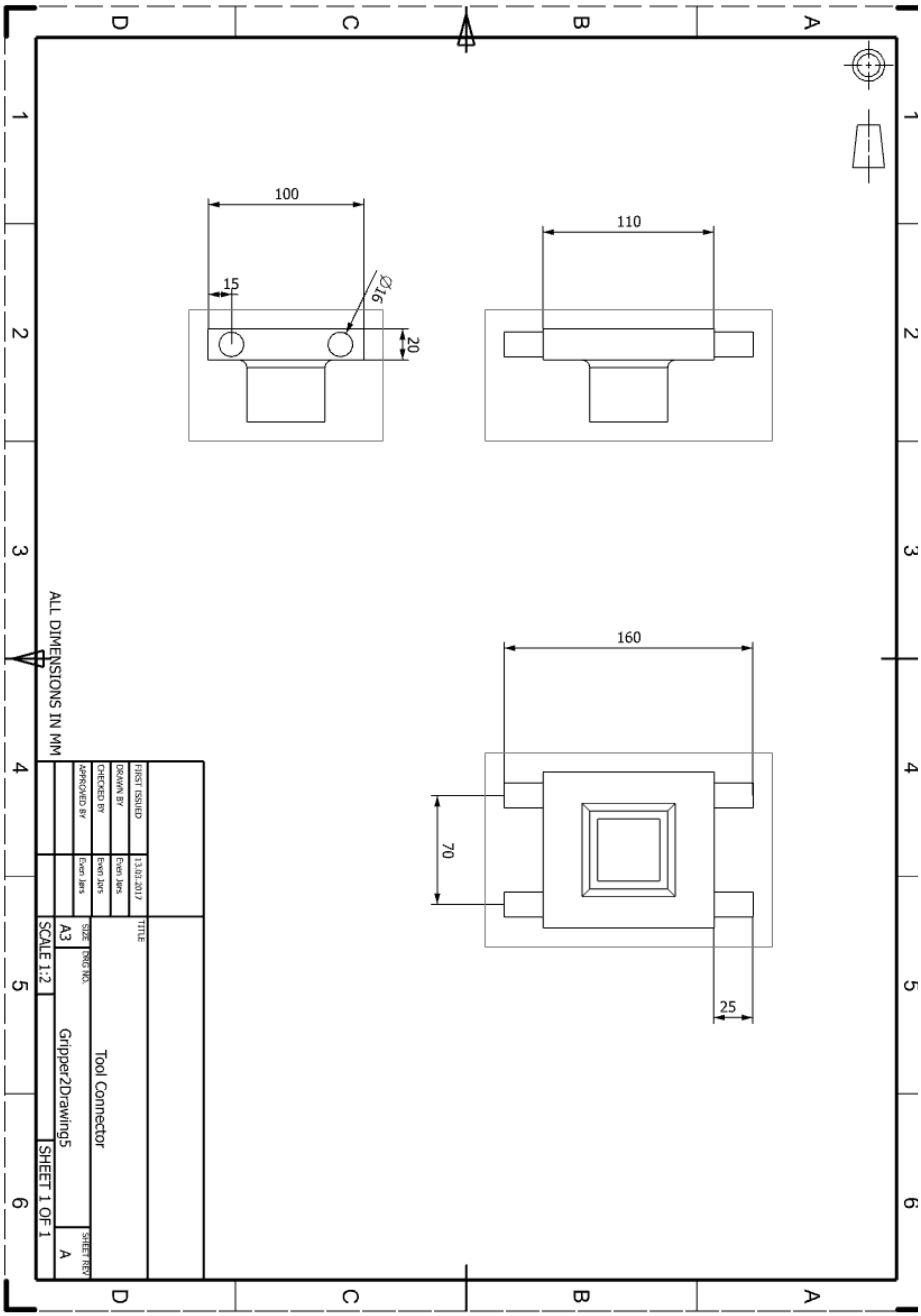

50°
125
45,8
80
R5
30
200
40
Ø16
R90
R70
101,5
ALL DIMENSIONS IN MM
FIRST ISSUED
13.03.2017
DRAWN BY
Even Jørs
CHECKED BY
Even Jørs
APPROVED BY
Even Jørs
TITLE
SIZE
A3
DRG NO.
Gripper2drawing2
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1


ALL DIMENSIONS IN MM
78,7
51,3
286,5
350
30°
5
130
80
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
13.03.2017
TITLE
SIZE
A3
DRG NO.
Gripper2drawing1
SCALE 1:3
SHEET 1 OF 1
SHEET REV
A



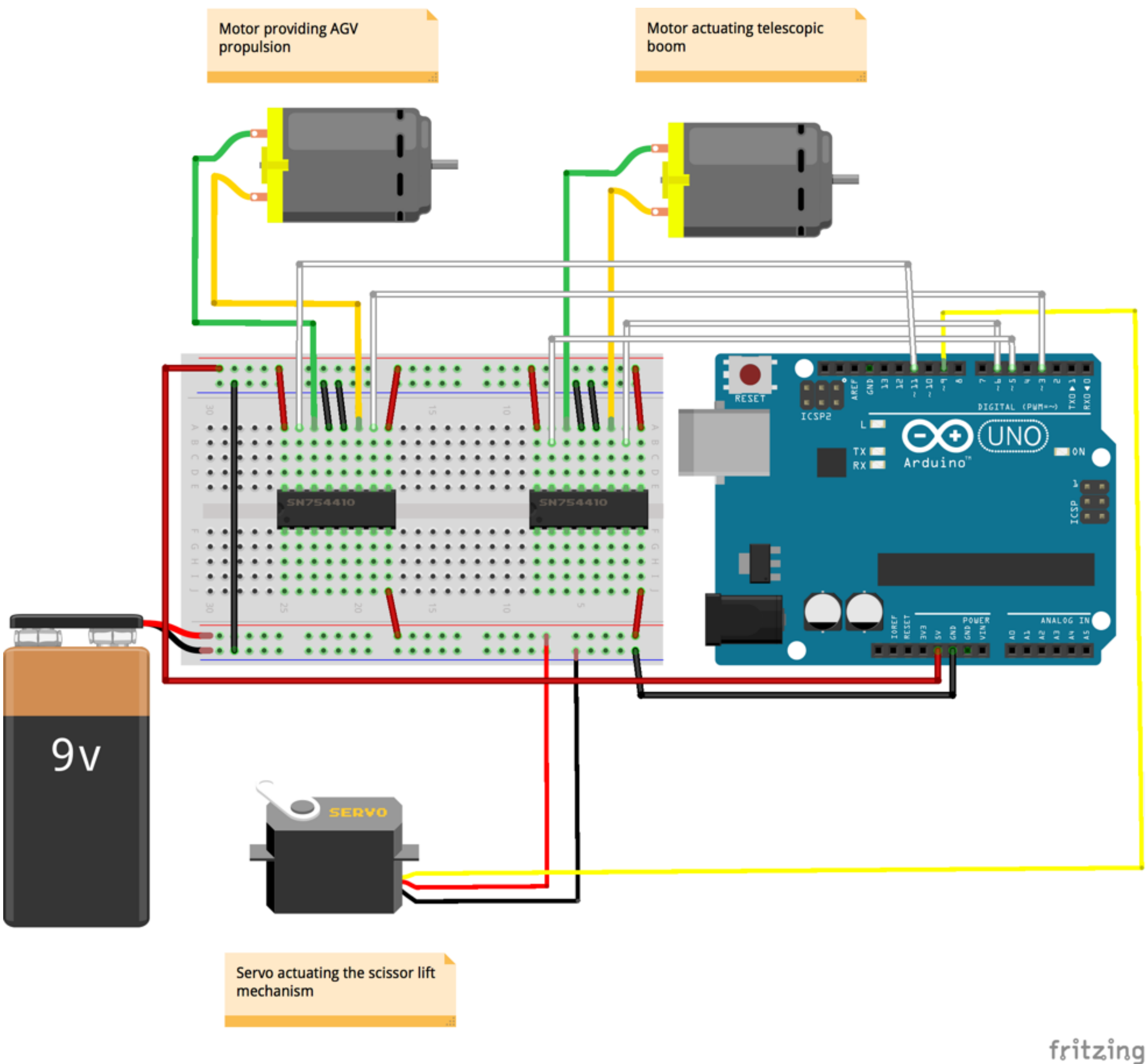
ALL DIMENSIONS IN MM
14,9
111
R180
R150
114,4
60
Ø16
157,5
10
20
100
60
Ø16
30
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
TITLE
Mechanism
SIZE
A3
DWG NO.
Gripper2Drawing3
SCALE 1:1
SHEET 1 OF 1
SHEET REV
A


120
R20
5
350
6 x stk
Ø16
30
ALL DIMENSIONS IN MM
FIRST ISSUED 13.03.2017
DRAWN BY Even Jars
CHECKED BY Even Jars
APPROVED BY Even Jars
TITLE Mothold2
SIZE A3
DRG NO. Gripper2Drawing4
SHEET REV A
SCALE 1:2
SHEET 2 OF 2

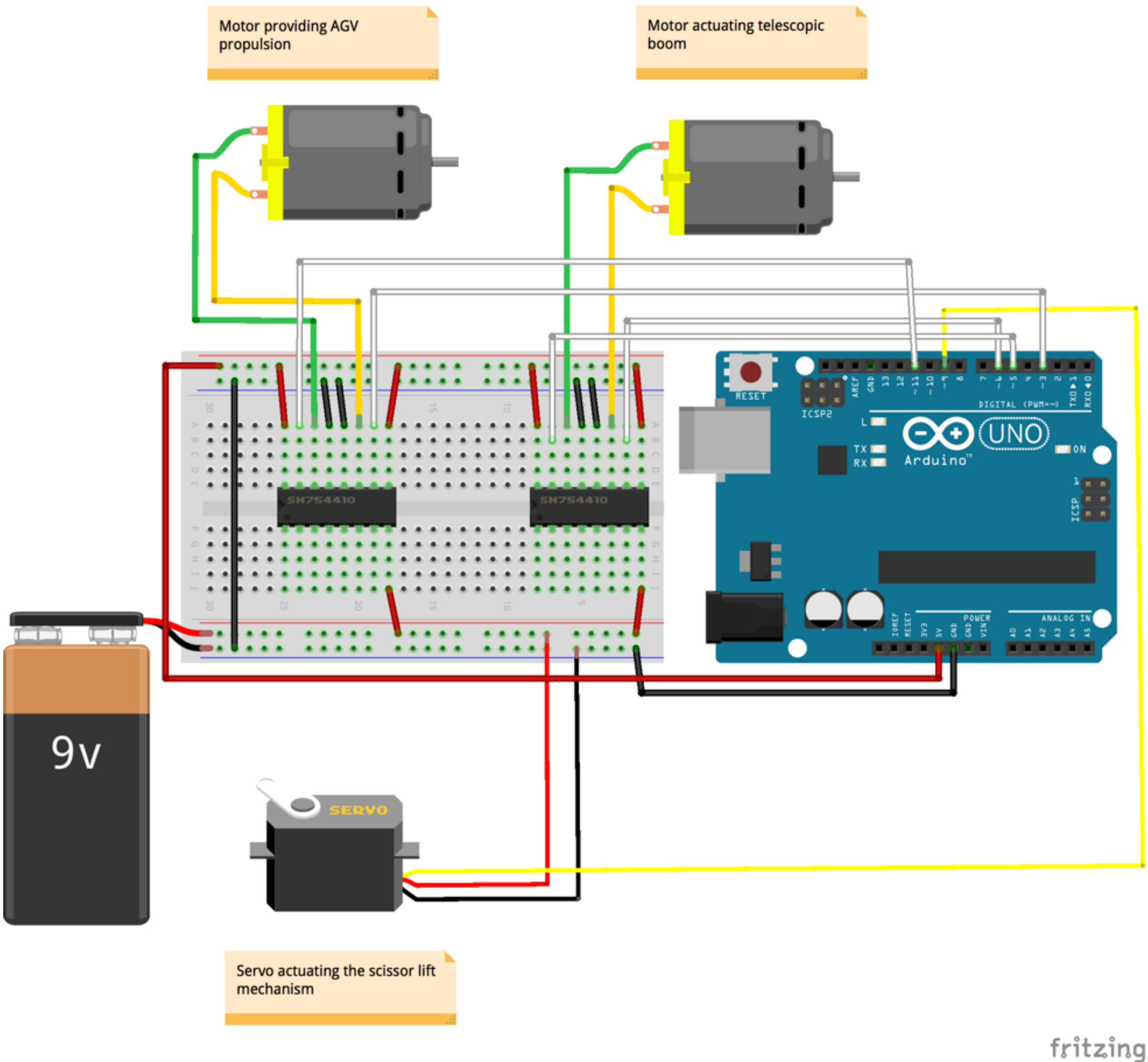

100
15
Ø16
20
110
160
70
25
ALL DIMENSIONS IN MM
FIRST ISSUED 13.03.2017
DRAWN BY Even Jørs
CHECKED BY Even Jørs
APPROVED BY Even Jørs
TITLE Tool Connector
SIZE A3
DRG NO. Gripper2Drawing5
SHEET REV A
SCALE 1:2
SHEET 1 OF 1

APPENDIX D: Wiring Diagrams

Wiring and Mechatronic Components of the Articulated Concept Prototype



Wiring and Mechatronic Components of the Cartesian Concept Prototype



APPENDIX E: Arduino Code

Cartesian Manipulator with AGV Propulsion

```
// CONTROLL KEYS

// 5 = Forwards

// 6 = Backwards

// 7 = UP

// 8 = DOWN

// 9 = IN

// 0 = OUT

#include <Servo.h>

Servo myservo;

int pos = 90; // variable to store the servo initial position

int output;

int fwdPin = 5;          //Logic level output to the H-Bridge (Forward)

int revPin = 6;          //Another logic level output to the H-Bridge (Reverse)

int frwPin = 3;          //Logic level output to the second H-Bridge (Forward)

int backwrdPin = 11;     //Another logic level output to the second H-Bridge (Reverse)


void setup() {

  Serial.begin(9600);

  pinMode(fwdPin, OUTPUT); //Set the forward pin to an output

  pinMode(revPin, OUTPUT); //Set the reverse pin to an output

  pinMode(frwPin, OUTPUT); //Set the forward pin to an output

  pinMode(backwrdPin, OUTPUT); //Set the reverse pin to an output
```

```
  myservo.attach(9); // Attaches the servo to pin 9
}
// Main loop, activating subfunctions based upon keys pressed
void loop() {
  if (Serial.available() > 0) {
    char var = Serial.read();
    if (var == '7') {
      up();
    }
    if (var == '8') {
      down();
    }
    if (var == '9') {
      in();
    }
    if (var == '0') {
      out();
    }
    if (var == '5') {
      backwards();
    }
    if (var == '6') {
      forwards();
```

```
    }
    if (var == '4') {
      pause();
    }
  }
}
void up () {
  myservo.write(103);
  delay(900);
  myservo.write(90);
  delay(10);
}
void down () {
  myservo.write(83);
  delay(800);
  myservo.write(90);
  delay(15);
}
void in () {
  output = 250;
  analogWrite(revPin, output);
  delay(50);
  output = 10;
  analogWrite(revPin, output);
```

```
  delay(20);
}
void out () {
  output = 250;
  analogWrite(fwdPin, output);
  delay(50);
  output = 10;
  analogWrite(fwdPin, output);
  delay(20);
}
void forwards () {
  output = 180;
  analogWrite(frwPin, output);
  delay(100);
  output = 10;
  analogWrite(frwPin, output);
  delay(10);
}
void backwards () {
  output = 250;
  analogWrite(backwrdPin, output);
  delay(100);
  output = 10;
  analogWrite(backwrdPin, output);
```

```
  delay(10);
}
void pause (){
  delay(500);
}
//END
```

Articulated Manipulator Concept with AGV Propulsion

```
// CONTROLL KEYS
// 5 = Forwards
// 6 = Backwards
// 1 = Manipulator start position
// 2 = Tool insertion
// 3 = Cover handling
#include <VarSpeedServo.h>
VarSpeedServo servoLeft;
VarSpeedServo servoRight;
int pos = 0;
int fwdPin = 5;           //Logic level output to the H-Bridge (Forward)
int revPin = 6;           //Another logic level output to the H-Bridge (Reverse)

void setup() {
  Serial.begin(9600);
  servoLeft.attach(11); // Attaches the servo on pin 9 to the servo object
```

```
  servoRight.attach(10); // Attaches the servo on pin 11 to the servo object
  servoLeft.write(80); // Servo 1 start position
  servoRight.write(50); // Servo 2 start position
  pinMode(fwdPin, OUTPUT); //Set the forward pin to an output
  pinMode(revPin, OUTPUT); //Set the reverse pin to an output
}
void loop() {
 if (Serial.available() > 0){
    char var = Serial.read();
    if(var == '1') {
      Starting();
    }
    if(var == '2') {
      Inserting ();
    }
    if(var == '3') {
      CoverHandling  ();
    }
    if (var == '5') {
      Backwards();
    }
    if (var == '6') {
      Forwards();
    }
```

```
}
void Starting() {
servoLeft.slowmove(70,50); //20,30
servoRight.slowmove(50,50);//80,30
}
void Inserting() {
servoLeft.slowmove(50,250); //20,30
servoRight.slowmove(30,250);//80,30
}
void CoverHandling () {
servoLeft.slowmove(70,100); //20,30
servoRight.slowmove(30,100);//80,30
}
void Forwards () {
  output = 180;
  analogWrite(fwdPin, output);
  delay(100);
  output = 10;
  analogWrite(fwdPin, output);
  delay(10);
}
void Backwards () {
  output = 250;
  analogWrite(revPin, output);
```

```
  delay(100);
  output = 10;
  analogWrite(revPin, output);
  delay(10);
}
//END
```

APPENDIX F: FANCU M-420iA and M-421iA Datasheet

M-420*i*A/M-421*i*A™

FANUC Robotics

Basic Description

The M-420*i*A series is FANUC Robotics' latest-generation, high-performance, high-speed family of industrial robots. Based on a simple and reliable design, the M-420*i*A and M-421*i*A provide sophisticated motion control and consistent performance with high productivity. The series is supported by the intelligent robot control system.

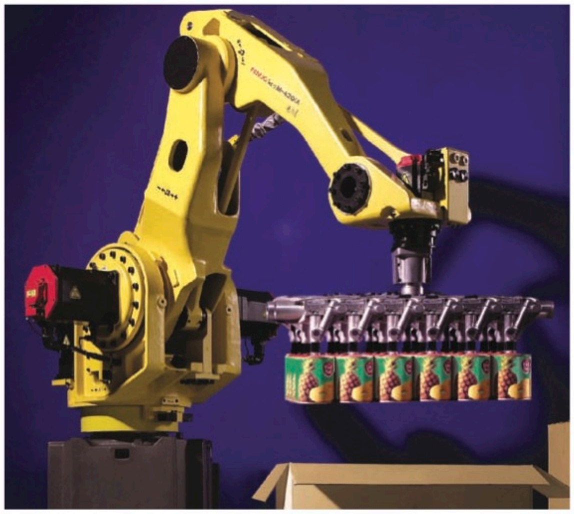
The M-420*i*A is a four-axis, modular construction, electric servo-driven robot designed for high-speed case packing and material handling applications. The M-421*i*A is a two-axis variant designed for the high-speed top-loading packing market.

M-420*i*A/M-421*i*A, the Solution for:

- High-speed packaging
- High-speed palletizing
- Machine loading
- Mechanical assembly

Benefits

- Features highest motion speeds in its class for maximum performance and productivity.
- Highest payload in its class helps achieve maximum throughput by handling multiple parts.
- Four-axis dexterity enables access to multiple packaging lines with one unit.
- Additional auxiliary amplifiers available in the robot controller offer ability to control complete high-speed packaging line with robot controller.
- FANUC's *i*RVision™ (Integrated Robot Vision) Option for Visual Line Tracking provides an integrated vision based solution for locating randomly-oriented product on a moving line for robotic picking and packing operations.



Features

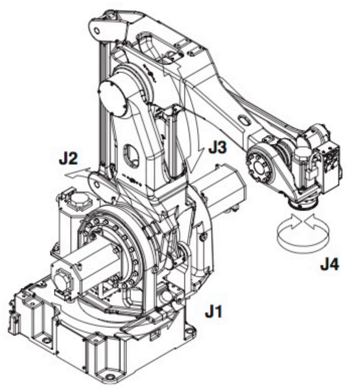
- M-420*i*A - 4 axes of motion, 40 kg capacity.
- M-421*i*A - 2 axes of motion, 50 kg capacity. Waist and wrist rotation removed from four-axis unit.
- *i*Pendant™, a color, Internet-ready teach pendant for even easier programming and custom cell user interface design.
- Large work envelope with 1855 mm horizontal reach developed around packaging applications.
- Repeatability of +/- 0.5 mm at full speed and full payload within entire work envelope.
- Linear motion speeds up to 4200 mm/sec.
- Dedicated pneumatic and electrical (8 digital inputs/8 digital outputs) connections at wrist to simplify user's end-of-arm tooling design and integration.
- Material handling style teach pendant with large LCD screen and ergonomic design offers intuitive control over automated process.
- Sealed bearings and brushless AC motor drives provide protection and improve reliability.

Options

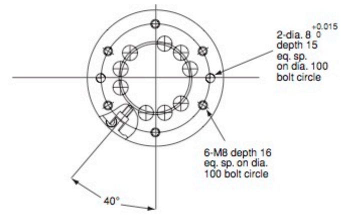
- M-420*i*A high-speed wrist option, J4 wrist speed increases from 350 to 720 degrees/sec. for applications that require high-speed wrist motions. Maximum payload decreases from 40 kg to 30 kg.
- *i*Pendant is also available with touch screen support.
- Various robot connection cable lengths for flexible cabinet placement and optional track rated cables.
- A cleanable unit coated with white polyurethane to meet requirements in typical secondary food packaging applications.
- Monochrome pendant available.
- FANUC's *i*RVision system delivers high performance 2-D and 3-D machine vision capabilities with FANUC reliability. Additional option for Error Proofing can provide integrated vision based capabilities to check for product completeness before product is packaged or further operations are performed.

M-420*i*A Dimensions

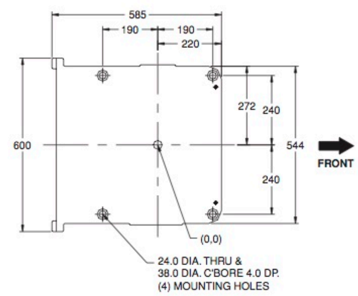
Isometric



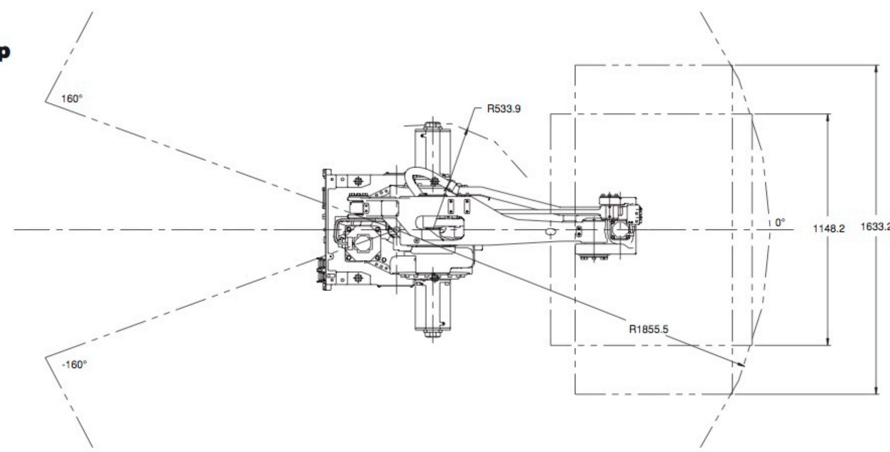
Wrist

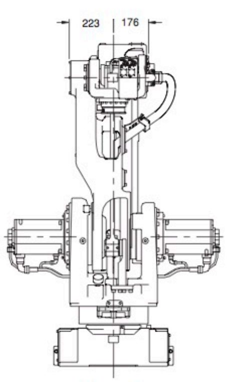


Footprint

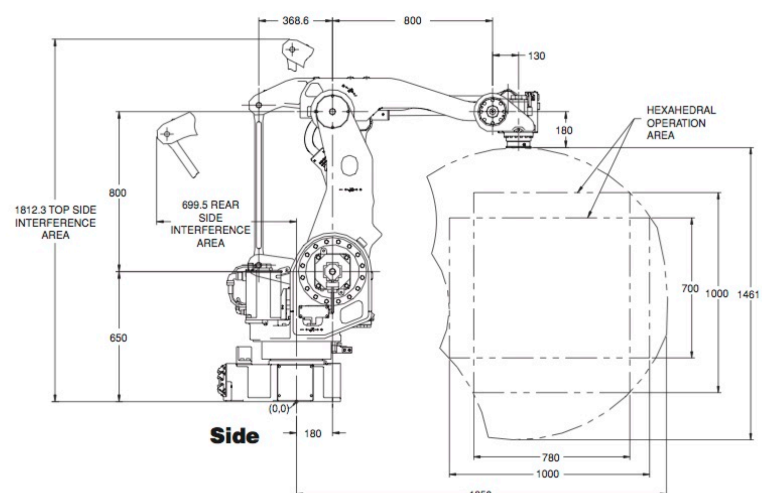


Top





Front

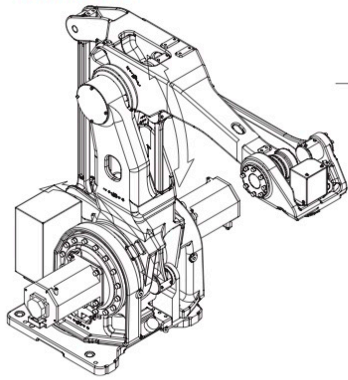


Side

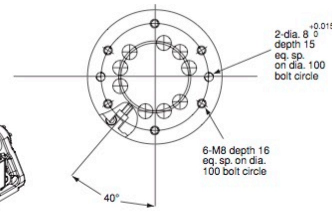
Note: Dimensions are shown in millimeters.
Detailed CAD data are available upon request.

