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Concept Development of Automated Unit Performing Anode Covering Operation in Aluminium Electrolysis Plant

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Concept Development of Automated Unit Performing Anode Covering Operation in Aluminum Electrolysis Plant

With a Heuristic Approach for Early-Stage Product Development in Extreme Environments

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Abstract

This thesis goes into early-stage (Fuzzy Front End) concept generation for comprehensive, multidisciplinary projects in extreme environments, such as a fully autonomous unit performing anode covering in an aluminum electrolysis plant. Through cycles of low resolution prototyping of product concepts and relevant environment effects, the author elaborates assumed objectives related to the operation and the hazardous pot environment. The development process applies high flexibility, with rapid, qualitative testing of prototypes. This may continuously change or dispose initial objectives for the product, as a natural part of the concept detailing. This guides the suggested product and operation concepts towards accomplishing objectives with sufficiency.

Norwegian Abstract

Denne oppgåva ser på generering av tidlegfase-konsept (Fuzzy Front End) for omfattande, multidisiplinære prosjekt i ekstreme miljø, slik som ei heil-autonom innretning for anodedekking i primæralumniumproduksjon. Gjennom syklar med lågnivå prototyping av produktkonsept og relevante miljøeffektar, utdjupar forfattaren antekne målsetningar relatert til produktet og eit utfordrande smelteomnsmiljø. Tilnærminga har høg fleksibilitet i utviklingsprossessen med rask, kvalitativ testing av prototypar. Dette vil fortløpande kunne endre eller forkaste initielle målsetningar for produktet, som ein naturleg del av konseptdetaljeringa. Dette leier dei føreslegne produkt- og operasjonskonsepta mot å nå målsetningane med tilfredsheit.

Preface

This master thesis was conducted as a part of the M.Sc program at the Department of Mechanical and Industrial Engineering (MTP) at the Norwegian University of Science and Technology (NTNU). The work is tied to the research group TrollLABS (supervisor Martin Steinert) and its understanding of the Fuzzy Front End of product development. The objective of the project was set in collaboration with Alcoa Mosjøen (Live Spurkland), which has been a central corporate partner throughout the project.

The master thesis is a continuation of a pre-master thesis written together with Even Jørs in the fall of 2016. The project thesis addressed research of automatization potentials in the primary-aluminum industry and is the foundation for this thesis.

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Abbreviations

Abbreviations here. This section is not mandatory, but can be very helpful to the reader. Please remember to always write the full meaning the first time you include an abbreviation.

ACU	Anode Covering Unit
AGV	Automated Guided Vehicle
DoF	Degree of Freedom
FEE	Fundamental Earth-moving Equation
MDF	Medium Density Fibers
NPD	New Product Development
RCC	Remote Center of Compliance

List of Expressions

Anode Change The operation at which a pair of used anodes are changed for new one. This involves applying a considerable amount of mass for covering the new, bare anodes with a 7-10 cm mass layer. Anode change happens with about 30-days-intervals for the same location on the same pot.

Anode Covering The physically covering of an anode with cover-mass.

Anode Covering Operation The full operation of physically covering an anode, from when the pot interior is accessed after removing the pot cover, to when it is ready to close the pot cover.

Anode Covering Unit The author's work title of the overall concept for performing anode covering automatically.

Compliance The ability of an object to yield elastically when a force is applied ("Definition of COMPLIANCE" 2017).

Cover-mass The gravel-cement-like mass used to cover anodes from air-exposure in the electrolysis process.

End effector End of arm tooling; generic term for all functional units involved in direct interaction of the robot system with the environment or with a given object. These include grippers, robot tools, inspection equipment and other parts at the end of a kinematic chain (Monkman et al. 2007).

Front Plate The plate the lower part of the pot covers are resting on. A part of the static infrastructure of the pot, and the lower edge when accessing the pot interior.

Joint Space The vector space where values of a robot's joints are defined (typically in radians (rotary) or millimeters (prismatic)).

Manipulator Robots with a fixed base. Consists of a sequence of rigid bodies (links) interconnected by means of articulations (joints). Holds an end-effector that performs the task that is required of the robot. (Siciliano et al. 2010).

Operation Environment The author's definition of a physical environment a certain product experiences during operation. Not to be confused with the computer software definition.

Operational Space The space in which the manipulator task is specified (Siciliano et al. 2010).

Over-covering When redundant cover-mass is left in piles or ridges where it potentially solidifies into crust, causing severe problems of later removing it. Normally refers to mass close to the yokes or the pot interior sidewalls.

Path A purely geometric description of motion based on a locus of points in joint space or operational space (Siciliano et al. 2010).

Pot Cover The aluminium covers separating the pots' interiors from the exterior environment (potroom). 26 for each pot.

Potroom The aluminium smelting hall.

Raking The current action of distributing cover-mass over the anodes using the rake-tool.

Trajectory A path where a timing law is specified (Siciliano et al. 2010).

Workspace An index of manipulator performance, which is the region described by the origin of the end-effector frame when all the manipulator joints execute all possible motions. Reachable or dexterous. The latter describing the region when attaining different orientations, while the former is the region reached by the end-effector frame with at least one orientation (Siciliano et al. 2010).

1 Introduction

Rooted in the early stages of product development, this paper discusses a heuristic approach for early-stage product development of an unmanned, fully autonomous unit performing anode covering in an aluminum electrolysis plant. The smelting pots are processing raw aluminum-oxide (alumina) into aluminum.

1.1 Background and Motivation

The corporate partner (Alcoa Mosjøen) in this project 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-aluminum production facilities have manual labor engaged in an extreme environment of high temperatures, molten metal baths and toxic gas and dust. To further improve their production, the corporate partner seeks to automate repetitive tasks in their production such as the anode covering in the smelting pots.

Key interests lay in highlighting automatization potentials within their facility, generally, and explore concepts to sustain production when saving workers from the harsh anode covering operation, specifically. All workers at the corporate partner seem to wish a fully automated concept for this operation welcome.

Anode covering is a crucial task that needs to be done to ensure an effective and stabile primary aluminum production. Since this process is not currently under development, the findings from this thesis will have high potential for sparking the further process towards implementation. This is also mentioned in the concluding statement to this thesis by the corporate partner in section 6.1. The master thesis will have no restrictions related to prior work on the topic, however will bounce with more thoroughly background information and problem findings in the pre-master thesis in appendix H.

1.2 Problem description

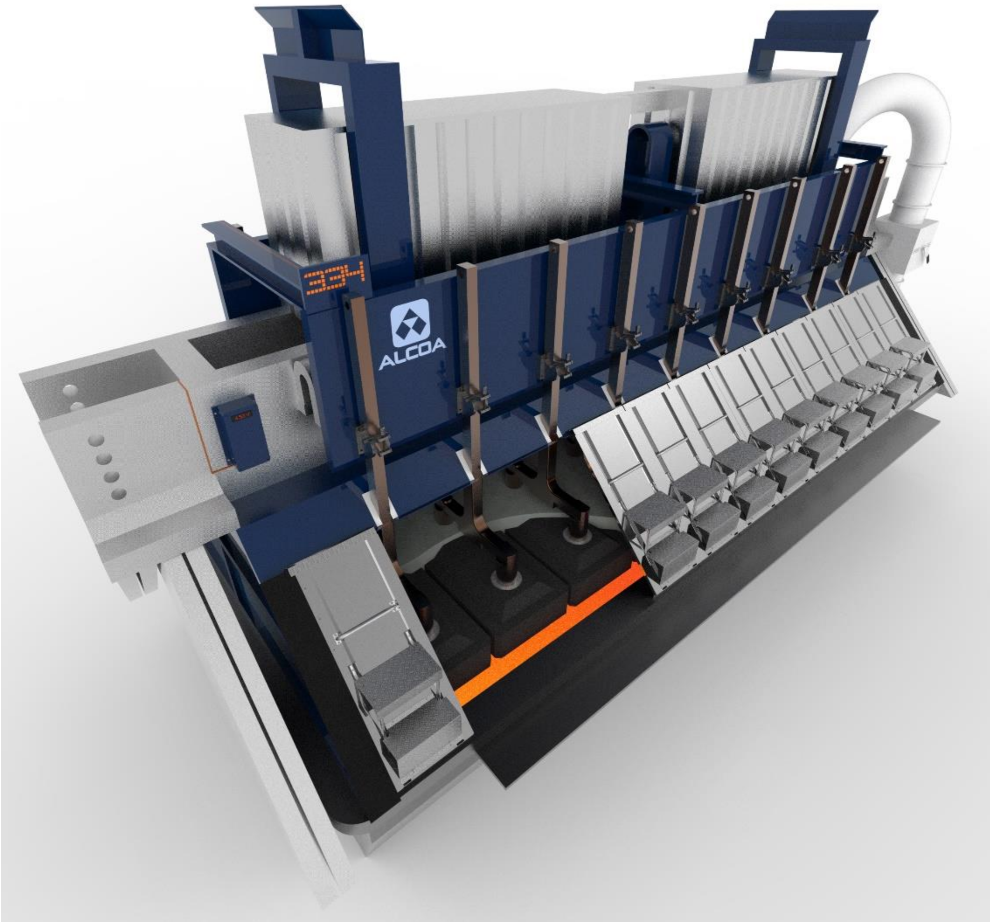

Figure 1.1: Modelled aluminum electrolysis pot where three pot cover are removed to reveal the pot interior. An intentional intersection in the cover-mass reveals the carbon of the anodes placed in the electrolyte cryolite bath.

In the electrolysis process in a primary-aluminum smelting pot, large carbon anodes are placed in a cryolite bath at high temperatures. Cryolite is a salt-based electrolyte where primary aluminum is produced from alumina. The anodes are covered with an alumina/sand/gravel mixture (from here referred to as *cover-mass*) for thermal insulation of the electrolyte bath and to prevent unwanted oxidation of the anodes. Oxidation will occur if the anodes' carbon is exposed to the surrounding air over time. The cover-mass hardens over time, with a rate highly dependent on temperature and frequency of physical interaction. The hardening is gradually, however being untouched for more than about five day makes the cover-mass turn into an extremely hard, concrete-resembling *crust*. As a part of the electrolysis process, the anodes' carbon is slowly sunk into the electrolyte bath by the attached, current-leading yokes, which are made from copper. The rate of changed yokes are about a month, and anode covering should be performed frequently within that timeframe. Mover information on the electrolysis process are featured in the first sections of the pre-master work in appendix H.