M-421*i*A Dimensions

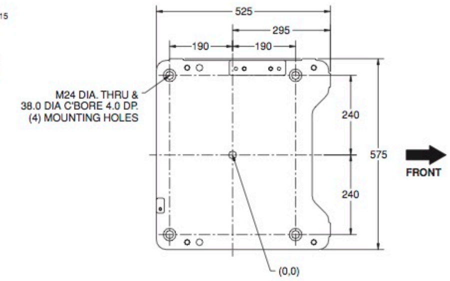
Isometric



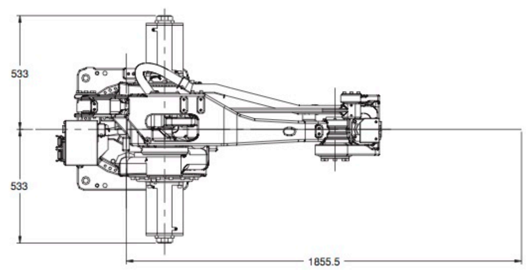
Wrist

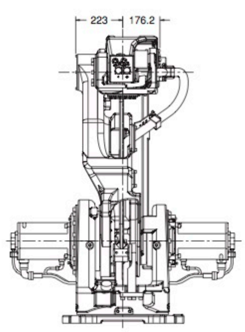


Footprint

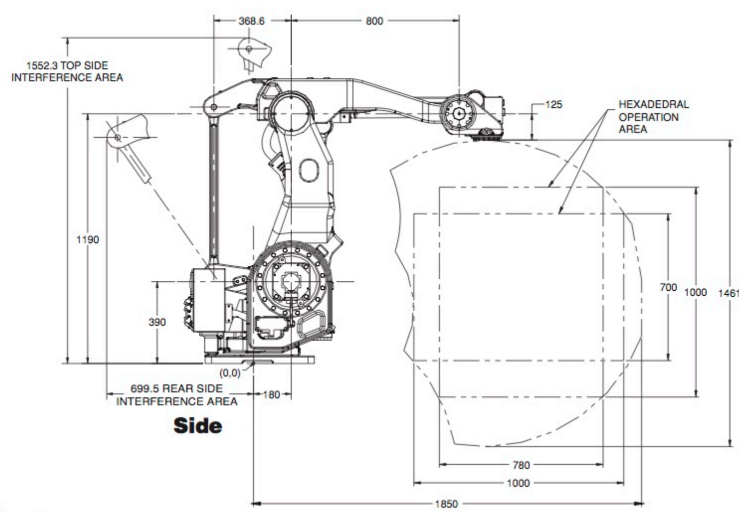


Top



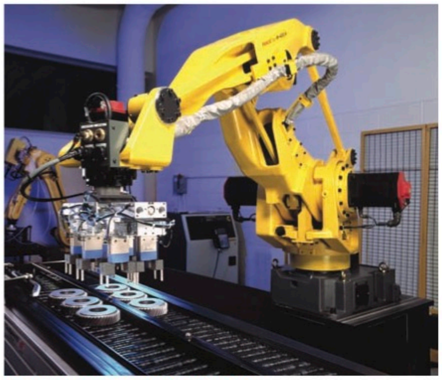


Front



Side

Note: Dimensions are shown in millimeters.
Detailed CAD data are available upon request.



High-Speed Material Handling

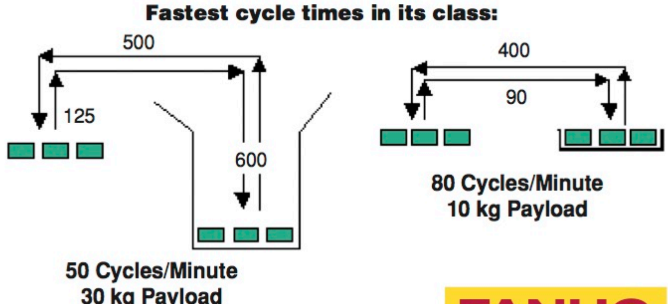
High-Speed Packaging

High-Speed Mini-Palletizing

M-420*i*A/M-421*i*A Specifications

Items		M-420*i*A	M-421*i*A
Axes		4	2
Payload - Wrist (kg)		40	50
- High-Speed Wrist (kg)		30	-
- J3 Arm (kg)		10	10
Reach (mm)		1855	1855
Repeatability (mm)		±0.5	±0.5
Interference radius (mm)		543	-
Motion range (degrees)	J1	320	-
	J2	115	115
	J3	110	110
	J4	540	-
Motion speed (degrees/s)	J1	180	-
	J2	200	200
	J3	200	200
	J4	350	-
High-Speed	J4	720	-
Wrist moment N-m (kgf-m)	J4	98 (10)	98 (10)
High-Speed	J4	68.6 (7)	-
Wrist inertia (kg-m^2)	J4	2.6	2.6
Mechanical brakes		All axes	All axes
Mechanical weight (kg)		620	520
Mounting method		Floor	
Installation environment:			
Ambient temperature °C		0 to 45	
Humidity		Normally: 75% or less Short term (within a month): 95% or less No condensation (No dew or frost allowed)	
Vibration (m/s^2)		4.9 or less	

Fastest cycle times in its class:



Intelligent Robot Solutions

FANUC Robotics

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Fax (248) 377-7362

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Charlotte, NC
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Chicago, IL
(847) 898-6000

Cincinnati, OH
(513) 754-2400

Los Angeles, CA
(949) 595-2700

Toledo, OH
(419) 866-0788

Toronto, Canada
(905) 812-2300

Montréal, Canada
(450) 492-9001

Aguascalientes, Mexico
52 (449) 922-8000

Sao Paulo, Brazil
(55) (11) 3619-0599

marketing@fanucrobotics.com
fanucrobotics.com

APPENDIX G: Yaskawa Motoman MPK50 Datasheet

YASKAWA

HIGH-SPEED CASE PACKING

MPK50

CASE PACKING | PART TRANSFER | PICK AND PLACE | PALLETIZING

Rockwell Automation
Encompass™ Product Partner
Americas

KEY BENEFITS

Fast and powerful

Easy to use

Highly reliable

Unlimited application possibilities

SPECIFICATIONS

50 kg payload

±0.5 mm repeatability

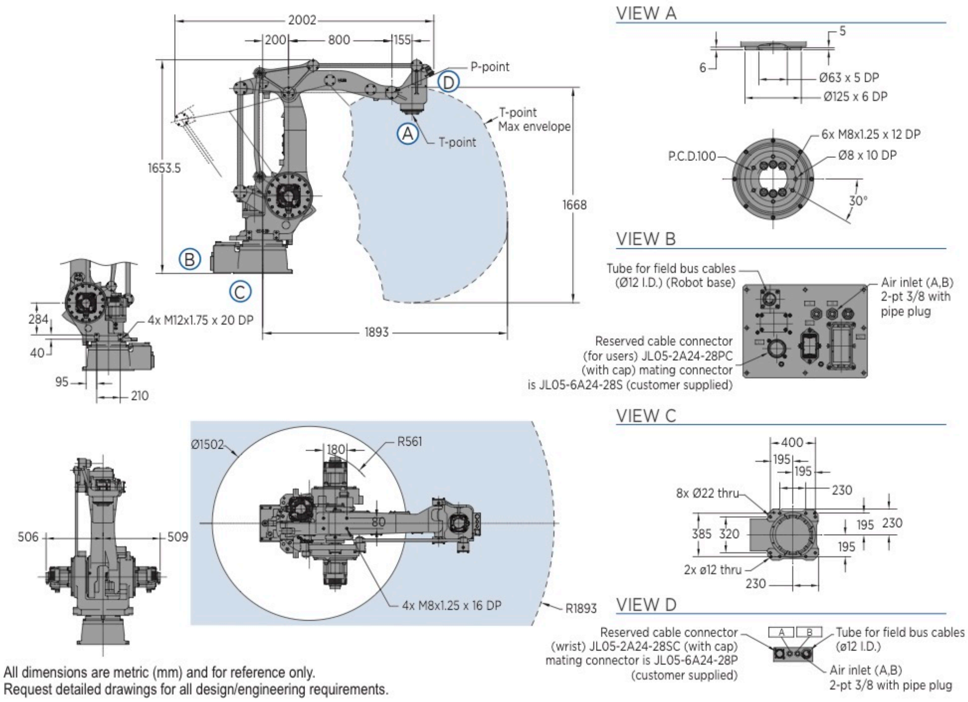
Maximum Reach:
(H) 1,893 mm x (V) 1,668 mm

CONTROLLERS

☑ DX100 ☐ FS100 ☑ MLX200

- 4-axis, 50 kg capacity robot specifically designed for high-speed case packing, layer forming and palletizing applications.
- Slim design with 360° work envelope, horizontal reach of 1,893 mm and vertical reach of 1,668 mm provides unmatched agility.
- T-axis high moment of inertia provides ability to carry heavy payloads without compromising performance, even when load is unbalanced.
- Internally routed airlines and electrical wires eliminate cable interference, enhance life of the cables and improve reliability.
- Internally routed fieldbus connection to T-axis/tool.
- Cable mounts along both sides of robot provide easy routing.
- Auxiliary equipment (maximum of 10 kg), such as valve packs, can be mounted on upper arm to simplify gripper design or reduce gripper interferences.
- Available on DX100 or PLC-controlled MLX200 platform make the MPK50 robot ideal for a wide variety of applications.
- Model variations for food production, pharmaceuticals or automotive parts:
  - XP (eXtra Protection) provides IP65 robot body and IP67 wrist.
  - Food grade option with NSF-H1 certified food-grade lubricants.
  - Anticorrosive paint that withstands harsh caustic cleaners (pH 3-11).

MPK50 ROBOT



All dimensions are metric (mm) and for reference only.
Request detailed drawings for all design/engineering requirements.

SPECIFICATIONS

Axes	Maximum motion range [°]	Maximum speed [°/sec.]		Allowable moment [N•m]	Allowable moment of inertia [kg•m²]
		DX100	MLX200		
S	±180	185	185	12	-
L	+80/-35	215	160	13	-
U	+15/-10.5	215	160	7	-
T	±350	374	374	-	5.5

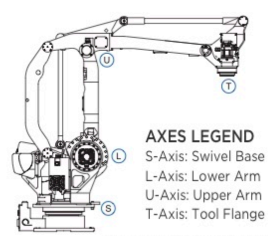
Controlled axes	4
Maximum payload [kg]	50
Repeatability [mm]	±0.5
Horizontal reach [mm]	1,893
Vertical reach [mm]	1,668
Protection (IP rating)	
Standard	Body: IP54; Wrist: IP67
XP version	Body: IP65; Wrist: IP67
Weight [kg]	670
Power requirements	
DX200	3-phase; 240/480/575 VAC at 50/60 Hz
MLX200	3-phase; 200/230 VAC at 50/60 Hz
Power rating [kVA]	
DX200	4.0
MLX200	6.0

OPTIONS

Extended length manipulator cables

Robot risers and base plates

Wide variety of fieldbus connectivity



Representative 4-axis model

Yaskawa America, Inc.
Motoman Robotics Division

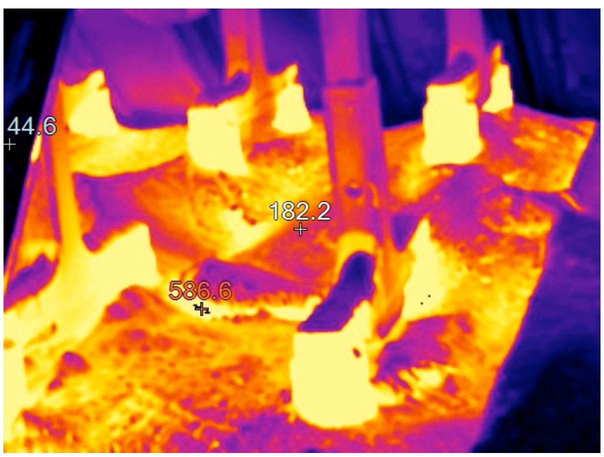
100 Automation Way
Miamisburg, OH 45342
Tel: 937.847.6200
Fax: 937.847.6277

motoman.com

YASKAWA

APPENDIX H: FLUKE Ti27 Report

Image	IR000965.IS2
Image Time	14.11.16 10:39:16
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	44.6 °C to 586.6 °C
Average Temp	190.3 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)



IR000965.IS2

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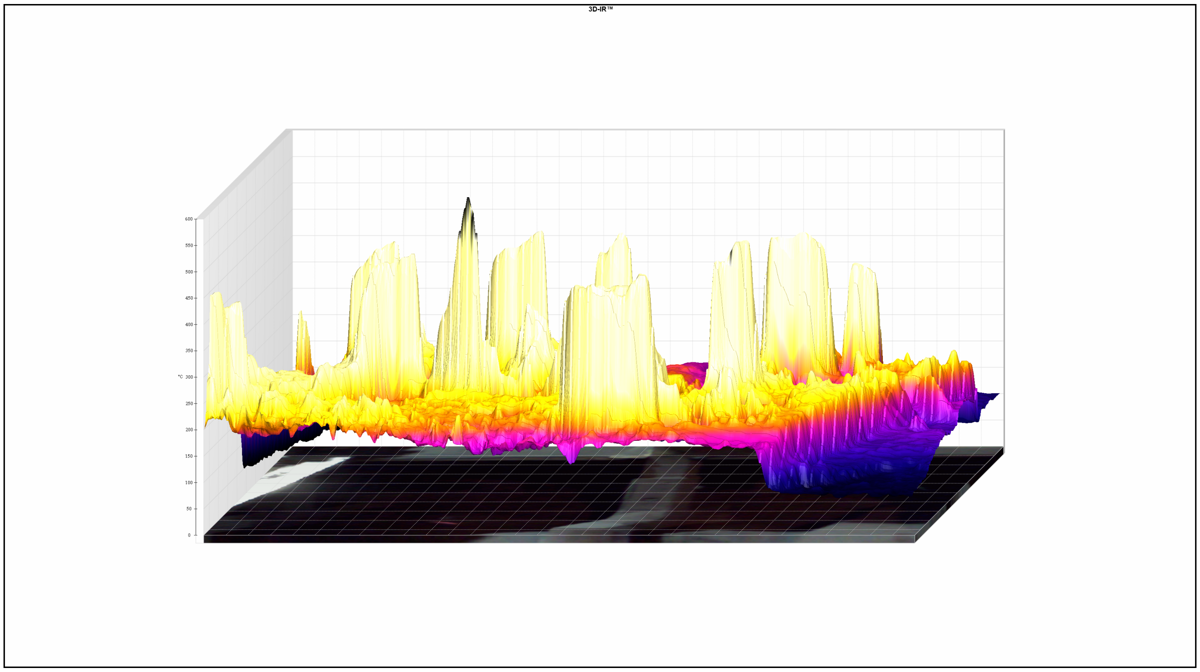
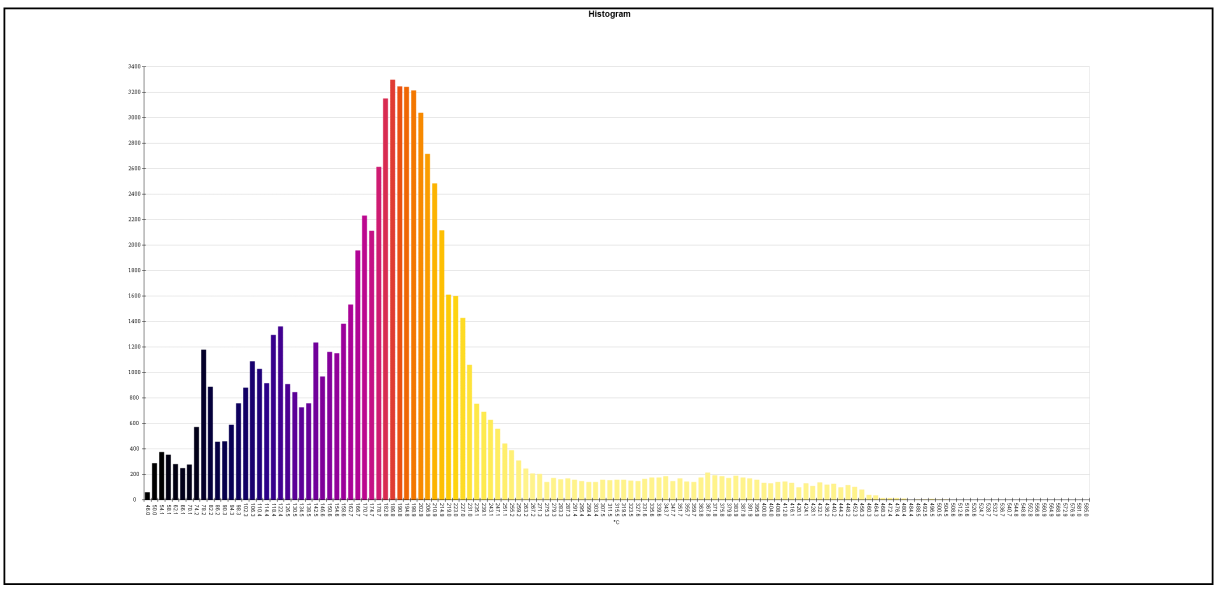
Visible Light Image

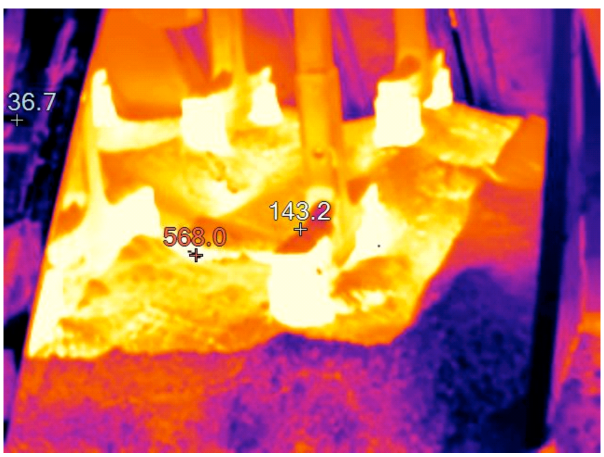




Main Image Markers

Name	Temperature
Centerpoint	182.2°C
Hot	586.6°C
Cold	44.6°C

Image	**IR000966.IS2**
Image Time	14.11.16 10:39:16
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	44.6 °C to 586.6 °C
Average Temp	190.3 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)



IR000966.IS2

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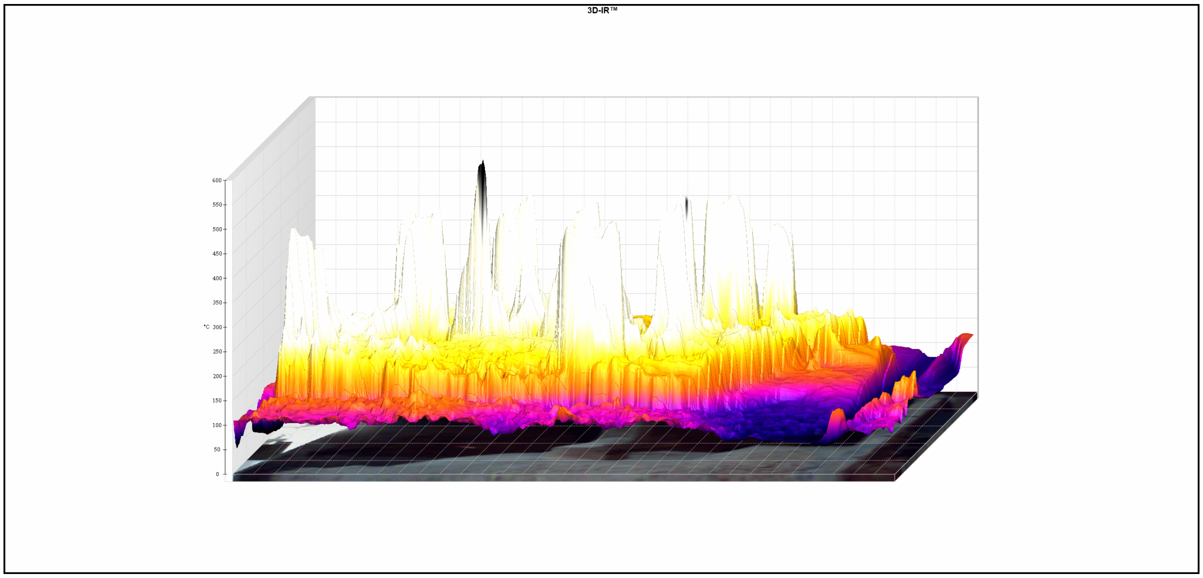
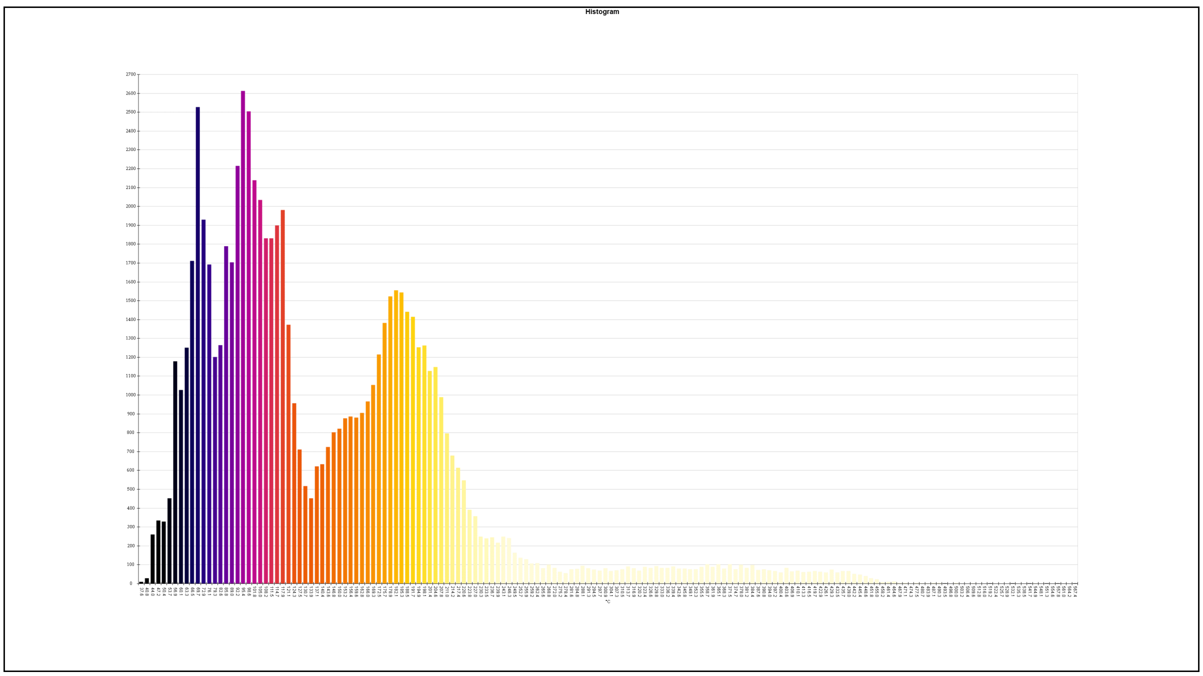
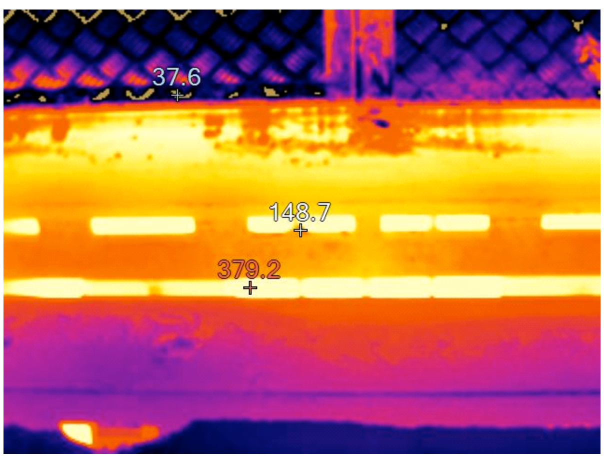
Visible Light Image