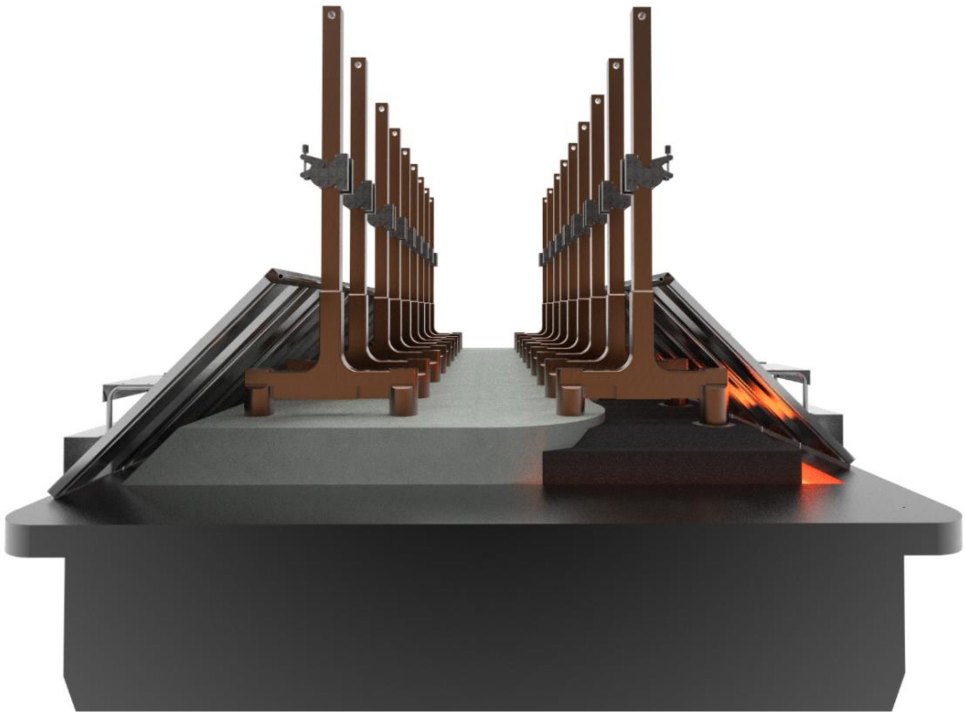

Figure 1.2 CAD of the pot interior showing the composition of anodes. Removed cover-mass reveals anode carbon to the right in the figure. Alumina-feeders stationed in the pot center are not featured.

The concept development of a fully autonomous unit performing covering of anodes with cover-mass was selected. This was based on the corporate partner's high motivation for exploring the respective field and the author's (the writer of this thesis) own argumentations on a relevant topic to extend from the pre-master work. The product concept for performing anode covering is from this point referred to with an abstract work-title: "anode covering unit" (ACU). The corporate partner introduced few demands but a desired mobility of the ACU, applicability to work at several pots without any stationary infrastructure. This is one of the most important qualitative restrictions set for the concept. An initial requirement list is featured is section 3.3.4.

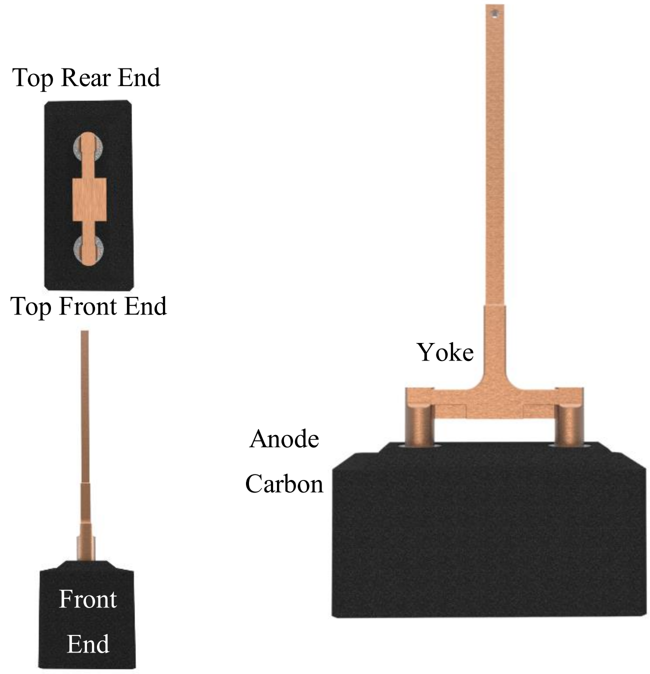

Figure 1.3 Anode geometry with relevant expressions.

The actions needed for covering anodes in a sufficient manner is from now on referred to as the *anode covering operation* or *operation* for short, which will be developed into an autonomous state during this thesis. Along with identifying product solution opportunities, defining the ACU operation will be a central part of this thesis' findings.

1.3 Research Questions

A couple specific research questions for the thesis are highlighted in the list below. These are compact questions also describing thesis' vision.

- **How can we generate relevant early-stage design concepts in multidisciplinary comprehensive projects with high uncertainty of applicability of the product's solution(s) and task(s)?**
- **How can we facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development?**

The latter question is also taken further in (Winjum et al. In press) found in appendix G, where this thesis is a central case-example.

1.4 The Thesis' Structure

Following this introduction, the reader may find an informal text on the thesis' approach in the concept development in section 2. Its focus fixed in the very early-stages of product development is compared to other state-of-the-art approaches in the same phase. How the thesis is built-on and inspired by established principles of early-stage development, and follows the approach of (Winjum et al. In press), is highlighted.

Section 3 looks at the different aspects concerning operation and environment of relevance to this thesis. A thoroughly go-through on the current operation of anode covering, what is considered most critical for automatization yields more information regarding the challenge. This escalates in the screening of immersion done at the corporate partner's plant in Mosjøen, before a set of initial requirements are stated along with key metrics that could be most relevant for the concept detailing.

The by far most comprehensive part of this thesis is the journey on concept detailing found in section 4. This section describes the chronological approach of elaborating objectives to eventually detail an overall product solution by highlighting and combining product solutions for different objectives parallel to clarifying the tasks that should be performed. The approach applies the principle of probing (prototyping) both the product functions and the relevant environment effects regarding each objective. Each objective provides an environment probe highlighting the considered relevant environment effects prototyped. Similar, a product probe is featured, providing iterations on product solution concepts aiming for the respective objective. The product probes tend to be the most comprehensive, and features analytic evaluation of the qualitative test made with the prototypes. The amount of content on each objective varies considerably, however this was intentional with respect to the development approach's flexibility in moving between objectives. Each objective contains a summary with the most important findings in a list-format. Section 4.1-4.3 goes mainly into the initial understanding of how a tool may be designed for the objectives and cover-mass interaction specifically. Section 4.4 and 4.5 feature more content related to robotics and control.

Thoughts on the development process, a general discussion on the concepts generated and what should be particularly considered further, is found in the thesis' discussion-section 5. The thesis rounds of with a concluding summary in section 6.

A large volume of support literature is found in the appendices, e.g. the pre-master thesis and the author's (in press) paper featuring the master thesis work as its main case-example. It is worth noting that referring to relevant theory, discussions of problems and design-build-test evaluations are done with respect to each individual prototype, and thus featured within the different probe and prototype headers.

For the corporate partner, section 4, 5 and 6 is likely the most interesting. The author's learnings tend to accumulate in the later sections.

2 The Development Process

Looking at the whole process of product development, the thesis' approach is concentrated in the earliest stage, most relatable to the Fuzzy Front End (Koen et al. 2002), (Edelman and Leifer 2012), (Leifer and Steinert 2011). The author applies much of the iterative generating and analyzing approach of Leifer & Steinert where low resolution prototypes of concepts are designed, built and tested with high flexibility (Smith 2007) and a multidisciplinary knowledge-set in mind (Gerstenberg et al. 2015). Section 2.1 highlights some of the different definitions and approaches of development in the very initial phases of a product development project. Section 2.2 explains the main aspects of the thesis' approach and relates it to other state-of-the-art approaches.

2.1 The Early-Stage Development in Different Approaches

The "Opportunity phase" or "phase 0" by (Ulrich and Eppinger 2012) shows several similarties to the approach of this thesis. Ulrich & Eppinger address this as an "opportunity tournament" arranged to feed the subsequent product development process with exceptional alternatives. The alternatives sprung from this phase are initially identified through a large set of "raw" opportunities, which have been filtered through exploration in order.

The well-established stage-gate approach, which is described by ("The Stage-Gate® Product Innovation Process | Stage-Gate International" 2017) as a business process and risk model of NPD. It designates its "Stage 0 – Idea discovery" to generate new ideas and weights discovering of business opportunities. Chronologically, this phase would be relatable, however differs fundamentally with its focus on risk governance and business output this early.

(Pahl et al. 2007) introduce several neat tools for arranging a general approach of developing a concept. Their ways of establishing function structures and methods for task clarification has been inspiring tools in the thesis work. However, their generally strict sequential approach of clearly defining a task, then designing concepts, were too rigid to pursue with certainty for this project.

Working toward conceptualizing automatization solution to be applied inside an aluminum electrolysis pot immediately set the spotlight on the environment aspect, and could easily be relatable to Design for X techniques that provide guidelines for developing a product for a particular life-phase or virtue (Holt and Barnes 2010). Such virtue for this project could be “design for extreme environments”, where conditions meeting this definition of environment-type is discussed in (Winjum et al. In press). However, due to the loads of uncertainty of tasks and conditions, a prototype-driven exploration of functional sufficiency in product solution versus relevant environment effects has been pursued at the benefit of the more optimization-minded Design for X approach in this early phase.

2.2 A Heuristic Approach for Early-Stage Product Development in Extreme Environments

This approach is taken from (Winjum et al. In press), where the research question of how one may facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development, is asked. The paper leans towards anticipated problem spaces for products in extreme environments, discusses the definition of “extreme” for such case, and suggests an approach to detail early-stage product concepts for such contexts. This is partly based on the works in this thesis.

The aluminum electrolysis pots provide unclear conditions. It is an extreme, varying and complex environment for an autonomous product to interaction with. This project is a case where it is particularly hard to know or learn the required amount about the conditions prior to the product development. This makes it challenging to clearly defined tasks and identify opportunities for relevant product solutions. There are little to no data about the conditions, and which acquiring is likely to demand considerable efforts for legitimate specifications in the early stage. The relevance for defining an operation for anode covering would also be uncertain.

Additional to the hazardous operation environment, the tactile conditions for an automated solution to interact with are particularly demanding, with many exceptions and generally high, physical uncertainty, seen in a robotics context. How much of the current operations for anode covering is highly based on human intuition is thoroughly highlighted in section 3.

The main aspects of this approach lay in defining an *overall objective* for the project. By *probing* the overall objective, numerous new objectives may be defined or *elaborated* from its parent objective. Applying probing on the different objectives may lead with it product solutions, a new objective, or maybe a new understanding of the environment and its interaction with the product. This shows the importance of having a focus on the operation environment, which must be consistent to properly evaluate product sufficiency. Therefore, the author chooses to explicitly probe both the product and the environment in the pursuit for understanding how the environment and the automated product may interact. The content of probing, product/environment prototypes are highlighted in the following sub sections.

2.2.1 Probing

The term "probing" is adopted from (Gerstenberg et al. 2015) and is inspired from the model stated by (Leifer and Steinert 2011). It explains how asking generative design questions (GDQ), based on a few known design requirements, is a way of divergent thinking. This should widen the specter of design concepts, before asking the deep reasoning questions (DRQ), which converges toward design decisions from analytic reasoning. Gerstenberg and his colleagues emphasize the multidisciplinary dimension in the iterating process of designing, building and testing concepts. For the disciplinary complexity provided in this thesis, keeping an open mind and vigilant look for different disciplines' relevance in the different objectives, will been crucial.

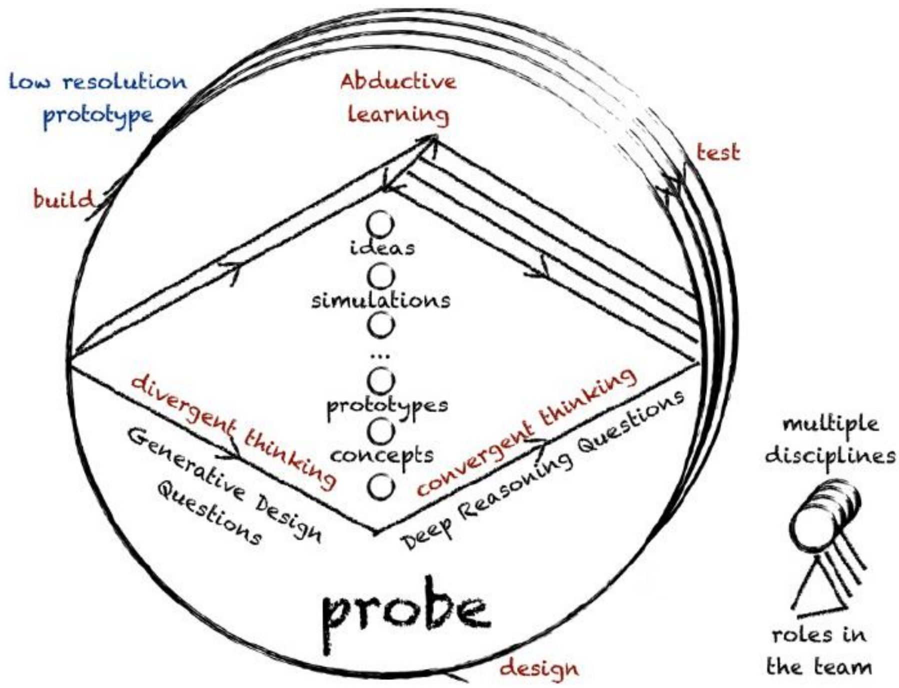

Figure 2.1: Probing cycle adopted from (Gerstenberg et al. 2015) as seen in (Winjum et al. In press).

The main purpose of probing is to find solutions to the evolving problem by abductive reasoning and to continuously update the understanding of the problem. During probing of objectives, one of the most important mindsets is to be opportunistic, to find, recognize and take chances that present themselves. Another benefit is the possibility to abandon disadvantageous concepts, "dead ends", in an early stage at the lowest cost and involvement possible.

The way of exploring and experimenting in this thesis are heavily inspired by the definitions of (Smith 2007) on experimentation. He defines it as "learning by trying out things" or "the process of an action followed by an observation". The author wants to underline that "learnings" in the context of this thesis are not necessarily isolated to output from testing, but that the design-build-test approach supply learning outcome in all the steps, from the very moment a concept is thought of, till it shows its potential in a prototype and is potentially iterated. Inspired from the prototyping approach by (Leifer and Steinert 2011), the author strives to accelerate the learnings in the objectives early through low resolution prototypes, preferably in a tangible form. Leifer & Steinert states further interesting examples of what a prototype might be in this phase. A prototype may take the form of *sketches and figures* to communicate the concept; as *models* to convey external properties; or as *functional* prototypes in the sense of letting us observe its achievement or failure of an objective. (Smith 2007) generalizes the actions of prototyping above as "kinds of experiments", exemplifying many relevant actions applied throughout this thesis.

The author prefers adopting an agile way of exploring concepts, not just within a probe regarding a specific objective, but also between objectives. One could then remain flexible with respect to the overall objective and the overall concept of a product that goes with it. In this thesis, succession of probing an objective does not necessarily involve continuous converging on a solution until sufficiency is proved. It may rather be based on that:

- Sufficient knowledge on feasible product solutions is generated to proceed with another objective. It is desired to preserve some ambiguity within the probing of the different objectives to remain flexible in pursuing a concept for the overall solution (Leifer and Steinert 2011), (Smith 2007).
- New findings/observations downgrade or eliminates the value of proceeding probing on the current objective.

- New findings/observations introduce objective(s) of higher priority that might radically change the overall solution, and should rather be pursued.

To some, this may resemble the Go/Kill/Hold/Recycle decision-making in the stage-gate approach ("The Stage-Gate® Product Innovation Process | Stage-Gate International" 2017). However, decision-making is per definition not executed in predefined stages in this thesis. Rather, high flexibility is adored. (Smith 2007) suggests experimentation as a perfect fit for dealing with uncertainty effectively, and thus introducing flexibility in the development process where objectives and functions are prone to change throughout the project.

The author sums up the probe with four important aspects:

- Ask DGQ to generate design concepts from initial requirements or tasks, then converge to design solutions by asking analytical DRQ.
- Preform iterative cycles of diverging and converging on concepts.
- Concepts are evaluated through a design-build-test approach with low resolution prototypes.
- A multidisciplinary approach towards the solution space is beneficial for understanding the roles of the different disciplines in the product solution.

2.2.2 Product/Environment Prototypes

How product prototype models and the test environment models are entangled has been researched by (Tronvoll, Elverum, and Welo 2016). They point on how the iterative design-build-test cycle also applies for improving the test environment, not only the product. This way, they see a confidence-increase in the test results. Prototyping the environment and possibly iterating it, is a central part in this thesis.

Further approach for interpreting the extreme environment is founded on much the same idea-set as *set-based design*. (Smith 2007) compares point-based design – where the perceived best course is selected, to set-based design, which maintains options and possibilities to preserve flexibility. The emphasis on evaluating constraints separates set-based from point-based. Smith exemplifies this difference through a mountain hiking analogy, where set-based hikers typically spend time understanding the terrain, as opposed to the point-based hikers following a map straight to the nearest peak. This focus on constraints is central in the thesis approach, however imposing clearly defined constraints as Smith suggests, is not easy when dealing with environment uncertainty.

Applying extreme environments to the analogy, constraints of different levels are all that surrounds the hikers. Mud and snow-shelves may be mapped constraints by the set-based hikers, however if snow and mud is all that surrounds the mountain-top, finding a clear path is hard and priorities must be made. The author suggests to continuously evaluate what is essential to reach the top. For the hikers, crossing mud-land may be essential to continue upwards, at least. The author suggests then poking a stick into the mud to check the depth. Maybe through in some wood or stones to jump to help then jump across. Quickly checking how wet the mud is may help them decide to walk across. How their perception of the challenges might change is intriguing to relate to as a developer in the early-stages.

Continuously experiencing and evaluating the environment in such a way generates valuable knowledge to traverse the environment challenges. The focus on constraints through explorations makes the developer better equipped to debate and evaluate its opportunities when elaborating on loosely-defined objectives. The approach is resembling the approaches of wayfinding or wayfaring, described in (Edelman and Leifer 2012), (Leifer and Steinert 2011) and (Gerstenberg et al. 2015).

3 Aspects of Operation and Environment

In this section, the most important aspects of the current (AS-IS) operation of anode covering is considered. The pre-master thesis explored the pot environment and potentially applicable technology for all the different aspects of automating the currently fully manual anode covering procedure. Potential sensory solutions for comprehending the cover-mass surface, identifying pot covers for automated interaction, along with concepts for altering the pot covers, were particularly highlighted.

The author will next highlight the most prominent challenges regarding automatization in the pots' environment. This involves both the demands regarding the space-boundaries and the extreme aspects of environment conditions. Appendix A features the author's initial thoughts on the automatization potential of the anode covering operation. These were reflections based on the pre-master work on how the operation may be decomposed into potential objectives for the ACU. From this discussion, an *overall objective* for the product concept considered in this thesis, is established.

A statement of the overall objective initiates the probing on product and environment conducted at the corporate partner's aluminum electrolysis plant in section 3.3.

3.1 The AS-IS operation of anode covering

The AS-IS operation of anode covering is described in a chronological order in section 2.2.1 in appendix H, based on information of the routines of anode covering at the corporate partner. Its central role for understanding what actions are involved to perform "sufficient" anode covering, calls for a review in this section.

The anode covering operation is a sequence of loosely defined tasks where a worker manually check and distribute cover-mass on-top the carbon of the anodes in the pot. Initial actions by the worker, such as *accelerating the ventilation* and *removal of pot covers*, are not a part of this thesis. The automatization potential of the latter concept is soundly research in the master thesis by M.Sc student Even Jørs, previous partner on the pre-master work. Succeeding these actions, the worker should pay attention to the state of the anodes and the cover-mass, and whether it is necessary to proceed with mass distribution to cover any potential exposure of the anodes or visual cavities into the pot's bath. This unfortunate but unavoidable occurrences are based on deviations in the cover-mass layer, from what is ideally an even layer of mass with 7-10 cm margin normal to the top on the anode's carbon.