Name	Temperature
Centerpoint	143.2°C
Hot	568.0°C
Cold	36.7°C

Image	**IR000967.IS2**
Image Time	14.11.16 10:43:09
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	37.6 °C to 379.2 °C
Average Temp	117.7 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)
DSP Version	1.2.18
OCA Version	1.2.18



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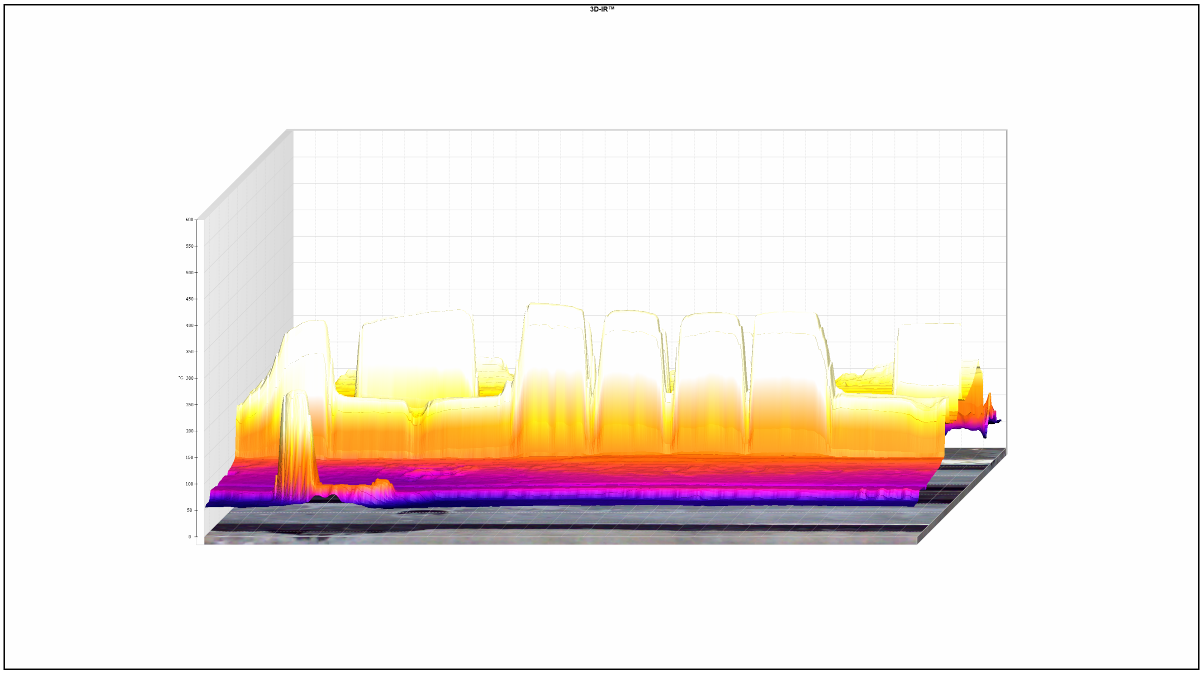
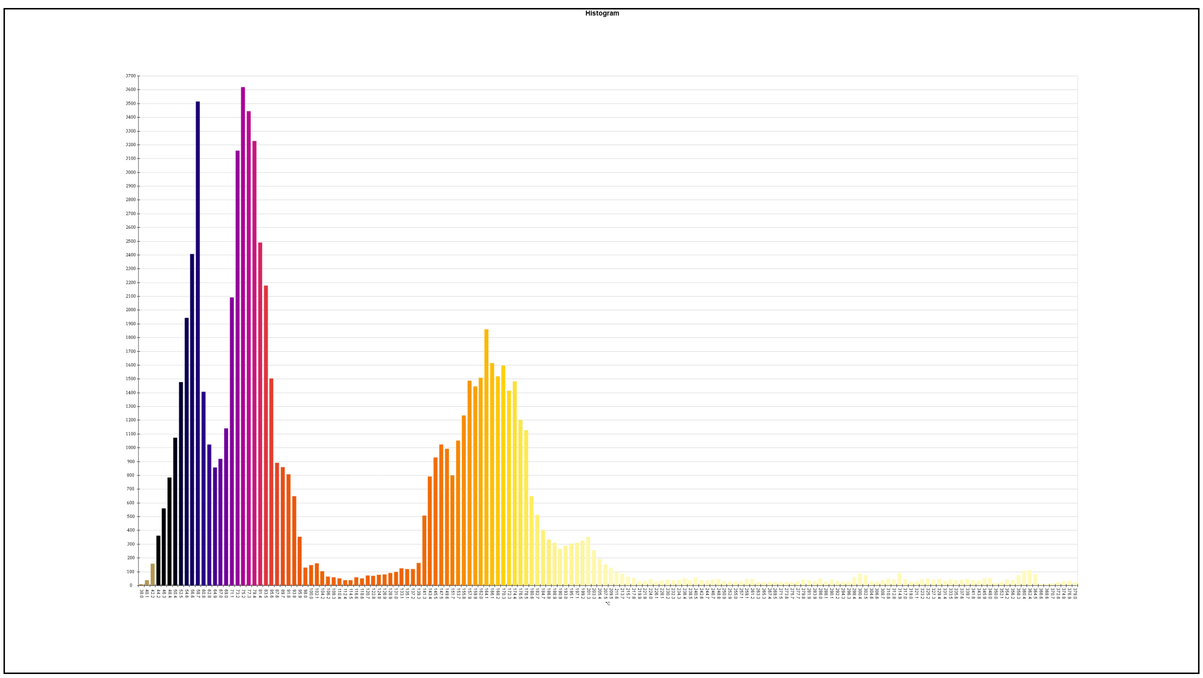
Visible Light Image

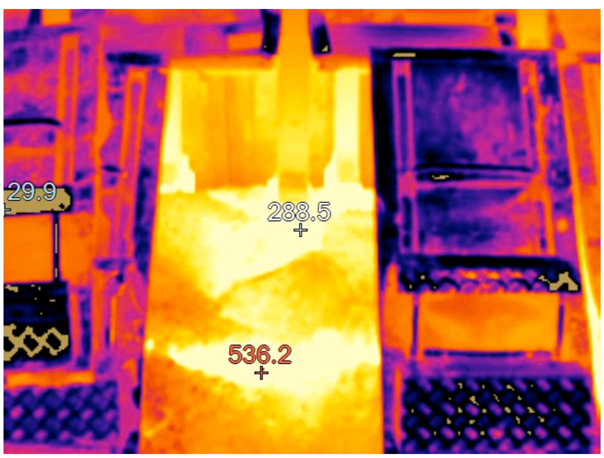




Main Image Markers

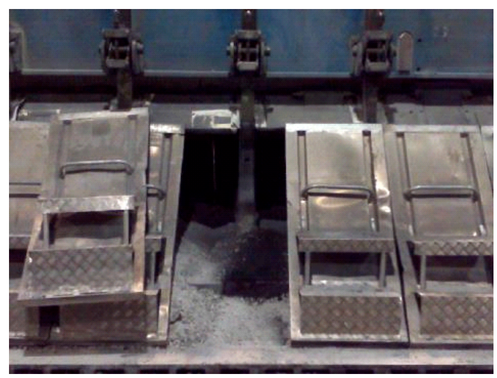
Name	Temperature
Centerpoint	148.7°C
Hot	379.2°C
Cold	37.6°C

Image	**IR000968.IS2**
Image Time	14.11.16 10:45:59
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	29.9 °C to 536.2 °C
Average Temp	107.8 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)
DSP Version	1.2.18
OCA Version	1.2.18

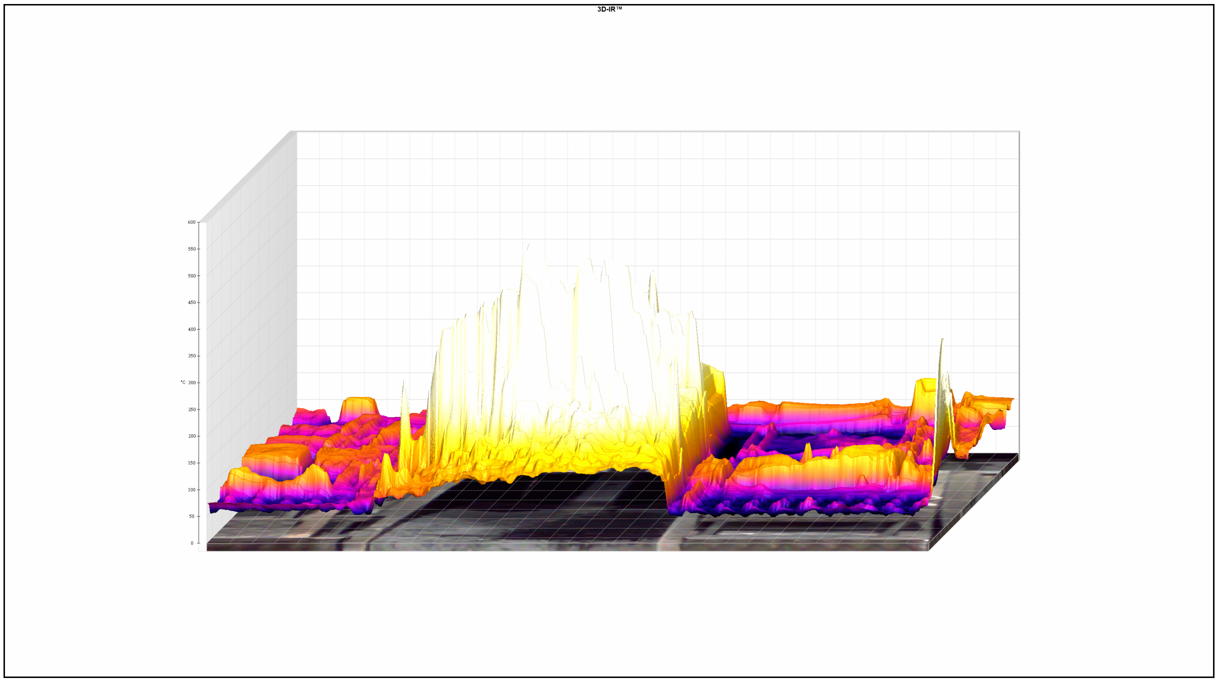


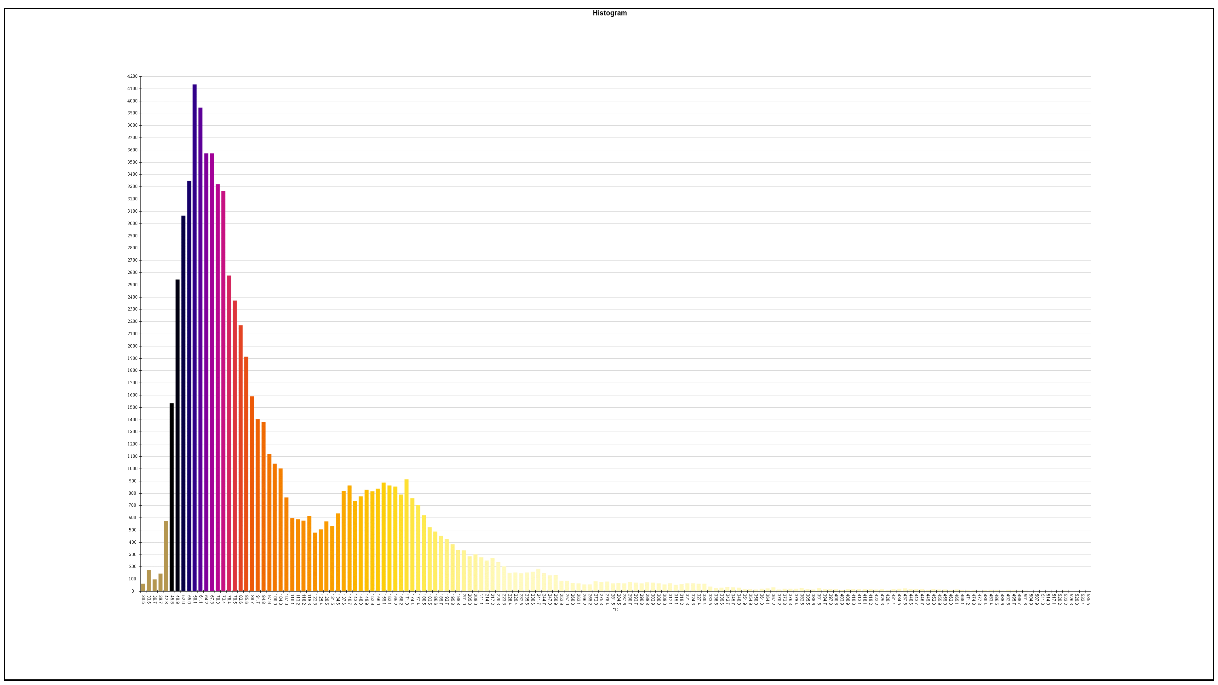
IR000968.IS2

11/14/2016 10:45:59 AM



Visible Light Image





Main Image Markers

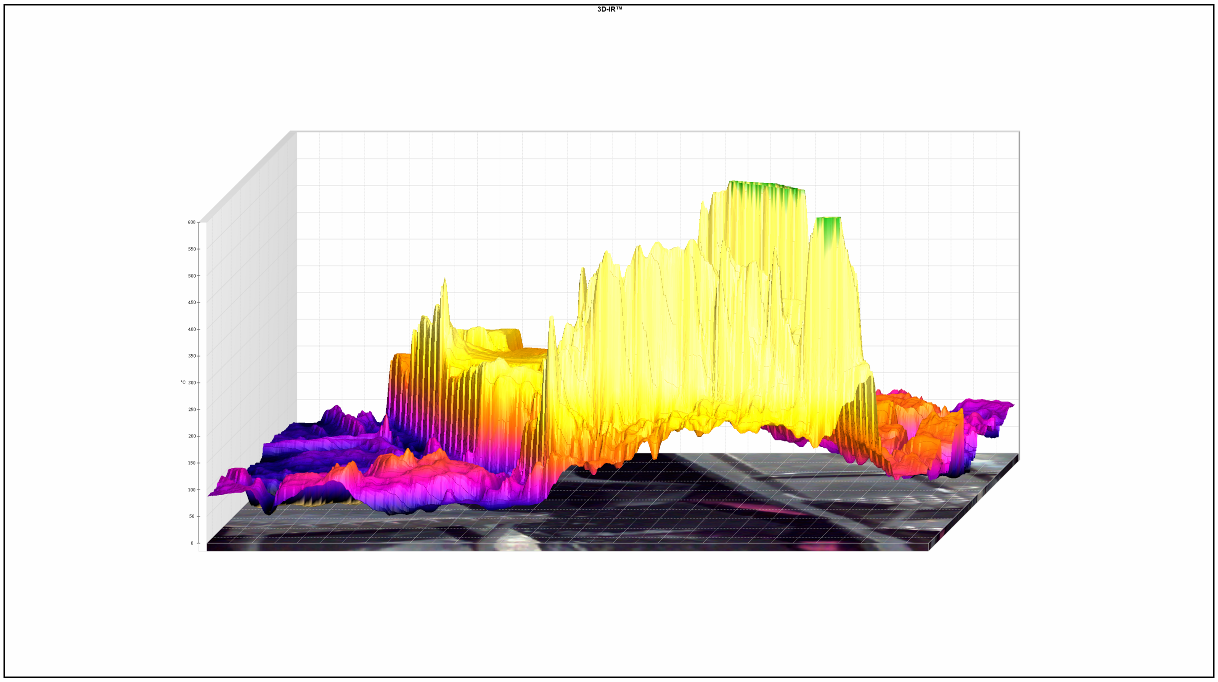
Name	Temperature
Centerpoint	288.5°C
Hot	536.2°C
Cold	29.9°C

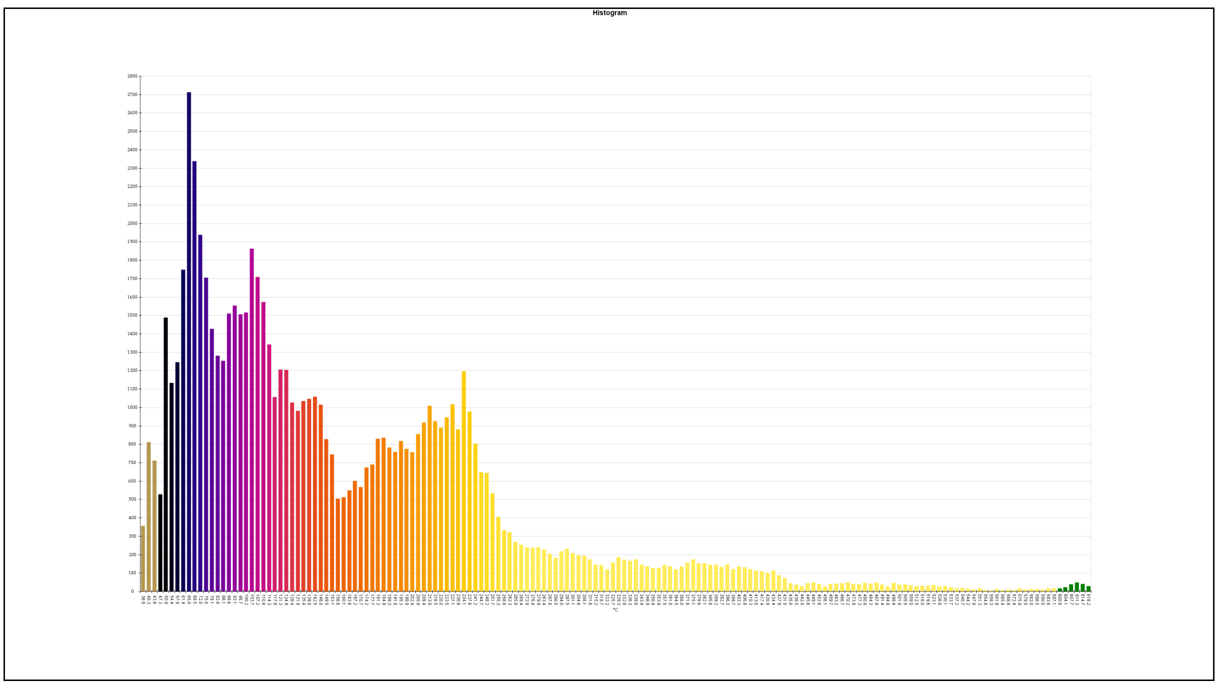
Image	**IR000969.IS2**
Image Time	14.11.16 10:46:49
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	35.7 °C to >620.0 °C
Average Temp	161.2 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)
DSP Version	1.2.18
OCA Version	1.2.18

IR000969.IS2

11/14/2016 10:46:49 AM

Visible Light Image

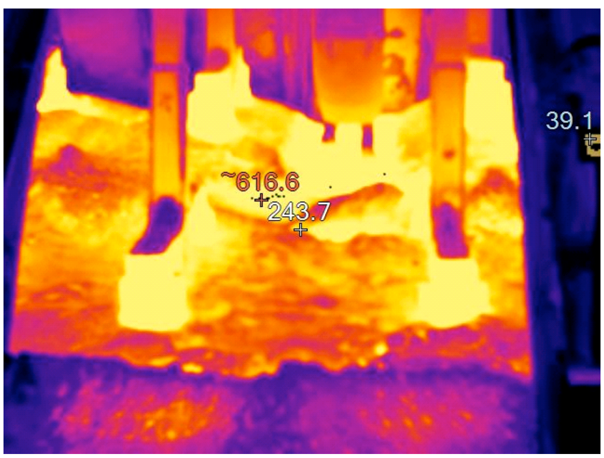




Main Image Markers

Name	Temperature
Centerpoint	375.2°C
Hot	>620.0°C
Cold	35.7°C

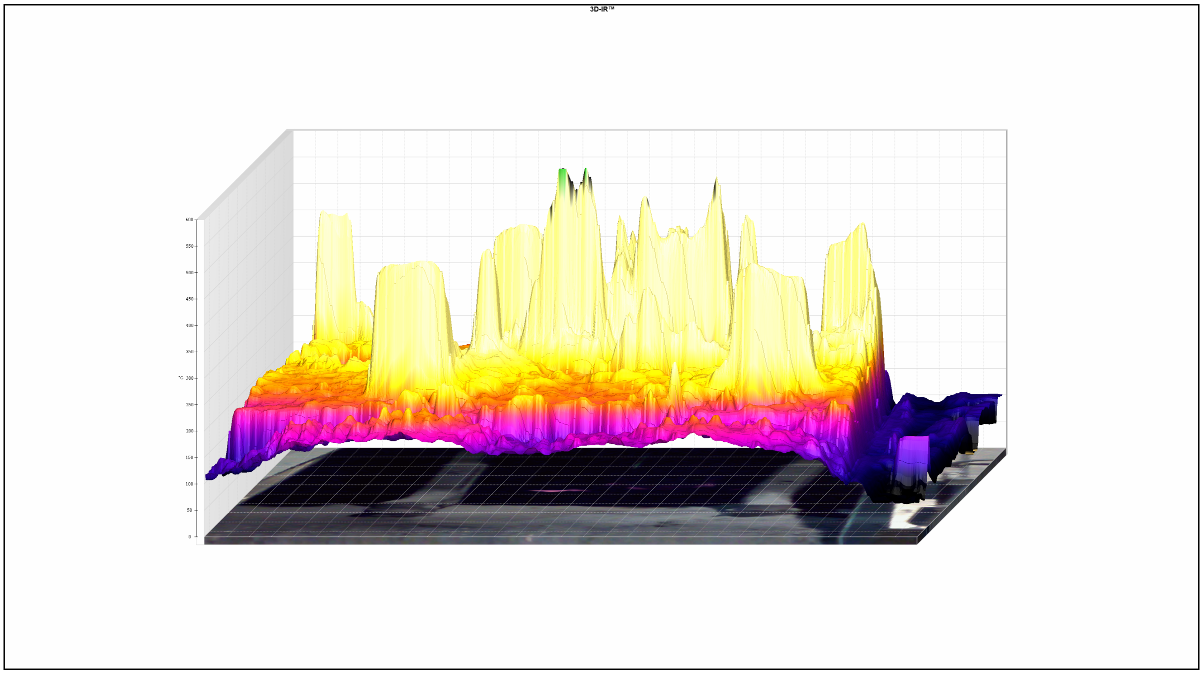
Image	**IR000970.IS2**
Image Time	14.11.16 10:47:55
Emissivity	0.95
Background Temp	32.7 °C
Transmission	100%
Image Range	39.1 °C to ~616.6 °C
Average Temp	206.6 °C
Camera model	Fluke Ti27
IR Sensor Size	240 x 180
Camera Manufacturer	Fluke Thermography
Calibration Range	-10.0 °C to 600.0 °C
Camera serial number	Ti27-12060547 (9Hz)
DSP Version	1.2.18
OCA Version	1.2.18

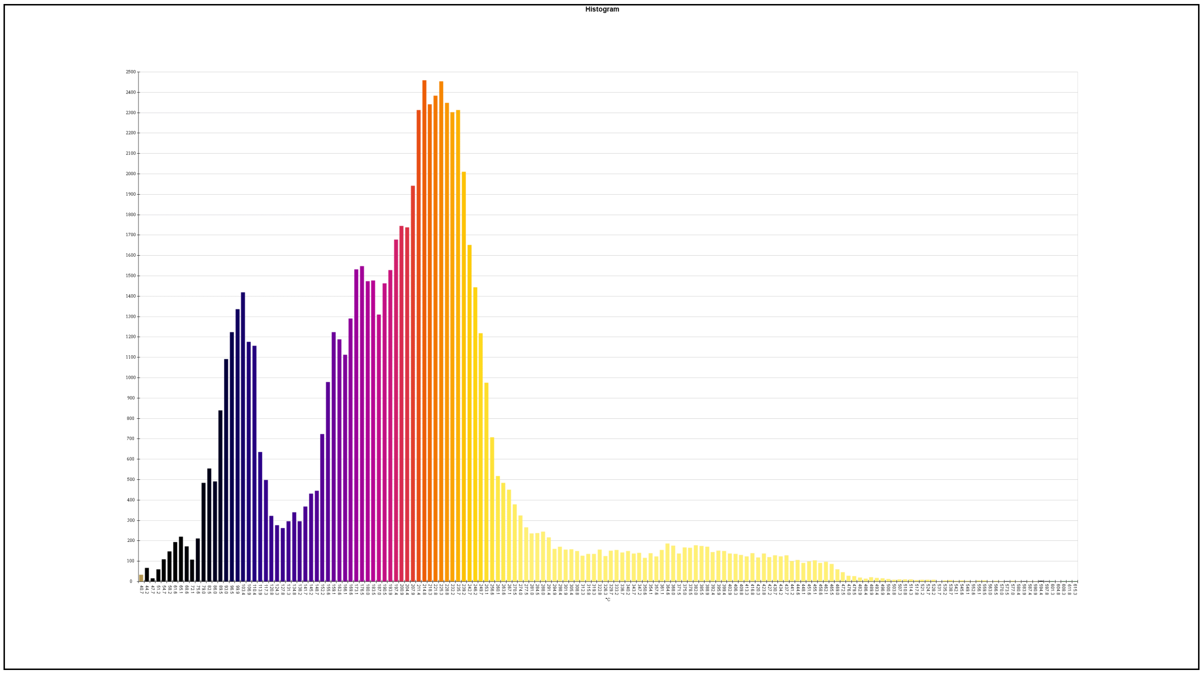


IR000970.IS2

11/14/2016 10:47:55 AM

Visible Light Image





Main Image Markers

Name	Temperature
Centerpoint	243.7°C
Hot	~616.6°C
Cold	39.1°C

APPENDIX I: Risk Assessment

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Department of Engineering Design and Materials **Dato: 13.09.2016**

Linjeleder: Torgeir Welo

Deltakere ved kartleggingen (m/ funksjon)**:** Martin Steinert, veileder/ Andreas Wulvik, Stud.ass./ Jørgen A. B. Erichsen, Stud.ass./ Jardar Winjum, student/ Even Jørs, student *(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)*

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave for Jardar Winjum og Even Jørs. Process automatization concepts in extreme environments such as aluminum electrolysis.