These deviations do normally stand out visually as significantly uneven terrain, exposed carbon, or glowing cracks in the crust due to the continuous lowering of the anodes into the bath. The presence of such deviations qualifies for covering, and the worker normally initiate this by using a rake to *shove mass from the exterior front plate of the pot, thus cleaning it from spilled cover-mass.* This redundant mass is often *pushed towards the anode's top front* to prevent frequent anode exposure in that area. Next, the worker evenly distribute mass from loose cover-mass into cavities, ideally levelling it with the 7-10 cm thickness buffer, or at least visually covering it. Generally, this is referred to as *raking*.

Anode exposures or cavities are likely to appear near the anode sides, front and back, as the anode is lowered into the bath. Particularly in the front and the back it is common with a natural slide of newly applied mass into the bath or front plate short after the first insertion of an anode. Cover-mass on the surface often appears as small tops or ridges in areas that has not sunk into the bath together with the anode, and may occasionally have partly solidified into crust. In the rare, unfortunate case of loading too much mass onto the anode after the anode change, *over-covering* occur. This scenario is featured among the profound errors of anode covering in appendix B.

In the uncommon case of a general lack of mass to fill in the cavities, the worker feeds alumina from one of three different tap points in the pot, and distributes it using the rake. The worker regulates the fed amount manually with valves in the pot ceiling.

As mentioned in the thesis-introduction, a critical feature of the cover-mass is its tendency to harden into a concrete- or ceramic-like crust when heated over time in the pot. The cover-mass is then assumed to be completely immobile, and must be removed with heavy machinery at anode change. If considerable hardening has occurred, a "better-luck-next-time"-principle is mostly followed, whereas *alumina (new mass) is added* from the pot's feeders to fill potential cavities, instead of trying to move hardened, fused patches of cover-mass. Crust is first identified by the worker from visual inspection, intuition, and even more from a force-feedback using the rake.

The procedure is finished with a visual confirmation, making sure there is no wasted mass left on the front plate by doing a swipe with the rubber on the rake, cleaning the plate. This mass is often utilized to cover any exposure or cavities in front of the anode. Cleaning the plate is considered a standard routine for the worker regardless of the need for raking and covering throughout the anode, and should be performed at every operation.

Further handling of the pot covers regarding the AS-IS anode covering is not considered in this thesis. A complete flow-chart of the current, manual operation is given in appendix H.

3.2 Prominent Challenges of the Operation Environment Regarding Automatization

3.2.1 Operational Space Boundaries

In the pre-master thesis, we state that the amount of pot covers removed for pot interior interaction should not exceed two-three pot covers. This yields a width of the ACU's access area to the pot interior equivalent to about 2-2.5 anodes. This is a natural area to check and cover in one operation. A wider access area may cause unfortunate amounts of gas and thermal leakage from the pot. Removing less than two covers of access are deemed insufficient in terms of handling-time. The allowed *operational space* (Siciliano et al. 2010) is based on the depth through the pot, and the height and width of the access area. Metrics in this is featured in table 1 in section 3.3.4.

Figure 3.1:Access area to the pot interior when two pot covers are removed.

3.2.2 Physical Obstacles, Crust and Required Workspace

Yokes, alumina feeders and feeder points are all geometries that must be avoided in the ACU's trajectory planning. As mentioned in appendix A, the general pot geometry metrics are known, including the yokes and the top of the carbon on the anodes. Consequently, location-data if these geometries may be imported in the ACU's trajectory planner ahead of operation. This may also be utilized to estimate the surface layer of cover-mass and sensible inclines for covering between anodes of different heights.

Surface and crust conditions, however, is way more chaotic with no known location data tied to it but the estimate of 7-10 cm above the anode carbon. The corporate partner confirms that an increased thickness in the cover-mass layer will increase the local thermal insulation which may somewhat lower the hardening rate on the surface. Consequently, a larger amount of movable cover-mass may be left on the top. The hardening is prominent within just hours, and an excessive solidification of the whole mass layer on an anode could happen within 1-3 days. Cover-mass sliding into the bath and uneven hardening of mass are factors causing unpredictable topography above and around the anodes and movability of the cover-mass.

Regarding the ACU's required *workspace* (Siciliano et al. 2010), the corporate partner requires sufficient covering on the rear sides of the anodes. Thus, at least reaching the *pot center* (vertical center axis between the access areas on each side of the pot) for operation is necessary. Also, a maximum length orthogonally outward along the floor from the pot's side is set to two meters. This is with respect to safety zones, passing traffic and simultaneous operations on near-laying pots.

3.2.3 Miscellaneous environment hazards

In (Winjum et al. In press) a definition and the prominent aspects of an extreme environment is discussed. The aluminum electrolysis pot in thesis is a central case in the paper, used to exemplify such extreme environment conditions where testing hazardous effects individually with the product concept when deemed relevant to the function is central. The author underlines in the paper that combining environments effects manifested as prototypes, one-by-one, is desirable to obtain certainty around causality in the qualitative tests.

The hazardous effects in the pot is more thoroughly discussed in pre-master work. The approximately static magnetic field, the high temperatures, the fine, toxic dust and the corrosive gasses are among the most prominent. The corporate partner estimates the magnetic field to be about 250 Gauss, but may vary with the amount of electricity through the pots. One of the corporate partner's supplier on potroom machinery reveals functionality of e.g. electromagnetic motors when properly shielded.

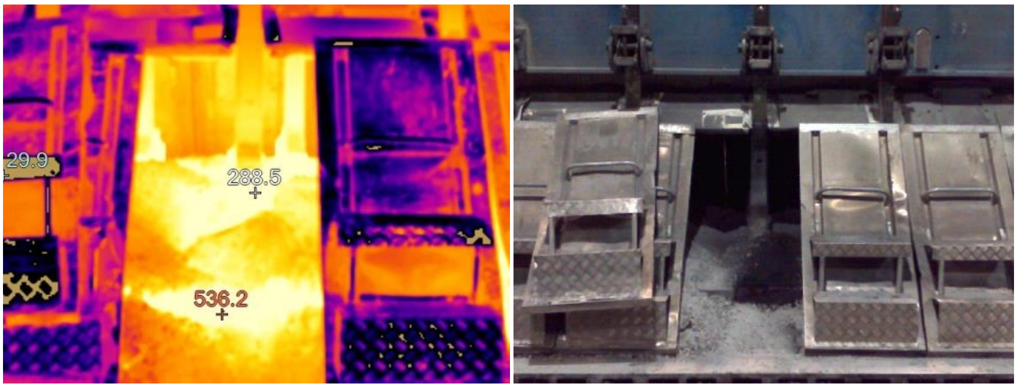

Figure 3.2: Thermal image of the pot interior (left). The maximum, minimum and center temperature in the image are indicated. An extended view in RGB is shown to the right.

Temperatures are generally high inside the pot relative to the ambient temperature, but also varying a lot form the pot's air, to the cover-mass surface, to the cryolite bath. During winter, the ambient temperature (in the potroom) may be well-below -20 °C. By studying temperature data acquired by the corporate partner, using a thermal camera ("Fluke Ti27" 2017) a complex set of temperatures was revealed. These and earlier measurements by the corporate partner estimates the pot's air-temperature to be about 100-250 °C, the visual cover-mass surface-temperature to be ranging from 200-500 °C, and open cavities to yield local temperatures from 500-900 °C.

Other aspects in the environment might be of importance to the overall solution, such as dust and corrosive gasses. The concept detailing has avoided mechanisms prone to dust, however dust and gasses are effects that have not been considered as special concerns to the objectives in the early phase of the project. They are considered by the author to regard later (more detailed) shielding and optimized solutions.

3.3 Product and Environment Probing at the Aluminum Electrolysis Plant

The previous research on technology feasibility for sensing in pot interior (appendix H), provided a general insight on the conditions and the anode covering operation. Together with continuous information from the corporate partner and own reflections on the automatization of anode covering, the author posed the following overall objective, which should be pursued with terms of full automatization: *Sufficiently cover potential cavities and anode exposures*.

As mentioned in section 0, the author adopted the probing cycle by Gerstenberg (Gerstenberg et al. 2015) as a way of immersing with existing products and environment relevant to the overall objective. In this case, it was arranged a visit to the corporate partner at Alcoa Mosjøen aluminum-plant. Natural cycles of literally asking DGQ was conducted through observing the operation of anode covering, oversee other pot interior operations, and explore equipment and machinery operating in the pot. Corporate partner personnel were present at all actions. These were important benchmarks and rapid cycles of learning. Even more important was the physical experience of the pot interior. Performing the anode covering in person was an essential test for further understanding of relevant tasks and the environment. Especially tactile information regarding the consistency of the cover-mass surface was a valuable experience. Through the environment probing, contours to define *sufficient* anode covering were revealed, and which tasks may or may not be executable for the ACU. The probing of product and environment were concurrent during the visit.

3.3.1 Product Probing

The author made sure to keep all disciplines in mind during the product probing, thus grasping their prominence in the applied equipment. It was interesting to witness their role in product functionality, pondering on how it would suffice in an automated unit. The author had a vigilant look on how the use of electronics, sensory, materials and actuation is currently applied and located during operation.

Some examples of divergent questions regarding the products made at the plant was:

- What products do operate inside the pots, and how?
- How may one perform the different legs of current anode covering?
- How is the blasting of cover-mass at anode change performed?

Some convergent questions were:

- Were the products fulfilling their functional purpose, why not?
- Why did the product affect the environment, or why not?
- What changes should be made for a potential new probe iteration on the design concept?

In the following sub-sections, a few interesting cases of equipment applied in the pot interior are highlighted.

3.3.1.1 The Feeding-Wheel Mechanism

The AS-IS way of handling cover-mass is either by using the rake during "fine and light" distribution of mass, or by the "rough and heavy" way of the cell-feeder. The latter is currently only used when new anodes are inserted into the pot. As seen in Figure 3.3*: Feeding of cover-mass on newly inserted anodes.* , a considerable amount of mass needs to be applied for covering the bare anodes with a 7-10 cm mass layer. Mass is relieved by a feeding wheel mechanism from a tank hanging in the traverse crane in the potroom. The current tank-solution is dependent on the crane and uses gravity to achieve the speed of the cover-mass at the deposition-pipe's output. The crane would not be designated to assist in regular anode covering. The thin-walled steel-pipe seen in Figure 3.3, is mechanically connected to the tank, but is however manually guided by hand force in terms of aiming the cover-mass.

Figure 3.3: Feeding of cover-mass on newly inserted anodes.

During the probing did the operation appear very efficient. Seen in the context of controlling it may however seem too inaccurate and somewhat random to be executed in the same way with an open-loop application alone. Figuring out where to aim and provide feedback seemed challenging. Where computer vision could have been a feasible tool for feedback and verification, dusting and a dim interior expands the number of potentially challenging objectives that must be met. A downscaled solution still seemed very interesting to pursue due to the high efficiency and simplicity of the operation.

Figure 3.4 Pristine conditions after anode change.

3.3.1.2 The Rake

The rake is the common tool for covering anodes and distributing cover-mass delicately inside the pot. It is also used to clean cover-mass from the front plate. The very simple construction has no moving parts and consists of a 1.5 - 2.0 m aluminum pipe which is used as shaft and is welded to an aluminum-angle of Al6063. The aluminum-angle is bolted to another angle, which together clamp a strip of styrene-butadiene rubber, cut from car tires. The rake is seen in Figure 3.5. Its simple design is a valuable benchmark, especially on material applications for repetitive operations of anode covering. The aluminum structure has a lifetime over several years, however the most common cause of product failure is wearing and burning the rubber-strip, which fails way more frequently. If used very incautiously, such as keeping the rubber in touch with particularly hated areas, like resting on crust, descended into cavities or held by glowing anode exposures, the rubber would need changing after merely one single work-shift. The corporate partner provides no estimate on the common “lifetime”.

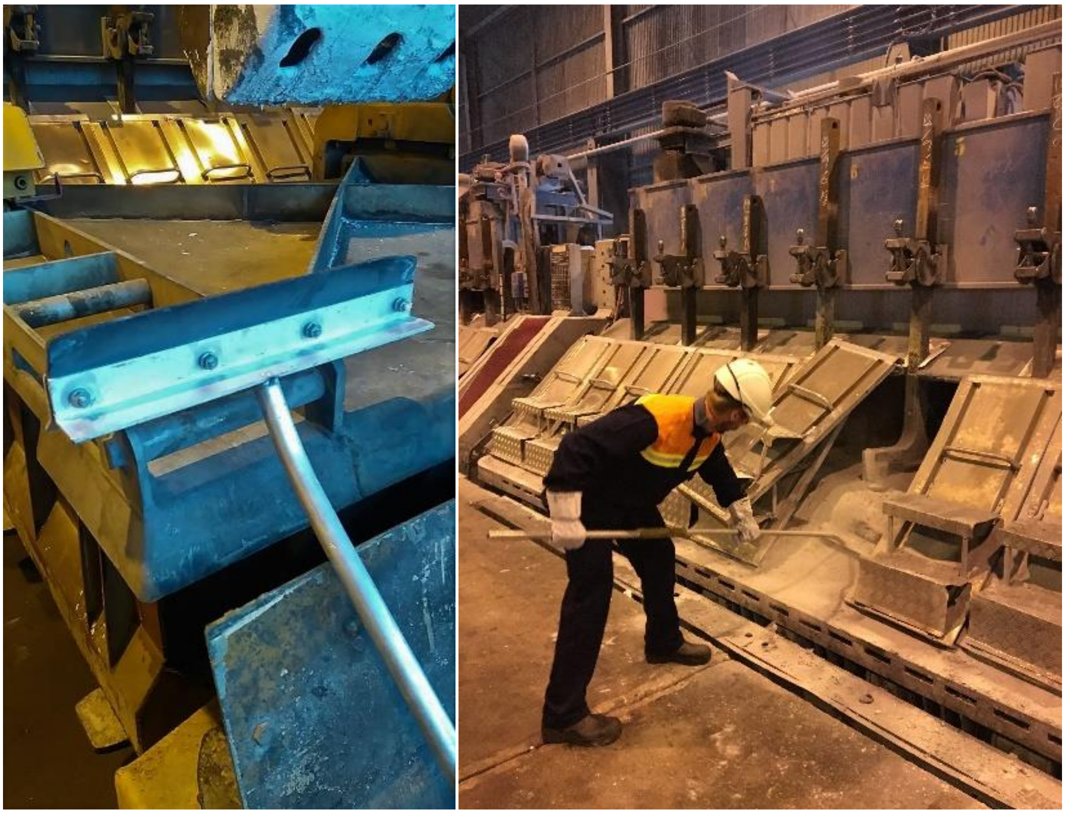

Figure 3.5:The rake (left). The author performing anode covering, caught in the middle of sweeping cover-mass from the front plate and up against the anode's top front.

Shoveling the mass was tested by the author. The applied force was naturally very dependent on the amount of moved mass and the friction surface in the terrain. The very fine powder gave the mass a high friction factor, and combined with varying topography and the underlying, hard crust, executing smooth movement was hard. This yielded varying loads on the tool and made it jump at incidents of crust and gravel. However, experienced workers have of course developed good techniques to handle this relatively efficient. The workers typically use the rubber-strip on the rake when distributing cover-mass. It features elastic properties to flex at incidental hard spots, as opposed to the aluminum angle. It also remains stiff enough to transport mass.

During inspection and questioning, it was revealed that the level of moveable cover-mass depends heavily on the initial distribution immediately succeeding the anode change. The current feeding of cover-mass at anode change is basically done by eye and experience, and thus leaving the layer somewhat random and uneven. The level of cover-mass, consequently the amount which is moveable, would differ from anode to anode. The worker also have to use the rake at anode change to achieve a proper distribution and foundation for later anode covering.

In cases where the worker faces thin, fragile peaks of crust, such as those commonly found on the front top, the worker would typically try to decrease it. How much this is practically attempted is debated, as such efforts normally are futile. Any attempts would typically involve smashing crust edges with the rake's lateral. However, in general, the crust is left for the crust-breaker at anode change or for the crust to naturally fall into the bath. When the worker faces over-covering and excessive crust in places where it fastens to the exterior, such as the yokes or pot side walls, the worker would file a report on severe error in operation. These types of errors are almost exclusively originating at anode change.

3.3.2 Environment Probing

This section takes us the first step in the approach on how to identify, prioritize and tie relevant environmental effects versus the prototypes of product functions that relates to the different objectives. This first probe on the pot's environment at the corporate partener is about testing and exploring several scenarios of different conditions. This is to highlight different perspectives on the overall objective and asking questions to figuring out more on *sufficiency*. Some environmental effects are approximately static. Others are constantly changing, depending on other effects inside the pot, such as the hardening rate depending on interaction and temperature, which again depends the anodes' age (within their monthly cycle). Consequently, this changes the functions required to solve the objectives.

Using scenarios is much similar to the scenario testing suggested by (Pahl et al. 2007). They suggest creating scenarios that consider all stages in the product's life and thus derive further requirements. Rather than tying scenarios to product-life stages, the author here uses different pot interior scenarios for gaining insight on the relation between the product and the different environment effect's prominence during testing. This should detail the operation and highlight extreme cases of deviating conditions which might reveal unforeseen needs. By applying the existing product (the rake in this case) in said scenarios for the overall objective, I acquire instant knowledge on potential lack or sufficiency in functionality for this product solution.

Some divergent questions the author had in mind during the environment probing were:

- What environment parameters are prominent during anode covering?

- Which environment effects seem to influence the way raking and anode covering is executed?
- Which environment effects seem to influence the products' functionalities while operating inside the pot?

The fundamental scenarios required for sufficient operation were selected and highlighted in the following sub-sections. A few important extreme cases where the ACU should file an error report and proceed to the next operation is found in appendix B.

3.3.2.1 Scenario: Mass on front plate with cavities in front of anode

This is the most common scenario and the core of the anode covering operation since it will inevitably occur between practically every covering interval. As the anodes are lowered, the cover-mass foundation is altered, which makes some mass slip. However, such extensive anode oxidation seen to the left in Figure 3.6 may not be common, however illustrates the phenomenon. The picture to the right is a more frequent scene.

Figure 3.6:The scenario of cover-mass on the front plate and exposure or cavities in front of the anode.

There was an obvious need for hindering further oxidation by covering the cavity in front, and clean the front plate. Cleaning the front plate was important to keep the pot exterior tidy and non-slippery, and being able to put the covers properly in place after operation.

Any cover-mass on the front plate was used as a resource for covering the cavities. *Sufficient* covering of cavities was in this case equivalent to *visually cover* them. If the cover-mass in the front incline was not moved, it would have solidified further and formed a crust ridge. This would have facilitated a permanent cavity in front of the anode, as the cavity's edges become immovable. Such ridges of crust are unpredictable obstacles that may complicate later covering. This phenomenon is seen emerging to the right in Figure 3.6. General cover-mass interaction may cause it to slide down on the front plate. Therefore, front covering and front plate cleaning should happen at the end of the anode covering operation.

From this scenario, the author revealed the following potential objectives which are practically mandatory at every operation of anode covering, listed in random order:

- Remove mass from front plate
- Break hardening mass in front incline to counter solidification
- Cover cavities in front of anode at slopes up to 45° from the horizontal plane
- Sufficiently cover cavities in front without considerable amounts of mass sliding back down on the front plate

3.3.2.2 Scenario: Decent surface conditions

Figure 3.7 shows common, decent conditions of anode covering, in the case where proper covering had been performed at anode change. In this scenario, little to no action was needed but the covering of a small crack behind the yoke causing exposure. Available mass needed to be transported and sufficiently distributed at the cavity. The prominence of crust beneath the cover-mass surface was not given. Before assuming it was loose and ready to move, a hardness check was performed by the author, bashing the rake on to the specific region of interest where moveable cover-mass was anticipated. The check revealed a loose layer of a few centimeters.

Figure 3.7 Decent surface conditions and a common scene in the first half of the anodes' life-cycle.

The potential objectives found from this scenario were:

- Test mass hardness to separate moveable mass from crust
- Transport mass at distances between 0-1.5 meters over rough terrain with varying hardness
- Perform sufficient covering of arbitrary cavities when mass has been brought

3.3.2.3 Scenario: Cavities behind anode

Identifying cavities at the rear end of anodes was done visually. Covering such cavities has been attempted from the opposing pot side, where a worker pushes cover-mass to the cavity using the rake with a one-hand grip at its very end, due to the long reach of 2.0-2.5 m. Of HSE reasons did the author not perform any cover-mass interaction at this scenario.