Er oppgaven rent teoretisk? (JA/NEI)**: NEI**

«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering.Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.

Signaturer: *Ansvarlig veileder: Martin Steinert* *Student: Jardar Winjum og Even Jørs*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av TrollLABS workshop.	JW & EJ	Romkort	Romkort		
1a	Bruk av roterende maskineri	JW & EJ	Maskinens brukermanual, Maskinkort	Maskinkort, Sikringskabinett	Ukjent	
1b	Bruk av laserkutter	JW & EJ	Maskinens brukermanual, Maskinkort	Maskinkort	Ukjent	
1c	Bruk av 3D printer	JW & EJ	Maskinens brukermanual, Maskinkort	Maskinkort	Ukjent	
1d	Bruk av skjæreverktøy	JW & EJ	Ukjent			

1e	Bruk av samenføynigsmidler (lim og lignende.)	JW & EJ	Produktets brukermanual og datablad	Datablad	Ukjent	
2	Tilstedeværelse ved arbeid utført av andre.	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	
3	Arbeid i elektrolysehall	JW & EJ	Adgangskort, Alcoas dokumenterte rutiner	Alcoa online sikkerhetskurs	Ukjent	
4	Arbeid i mektatronikklab	JW & EJ	Romkort	HMS-kurs, Verkstedkurs	Ukjent	
5	Eksperimentelt arbeid	JW & EJ	Ukjent	HMS-kurs, Verkstedkurs	Ukjent	

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1	Bruk av Trolllabs workshop.								
1a-i	Bruk av roterende maskineri	Stor kuttskade	2	D	A	A	D	2D	Sørg for at roterende deler tilstrekkelig sikret/dekket. Vær nøye med opplæring i bruk av maskineri.
1a-ii		Liten kuttskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iii		Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iv		Flygende spon/gjenstander	3	C	A	A	B	3C	Bruk øyevern og tildekk hurtig roterende deler (Fres og lignende.)
1a-v		Feil bruk-> ødelagt utstyr	3	A	A	C	A	3C	Vær nøye med opplæring i bruk av maskineri
1b-i	Bruk av laserkutter	Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1b-ii		Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Bruk hansker ved håndtering av varme materialer.

1b-iii		Øyeskade-laser	2	D	A	A	C	2D	Bruk øyevern! Skru av laser når maskinen ved oppsett.
1b-iv		Brann	2	B	A	D	C	2B	Vær nøye med opplæring i bruk av maskin. Ha slukkeutstur tilgjengelig
1c-i	Bruk av 3D-printer	Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskin.
1c-ii		Innhalering av plast/ printemateriale	5	A	A	A	A	5A	Bruk åndedretsvern/ vernebriller
1c-iii		Feil bruk-> ødelagt maskineri	3	A	A	C	A	3A	Vær nøye med opplæring i bruk av maskin.
1d-i	Bruk av skjæreverktøy	Stor kuttskade	2	D	A	A	D	2D	Bruk skapre verktøy og riktig skjæreunderlag
1d-ii		Liten kuttskade	3	B	A	A	A	3B	Bruk skapre verktøy og riktig skjæreunderlag
1e-i	Bruk av samenføynigsmidler (lim og lignende.)	Eksponering på øyet	2	D	A	A	B	2D	Bruk øyevern, ha datablad tilgjengelig
1e-ii		Eksponering hud	4	A	A	A	A	4A	Bruk hansker, ha datablad tilgjengelig
1e-iii		Eksponering åndedrett	4	A	A	A	A	4A	Bruk åndedretsvært/ god ventilasjon. Ha datablad tilgjengelig.
1e-iv		Søl	4	A	B	A	A	4A	Ha papir/ rengjøringsmateriell tilgjengelig. Ha datablad

									tilgjengelig.
2	Tilstedeværelse ved arbeid utført av andre.	Se andres risikovurdering om sikkerhet betviles.	3	C	C	C	C	3C	Hold et øye med hva som foregår rundt deg.
3-i	Arbeid i elektrolysehall	Brannskade	3	B	A	A	A	3B	Følg Alcoas intrukser for verneutstyr nøye. Unngå opphold nær varme flater.
3-ii		Innhalering av støv og avgasser	4	B	A	A	A	4B	Følg Alcoas intrukser for verneutstyr nøye.
3-iii		Øyeskade – blending/fremmedlegemer	2	C	A	A	A	2C	Følg Alcoas intrukser for verneutstyr nøye.
3-iv		Klemskade	3	D	A	A	D	3D	Vær oppmerksom og lytt til fagfolk.
3-v		Elektrisitet- strøm	2	E	C	E	E	2E	Følg Alcoas intrukser for verneutstyr nøye. Vær oppmerksom og lytt til fagfolk
3-vi		Ødeleggelse av utstyr (magnetfelt)	3	A	A	C	A	3C	Følg Alcoas intrukser nøye, og hold all elektronikk og magnetifiserte gjennstander utenfor ovnområdet
4	Arbeid på mekatronikklab	Elektrisitet- strøm	3	B	A	A	A	3B	Typisk lite energi involvert. Bruk isolerte verktøy
5-i	Eksperimentelt arbeid	Vann-drukning	1E	A	A	A	D	1E	Bruk redingsvest i båt og lignende.
5-ii		Elektrisitet- strøm	3	B	A	A	A	3B	Typisk lite energi involvert. Bruk isolerte verktøy

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

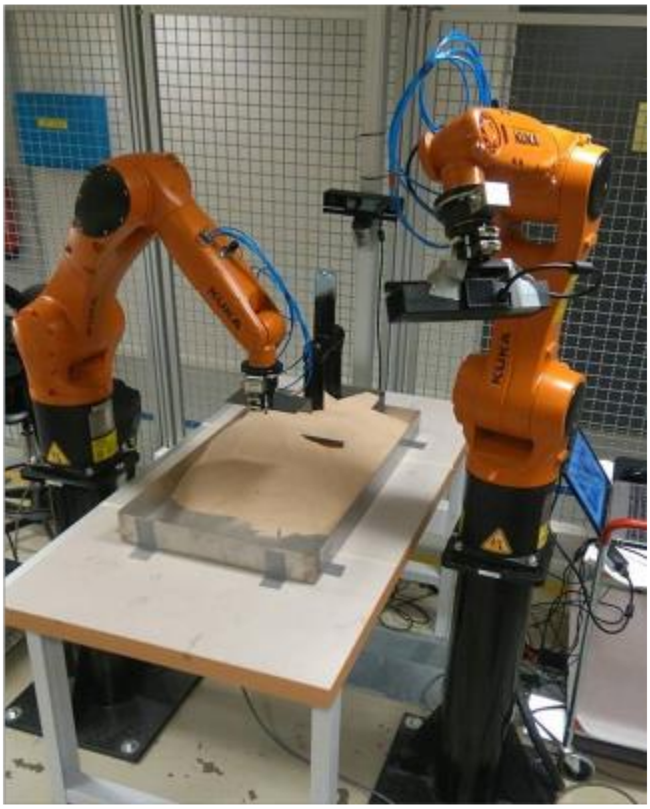
Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

APPENDIX J: Project Thesis

Notes:

The project thesis has been stripped from its appendix to reduce the size of the document. Grey boxes has also been put in areas of the paper where Alcoa-sensitive information has been provided. Due to the corporate partner's desire of information discretion, this has been removed from the paper.



Process Automatization Concepts in Extreme Environments Such as Aluminium Electrolysis

Summary

The aim of the thesis is to explore automation potentials for one of the core maintenance operations in primary aluminium production. The paper looks at the sequential steps of the process and evaluate design and technology applicable for solving the automation challenges.

The thesis addresses the development potentials for solutions related to both sensing and actuation in the aluminium potroom environment. Key findings from the research and tests performed is listed during the thesis and discussed at the end in a process-of-operations context. The research conducted reveals positive results in application of computer vision and thermal camera systems, especially 3D vision and colour recognition algorithms shows promise. Findings related to the pot covers addresses a desire for redesigns. This is to improve compatibility with automation changes. Proper shielding and compatible technology with the extreme environment will be a key factor for implementation success. This is a requirement for precise and robust actuation. The findings from the thesis will be the foundation for two master theses, spring 2017.

Jardar Winjum and Even Jørs
TMM4560 Project thesis

Supervisor: Martin Steinert
Co-supervisor: Andreas Wulvik

Industrial partner: Alcoa Mosjøen

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Abbreviations and dictionary

AGV – Automated Guided Vehicle

AR – Augmented Reality

CAD – Computer Aided Design

ETE – Extreme-Temperature Electronics

FoV – Field of View

FTE – Full Time Equivalent

HRI – Human-Robot Interaction

HSE – Health, Safety and Environment

ICP – Iterative Closest Point

IPK – Department of Production and Quality Engineering

IPM – Department of Engineering Design and Materials

MDF – Medium Density Fiberboard

PC – Point Cloud

PD – Product Development

QR – Quick Response

ROI – Regions Of Interest

ToF – Time of Flight

UR – Universal Robots

WOF – Workers On Foot

Norwegian to English jargon dictionary

Aluminiumoksid – Alumina/Aluminium oxide

Anodetæring – Anode corrosion, anode oxidation

Bad – Bath

Bluss – Flaring

Butts – End of anode rod or slang for used anode

Celledrift – Cell operation

Cellemater – Feeding wheel mechanism, used in the Tobb

Clad – Clad, the connection between the anode and the anode rod

Dekkmasse – Cover mass/material

Digle – Crucible

Endegavl – Pot end

Etterdekking – Anode coverage/covering

Kobberåk – Anode rod/yoke/

Krysset – Anode bridge

Kull/graphite – Carbon anode

Lavett – Crucible stand

Luftavbrann – Carbon oxidization or “air burn”

Ovn – Pot

Ovnsdeksel – Pot cover

Slagg – Sludge

Sleik – Rake tool, anode coverage tool

Slipp – Carbon anode released from rod during electrolysis (not good)

Smelteverk – Potroom

Sot – Impurities, carbon dust, soot

Støperiet – The foundry

Støv – Dust, slang for electrolysis powder or alumina

Tobb – Tank with cover mass, located in the traverse crane in the potroom

Valseemne – Rolling slabs

Åklapper – Anode patch

Section 1 | Thesis introduction

This thesis is written by Jardar Winjum and Even Jørs, both studying Engineering Design and Materials at IPM. It is written together with the research group TrollLABS (ref. prof. Martin Steinert) in collaboration with Alcoa Mosjøen. The thesis will be the foundation for further work in the following master thesis for both students.

Mass production of aluminium started in the very late 1800s and is today the second most-used metal in the world (Hydro 2012). Aluminium is also the third most abundant element in the earth's crust after oxygen and silicon, and is one of the metals considered 100% theoretically renewable. Aluminium's renewability is one of the main arguments for its potentials as a sustainable material for the future. Alcoa is a world leading producer of primary and wrought aluminium. With one of their corner stone facilities in Mosjøen, they wish to increase their competition advantage with higher turnover per employee and at the same time increase their standard of HES. Operations in their primary aluminium production facilities have human workers engaged in an extreme environment of high temperature, extensive magnetic fields, and toxic gas and dust. To further improve their production of primary aluminium, Alcoa seek to automate repetitive tasks related to their processes.

The aim of the thesis is to explore automation potentials for one of the core maintenance operations in primary aluminium production. The project scope has been limited to the potroom environment, i.e. the whole melting facility. There will be a short introduction to the aluminium industry and performed an evaluation of which process shows most promise in relation to automation. The paper will analyse the operational sequential steps of the process and evaluate different technology applicable for solving the challenges. The main weight of the thesis reviews different alternatives of sensory, while means of actuation and concept design is also featured. Key findings from the research and tests performed will be listed during the thesis and discussed at the end in a process-of-operations context.

Section 2 | The challenge at hand

Section 2.1 | Facility and operations

This section contains essential information related to aluminium industry.

Section 2.1.1 | Primary aluminium production

In its essence, the life cycle of aluminium follows seven steps (Hydro 2012): Bauxite mining, alumina production, primary aluminium production, semi-fabrication, product manufacturing, use phase and recycling.

The raw material Bauxite can be found a couple of meters below ground near equator. From mined Bauxite, Alumina is extracted through a refinement process consisting of hot caustic soda and lime. The Alumina is subsequently brought to the potroom where it is used in the production process of primary Aluminium together with carbon and great amounts of electricity. From the pots, molten aluminium is brought to the foundry where it is casted into rolling and extrusion slabs. Both the potroom and foundry processes are found at the production facility at Alcoa Mosjøen. After casting, the slabs are sent to the semi-fabrication and product manufacturing of aluminium products, where forming processes are applied to shape the metal into products the use phase. Ideally, after the use phase, the aluminium ends up being recycled and looped back to semi-fabrication as secondary aluminium.

Section 2.1.2 | Alcoa Mosjøen melting cells and potroom environment

The two most common methods of producing primary aluminium are the Söderberg ("Aluminium Smelting" 2016) and the prebake process. At Alcoa Mosjøen they use the prebake pot technology. Simply put, these melting pots continuously dissolve alumina into molten aluminium through electrolysis with carbon as anode and cathode. Pure alumina has a melting point of 2072°C. This is lowered to 920-980° by the use of cryolite. Cryolite is mainly a salt mixture consisting of Natrium and Aluminium fluoride. The cryolite is also known as the bath or the electrolyte in the melting pot, and has a bright distinct orange colour when molten. The bath is located between the anodes and the molten aluminium, in the bottom of the pot.

The prebake method is a continuous electrolysis process, where direct current passes from the carbon anodes, through the electrolyte and to the carbon lining and current collector bars, connected to the following pot. The anodes are connected to a copper bus-bar system, distributing the current while automatically suspending the anodes into the bath. As the carbon anodes are consumed, the suspension allows the anodes to have an ideal depth placement in the electrolyte. According to Alcoa, the carbon lining has an estimated life span of 4-6 years, while the carbon anodes needs to be changed each 28 days.

It is desired that the bath and anodes are completely covered at all times. By adding a gravel-like cover mass to the pot, a solid shell forms on top of the bath, also known as the crust. The crust is periodically broken as three automatic feeders locally break it and add alumina to the electrolyte. This keeps the concentration of alumina in the bath at a continuous and ideal rate. The alumina is stored in tanks on top of the pots. As the electrolytic process occurs, aluminium, which is denser than the cryolite, sinks to the bottom of the pot. Molten aluminium is depleted from the pots at Alcoa Mosjøen once a day from a designated extraction spot in the crust.

Figure 3: Pot room serial circuit layout

Each pot at Alcoa Mosjøen is equipped with 9 anode rods on each side of the pot, resulting in a total of 18 anodes. Access to the bath is given by manipulation of aluminium covers, located on both sides of the cell. Alcoa's pots have 13 covers on each side, resulting in a total of 26 covers. The covers are designed with a handle and two steps, with the intention of easy manoeuvrability and access to the top of the anode rods with ease. To prevent excessive gas leakage, there are specially fitted patches placed between the anode rods and the pot. The covers at Alcoa are often dented and damaged from the different activities surrounding the pot. The large tubing on the right of the pot is where the gases from the electrolysis are transported out for cleansing. The tanks on top of the cell is where the alumina is kept and is refilled by a transport system of tubes.

Figure 4: Cross section of pot at Alcoa Mosjøen

There is a lot of traffic and activity surrounding the aluminium melting cells. Here's a list of the most common activities and vehicles moving around in the pot rooms.

Section 2.1.3 | Key figures given from Alcoa Mosjøen

Section 2.1.4 | Identifying a potential automation project

Alcoa Mosjøen proposed early what they saw as a suitable automation project for this thesis, which was the pot operation referred to as *anode covering*. To ensure selection of the most fitting project, a list of potential processes to automate at the plant were gathered and evaluated before deciding. The list of identified prospects emerged as a result of insights during a summer internship at the plant and research conducted at a visit to Alcoa Mosjøen:

The list of options indicates that there are other feasible projects to investigate. Several of them are already initiated, restricting our development space and freedom to innovate. As the thesis will reveal, there are numerous technical challenges and exciting engineering related to automating the anode maintenance task. With backup from both Alcoa and TrollLABS, the decision was made to revolve this thesis on how to automate the process of anode covering.

Section 2.2 | Anode covering

Anode covering can be described as a maintenance operation in the primary aluminium production, where the carbon anodes are protected from oxidation from the environment. This is performed by operators distributing a gravel-like cover mass with rakes over the carbon anodes (see figure 5), preventing air to reach the anodes. The cover mass is applied to the pot when used anodes are replaced with new ones, and is dispersed with a feeding system mounted on a traverse crane.

Carbon oxidization is unwanted in the electrolysis process since it consumes the anode more rapidly, whilst not producing aluminium. Oxidation also leads to uneven consumption of the anodes. When the anode becomes asymmetric, it could ultimately result in an anode slippage. In other words, the carbon falls off the anode rod and into the bath, polluting it. The overall impact of poorly covered anodes are higher maintenance and power consumption, increased emissions of CO_2, heat loss and less aluminium produced.

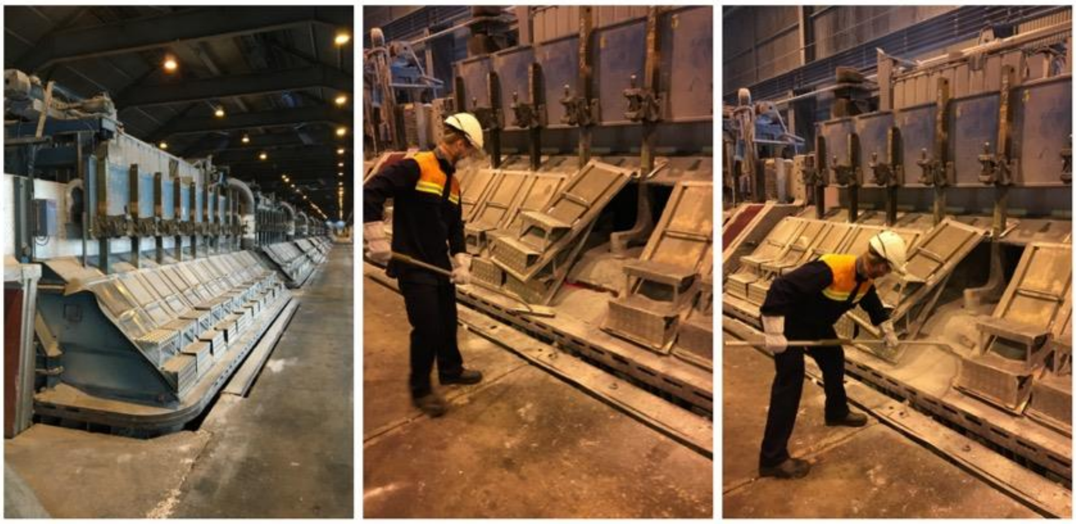


Figure 5: Picture far left displaying a row of melting pots at Alcoa Mosjøen. Last two pictures illustrate an exposed anode being manually covered with cover mass by an operator.

Each work shift performs their share of anode coverage. At the end of a full shift cycle, all pots should have been covered (1.7 times a week). The operators at Alcoa has four pots each to cover each shift, spending approximately 20-30 minutes. The anode coverage is later on controlled by process engineers at Alcoa for execution quality.

Protective equipment required for the task:

- Hard hat
- Safety goggles
- Heat and fire resilient underwear, suit, hood and gloves,
- Gas mask
- Protective and fire resistant footwear

Risks involved with the process:

- Fire damage
- Crush injury

- Dust and gas inhalation

There are a few special cases where cover mass maintenance should not be applied. In these scenarios, its desirable to leave cracks flaws in the cover mass. These are situations such as:

- The three alumina feeding spots in the pot.
- The aluminium extraction hole in the pot (which needs special handling).
- Gas and flame emission cracks in the crust, not close to anodes.
- Anodes that are soon to be replaced.

Section 2.2.1 | The process AS-IS

Performing anode covering today involves several operations in steps. The sequence below describes how the pots ideally are checked and maintained during anode covering:

1. **Accelerated ventilation**
   The operator opens a valve to accelerate the ventilation inside the pot. This is so the operator now can remove covers to access the bath. The operator closes the valve when the covering process is over.
2. **Removal of pot covers**
   The operator removes one of the end covers, placing it somewhere reachable, for instance on top of the pot cover next to it. When the operator is finished with the first end of the pot, he puts the end cover back. The second cover is moved and placed on top the end cover at the other end of the pot. As the operator works his way towards the pot end, he/she shifts the covers instead of lifting one after another. The process is repeated on the other side of the pot.
3. Using the rake
   The operator rakes the cover mass from the exterior front ledge of the pot towards the anodes. By the pot's interior ends, the edge of the pot should ideally be levelled with the height of the end anode. Redundant mass at the ends should be raked and distributed evenly over the end anode. All anodes should be covered by an even coat of covering mass with a 7-10 cm thickness. The process finished by cleaning out the exterior plate.
4. Alumina covering
   When cracks and gaps appear in the bath crust, the operator redistributes the existing cover mass in the oven, filling in the holes. If it is not enough cover mass, alumina from the tank can be used. Three valves located in the middle of the pot ceiling are reachable using the rake. Pulling or pushing these will release alumina. The valve closes by returning it to its initial position. The operator can now distribute the alumina to cover the cracks.
5. Proper anode coverage
   Quality control after anode coverage is audited by the following unformal standards:
   - Cover mass should be evenly distributed over and in between the anodes, with an ideal 7-10 cm layer thickness atop each carbon anode.
   - It is acceptable with anode exposure next to the three oldest anodes since they will soon be replaced. These exposures should be left alone or covered sensibly.
   - New anodes should be fully covered when inserted into the pot.
   - The area where the aluminium is tapped has its own coverage procedure.

Breaking down the process steps of anode covering, the flow chart in Appendix C visualises how an operator would ideally complete the task iteratively.

Section 2.2.2 | Motivation for process automation

There are several motivational factors for automating the anode coverage task. A big motivation is indeed that Alcoa themselves pose an interest of automating this process. According to the potroom manager, automating the process can reduce six full time equivalents (FTE) with today's production capacity. As Alcoa wish to expand production, the reduction impact on FTE can only be said to increase. Removing human error from the process will have a positive impact on aluminium production efficiency per anode, and also giving lower maintenance and power consumption costs, less emission of CO_2 and reduced heat loss. In other words, a more profitable and sustainable production of primary aluminium.

Automation of the process will reduce the amount of human traffic and labour in the potroom, which is stated as a prospect goal at Alcoa Mosjøen. This will also lead to a positive impact on the overall HSE at Alcoa. In addition to Alcoa's economical and sustainable perspectives, the anode covering is a nuisance for the operators who performs the task. Feedback from conversations and interviews during summer internship points out that it is tough and hazardous work. Not a single operator opposes automation of the process. On the contrary, it cannot be implemented soon enough. Supporting this, is Alcoa Mosjøen's policy stating that no operator will be fired in relation to automation at their facilities.

Anode covering is a crucial task that needs to be done to ensure an effective and stabile primary aluminium production. Since this process is not currently under development, the findings from this thesis will have a higher chance of implementation at Alcoa. The thesis will also have no restrictions related to prior work on the topic. As most processes at the potroom are located close by or inside the pot, result from the thesis might also solve challenges related to the other automation projects initiated at Alcoa, such as the crane system project.

Section 2.3 | Planning ahead and defining the project

To ensure continuous progress and efficient collaboration, it was decided to base the thesis teamwork inspired on an Agile SCRUM approach (Cohn 2016). To better understand the challenges related to anode covering, it was also decided to break down the process and look into the separate sequential steps of the operation. Goals and subtasks were written on Post-It's and put into either the sprint backlog, sprint or completed catalogue. The work was planned through biweekly sprints, where tasks where either completed during the sprint, reprioritized or removed completely from the progress plan.

With a clear definition of the process, the next priority was to understanding and define the challenges related to the task. The initial steps were to seek insight and knowledge from local resources at TrollLABS and experts in the field of aluminium production and industrial automation. During the summer internship, a CAD model of the melting pots where created (Appendix A), based on blueprints from Alcoa. To prepare for interviews and have a visual aid when communicating the project to external recourses, a demonstrator prototype of an aluminium melting pot was created from the CAD model. Renders of the same CAD model were made to illustrate the most crucial parts of the pot.

Figure 6: Demonstrator prototype of aluminium melting pot made out of laser cut MDF

A two-day trip to Alcoa's facilities in Mosjøen was organised with prof. Martin Steinert and the PhD-candidate Andreas Wulvik and Jørgen Erichsen from the Engineering Desing department at NTNU. The trip led to valuable information in context of pot operations, with Alcoa allowing us to take part in the everyday aluminium production at their facility. Conversations with the potroom manager and automation engineers gave us a broader picture of the current automation at Alcoa. A large meeting was conducted, where all employees at Alcoa Mosjøen were invited to address potential challenges related to automation of the anode covering task. The session generated over 180 critical questions concerning the thesis, addressing real concerns from people working in at the plant.

Section 2.3.1 | Interview with Amund Skavhaug, prof. IPK

Amund Skavhaug is a professor at IPK with expertise in cybernetics, robotics, automation and computer vision. The interview (Appendix D) was arranged with hope of getting insights related to industrial automation and state of art vision-technology. First, we introduced the thesis and the current progress of the project. His first comment was related to how we should approach the challenge of automating the operation. Amund proposed that we should apply a feasibility study, dividing the task into operational steps. Following the feasibility study there should be deeper exploration of different options and research on state of the art articles. He agreed with pursuing anode covering as topic, as it is not a "critical path" in Alcoa's automation program. He recommended us to look into cover handling and suggested a possible sequence for development of pot cover actuation:

- Develop mechanism for pot cover actuation
- Automate the handling mechanism
- Integrate the solution on a base system
- Apply sensors to get the system autonomous

Amund also pointed out sensors he thought would be applicable for potroom automation:

- Vision sensory such as 3D, 2D and thermal camera
- Laser sensors for distance measurement and scanning, recommending the LIDAR sensor
- IR-thermometers for temperature detection
- Ultrasound

He envisioned that a fully functioning sensing system would need a combination of more than one of these sensors combined with some sort of video analysis software. He gave us contact information to Adam Leon Kleppe, a PhD-candidate at IPK doing his thesis on robotic vision. He stressed that implementing vision components would require a plan to prevent dust from the environment to cover up the sensory. The conversation resulted in some constructive feedback, a list of sensors to test out, and some positive confirmation related to our process so far.

Section 2.3.2 | Interview with Adam Leon Kleppe

Adam Leon Kleppe is a PhD candidate at IPK working with visual sensory for his thesis, especially robotic vision. In this interview (Appendix D) it was discussed how vision can be used to gain data in the potroom and trouble sources to expect from the environment. He warned us of open flames which can create noise through heat radiation. Also, the detection of pot covers could be a challenge as aluminium is quite reflective, which is an issue in relation to 3D vision. Utilizing colour tags, AR or QR codes on the covers could solve this minor issue. By reducing the field of view, eliminating surroundings and only focus on the relevant areas of the pot, readings can become more accurate and processing time be reduced. To identify exposures in the crust, he suggested the use of colour recognition algorithms, which might be able to recognize the glowing colours occurring in these areas. The thought of a fixed camera installation in the pot where discussed. According to Adam, it would either require multiple sensors or a camera able to move in the pot, making it rather difficult to apply at the 404 pots at Alcoa.

Besides vision, we got a tip relating to the magnetic fields. Electric servos might be influenced by the surrounding field, making them unpredictable and inaccurate. It was suggested to check out hydraulic or pneumatic industrial robots as they do not utilize the same technology. Regarding distribution of cover mass, it was discussed if a rake was the best tool for the actuation. As the anodes today are covered by a canon when replaced, perhaps this could be used for anode covering as well. A canon can be simpler to actuate and require less degrees of freedom in relation to movement. It can also point and shoot, and does not need an exact distance to the target. However, complex calculations of the inconsistent, gravel-like mass flow is likely to be drawback.

Section 2.3.3 | Setting the scope: Addressing the problem areas

From the information conducted during the initial research phase, the problem areas where the project effort should be concentrated, emerged. A challenging factor which is unavoidable in this thesis is the extreme environment of the potroom. Whatever concept or solution chosen, the environment needs to be taken into consideration. In the potroom there is fine dust, seasonal temperature variations and intensive magnetic fields. Inside the pots there are also extreme temperatures and corrosive gasses to account for. Tackling the environment is critical for automation success.

To narrow down the scope of the thesis, it will not address potroom mobility challenges. As Alcoa already have projects related to both crane and AGV automation in the plant, the solutions for mobility will hopefully be solved by their own automation engineers. The thesis will therefore concentrate on actions that concern the individual pot in relation to anode coverage. The main areas of interest categorized as the following:

Section 2.3.3.1 | How to sense in the potroom environment

A self-dependent automated system relies on stream of data input to preform decisions. This project depends heavily on our concept being able to sense and make evaluations similar to what the operators have to make every day. Either it needs to know where it is located by the pot, how it should identify a cover, evaluate the state of the pot or ensure that it does not harm any of the operators close by. Finding the ideal sensory suitable for the aluminium production environment will therefore be a large priority in this thesis.

Section 2.3.3.2 | How to access the inside of the pot

Given that the system is able to sense and operate in the potroom, how will it manage to get inside a pot? The operators see ergonomic difficulties related to how the existing pot covers today are handled in the potroom. This will not necessarily be easy for a robot to handle either, thus a re-evaluation of the current cover design and the AS-IS way they are handled will be beneficial for a more affordable, realistic solution of automation. We consider this to be a central topic in the project.

Section 2.3.3.3 | How to actually perform anode coverage

When our automated operator has gained access to the pot interior, how will he then detect a need for anode covering maintenance? How will he know how to do it? Perhaps the most obvious part of the thesis, but heavily dependent on solving the two prior challenges is how to actually distribute the cover mass to cover up cracks or prevent them from propagating in the pot. This will be the third and last challenge the thesis will address.

Section 3 | Product development for extreme environments

The potroom environment limits and constrains the solution space of the automation development process. Specifying what is wished to be performed, while at the same time design for the constraining surroundings might be the key to project success. Taking the restrictions into account from the start of the development process can also spare rework time and resources compared to adapting a final design to the environment challenges. This section addresses the complications and restrictions the potroom environment might apply to an automation system, and different approaches to bypass and conquer these vulnerabilities.

Section 3.1 | Magnetic fields

Perhaps the biggest obstacles for automation in the aluminium electrolysis plants is the magnetic fields generated by the melting pots. It is worth mentioning that an effective aluminium production requires stable usage of power, which leads to a rather steady magnetic field surrounding the pots. The challenges occur when we wish to move something throughout the potroom and induces unwanted current in electrically inductive materials. Feedback from Alcoa related to electronic devices such as mobile phones and computer screens points out that older technology would shut down or malfunction. Newer computer screens and touch phones is not really affected. This might be related to today's technology depending less on analogue components.

Pneumatic and hydraulic systems are known for being dependable in magnetic environments (Gassert et al. 2006), and can already be seen applied on trucks driving in the potroom and actuating in the pots. As the pneumatic and hydraulic robotic technology is evolving, the movement accuracy has also increased and are today satisfactory. These systems are therefore quite tangible to implement. Regardless of how the actuation is performed, most sensors and control systems will need to depend on electronics. Protecting control systems from magnetic disturbances is a common problem and can be eliminated by applying electromagnetic shielding ("Electromagnetic Shielding" 2016). This is often solved by covering the units with conductive or magnetic materials, which is often referred to as a Faraday cage. A Faraday cage absorbs the magnetic radiation and isolates the electronic system. This will most likely be utilized as a part of the overall final concept.

An actuation system will depend on strength and robustness. Minimizing use of ferrous metals such as steel in chassis, tools and larger parts, needs to be considered, as it might be attracted by the magnetic fields. This can influence accuracy of operation. Exploiting metals like Aluminium, which is not ferrous, can eliminate this issue.

Section 3.2 | Temperature

According to Alcoa, the potroom temperature can be quite intense, varying from an -30°C at winter time to 60-70°C during summer. Inside the closed pots, the air temperature is quite constant all year, being at approximately 150-200°C. Under a layer of cover mass, the molten cryolite bath has a temperature just below 1000 °C. "Traditional" electronics has a temperature range of -55 to +125 degrees Celsius ("Extreme-Temperature Electronics" 2016). Compared to the general potroom temperature, it should be possible to use most electronics without having to much trouble. Though extreme cold during winter might impact battery capacity if battery would be considered a part of the solution.

The molten bath temperature is not of great concern, as it is mostly shielded by the cover mass inside the pot. It is worth mentioning that cracks and holes in the cover mass occur frequently and might result in an increased local temperature as gas and flames emit. Shielding against direct flames and bath splash would therefore be worth a thought for any parts that are used inside the pot, especially near the bath crust.

The main challenge of heat is related to the average inside pot temperature. Having components inside the pot atmosphere over time will damage traditional electronics as it succeeds the upper maximum of temperature. Minimizing spent time inside the pot and breaks between operations would be possible actions to minimize the impact of the internal pot temperature. Having a concept that systematically relies on cooling breaks will not be ideally efficient. To make the system even more robust and capable of surviving hot operations, utilization of ETE ("Extreme-Temperature Electronics" 2016) could be recommended. ETE can be utilized for most electric circuitry and have use temperatures well beyond 200 degrees. For those components where ETE cannot be exploited, different sorts of cooling systems can be implemented.

Section 3.3 | Corrosive gasses and dust

The concentration of corrosive gasses in the primary aluminium production is not that severe, making this more relatable to operator HSE. As trucks are working by and inside the pots daily, corrosion of the system will rather be a maintenance issue. Reducing the chance of corrosion could include the usage of anti-corrosive materials, such as stainless steel and aluminium. As an alternative to or as a combination with this counter measure, anti-corrosive coating can be applied. For moving parts and joints that might allow gas to enter the system, air tight protection such as seals and gaskets can be applied.

Both alumina and the cover mass used to produce aluminium generates dust in the potroom. One of the by-products from the aluminium production is an ultra-fine dust that escapes when the pot covers are removed from the pot. The amount of dirt and dust in the potroom can gradually over time impact and restrain moving parts. It can also cover sensory, render the system in need for maintenance. Similar to gas, this can be bypassed by applying air tight protection enclosing moving and rotating parts. For optical sensors with the need of clean lenses, usage of pressurised air to blow away dust can be considered.

Section 4 | Generating concept ideas

Based on the threefold categorization of the thesis, ideation on concept suggestions where done. This was completed through sessions of brainstorming and sketching with colleagues. With the intention of gathering as many wild ideas as possible, followed by a feasibility filtering, leaving the most potential concepts left.

Section 4.1 | Ideation on sensory

We had gathered many sensor suggestions through research, interviews and feedback from colleagues before starting the ideation session for applicable sensory. An important part of the sensory ideation process was considering which of the sensors could capture the greatest amount of data from the environment. In this context 2D and 3D imaging stood clearly out as a valuable sensor to utilize, closely followed by thermal imaging. Another factor was looking at which sensory had the largest implementation potential with the potroom environment taken into consideration. The sensory evaluated was:

Vision sensory with potential applications

- 2D imaging
    - Colour detection
    - Pattern and shape detection
    - Corner detection
    - Surveillance and monitoring footage
- 3D imaging
    - Scan and compare topography
    - Detect revealing details in topography
- Thermal imaging
    - Temperature zone sensing
    - Colour detection

Other sensory with potential applications

- Laser sensors
    - Distance measurement and scanning
- CO_2 sensors
    - Measure levels and differences of CO_2

- Radar and ultrasonic sensors
    - Environment scanning

Of these sensors, vision sensory was primarily chosen as the most important to explore in the thesis. CO_2, Radar and ultrasonic sensors would yield less information and require additional data for usage in the case of anode covering automation. They were therefore not included in the further development process. Laser has the ability to track distances with high accuracy and frequent feedback. Laser was therefore also brought further to testing.

Section 4.2 | Ideation on pot covers

It seemed natural to split the pot cover ideation session into two topics: Pot cover design and pot cover handling. Addressing the AS-IS situation of the pot covers unveiled overall design improvement potentials and improvement possibilities in relation to automation. Altering the pot cover design can positively affect the handling of pot covers additionally. As basis for the concept generation, a mind map of "Why", "AS-IS", "How" and "Handling" was created.

Figure 7: Whiteboard mind map from the brainstorming pot cover and pot cover handling ideation session

Section 4.2.1 | Cover design ideation

From preliminary research, we had that the current pot covers used at Alcoa Mosjøen are made out of aluminium, weighting 12 kg each. The weight is noticeable by the operators as each pot has 26 covers that needs to be moved during anode covering. The lifting weight would also restrict the options related to actuation alternatives. Reducing the weight of the covers would therefore be preferable. Constraining weight reduction is the 2 500 covers that yearly need replacement in result to damages. For automation sake, the state of the covers need to be as high as possible. Robustness is therefore a restricting factor on weight reduction. If damages occur, the pot covers need to be easily replaced.

The current pot cover handles are designed for easy lifting but is placed too high up on the cover, distanced from its centre of inertia. This makes the pot covers awkward and little ergonomic to lift by its handles. Operators prefer to grab the covers from the underside of the pot cover footsteps instead, as it is easier to reach. With arms stretched out, they lean the cover against their thighs to save energy and maintain a less stressful body position.

With 9 anodes on each being shielded by 13 pot covers, the numbers of pot covers vs. anodes don't add up. For automation sake, it would ideally be possible to remove only one pot cover to replace an anode or perform anode covering. While designing the pot covers for automation, it should be possible for operators to move them as well. The ideation on cover design yielded the following list with constraints and important factors that should be considered when redesigning the pot covers:

The pot covers should:

- Be possible to handle manually by operators
- Consist of multiple detachable covers
- Be robust
- Be produced within a given set of tolerances
- Not interfere with pot operations such as anode covering
- Be easily replaced
- Be cheap to produce

The "How" part of the mind map states different concepts of redesigning the covers. Some of the most potent ideas where:

- Hinged pot covers
- Minimalistic pot covers
- Less but bigger pot covers
- Horizontally split fixed pot covers
- Permanently fixed pot covers with hatches
- Foldable pot covers
- Pot curtain/covers sliding on rails

By evaluating the concepts of design in light of the set of constraints, we found that bigger but minimalistic covers and hinged pot covers had the highest chance of improvement compared to the AS-IS pot cover situation.

Section 4.2.2 | Cover handling ideation

The ideation on pot cover handling was conducted with a focus on the technology applicable for grabbing, lifting and general motion of the pot covers. A stationary automated pot cover system was quickly rendered less interesting as it would be expensive to install and maintain. It was rather discussed if an industrial robot unit would be most suiting for the handling. A custom system of linear and rotational actuators could also be built specifically for pot cover manipulation. The operation space of such a robotic system could be moving at floor level or be attached to the traverse crane at Alcoa. Actuation and how the physical handling could be performed are summarized in the following lists.

The ways of actuation identified as potential

- Manual actuation
- Pneumatic actuation
- Hydraulic actuation
- Electromotor actuation

The physical handling of the covers pot covers could be performed by

- Grippers
- Suction cups
- Hooks

Section 4.3 | Ideation on cover mass handling

Anode covering today involves moving existing excess mass to areas where covering is needed. Situations where excess mass is not available, alumina is used instead. To perform cover mass handling, it would be tempting to use the existing rake tool design with a robotic manipulator of some kind. To not jump to conclusions, ideas where generated to identify if there were other potential ways of distributing the cover mass.

Mass handling ideas

- Multi-functional rake tool (raking and hammering of crust)
- Internal pot distribution system driven by pressurized air
- Mass suction and blowing system, inspired by leaf blowers

Section 5 | Concept prototyping and testing

In this section we explore the possibilities of what we think are the most promising technological approaches generated in section 4, directly linked to the main problem areas stated in section 2.3.3. Section 5 is therefore divided into three subsections, the first concerning pot cover concepts, where cover designs are discussed related to easier access. We describe the principle designs more in detail than in section 4 through mock-ups of what we think has most potential for further development.

Next, we dive into sensor related technology concepts, where different sensors and data processing techniques are evaluated for different sensor-related problems in the overall process. This is where we have focused our testing in this thesis. Last, we have a look at actuation potentials, where we demonstrate simple robotic operations in a test setup and discuss other research on relevant actuation solutions.

The overall automation process concerns everything from identifying a pot cover to finally execute mass distribution. The concepts are varying in detail, and the reader would expect more elaborated discussions and testing on concepts where we either find the related problems very challenging, and need to be sufficiently highlighted, and/or the concept's technology has high potential for handling *multiple* challenges in the overall process.

All individual concepts and tests on sensory in section 5.2 have a list of most interesting findings.

Section 5.1 | Pot cover concepts

Two concepts for pot cover redesign are presented and discussed in this section. The redesigns are based on our ideation on pot cover handling and design in section 4.

Section 5.1.1 | Hinged pot covers with detachable, spring-loaded hinge pins

Section 5.1.1.1 | Description and initial mock-up of concept idea

This Lego mock-up shows three covers with the hinged solution applied (1). You should be able to unhinge the covers at an arbitrary cover transition (2). Springs in the hinges will assist in opening of the pot covers, and keep them in an upward equilibrium (3). Even three pot covers could be lifted, if

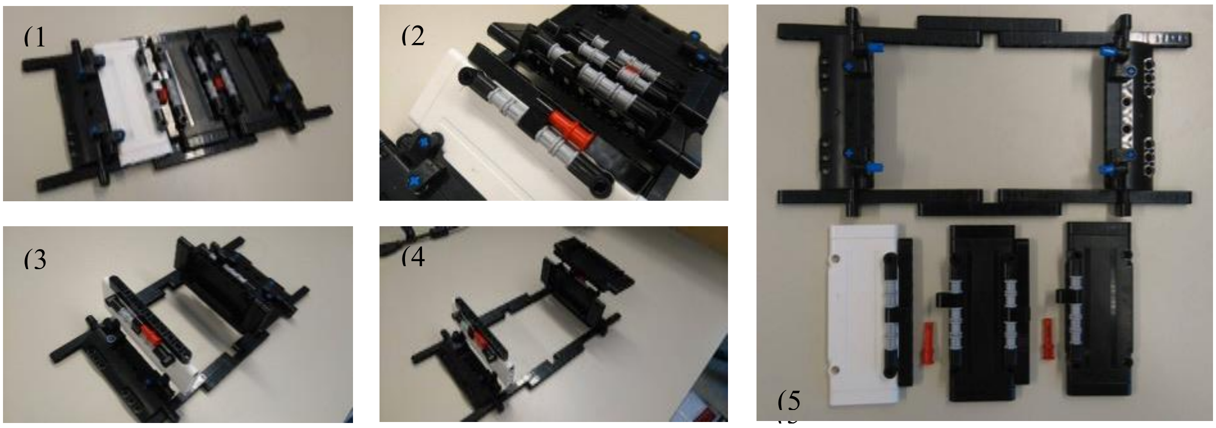


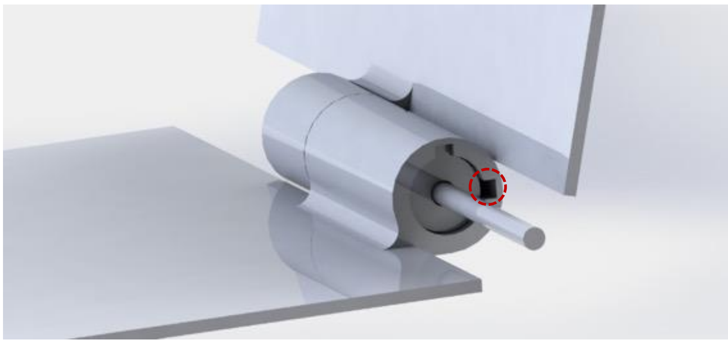
Figure 8: Lego mock-up of hinged pot covers. Numbers 1-5 are related to the description in the text.

more space is needed (4). Slight pot cover design changes must apply (5).

Gravity shall assist in closing the pot covers, and dampening will make the motion in both directions of rotation stable. Opening and closing are initiated with external mechanical impulses on the covers. The concept aims to improve the user experience for operators handling the pot covers and improve the design for automation. This is performed by removing heavy lifting for the operators and assisting the automation of anode covering by eliminating the need for lifting whole pot covers during operation.

Section 5.1.1.2 | Closer look at hinge pin design

The spring-loaded hinge pin consists of two sections, the front containing an integrated torsion spring that is rotated with torque from a centred pin shaft, relative to the other, rear bearing section. The wedges on top of the pin are intended to slide in and out of slots in the outer sections of the hinges, making the pin detachable. Keep in mind that this is only a rough concept for early familiarization with the idea. See Appendix C for a thorough report describing how the hinge pin concept could be produced through additive manufacturing processes.



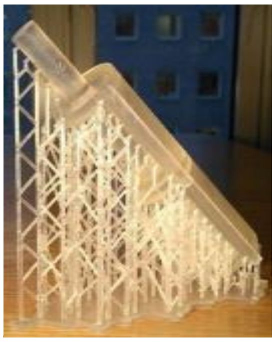


Figure 10: Cross-sectional hinge-pin prototype produced with VAT Photopolymerization. The prototype is made for physical evaluation of the prototype's structure. Here with support still attached.

Figure 9: Rapid hinge pin assembly. When the pot cover surfaces lay parallell to one another, the spring experience a 90 degree torsionional force. By pulling the pin shaft, the wedge on the pin's front section can slide into the free slot space marked with the red circle, thus releasing the covers from one another and still keep the spring tension. The spring remains loaded in the left cover untill the covers are hinged back together by an operator. Friction and bearing issues, damping and mechanical stops are in development.

Figure 9: Spring loaded hinge pin, enclosed (right) and cross-sectional (left). The front section contains the torsion spring, accumulating torsional energy between the front and rear section. The rear section contains a chamber available for potential viscous or friction dampening designs. The design is purely mechanical for better coping with the harsh environment.

Section 5.1.2 | Minimalistic pot cover concept

The minimalistic pot cover is a rough concept that aims toward a remake of the existing pot cover, only lighter and more functional, while still being cheap to produce. Excess weight can be eliminated by removing the unused handle, reduce the number of steps and perform topology optimization to get the cover as lean as possible without losing its stiffness and strength. Placing strategical slots in the step for operators to grab the pot cover by can improve balance and the ergonomics. The step can also be made curved on the edge to be more comfortable to place against the thigh when lifted.

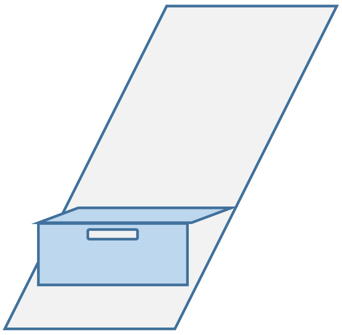


Figure 11: Rough sketch of the minimalistic pot cover concept. The handle and one of the steps are removed, and slots in the step is added for grabbing and moving the pot cover.

For automations sake, making the pot covers leaner and lighter will make the actuation less stressing on the system. It could also mean that it would be possible to increase the size of the pot cover, reducing the number of pot covers needed on each side of the pot. This would be beneficial in light of efficiency and that there would only be need for removing one pot cover at the time when operating in the pot. The redesign could also include a feature making it easier for a lifting mechanism to grab hold of the pot cover. This concept was not physically prototyped and tested in the thesis, but might be further developed during the master thesis.

Section 5.2 | Sensory concepts, testing and processing

We have considered sensory testing and processing to be our core research in this project. Based on our ideation from section 4 we take a closer look at 2D and 3D image processing in particular, due to the many applications and high gain. We also test price-friendly user-electronics, to evaluate potential gain from very affordable technologies. This is kept to range and thermal sensory.

We also look into what some of the state of the art thermal inspection technology can give us.

Section 5.2.1 | Image processing concepts and testing

2D image processing might in particular be a strong tool for quick identification of clues regarding the need for mass covering or detection of anodes, covers, yokes etc.