Figure 3.8 Example where cavities appear at the anodes' rear end.

Generally during such incidents may the height difference between the opposing anodes influence, and possibly hinder, the worker's access with the rake to shovel mass to the cavity. The long reach and the varying location of the cavities would require particularly comprehensive manipulator kinematics. Figuring out a way to plan proper trajectories would be essential. Maneuvering and acquiring proper access at different anode heights would also influence the concept of the end effector's function and geometry.

This scenario introduces problem areas in the pot center, and does from an operation environment and technological view stand out as way more challenging than the previous scenarios. A necessary full submersion of the product in the hazardous pot interior, together with a demanding workspace, terrain, movement pattern and plenty of obstacles, are the most prominent problem areas. Potential objectives are:

- Establish the ACU's required workspace
- Obtain a reach and access to potential cavities at the anodes' rear side
- Bring cover-mass to cavities at the rear end of nodes
- Generate concept for end effector path planning and control during anode covering
- Detect unpredictable obstacles
- Collect cover-mass from external depot

3.3.3 Probing Summary and Enlisting of Elaborated Objectives

The above probing was essential for elaborating the overall objective.

An important aspect that applies to the anode covering in general is the actual movement of the cover-mass. The objectives found during the environment probing in section 3.3.2 seek to fulfill the overall objective directly. From the product probing, the author got the impression that only perform either cover-mass deposition or cover-mass movement by physical interaction, could be suboptimal. However, hindering solidification seemed particularly beneficial for facilitating proper anode covering, especially in the front, which indicated that physical surface interaction should be a part of the ACU's operation.

Any attempts by the ACU on detecting the cavities and find their locations will not be covered in this thesis, beyond what is touched in the pre-master work.

After going through the above product/environment probing, the overall objective has been detailed into a list of potential objectives, given in random order. Where some objectives were considered of less importance than others, some were naturally incorporated within solutions to others objectives. Based on the most essential actions in the current operation and how these should be automated, a few objectives where prioritized to be featured explicitly in the concept detailing, starting with what seemed most critical. These are given in bold.

- **Remove mass from front plate**
- Break hardening mass in front incline to counter solidification
- **Cover cavities in front of anode at slopes up to 45° from the horizontal plane**
- Sufficiently cover cavities in front without considerable amounts of mass sliding back down on the front plate
- Transport mass at distances between 0 - 1.5 meters over rough terrain with varying hardness

- **Detect unpredictable obstacles**
- Test mass hardness to separate moveable mass from crust
- Perform sufficient covering of arbitrary cavities when mass has been brought
- Establish the ACU's required workspace
- **Bring cover-mass to cavities at the rear side of anodes**
- Obtain a reach and access to potential cavities at the anodes' rear side
- **Generate concept for end effector path planning and control during anode covering**
- Collect cover-mass from external depot

3.3.4 Initial list of requirements

Inspired be the requirement list approach by (Pahl et al. 2007), this section feature a table providing a few wishes and demands set by the corporate partner and plant drawings, both quantitative and qualitative as such.

Initial list of requirements for ACU			
	<u>Usable potroom floor area</u>		
W	Distance along the pot's side:	<5000	mm
D	Distance orthogonally from pot's front plate:	100 – 1500	mm
	<u>Pot interior space</u>		
D	Reach into pot center from front plate:	>2500	mm
D	End effector width inside pot:	<300	mm
D	Height relative to pot's front plate:	-200 – 500	mm
	<u>Qualities</u>		
D	No stationary equipment should be applied to the pot as a part of the solution.		
D	No altering of the existing pot geometry.		
D	Should not depend on changing other operations in the potroom.		

Table 1 Initial list of requirements from corporate partner and pot drawings. D=Demands. W=Wishes.

4 Concept detailing

This section comprises the journey of detailing concepts concerning the ACU's functionality with respect to its operation environment for its different objectives. The journey starts with highlighting the newfound objectives from section 3.3.3 in the chronological order of approaching them in the thesis. In the previous section, prioritizing objectives was based on their importance and frequency in the current operation. However, as the probing of objectives progress, priorities might change as the author's view on the overall objective changes. Each objective is approached with the Product/Environment probing, asking resembling questions to those exemplified in section 3.3.1 and 3.3.2. Questions will not be asked explicitly at each probe, but are an implicit part of how concepts are generated and evaluated.

Environment prototypes are evaluated along with questioning the sufficiency of function in the product prototype within the product probes. Although not being prioritized for featuring in prototypes, some environmental effects may, to some degree, have an influence on the products' functions. These effects are either considered be more relevant to test at a higher concept level, or neglected due to the current lack of knowledge of its actual influence.

4.1 Objective: Remove mass from front plate

Removing mass from the front plate is an objective relevant for every operation, which sets a clear demand for some of the ACU's most basic functionality. It should apply physical forces on the cover-mass – enough to initialize and maintain mobility until a desired length of the front plate has been cleaned. As mentioned in section 3.3.2.1, mass primarily slides down on the front plate as the anodes are lowered and thus alters the foundation of the cover-mass. The objective was elaborated in the subsequent sections of probing.

4.1.1 Environment Probing

By zooming into the operation environment just around the front plate, the plate itself resembles a heavy iron beam welded to the pot's cathode. It features a matt metallic surface and stays normally in the temperature range of 100-200 °C. Due to a probably rapid interaction, the heat effect is not initially considered as crucial to cover-mass removal.

Due to the high pot currents and thus high magnetic fields, the front plate is highly magnetized, applying considerable magnetic forces on any magnetic object within close distance. Magnetic articles in any potential product directly interacting with the plate should ideally be avoided, unless heavy actuation-solutions are considered to manage smooth movement under such forces. This may be relevant in later iterations where material assignment would be dealt with.

Testing product prototypes for moving cover-mass required cover-mass. The cover-mass found at the corporate partner's plant contains toxic, condensed hydro-fluoride (HF), which made it little suited for simple testing in the workshop. Besides the HF's long-term corroding effect, it seemed to play no part in the mass' macro-mechanical properties. These properties should be represented in a prototype. The cover-mass, as known from the scenarios in section 3.3.2, features very fine ash, condensates, alumina and dust along with bigger parts as gravel and crust typical in the size range of 5-20 mm width.

The even metallic surface of the front plate and its friction-factor was likely to play a role in testing. Testing on other surfaces may be misleading.

4.1.1.1 The Cover-Mass on a Metallic Surface

(Terzaghi, Peck, and Mesri 1996) highlight ways to interpret and analyze soil for engineering practice. They state that the smallest soil constituent will almost entirely determine the general character of mixed-grain soils. They exemplify this with refereeing to concrete's behavior being primarily dictated by the fine cement's mechanical properties.

The cover-mass is clearly inhomogeneous both regarding the constituents' size and ingredients. To replicate the composition of course and fine materials in loose cover-mass and thus featuring the mechanical effects of the mixed constituents, 0-6 mm fine dry-concrete was combined with 30-50 mm gravel in a cover-mass prototype. It was distributed on an iron-plate for testing as seen in Figure 4.1.

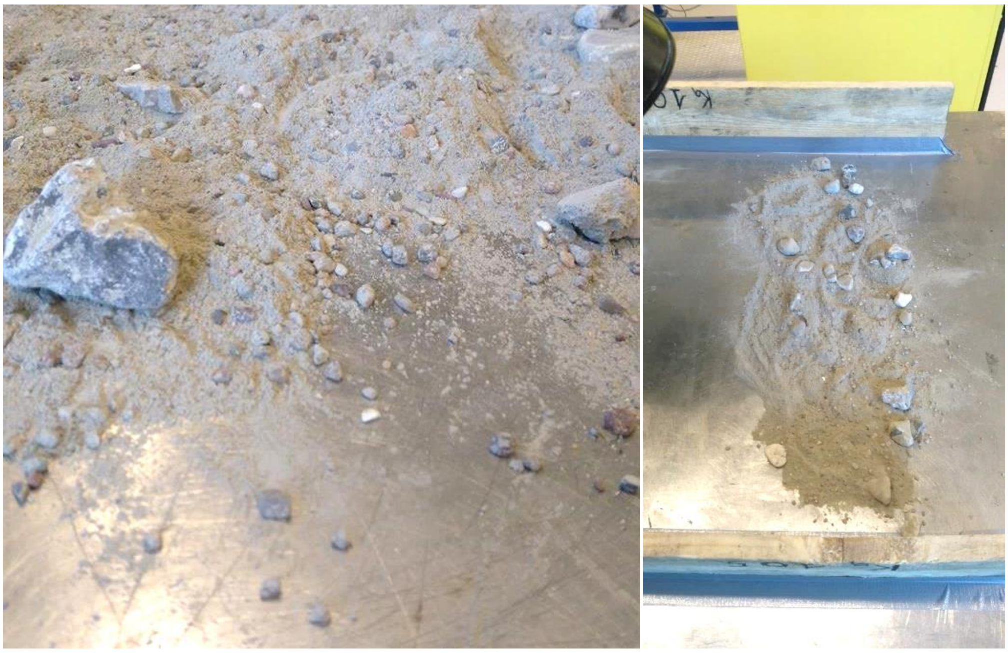

Figure 4.1 The Cover-Mass prototype distributed on a metallic surface.

In the attempts of moving the mass on the metallic plate, as described in the subsequent section, the cover-mass prototype showed a lesser extent of dust whirling in the case when shoveling was applied, similar to the cleaning procedure at Alcoa. This might come from an underestimation of the cover-mass's fineness, but most likely from lacking the high suction effect from the pot's ventilation in the test.

4.1.2 Product Probing

This section goes into generating potential product solutions for moving cover-mass on a metal surface, perform simple testing together with the environment prototype, observe, then evaluate and discuss the observations. It felt natural to look for solutions for similar, but more generic tasks such as those performed by earthmoving machinery. The analysis of automation approaches of earth-moving and soil cutting mechanisms by (Singh 1997) and (Pan and Callejo 2016) were some traditional benchmarks. The use of air pressure for duct cleaning by (Holopainen et al. 2003) and theories of rubber friction by (Persson et al. 2005), also provided inspiration on potential ways to meet the objective. These sources were important inspiration in the objective of path planning and control in section 4.5. Along with general, commercial benchmarking ("Earthmoving | Construction Equipment" 2017) on machinery for soil cutting, earth- and grain-moving, concepts were generated. Some simple approaches on front plate cleaning are illustrated in Figure 4.2. below. Some principles are further explored through simple prototypes and testing in the sub-sections.