As discussed in section 2.1, among the key identification parameters are the visual signs of exposure of the anode and cracks in the crust. These signs stand out as areas of distinct colours, shades or topography, or a combination of these. We want to process images to find a way to detect these areas, or the transition between the areas and the ambient environment, with certainty. These will potentially be labels for mass covering need.

The covers and yokes have distinct visual features, whether it is brightness, shape or colour. In the following sub sections, we tried out some image processing algorithms for handling specific features.

Section 5.2.1.1 | Harris corner detection

The Harris detector is computed from image gradients, based on what is called an autocorrelation matrix or structure tensor, A:

$$A = \begin{bmatrix} \langle {I_x}^2 \rangle & \langle I_x I_y \rangle \\ \langle I_x I_y \rangle & \langle {I_y}^2 \rangle \end{bmatrix}$$

I_x and I_y are the partial direction derivatives according to an image patch over the area (u, v) of the image I. It will capture the intensity structure of the local neighbourhood to each pixel, and will from the eigenvalues of A be able to determine the corner strength of the evaluated area. Two large eigenvalues indicate a corner (Corke 2011). However, in the Harris & Stephens algorithm used below, this is solved with particularly computational efficiency, only finding eigenvalue equivalencies from the following equation:

$$C_H(u.v) = \det(A) - k \cdot tr^2(A)$$

The factor k is a sensitivity parameter. For a colour image, the structure tensor is computed using the gradient images of the individual colour planes which is slightly different to first converting the image to greyscale. In practice the use of colour defies intuition – it makes surprisingly little difference for most scenes but adds significant computational cost (Corke 2011).

Figure 12: Applied Harris corner detection algorithm on pot images in MATLAB.

The algorithm is robust to change in illumination and orientation; however, the detector is not scaling invariant. Therefore, the corner strength will ultimately change according to zoom and image resolution.

The green crosses on the image set in figure 13, indicate the image patch areas where corner strength according to a given lower sensitivity threshold (default 0.01) are shown ("Harris–Stephens Algorithm" 2016). These will only be detected in a specified region of interest in the images to avoid unnecessary computation and lower incorrect detections when processed in MATLAB ("MATLAB & Simulink" 2016). The images are processed from their greyscale variant and evaluated from change in brightness, and then the detected corners are fitted to the original images. A cluster of detected corners may be used to identify a crack area in the crust.

Section 5.2.1.2 | Red area tracking

In this section we use MATLAB to post-process arbitrary pot images and detect red areas. The image is converted to greyscale (intensity) form and the red stimulus is extracted and noise-filtered. It further extracts binary areas of pixels, where white pixels (pixel value equal 1) indicates luminance above a certain threshold, which here is equivalent to "redness" in the image. These areas are our detected areas of interest, and are visualized in the figure below. We can then call for pixel location of these regions. This can also be performed real-time, and we can then identify relevant areas continuously by processing images from a video-stream.

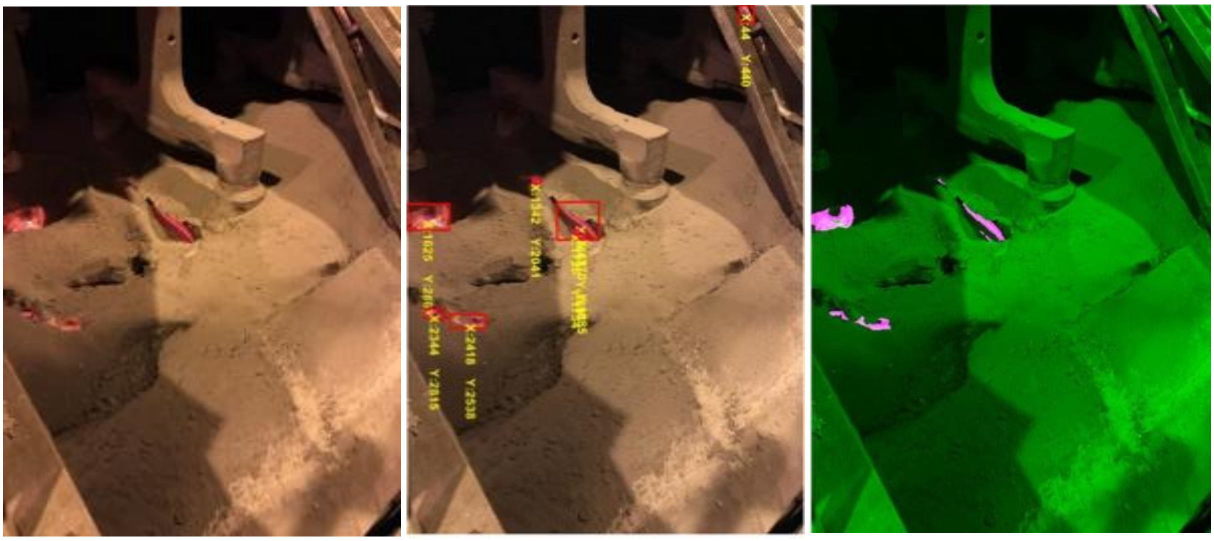


Figure 13: Left: Original pot image imported to MATLAB. Middle: Centred pixel location of the detected red areas. Right: Original and binary image fused to visualize detected areas.

Section 5.2.1.3 | Colour-contour detection

This algorithm builds on much of the same functions and code flow as the previous subsection, however parameters and the intent is changed. Here we want to detect covers, and we utilize the covers bright, reflective surface and extract the brightest pixels in the image, defined by intensity thresholds, and then set the remaining pixels to zero (black). This is illustrated in the upper right picture of figure 16. The cover stands out as the bigger object when converted to a binary representation, and we can detect the cover boundary. Neighbouring bright objects and varying lighting introduce errors in the cover boundary and

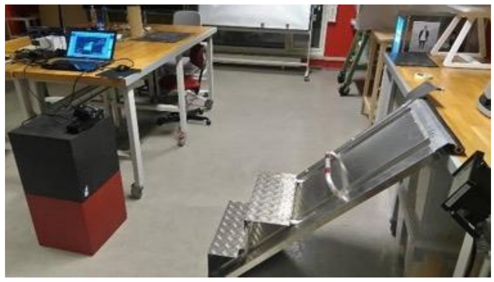


Figure 14: Cover-image-processing test setup. A Microsft Kinect V2 and a Grundig mini-projector are placed 1.5 meters from the cover handle, with the Kinect camera at about the same height.

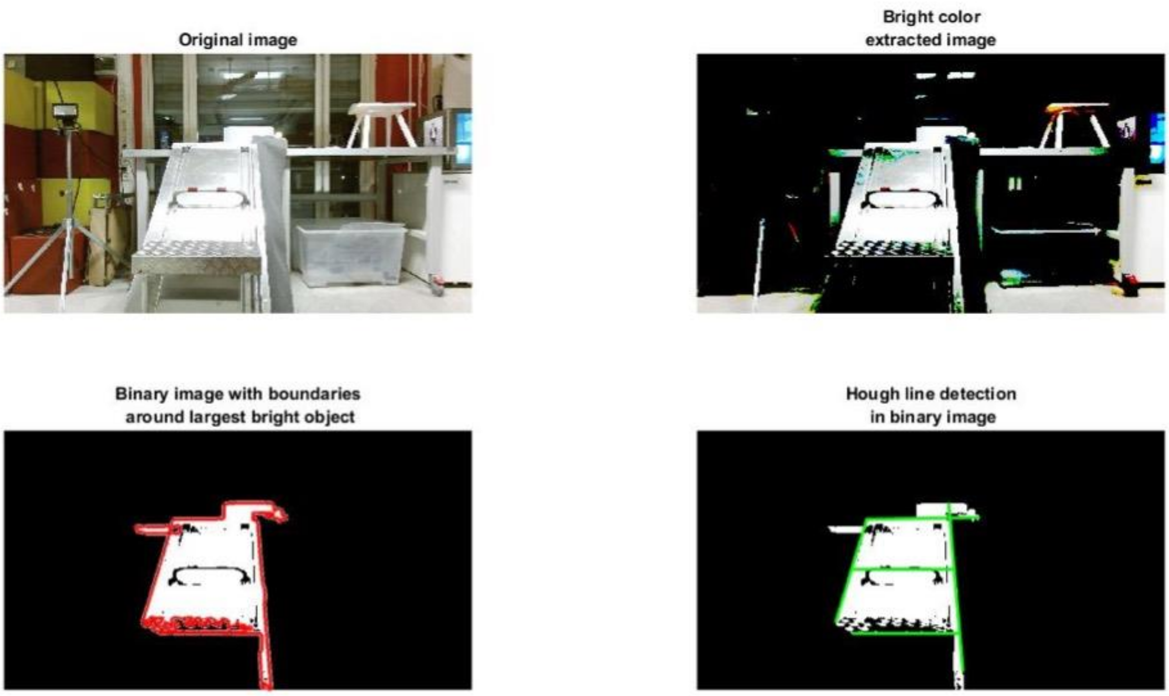


Figure 15: Contour and Hough lines related to the biggest, bright object in an imported image in MATLAB.

interior. A Hough line detection algorithm is applied on the binary image to try identifying the critical lines of the cover, also finding the distinct cover handle in the interior.

In the case when several bright objects are of interest, as for instance a rack of two or three covers in the image, we can choose to identify and process two or three of the objects in the image instead of just the one.

Section 5.2.1.4 | Important findings on image processing

- Harris corner detection is considered computational efficient whereas image feature detection goes.
- Harris responds poorly to change in scale and consistency between different camera views, however responds strongly to fine texture.
- We get consistent clusters of detected Harris corners around cracks in the pot. This is due to big changes in the local image area brightness. It still has a critical weakness of not being able to separate detected corner clusters from incorrect clusters. It does not handle scaled pictures consistently.
- Real-time analysis is manageable, and performed quickly on both corner detection and colour tracking.
- Corner detection, red area tracking and biggest object contour detection, do all have its clearly strongest responses when there is a direct FoV into the pot's interior or onto the specific object. This neglect irrelevant areas pre-processing. This is substantial to avoid excessive errors.

Section 5.2.2 | 3D computer vision concepts, testing and processing

3D computer technology has the strength of giving information of features in 3D space relative to the camera. In this section we look into how Microsoft Kinect V2 ("Kinect Hardware" 2016) was used as a 3D Camera test platform to process 3D scanned point coordinates. The point coordinates are arranged in a dataset structure referred to as point clouds (PC). The Kinect V2 uses the concept of time-of-flight (ToF) to calculate the distance from the cameras IR laser diodes to the reflecting object surface. The pixels in the IR camera are only susceptible for IR readings in phase with the light bursts

Figure 16: Anode covering mock-up. Centred view and +-35° side views from Kinect.

from the diodes, thus drastically increase the consistency and quality of readings compared to other ToF sensors.

Point cloud information ("3-D Point Cloud Processing" 2016) could be helpful in several of our problem areas, and can potentially prove to be a key sensor at several stages in the overall covering-process. We have looked further into what we think are the most central areas of gaining PC information, and also challenged hypothesises on the Kinects performance on pot related surfaces.

The principles described in the process list below have been tested in a setup at the university's robotics lab at IPK. A scaled anode mock-up was placed in a tub of sand on a table between two KUKA Agilus KR 6 R900 sixx robot arms ("KR 6 R900 Sixx (KR AGILUS)" 2016). For the scanning, a Kinect V2 was mounted on one of the KUKA's end-effectors to achieve the repose mentioned in point three in the process list below, accurately.

The scanned PC is first captured in the Microsoft 3D Scan app for Kinect (“3D Scan with Kinect” 2016), where it is noise filtered, then further post-processed in MATLAB.

Executing this process of acquiring and post-process 3D scans from the pot was first planned in the following order:

1. **Repose 3D camera to an optimal FoV.**
   Here again it is all about neglecting irrelevant objects in the FoV to a highest extent. Considering all pots to be somewhat equal geometrically, a manual one time optimal-view-calibration can be performed and will remain as a calculated guess of optimal orientation for later scans. Kinect V2 has an optimal performance range between 0.5-4.5 m, a horizontal FoV of 70.6° and a vertical FoV of 60° (Leif Erik 2015). It should be calibrated accordingly, and still neglect all but pot interior in the FoV.

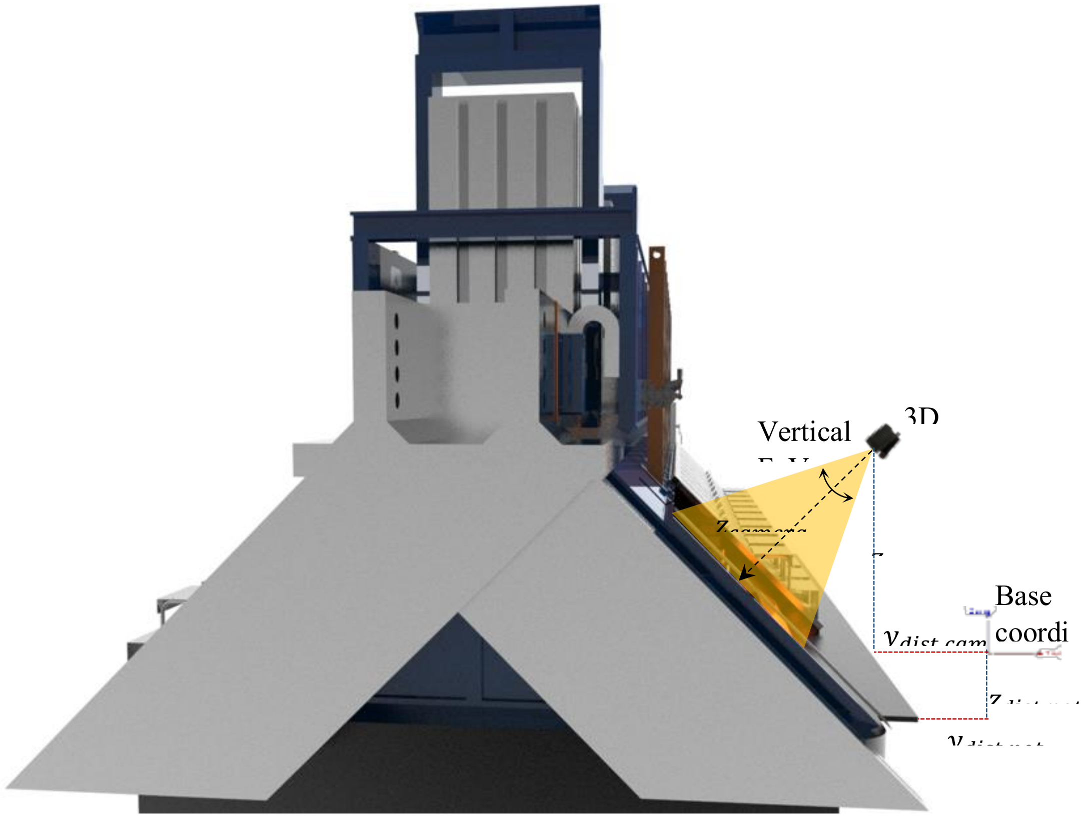


Figure 17: Optimal pose of camera relative to its base of operation, which again has a known position relative to the pots edge. The vertical FoV should be calibrated tangent to the pot opening, and the camera should be within the optimal performance range relative to the reflective surface.

2. **Find reference point and/or perform forward oriented scan.**
   This reference geometry could for instance be the yokes, as they don’t change much in appearance from scan to scan, and has a somewhat constant position relative to the carbon anodes we want to cover. Finding the exact, real pose of the camera relative to the yokes is essential for accurate anchoring and comparing the scan to the reference geometry. This could either be done by using some sort of alternative algorithm on 2D imagery to detect corner points, colour or lines, or some sort of labels from local pixel patches. Then these patches could correlate into respective pixels in 3D imagery, i.e. the scan. Reference geometry could ultimately be anchored to these labels and the scan-processing could start.

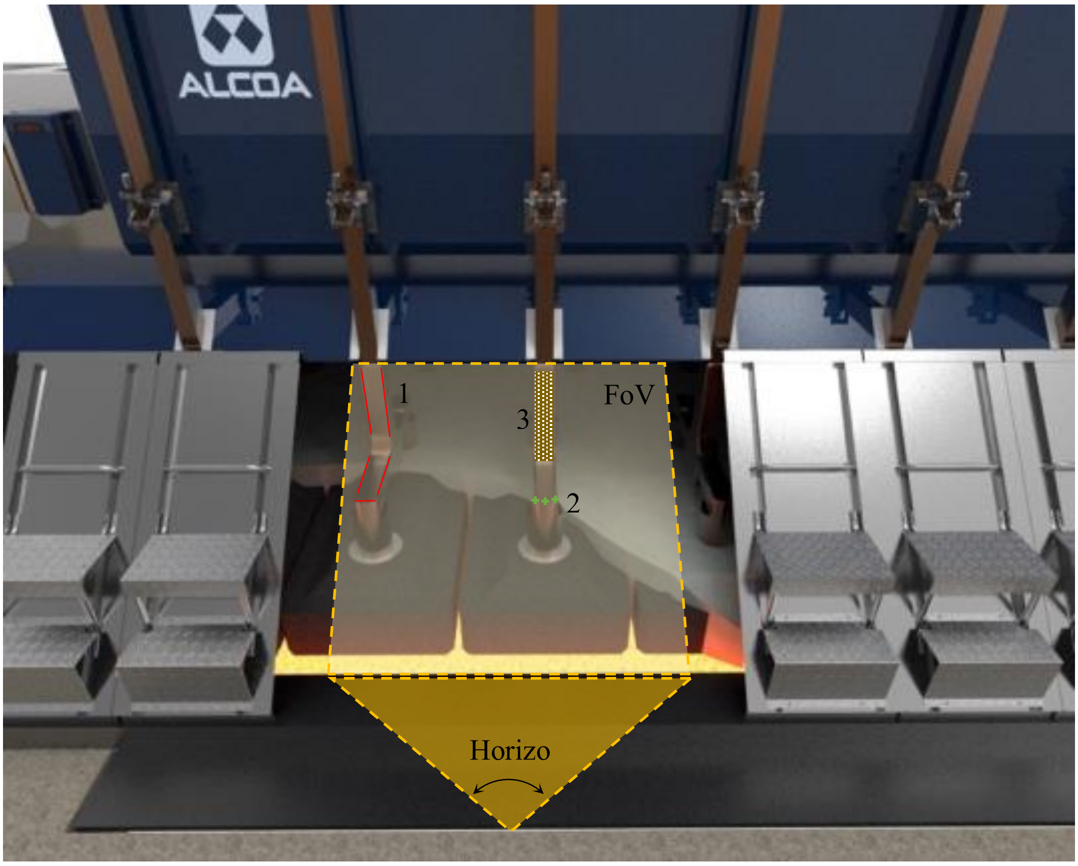


Figure 19: The field of camera view from the front of the pot. 1. Lines detected on yokes as labels for reference geometry. 2. Corners detected on yokes as labels for reference geometry. 3. The scanned yoke as PC, later fitted to a reference PC.

Alternatively, we can let the yokes be big labels themselves, include them in be scan, and challenge iteration algorithms to properly stich the scan to reference.

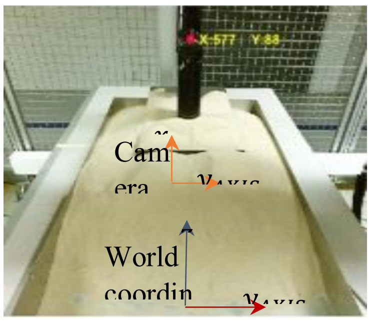


Figure 18: Red label on mock-up found in the forward oriented FoV with the red area detection algorithm in section 5.2.1.2.

3. **Repose camera for side view scan. (Optional step)**
In the case a scan does not have the desired quality to anchor it to reference we can choose to reorient the camera into 30°-50° offset, sideways scans. These scans can be transformed and finely stitched into the original forward oriented scan, thus enhance the saturation of points needed. We attempted this in two different ways.

In the upper plot in figure 21 we see an attempt of MATLAB using its iterative closest point (ICP) algorithm to find the transformation between the forward view cloud and the right side view cloud. The clouds are then plotted on one another accordingly. ICP solves an estimate for the transformation

$$T = \begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}$$

between the two points clouds, where R is the rotation matrix between the clouds and t is the translation vector (Bruno 2010). This is done by iteratively minimizing the quadratic error

$$e^2 = \frac{1}{N}\sum_{i=1}^{N} \|y_i - (Rx_i + t)\|^2$$

between the points in cloud x and y (Olav 2016). Big cloud scans, with many irrelevant points near the cloud boundaries, call for long processing time. The high amount of non-corresponding points between the PCs might make the ICP's quadratic error to not converge to a satisfying minimum.

The other approach is to first export the known transform between the PCs (read from the controller in our test setup) and then apply it on the right side view point cloud. Set in a familiar world coordinate system we could intuitively neglect irrelevant points for faster processing further on.

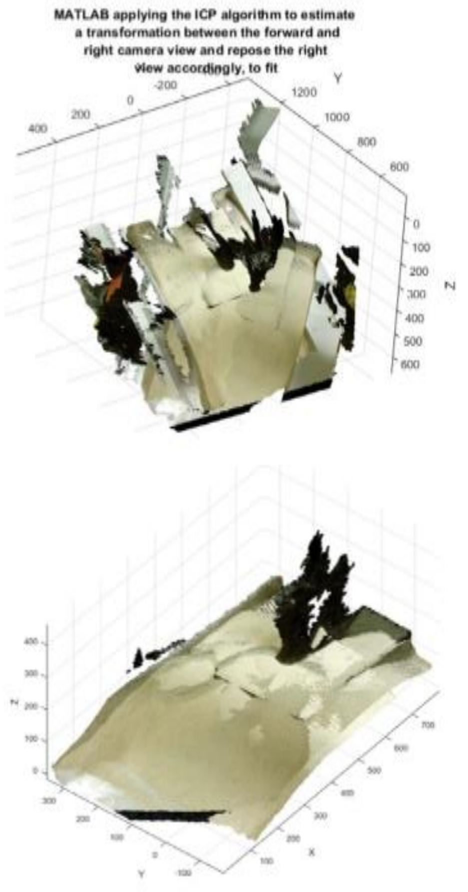


Figure 20: The upper merge is performed by the ICP function in MATLAB on raw cloud scans. In the lower merge, the scans are first transformed with a known transformation according to the robot arms joint angles to our familiar world coordinate system. The PCs are then roughly aligned and most of irrelevant points could intuitively be removed. Even for this approach we see a slight displacement in front. Axes in mm.

4. Post-process scan(s) and detect mass level or anode exposure.
Several post-processing approaches are described in the sub sections below. These will either try to find the locations of anode exposure or deviations in mass level.

Section 5.2.2.1 | Point cloud processing – detecting intersection of scanned PC and reference anode PC

When the scanned PC is satisfyingly fitted to a reference geometry, here a PC of the mock-up anode, we can look at the intersection between the clouds. The reference geometry is slightly bigger than its real, scanned version, and where the scanned PC is breached we have indicators of anode exposure. Even though this might in some cases indicate an exposure even though it technically is not, the cover in those cases would be so thin it would probably benefit from extra mass in those areas anyway.

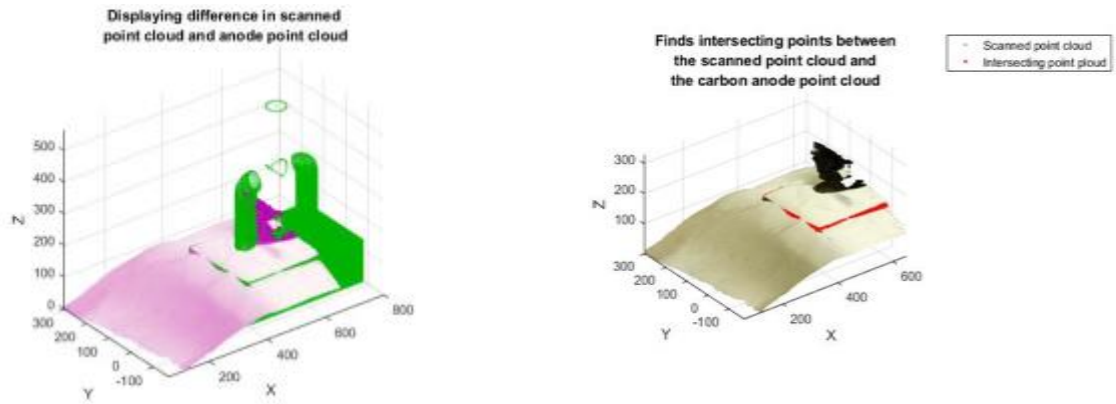


Figure 22: Scanned PC and reference anode PC intersected. The intersected areas could be isolated into separate PCs as shown in red to the right. Axes in mm.

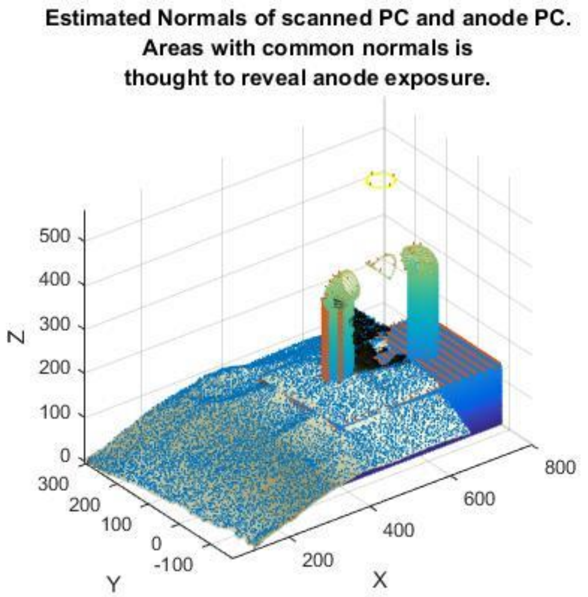


Figure 21: Display of normal vectors of both the scanned PC and the reference anode PC.

Section 5.2.2.2 | Point cloud processing – normal vector comparison of scanned PC and reference anode PC

When the scanned PC is satisfyingly aligned as reference geometry, here a PC of the mock-up anode, we can compare the PCs normal vectors. Areas of vectors in the clouds with common location and direction could indicate common surfaces. If the scan has a common surface with the anode reference PC, it could describe the location of anode exposure. Common normal vectors have not been successfully extracted in this demonstration. The scanned PC has a relatively high discretization error when compared to the real surface, but more importantly the density of irregular curves in the scan makes MATLAB produce local normal planes from neighbouring points (six by default) with high risk of error ("Estimate Normals for Point Cloud - MATLAB" 2016). Combined with the course set of vectors, we will experience excessive errors on a macroscopic scale which yield incorrect, non-intuitive vector orientations on surfaces that actually appears straight in the scan. Also non-straight grooves could falsely be evaluated as straight. This makes this specific demonstration very susceptible for errors with poor outcome at high computational cost.

Section 5.2.2.3 | Point cloud processing – detecting topological regions of interest relative to reference plane

Knowledge about the pots cover mass topology does not only tell us if there is a need or redundancy of mass or presence of cracks, but could ideally take us straight to the next stage and give us the location and even volume of cavities or bumps according to sets of preferred levels of mass, or *reference planes*.

The goal with this processing approach is to compare scanned PC with the reference planes. The references make out the boundaries for spaces containing points (mass) of interest. Points that for instance breaches the boundary of a horizontal plane atop the anode in an upwards direction will be isolated and split into a separate PC assigned as redundant mass. Opposite will points breaching the boundary downwards be isolated as a PC of cavities. These separated PCs could then be processed further to tell us the volume of needed or redundant mass, and the respective location relative to our known references.

In this demonstration the forward scan has sufficient saturation of points to be evaluated according to a tilted reference plane in front of the anode, with no further stitching of more scans. The reference plane is here manually fitted between the anode front top and the ledge in front of it.

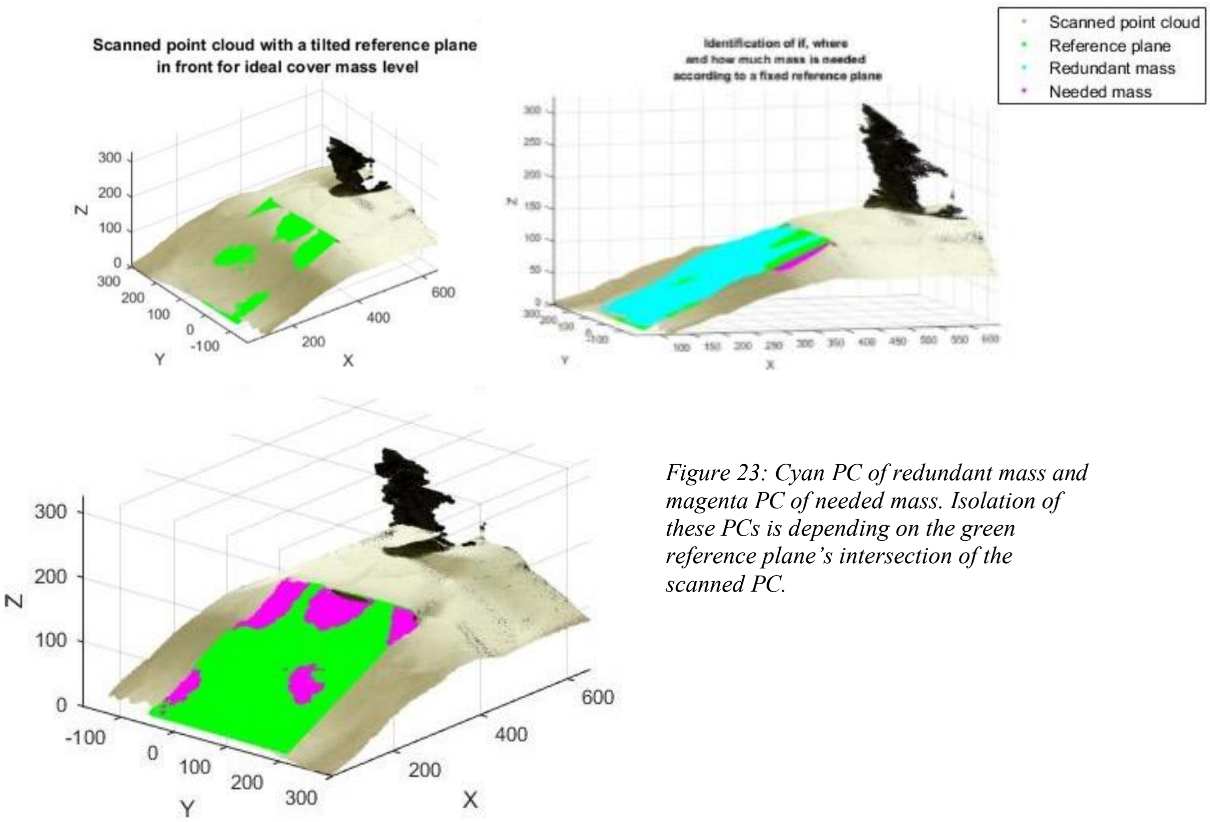


Figure 23: Cyan PC of redundant mass and magenta PC of needed mass. Isolation of these PCs is depending on the green reference plane's intersection of the scanned PC.

Section 5.2.2.4 | Point cloud processing – detecting coloured regions of interest

Another feature the Kinect V2 has is the ability to perform a scan with 1920x1024 resolution of coloured points. As in section 5.2.1.2 on red area tracking, we could utilize coloured features in the scan to find regions of interest, but now as points in 3D.

In this demonstration we have extracted those points of very dark colour in the scanned PC, into a separate PC, displayed in cyan in figure 25. Since the mock-up yoke and anode are both black, this method tells us the location of the scanned yoke and exposed anode. We can get this information from the scanned cloud only, with no need of comparing it to any reference geometry. The parameters could be tuned to colour thresholds more relevant to the actual pot environment.

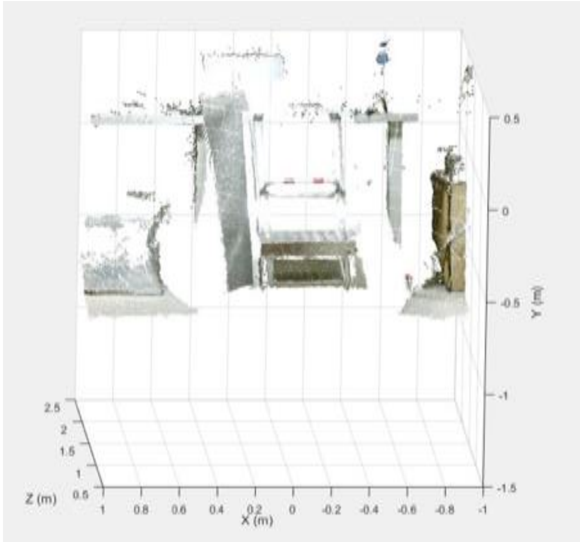


Figure 24: Points with specific colours could identify yokes, cracks or anode exposure.

Section 5.2.2.5 | Rapid pot cover scan with Microsoft Kinect

In our camera-cover test setup we also ran a test on scanning the cover with the depth camera and stream the PCs into MATLAB. A still image is shown in figure 26 when the camera is positioned in front of the cover as shown in figure 15 in section 5.2.1.3.

Here we clearly see how poorly the depth reading is when pointed at a very reflective, tilted plane. Next to all signals aimed at the covers surface are deflected. With rougher surfaces, some light is likely to return to the camera. When the Kinect is reoriented close to the cover surface's normal we get better readings, but a fully satisfying saturation of points is still not met. This reveals the Kinects vulnerability in scanning smooth, highly reflective surfaces.

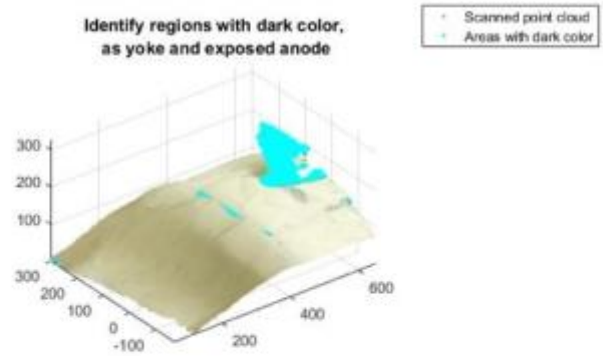


Figure 25: Pot cover 3D point scan with Microsoft Kinect. The image is taken from a PC stream to MATLAB.

However, the rounded cover handle stands geometrically out from the straight cover surface, and is likely to at least return *some* light to the camera at most camera orientations. This makes 3D camera also an interesting application for cover handle identification. Colour point detection from section 5.2.2.4 could potentially be used to identify the handle by isolating the red points. The estimated amount of red points could help us isolating a PC for the handle, and we will know its location.

Section 5.2.2.6 | Rapid scans of heated surfaces and flames with Microsoft Kinect

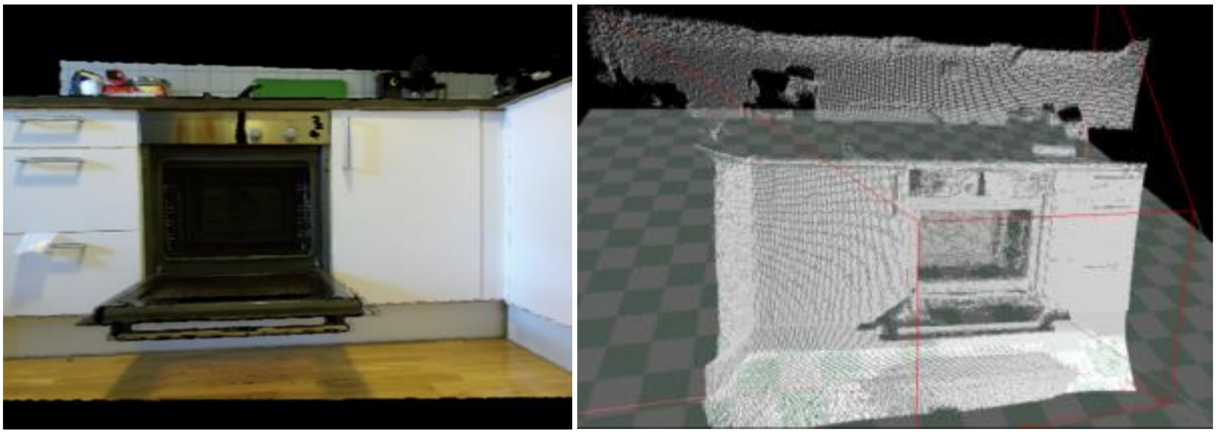


Figure 26: Microsoft Kinect placed in front of an open baking oven preheated to 250 °C. One can clearly see depth point readings from the heated interior of the oven.

The Microsoft Kinect was tested on getting consistent readings when certain objects, surfaces or scanned environments were heated several hundred degrees Celsius above room temperature. The rapid tests of depth reading in figure 27, 28 and 29 shows that the Kinect has potential of operating from an environment at room-temperature and being able to deliver depth readings from objects and surfaces at several hundred degrees Celsius. Flame torch in front of scanned surfaces does not seem to have any critical effect on the surface reading.

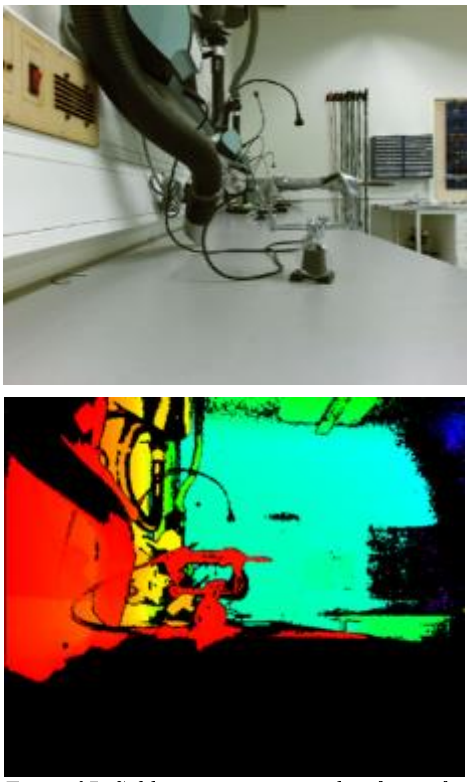


Figure 27: Soldering iron mounted in front of Microsoft Kinect and heated to 450 °C (top). Point cloud stream is shown with red indicating close distance and blue far off (bottom). The 450 °C tip of the iron is not neglected by the Kinect. Neglected areas are black.

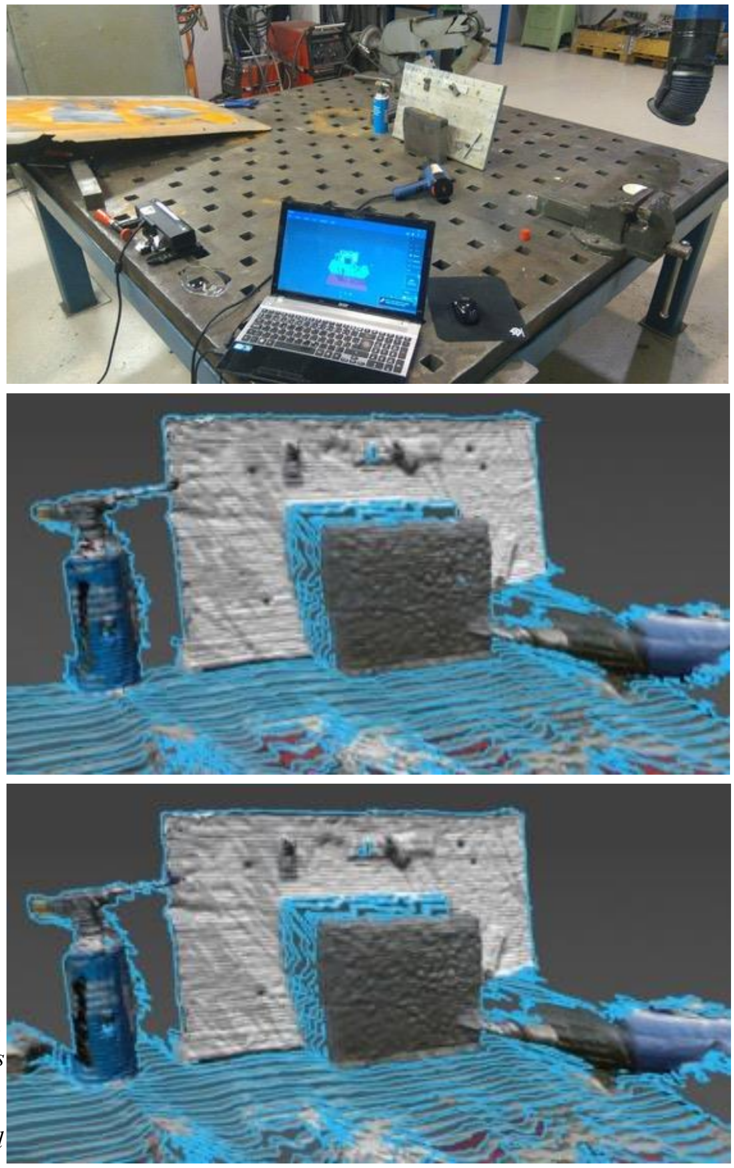


Figure 28: Test setup (top) for visualizing the difference between PC scan of surfaces at room-temperature (middle) and with a torch and warm-gun in front of, and pointing towards, the surfaces during the scan (bottom). Heated temperature is unknown. No critical distortion or neglection of points are noticeable on the heated flame-covered surfaces.

Section 5.2.2.7 | Important findings on 3D camera testing and processing

- Utilizing known transforms between different scan orientations seems to be accurate and computational efficient.
- A focused FoV into the pot interior is key to accurate and efficiently post-process, neglecting as much irrelevant data from the scan as possible.
- With the use of 3D scan and comparing it to reference geometry, we may calculate the amount of redundant and needed mass, and localize the area in the pot interior.
- Effective and accurate ways of merging 3D scans to reference geometry is a challenge.
- Utilizing colour in point clouds helps us with feature segmentation in the 3D scan dataset. We will then handle less data types when performing a 3D scan. This might lead to higher computational costs compared to similar algorithms in 2D image processing.
- Light-based depth sensor signals are mostly deflected on the aluminium pot cover surfaces when not close to the cover's surface normal. Appears to be a poor choice for identifying whole covers.
- Labels on the pot cover handles makes 3D camera applicable for localization of these.
- 3D cameras are susceptible to varying environment-temperature-related errors. The crystals performance in the IR-lasers is depending on the environment temperature (Kleppe interview,

Appendix D) (E. Lachat 2015) When the camera is isolated at an environment close to room-temperature, the hypothesis of 3D cameras having poorer performance at reading depth values from heated surfaces or interfering torch flames has not been visually disproved in our tests.

- Proper shielding of the device seems to be the key for consistent performance (Kleppe interview, Appendix D) (E. Lachat 2015).

Section 5.2.3 | LIDAR scan concepts and testing

Section 5.2.3.1 | About LIDAR Lite V3

This sensor device is based on the calculation of ToF, using the known speed of light. A near-infrared laser signal is sent and received after reflected off a target. It transmits a coded signature of laser bursts, and awaits the same signature in return, which allows for effective detection and safer laser power levels (LIDAR Lite V3 2016).

There are two different configurations for the LIDAR Lite V3, the inter-integrated circuit (I2C) or pulse width modulation (PWM). In our testing, PWM is used. Then the controller counts how long a voltage pulse sent from the sensor is high at a digital port, in microseconds. This time is proportional to the ToF, and a pulse of 10 microseconds is equivalent to a 10 mm distance reading.

Section 5.2.5.2 | Testing

We want to perform quick tests of hardware to get a take on consistency and frequency of sensor reading, how it manages different surfaces and mediums. Quick desktop tests show a very accurate and stabile reading, +- 1 cm deviation when standing still. We also have consistent readings during movement of both objects in front of the LIDAR and also when moving the LIDAR itself. GARMIN states in the FLIR user manual that non-linearity occurs below one meter, however this did not feel critical before distances below 15 cm during our tests. Closest depth reading stops at 4 cm.

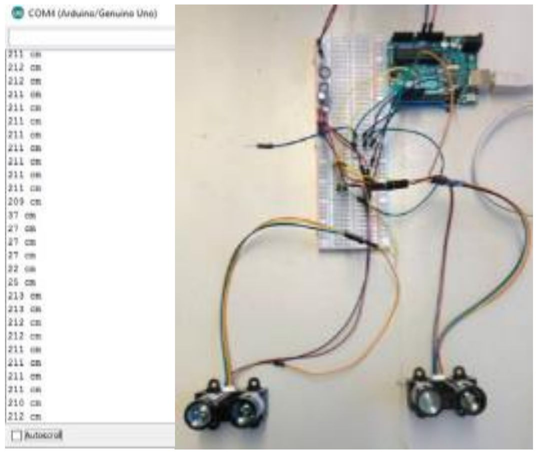


Figure 29: Two LIDAR Lite V3 hooked up to an Arduino Uno microcontroller for testing. Readings from one of the LIDARs when a flat surface is swiped above it is shown in the Arduino serial window to the left.

The LIDAR Lite V3 seems to cope very well with deflections angle when tilted, giving consistent reading all the way down to about 75° from the surface normal. It appears to be unaffected with transparent mediums interfering the flight of the laser, yielding good opportunities for shielding.

Section 5.2.3.3 | Potential applications

The frequent, accurate depth sensing from a LIDAR has several potential applications related to our mass covering challenges. Scanning whole surfaces accurately, i.e. looking for cracks and uneven cover mass could be tedious work for single laser point sensors, however finding key points standing physically out in the environment, fast and accurately, could be helpful. The following application takes into account the use of a LIDAR attached to an end-effector of some sort of manipulator with position feedback. This means we assume the LIDAR's position is known at all times.

Related to the problem on finding accurate key points for reference geometry as discussed in section 5.2.2 on 3D camera, we could benefit from fast, one-dimensional swipe scans to find accurate yoke positions. By cooperating with a camera, or based on position estimations and pre-calibrations, we can set a known LIDAR scan origin somewhere normal to the yoke rods surfaces in the pot-room opening. The rods square-like shape make them stand out in the pot room when doing a horizontal swipe scan from the LIDAR origin, located at a certain height. When rods are revealed, we can identify their current depth in the bath by doing vertical swipe scans down along the yokes at a certain distance. The yokes are all having a beneficial straight posture, so when the depth sensor discovers a steep change in depth when scanning downwards, we know it has reached the yoke buts. Doing this for all the

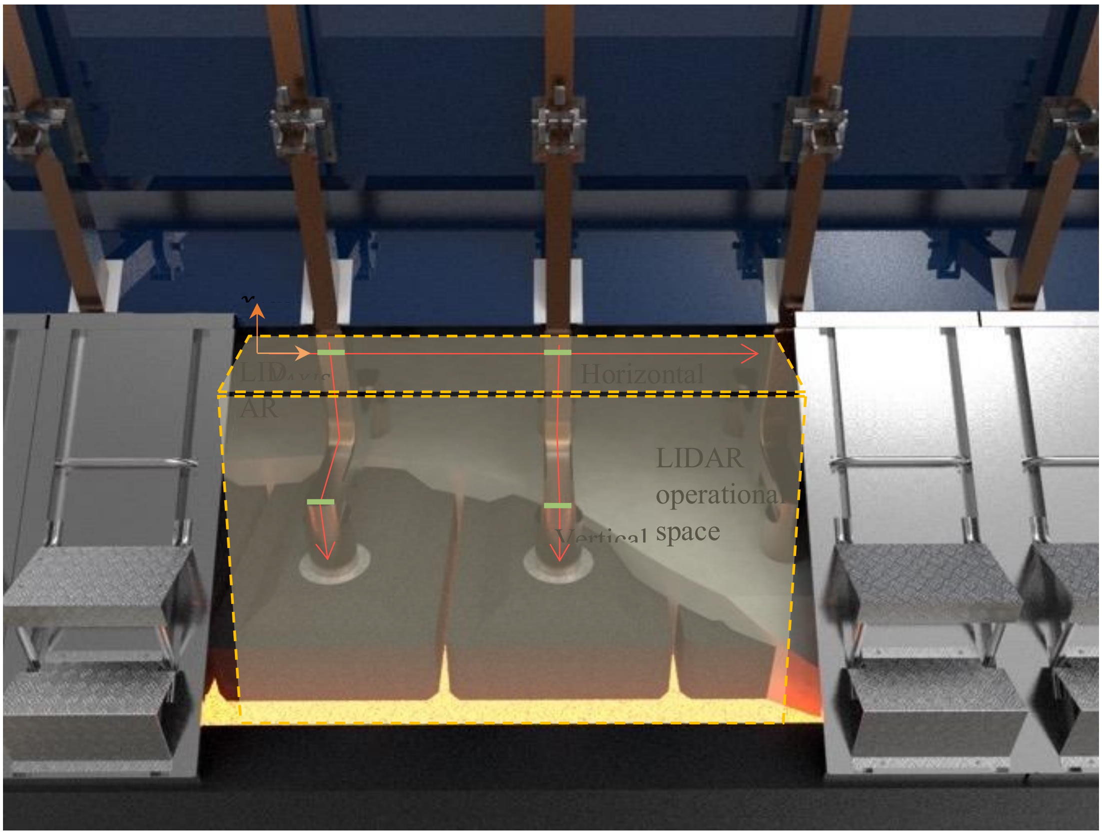


Figure 30: Yoke identification with LIDAR. First a horizontal sweep is made from the LIDAR origin, finding the rods (upper green labels). Next the LIDAR does vertical swipes accordingly, finding the yoke buts i.e. height of the yokes (lower green labels). From this we can get an accurate location of each anode in 3D.