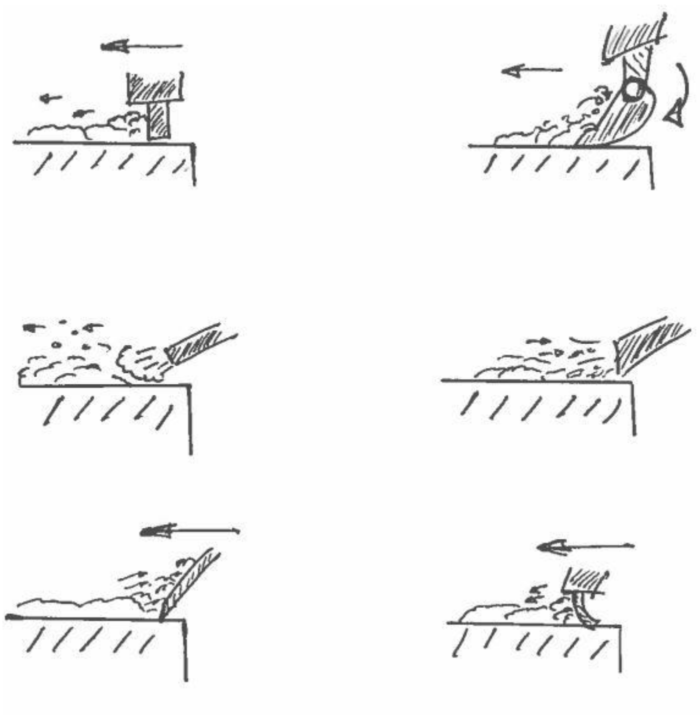

Figure 4.2 Working principles for removing cover-mass from the front plate. From left to right, starting at the top: shoveling; grabbing; blowing; suction; cutting; sweeping.

Shovel, grabbing and cutting mass seemed to be more relevant principles for later objectives, and was thus postponed until potentially reviewed. Suction may be very efficient in removing mass, however vision or peripheral distance sensory is needed to control the suction, as different amounts of mass may be present on the front plate. A vacuuming solution for this objective alone was difficult to justify with respect to the high price and the increased system maintenance following such an installation. It was therefore not prioritized at the time, however, remains on the map of potential solutions. Blowing and sweeping where considered interesting and are highlighted in its further iterations in the following sub-sections.

4.1.2.1 The Air Pressure Pistol

A regular 5-bar workshop air pressure pistol was used to demonstrate how air-flow may be used to move the cover-mass. An initial test was conducted by aiming the pistol at the distributed mass on the table with about a 20-cm distance, then applying a short impulse of air; full force for about one second. This resulted in extreme blasting of sand and dust whirling, several meters from the center of impact. The new distribution of mass on the table settled immediately after impact, forming the pattern shown in Figure 4.3 (left). A markedly trench in the material shows the effect, clearly, however considerable amounts of material was randomly distributed all over the hinter side of impact. This very random distribution and extreme amounts of whirling dust should be drastically lowered to achieve a sufficient solution. Any chance of extensive whirling of condensed HF in the potroom should obviously be avoided.

Figure 4.3 Air pressure pistol applied for moving cover-mass on metallic surface. Conditions after testing a shown. A diffusor can was applied in the iteration to the right.

A new iteration was conducted with a lower force at a wider field of impact. This was meant to decrease the dusting and utilize the pressure more effectively by moving a wider section of material in a more controlled manner. The pistol was hacked with a soda-can-diffusor, having several holes in it as a set of nozzles. This is shown in Figure 4.3 (right).

The can was very effective in reducing the force from the air flow for testing. The distance to impact had to be lowered to 4-5 cm for any effect. However, the effect was still quite significant when first getting within reach. The dusting was lower, but still very prominent in this iteration, meaning fine dust was moved effectively but still very randomly. The mass was still seen whirling up to several meters from impact. The gravel however, was not properly moved during this test, regardless of aim and distance to impact. A potential next step would be to apply a curtain or cover on the sides and above the nozzles to try channelize the dusting into the pot, away from the potroom exterior. However, with such amounts of dusting and random distribution of what is considered toxics around the room, even at insufficient forces for proper functionality, this concept for removing cover-mass from the front plated was not prioritized any further.

4.1.2.2 The Elastomer-Tool

Inspired from the rake and the principle for simply shoveling the mass away from the front plate, an elastomer-tool prototype was made from simply clamping several layers of elastomers together, thus forming a flexible flick. Five-millimeter mats of natural rubber were used due to the much similar material properties seen in the car tires (Styrene-Butadien rubber (SBR)) ("Rubber Materials, Rubber Material Selection Guide, Rubber Elastomers" 2017) used in the rakes at Alcoa Mosjøen and its simplistic form, facilitating customization in prototypes. It was desired to get close to the qualitative Alcoa-benchmark on rubber to begin with, due to their long experience of using it. However, no quantitative data on heat-resistance, fatigue or general lifetime was available. Estimates are stated in section 3.3.1.2, where the rake was probed.

Figure 4.4 Clamped natural rubber was used to sweep the metallic surface with excellent results.

According to the rubber-profile datasheets at (“Gummi Og Maskinteknikk” 2017) in Trondheim, natural rubber feature very good tensile strength along with good elastic and shear strength properties. During testing it showed very good results of cleaning, with little effort despite its friction properties. However, the datasheet estimates an operation temperature range from -40 to +90 °C on the natural rubber, relatively pour compared to other elastomers as Kalrez or HNBR, featuring temperature resistance up to 316 °C and 150 °C respectively. Nevertheless, fast swipes on the front plate is not likely to severely defecting any elastomer, and will potentially be tested in a later objective when other, more important product features have been decided. The elastomer tool was considered an excellent way of cleaning the front plate. In the case of accumulating cover-mass in front of the tool increasing the load, configuration and stiffness should be adjusted accordingly in later iterations.

4.1.3 Objective Summary

- Due to dusting and random distribution of what is considered toxics around the room, even at insufficiently low forces for proper functionality, the concept of air guns for removing mass from the front plated was not followed.
- The elastomer tool is considered an excellent way of cleaning the front plate. The tire-rubber handles the front plate operation well, and fast swipes on the front plate was not considered likely to severely tear the elastomer.

4.2 Objective: Cover cavities in front of anode at slopes up to 45º from the horizontal plane

Along with the objective of removing mass from the front plate, getting mass to the cavity emerging between the front plate and the anode carbon's front, is a frequent need. On newly inserted anodes it may be assumed up to a 45° slope of cover-mass between the anode carbon and the front plate. The angle is based on a conservative assumption made on the cover-mass's angle of repose, observations from a previous visit at the corporate partner and studied situation-pictures of the pot. As the anode is lowered, this angle should decrease if actions are made. These actions currently involve direct, physical contact with the cover-mass in the slope, preventing it from hardening, and ideally utilize the loose material to cover the emerging cavity by the anode carbon's front. This is the best known way to facilitate accomplishment of this objective.

Any action should be done in such a manner that excessive amounts of cover-mass gets spilled on the front plate, which would lower the chances of success in the previous objective. Even if loose mass may be present, after a few days it is almost always some extend of solidified crust underneath, taking a somewhat unknown, unpredictable form relative to the surface. From this description, we see several important effects the environment may impose on a product for this objective. As in the previous objective, heat is not initially considered crucial for testing product function within the following probes.

4.2.1 Environment Probing

From sketching and discussion with previous project partner Even Jørs and fellow students, several scenarios of slopes between the front plate and the anode carbon's front end was further evaluated from the first probe in section 3.3.2.1. It was important to highlight the ways the orientation of ACU's end effector and its *degrees of freedom* (DoF) would be challenged. A 45° should be represented in a prototype with randomly distributed cover-mass. Hard "crust" with a varying surface should then later be applied to the prototype, together with a front plate to qualitatively check for cover-mass spills. These where deemed the most important effects to initially test the critical product functionality for this objective.

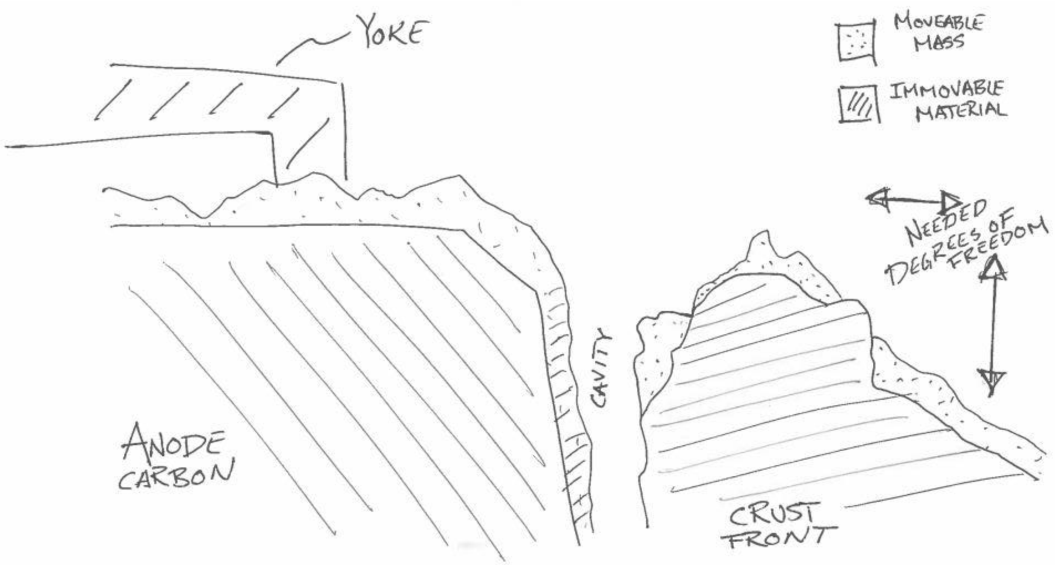

Figure 4.5 Case-sketch from a discussion where extreme crust solidification would result a permanent crust-ridge with a hinter-laying cavity.