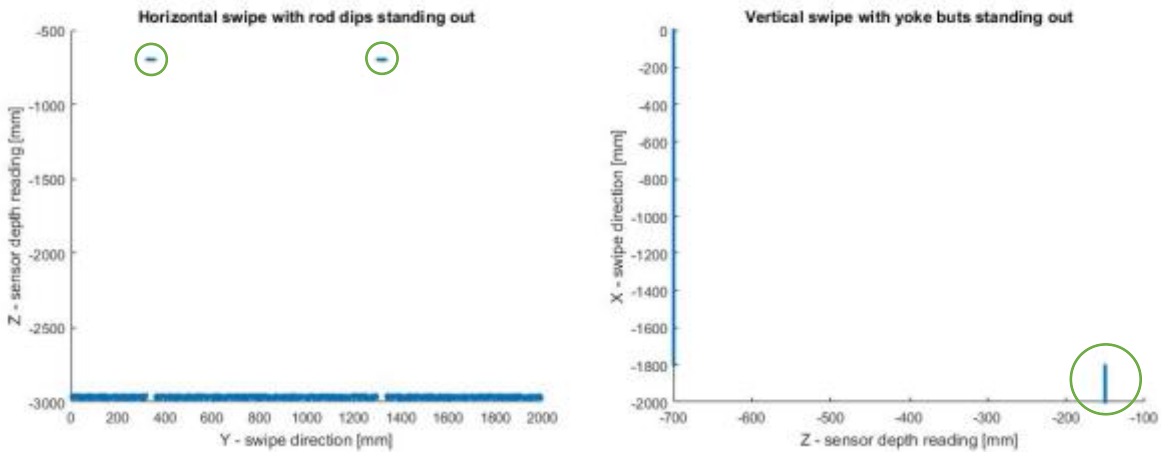


Figure 31: Yoke characteristics standing out in horizontal and vertical swipes. The readings we are looking for are marked with green circles. The blue lines are point depth readings. LIDAR origin at [X,Y,Z] = [0,0,0]. This figure is only an illustration, not based on actual data.

discovered yokes let us know the exact location of these in three dimensions. This concept is illustrated in figure 31 and 32.

We can then use software to calculate an optimal reference geometry for cover mass levelling based on the anodes relative height, and then anchor it to the known locations of the real yokes coordinate system. Next, we can for instance anchor a 3D camera scan to the reference, and compare them and evaluate the mass need. The long range of 40 meters makes the LIDAR-device applicable for actions well outside the pot interior, if only rough readings like just finding a yoke is needed. This makes it easier to avoid critical dust and heat exposure.

It is important to take into account the time needed to perform swipe scans over long stretches, at several yokes, and also the time in between scans. It is a clear trade-off, and attaching it to a position feedback manipulator could potentially be very expensive. A simple two-axis system should do for this type of actuation, unless the LIDAR device would be a part of a multi-configurative tool as discussed later in section 5.3.3.

Among other applications we have considered is combining two LIDARs mounted on a two-degree-of-freedom rotational joint made out of two servos making a 3D surface scanner. With the LIDAR we get a ray-reading of distance based on ToF of the laser reflection. This distance reading $\boldsymbol{r}$ may be generated together with the spherical angles $\boldsymbol{\vartheta}$ and $\boldsymbol{\varphi}$ of the LIDARs orientation in its reference frame. These angles may be found from servo angle readings in the sensor head. We can easily transform the spherical coordinates into Cartesian coordinates to get a detailed conception of 3D space relative to the sensor head. This space will then be generated from data points or vectors representing the LIDAR readings.

Alternatively, one could make the LIDAR point normally downward in the gravitational direction with the goal to sense the cover mass topography below it. This distance reading $\boldsymbol{r}$ from the LIDAR is then equal to the $\boldsymbol{-z}$ in Cartesian coordinates of the world frame (positive $\boldsymbol{z}$ pointing upwards). The $\boldsymbol{x}$ and $\boldsymbol{y}$ coordinates are found from applying linear actuators. The topography will then be generated from data points or vectors representing the LIDAR readings.

One can find more high-end versions with similar purpose to these concepts in products as for instance the SICK safety laser series (“Safety Laser Scanners / SICK” 2016).

Section 5.2.3.4 | Important findings on LIDAR

- Proper shielding due to temperature and dust sensitivity is vital for this piece of equipment. The long range gives us the opportunity to work outside such a zone, at the cost of accuracy when above five-meter distance to target.
- Gives consistent readings up to 75° deflections off the surface normal.
- A very responsive device in general, with +- 1 cm max deviations of depth readings when held still and connected to an Arduino Uno for processing.
- Works well through transparent mediums.
- Good at local point readings. Poor choice of equipment for big areas.

Section 5.2.4 | FLIR thermal camera testing

To identify cracks in the crust and anode exposure, a thermal camera could be utilized to highlight affected areas. Capturing thermal imagery from the pot and combine it with colour detection algorithms can yield accurate information related to which state the pot is in. Industry grade thermal cameras comes in a wide range of prices, starting at expensive. To quickly and cheaply perform tests, we got hold of a Raspberry Pi 3 (“Raspberry Pi 3 Model B” 2016) and a FLIR Lepton camera module (“FLIR LEPTON® Long Wave Infrared (LWIR) Datasheet,” n.d.) to get familiar with the technology. The FLIR Lepton module, seen in figure xx, is a longwave infrared camera, capturing footage at 80x60 pixels. The FLIR comes with a default recording software script for Pi which is modifiable through Python. When used with default settings, the camera outputs the highest temperatures identified in the scope of the camera in colours, rendering the rest of the surroundings grey. As default, it states nothing related to max/min measured temperature. Though the code is modifiable, it is also comprehensive, making it problematic to alter.

Figure 36: FLIR Lepton camera module and Raspberry Pi video test output

The FLIR was tested in a mock up pot environment, where heat sources were buried in sand with exposure to simulate cracks in the crust. The FLIRs ability to colourize only the hottest areas of the scope turns out helpful, minimizing noise from the hot surroundings. The camera also identifies four out of four heat sources with minor temperature differences.

Figure 37: FLIR visual results from mock up test of anode air exposure

To test the sensitivity of the FLIR, a heat gun and a propane burner was used and recorded with the Pi. The camera output differentiates between the heat from the gun and the propane burner, but identify both sources as hot. This indicate to some degree that the FLIR camera module can distinguish between high temperatures, but colourizing both despite hundreds of degrees in difference.

Figure 32: FLIR sensitivity test

Section 5.2.4.1 | Important findings on FLIR

The FLIR module lack valuable functions such as temperature tracking, it needs excessive additional programing to yield the most valuable data and has a minimal resolution of capture. The tests that has been conducted have therefore rendered the FLIR as a less obvious choice to investigate further in a master thesis. On the other hand, it has verified that thermal imaging can be utilized in the detection of anode exposures and crust cracks. Through contact with Alcoa, we have found that Mosjøen utilizes an industrial hand held thermal camera unit named Fluke Ti27 ("Fluke Ti27" 2016). More research regarding this camera system follows in the next section. Summarized, the findings from the FLIR tests are:

- Area temperature measurement is an important feature needed to identify and set reasonable thresholds for thermal capture.
- Setting reasonable thresholds will aid the removal of surrounding heat noise from the environment and make it easier to detect cracks and gaps.
- To be able to detect large as well as small gaps, sensitivity tuning of the camera system should be considered as temperature differences are expected.
- For optimal recording and accurate results, higher resolution camera capture would be ideal.

Section 5.2.5 | Fluke Ti27 and SmartView thermal imaging processing

The Fluke Ti27 is a state of the art thermal inspection camera in the lower price range. The model is handheld with low threshold for quick, manual inspections, mainly related to safety and cost saving inspections in the process industry, with an operating temperature range from -20 up to +600 °C. Cracks will then only be registered at a maximum temperature of a bit more than 600 °C, while their real temperature domain may actually be between 700-900 °C. This could make the thresholds for defining cracks from ambient mass not as striking as it really is, however, registered temperatures above what seems to be a 500 °C limit, defines a critical lack of insulating cover mass. This is based on visual evaluation of the reported data from the Fluke Ti27 in Appendix H.

Ti27 still has the feature of storing and transferring data for further analysis. In figure YY we see images from the quick report generator in Fluke's SmartView analysis software ("SmartView®" 2016). From SmartView we can export all temperature values with corresponding pixel values to text or .xml format, which will be the fundamental data for processing temperature based identification and localization of, for instance, crust cracks. Individual pixel temperatures are visualized in the 3D-IR plot in figure 34. This device fits well into a semi-automatic solution with human-machine collaboration. The hazardous process of acquiring image data could be automated, while processing the data externally could partially be handled by a human operator.

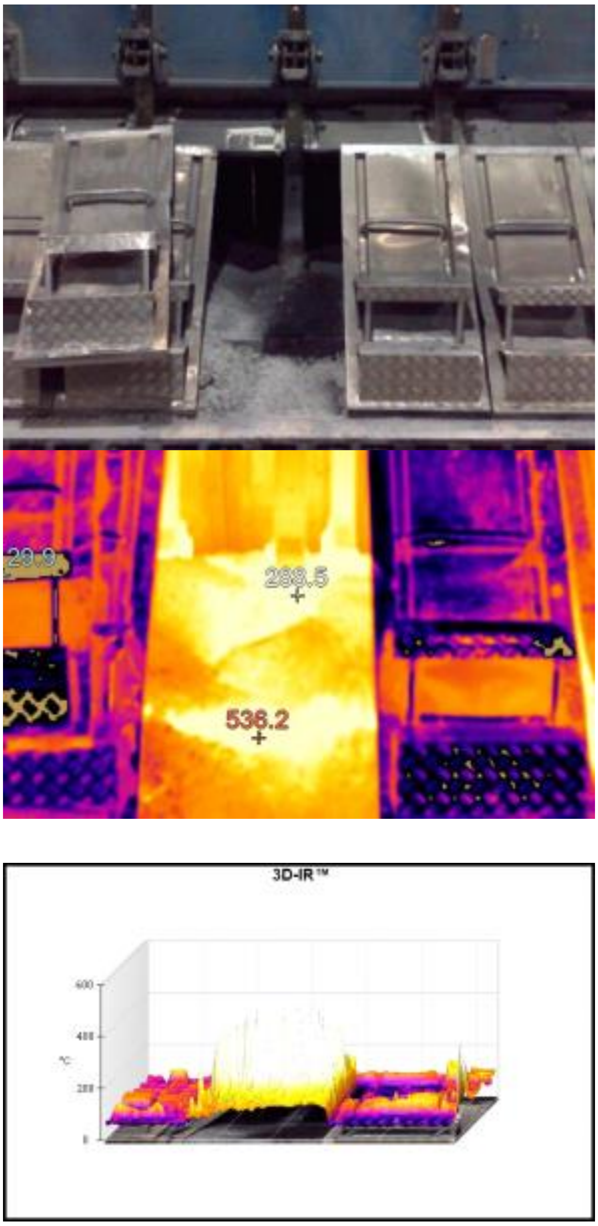


Figure 33: Fluke's SmartView post-processor. Maximum (red), Minimum and image centre temperatures are shown in the thermal image (middle). SmartView features 3D image plot of temperatures to evaluate the whole image visually by an operator.

Section 5.2.5.1 | Important findings on Fluke Ti27

- Temperature per pixel yields high resolute temperature datasets.
- It has a maximum temperature reading down to several hundred degrees below what is often the actual crack temperature (direct reading into cryolite bath). However, the device seems to be applicable for evaluating lack of insulating cover mass.

Section 5.3 | Actuation demonstration and research

Section 5.3.1 | Demonstration of cover mass distribution with KUKA Agilus KR6 R900 sixx manipulator

To get hands-on experience with industrial robots, efforts were made to get access to a robot rig for knowledge capture and testing. Not being able to get hands on pneumatic or hydraulic robots, we got hold of a set of KUKA Agilus KR6 R900 sixx manipulators at IPK. This type of industrial robots operates by electric actuators and would most likely not thrive in the environment of the potroom. Despite this, the KUKA robots was used in a rapid prototyping test session where 3D, 2D and thermal capture was tested in a mock up smelting pot setup. The robots were used as a place holder or representation for future actuation concepts to get an impression of what to expect in relation to:

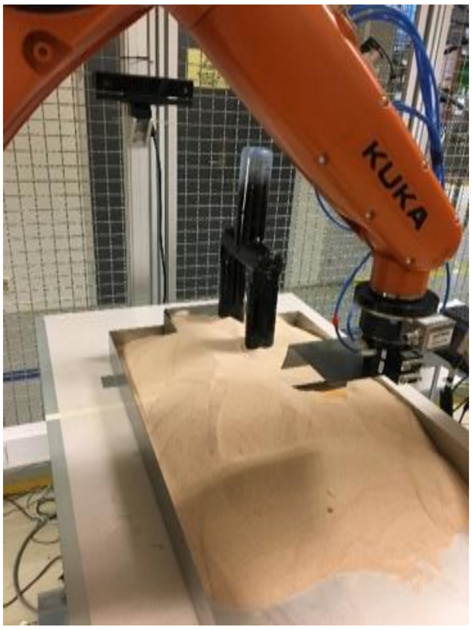


Figure 34: Demonstartion ofcover mass distribution with KUKA Agilus KR6 R900 sixx manipulator.

- Industrial robot precision and speed
- Industrial robot jogging and data system programming
- Weight and max momentum - what size of robot would be needed to perform the task
- Which degrees of freedom is sufficient to get the motions necessary to perform ideal anode covering
- What needs consideration when automating a robotic solution

During the test, the KUKA robots where jogged to perform a spotless anode covering and perform 3D image sweeps with the Kinect. Both yielded positive results without demanding considerable robot programming effort. During the test it was experienced that large momentums occur when the robot handled weight fully stretched out. This rendered the robot to lock down with a need of resetting. To ensure this does not happen in the potroom, over dimensioning pot actuator strength will be desired. It is reasonable to compare the KUKA robot experience with pneumatic and hydraulic industrial robots, as the main differences between these robots are the principles behind the movement, not necessarily the user experience or interface.

Section 5.3.2 | MRI Robotics – how to actuate in extreme magnetic fields?

A central question when discussing the actuation in the electrolysis pot is how the otherwise strong and precise electromechanical servo motor will cope when it is moving in the extensive electromagnetic field. As a benchmark to actuators operating under heavy electromagnetic fields we here take a closer look at research done on robots operating inside an MRI scan. The majority of MRI systems operate at 1.5 Tesla, though commercial systems are available between 0.2–7 Tesla (“Magnetic Resonance Imaging” 2016). Even though these robots perform gentle operations on humans, the actuators principle could be very relatable to our challenge.

Dan Stoianovici and his colleagues at John Hopkins institute in Baltimore writes about their use of robotics in MRI scans (Stoianovici, Song, et al. 2007). To cope with the environment their robot is first of all made out of non-magnetic and dielectric materials only, like plastics, ceramics, elastomers and so on. Earlier actuators for MRI used piezoelectric actuation, thus heavily limiting their operational space. Pneumatic actuation has barely been controllable.

Section 5.3.2.1 | Pneumatic stepper motor

In another paper Stoianovici presents his soundly controllable pneumatic stepper motor (Stoianovici, Patriciu, et al. 2007). Rotary discrete displacement is achieved by sequential pulsed pressure of three chambers ports moving an off-centred gearhead connected to a motor-shaft. The pressure is distributed remotely. Control is based on optic fibre feedback and regulated remotely with standard electric stepper indexers and motion control cards. Thus the motor is operating from air and light only.

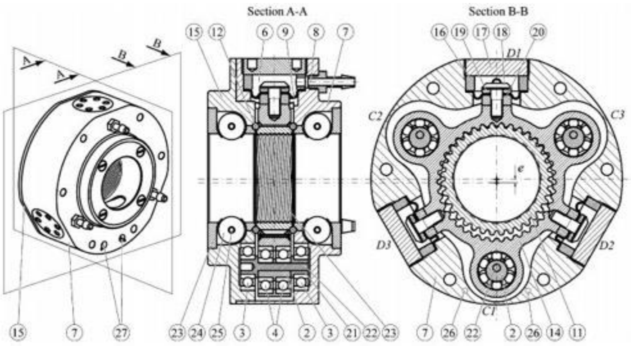


Figure 35: Isometric view and two cross sections of the pneumatic stepper motor. In section B-B we see the three chamber ports, the off-centred gearhead and the motor-shaft. This figure should only support the description in this thesis. Therefore, the numbers in the figure can be ignored.

The motor rotation is in direct relation to the number of input pulses, and its speed is related to the frequency of the pulses. Speed and torque will depend heavily on the performance of the pressure distributing system, and the motor is designed for slow-speed, accurate operations specifically. The motor holds its position under load without the aid of clutches or brakes. The design has several very interesting principles to handle actuation in magnetic fields that we may take into account for further research. This specific motor is not likely to suit our need, due its slow speed and light handling.

Section 5.3.3 | Tool-to-end-effector kinematics – design for tool and sensory collaboration

We may want to attach both tools and camera to some sort of manipulator with feedback control to get into the needed orientation for mass distribution or sensor readings. Finding an optimal FoV as stated in section 5.2 and 5.3 is one example where this is relevant.

Section 5.3.3.1 | Hand-eye calibration problem

In *A note on vision*, Egeland discusses the hand-eye calibration problem related to camera-assisted object-detection and -assembly, where high precision between the manipulator and handled object is needed. This problem is about finding the displacement from the end-effector frame of a manipulator, to the frame of a camera mounted on the end-effector. Frames are local coordinate systems, as mentioned in earlier sections.

We can relate this problem specifically to our image acquisition and camera scanning in section 5.2 and 5.3. When our camera need to position itself into an optimal FoV we need to take care of the kinematic challenge of getting the full transformation from the pot interior coordinate system p to our base coordinate system b, which is found to be:

$$T_p^b = T_e^b T_c^e T_s^c \quad (4)$$

Here we have e as the end-effector frame and c as the camera frame. T_e^b is found from regular forward kinematics and T_p^c from vision software, are both assumed to be known. Then equation (4) may be expressed as:

$$A_n X = X B_n$$

A and B are rewritings of the known transformations T_e^b and T_p^c, and $X = T_c^e$ is our unknown hand-eye transformation. X may then be solved iteratively with the least square sum for n different pairs of calibration (Park and Martin 1994). Ultimately finding T_p^b is a kinematic requirement for precise, closed-loop robotic operations in the pot. It may also be helpful if we want to merge a pot scan with reference geometry for mass comparison.

Section 6 | Discussion and evaluation of technology and potential applications

By picking our main battles; cover handling; identifying cover mass need; and actuation, we have focused on covering the technology we think has highest potential, still touching different price segments and complexities. How far could we get with simple device as a single LIDAR- unit, or how much did we actually achieve with the massive data from a 3D camera? We picked equipment that could potentially work together to achieve the best results or that could alone solve several of our problems, like finding both a cover's location and crust cracks.

We feel we have taken several concepts to a point where the equipment should be properly shielded and tested in the actual environment, to validate some of our current assumptions, or possibly reveal their deficiency on topics we have not yet thought of.

Section 6.1 | Fit our work to the actual process

Going through the overall process we discuss several alternative approaches based on our research.

1. **(Considered optional) External identification of cover need**
   This option to identify a need that has not been looked into in our project, however we think some of our concepts might be relevant for this kind of approach. We assume this will concern a permanent internal pot sensory device where robust, sophisticated shielding would be crucial for the device's operation quality and lifetime. We think the Fluke's thermal information technology is what would serve this purpose best. It is light-independent and way more position accurate than a single temperature probe, and resides within a product family with high commercial activity and development for similar environments. Temperature information could be monitored real-time with corresponding position estimates for an external covering unit to relate to. Overall it would depend on proper transmitting with a certain lifetime under these circumstances, which we consider this to be a long shot.
2. **Handle pot covers to get into the pot**
   This is a complex step where we think redesigning the covers current geometry would be very beneficial for automation purposes. Both reach, balance and weight are current issues, drastically increasing the spec of needed machinery for handling. Simple changes in the current features of the pot covers, as suggested in section 5.1.2, would at the least be a criterion for keeping the cover-handling hardware to the same price- and performance-proportions as the rest of the tech required in the remaining operations in the process. The hinged cover concept in section 5.1.1 will in theory, drastically decrease the need for heavy handling of covers and expensive, high duty actuators.
   Detecting the cover, we think is perfectly doable with either 2D or 3D readings. Detection marks might have to be applied, depending on chosen technology. This is also one way for the operating unit to also know where, and to where he is operating within the facility. This is logistics we have not gone in to, but could be valuable for efficient production planning.
3. **Identify need for covering**
   The best choice here would depend on further testing on what kind of technology would best cope with the actual environment after shielding. Both image processing and point cloud registration show promising ways of detecting the need, based most accurately on open crack colour. All vision based technologies demand a focused field of view into the pot's interior, neglecting irrelevant data from the view to a highest degree, for more accurate and efficient post-processing.

It should also be noted that the anode covering exceptions mentioned in 2.2 has not yet been taken into consideration when performing vison procession. However, this topic has been discussed in relation to Machine Learning (Kevin P. Murphy 2012) in Appendix E.

4. **Get knowledge on where we have too little or too much cover mass**
   We came far in processing point cloud data based on 3D scans with Microsoft Kinect to identify mass-need and -redundancy locations. This approach was based on comparing a scan to an ideal reference geometry in the processor. To get usable results from this, we need to fit our scan and references properly. Getting a proper fit is still an issue, but several ways where evaluated, where utilizing camera position feedback seemed most promising and computational efficient to generate the needed transform of scan and reference to a common system. Further testing using ICP on scans with more common points to the reference could benefit in a straighter approach to the same goal, however, we have not yet succeeded on this. It is possible that this process-step is redundant and overcomplicates the covering. We suggest however, that this stage poses the needed level of sophistication to hinder accidental over-covering, spill, dusting and most importantly: maintain a stable, well-executed covering with low emissions.
5. **Perform covering**
   This is likely to include some sort of pot room compatible manipulator doing controlled mass movement as mentioned in section 5.3. Further research on what compatible technology exists is the foundation for either moving further into robotics control, or potentially develop some sort of concept for a compatible manipulator, related to further research on similar topics as section 5.3.2.

Section 6.2 | Further work

The project thesis has been accomplished through a team effort with a joint final delivery. For the master thesis we suggest a collaborative project approach with a delivery of individual papers. With a root in the project thesis results, we see a possible two-split approach to the upcoming TrollLABS/Alcoa master thesis the next semester. By splitting into pot exterior and pot interior challenges in relation to the anode covering process, both students can benefit from the project thesis results. The selection of tasks has occurred naturally, as they coincide with the individual student's interest.

Section 6.1 | Pot cover design and handling – Even Jørs

This master thesis proposal addresses the exterior pot challenges related to automation of anode covering. The thesis can include research and development of one or more of the proposed categories:

1. Development of an improved cover design
   a. For automation handling
   b. For operator handling
2. Development of a lifting mechanism for cover handling
   a. How the cover handling can be actuated
   b. How should the lifting mechanism grab the cover
   c. Where and how will the cover be stored during pot operation
3. Development of the cover handling automation process
   a. Identification of cover location, distance, etc.
   b. Measures needed to perform the process autonomously

Important fields of study are engineering design, machine mechanisms and vision software. The two first tasks mostly concern design and machine mechanisms, while the third has a strong focus on vision software and program development.

Section 6.2 | Performing anode covering – Jardar Winjum

This thesis proposal wishes to continue the work regarding the mass covering in the aluminium pot, and more specific look deeper into actuation principles of moving mass. The thesis is thought to contain one or maybe two of the following main tasks:

1. Further develop vision software for pot environment, and specifically detection of cover mass level after a point cloud principle.
2. Develop and refine solution for importing data from the task above into kinematics algorithms for robot control. This will involve learning and usage of the open source Robot Operating System (ROS).
3. Continue the research from section 5.3.2 on environment compatible actuators, and develop a concept for the physical unit performing cover mass operations.
4. Demonstrate physically (or virtually) automatic mass covering with robotic actuation in test lab. The goal is to test potentially existing, compatible technology on actuation, and will be research driven. Point 1-3 will all be relevant research fields, along with trajectory planning.
5. Develop a fitting end-effector tool for cover mass handling for the task above. This goes further into the challenge of handling the varying mass consistency and surface hardness.

Important fields of study are robotics, control theory and vision software. The first four tasks revolve around this matter. Task 3 and 5 are more relatable to traditional product development. Prototyping, iterative testing and evaluation are expected in all tasks.

The tasks 3, 4 or 5 are the student's suggestions. The student then also suggests a "Wizard of Oz"-approach (Bernsen, Dybkjær, and Dybkjær 1994) for the other tasks in case its relevant to testing or demonstration of the selected task.

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