4.2.1.1 The Anode-Front Pallet

A pallet prototype was designed and built based on the pot's construction drawings to add realistic size estimates of the front plate and anodes and the distance and incline between them. The slope was adjustable. A massive, casted iron-plate was used as front plate, Leca blocks for the anode carbon and plywood as foundation in an adjustable incline. Several trays of papier-mache with different geometry featured the sought, hard crust-effect for this prototype. These were simple to take on and off to change crust quality. The cover-mass prototype from the previous objective was then finally applied, as seen to the right in Figure 4.6 .

Figure 4.6 Pallet prototype featuring the most basic effects relevant to meet the objective.

4.2.2 Product Probing

After generating a few ideas for concept to cover cavities by the anode carbon front, previous arguments on surface interaction converged the solution-space.

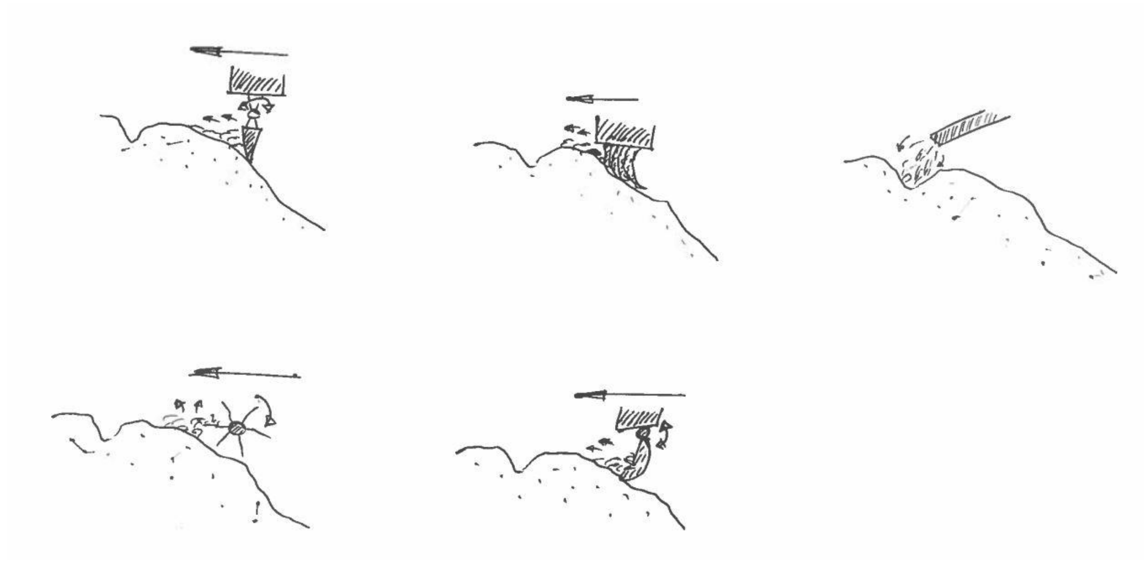

Figure 4.7 Working principles for getting cover-mass to cavities in front of anode. From left to right, startin at the top: shoveling with rotational compliance; sweeping with compliance; cover-mass depositioı shoveling-wheel; grabbing.

In the discussions leading to the Anode-Front Pallet prototype, product functionality was also debated. Ability to move hardening mass from the bottom of the slope up to the cavity or exposure behind the crust ridge would demand degrees of freedom to transverse and adapt to the uneven terrain and its unpredictable hardness. The tool should feature structural integrity to move cover-mass, but also avoid kinematic constraints and damaging itself and the ACU when hitting crust. This may happen as contact forces builds up between the end effector and the environment. *Compliant behavior* in the ACU (Siciliano and Khatib 2008) may solve this. This probe iterates on solutions of *passive compliance* through introducing elastic features within the surface-interacting parts of the prototyped tool. This approach uses the tool as a sort of *remote center of compliance* (RCC) to overcome crust obstacles. RCC is a principle commonly applied in automated assembly operations as mentioned by (Siciliano and Khatib 2008), and thoroughly analyzed by (Ciblak and Lipkin 2003) and (Whitney and Rourke 1986).

Making the tool move at exact locations where the cover-mass terrain is known (from for instance 3D scanning) should decrease the need of mechanical adaptation in the tool to the terrain. The ACU would then be able to identify points on the surface where interaction is needed along with planning a trajectory for moving the cover-mass using non-contact sensory. Still, from probing the slope in section 4.2.1, it was interesting to see if simple, maybe even linear, paths could be planned between known, real-time locations in the pot's infrastructure. In such case, an interpolated path between the front plate and the top front of the anode carbon could be used. Passive compliance in the ACU's tool was thought to save the overall solution from some intricate, exposed sensory solution, and even actuation of a manipulator-wrist.

4.2.2.1 The Spring Tool

In this concept, the tool should change its pitch-angle. Consequently, the function of tool-flexing in the direction of movement would hopefully prove sufficient. To achieve this form of compliance together with sufficient force to move the cover-mass, springs were applied to a triangle of MDF-plates, as seen in Figure 4.8.

It used two compression springs for the function of a torsion spring. The solution was based on what was fast and easily accessible in the workshop to obtain the desired function. The lower part of the tool, including the spring socket plate and the cover-mass-interacting plates, rotated around a static rod seen in the center of the sketch, making the tool able to flex.

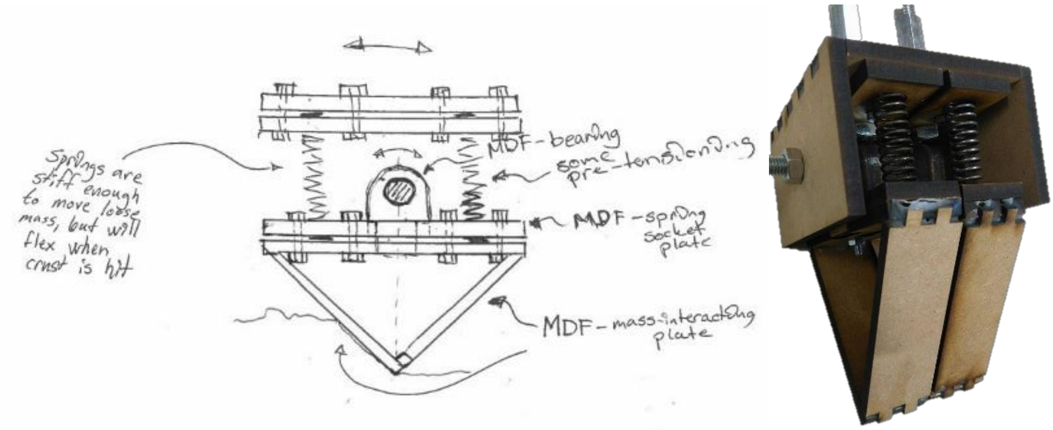

Figure 4.8 Initial sketch of the spring tool (left), and a prototype showing a variant with two segments (right).

Custom compression springs were made fast, and iteratively tuned to what felt as proper stiffness for the tools function. During prototyping, the author decided to add the function of dividing the tool into segments, thus making different parts of the tool able to flex independently as hardness in cover-mass and the terrain may change in the transverse direction of movement. Two segments were prototyped and tested.

The prototype of the tool was tested in the pallet prototype. The initial test was to move the tool by hand-force in a near linear path between the front plate and the anode top. The tool proved sufficient strength and stability to move the loose material and flexed at the "paper-crust", still moving material. Nevertheless, moving the tool normal to the slope, gave the impression of an insufficient number of DoFs. The tool was forced upwards and backwards when trying to achieve a linear path. Also, the spring-forces caused high acceleration in the segments after flexing over small bulges of crust, smashing the fine cover-mass partly into the air and away from the tool-path. In the next iteration, one of the segment's MDF-plates for moving mass was replaced with a stair-profile of rubber to introduce some more flexibility, but also a certain degree of dampening. Only one segment was replaced to try comparing the two, conducting the same test as for the initial tool segments.

This next iteration showed much of the same results as for the previous test, although the rubber stair segment seemed to make the loose cover-mass more adherent during movement. The rubber stair-profile seemed too compact to achieve any drastic changes in flexibility and dampening regarding the tool's degrees of freedom, but managed to maintained its good impression from the last objective of moving loose cover-mass in an effective manner.

4.2.2.2 The Rubber Fingers Tool

The rake benchmark and the good performance of rubber moving cover mass in other prototypes were the basis for continuing the application of rubber. Inspired from prototyping the tool with individual segments in the previous prototype, a configuration with a grid of rubber strips, or fingers, cut from five-millimeter mats of natural rubber was clamped vertically using MDF, machine screws and nuts. The rubber fingers may then move individually when hitting crust.

Figure 4.9 The rubber fingers tool was first made with rapid pattern features in CAD then cut accurately in a laser cutter.

The same testing procedure as in the spring-tool prototype was conducted, proving a sufficient way of moving the mass in the pallet prototype. The V-shaped profile on the rubber finger configuration was designed to yield a distributed impact on several of the sets of fingers when moving cover-mass in the slope. Although the test was considered successful, the new iteration should clearly feature a tighter grid of fingers. The current configuration was only stiff enough to move a two-four-centimeter high ridge of loose material, without sweeping over it. This should be improved. The clamping solution felt compact and robust, however, it seemed a bit over-engineered for its purpose, and should be review.

The tool was designed to fit with other functionality, such as a solution for the wanted vertical DoF for the part of the tool interacting with the crust. A new iteration on the poor attempt in the previous section led to exploring springs on bolts between the Rubber Fingers Tool and the end effector. This way, the tool would have the opportunity to flex vertically when hitting crust. At the same time, the springs would press the tool towards the slope, not risking the tool to "jump" over cover-mass by letting the tool move completely free, vertically. A combined solution of these and other functions is further tested and discussed in the objective in section 4.4.

4.2.3 Objective Summary

- Dividing the tool into segments, making different parts of the tool flex independently as hardness and terrain may change in the tool's traverse direction, was an interesting finding.
- When moving the spring-tool normal to the slope, it gave the impression of featuring an insufficient number of DoFs. Although working well on horizontal surfaces the concept failed to comply sufficiently in the slope with the presence of crust. Previous iterations of sketching and calculations of RCC need to be reviewed thoroughly to proceed with the concept.
- The rubbers fingers tool showed good promise to sweep cover-mass over crust in the slope. It was hard to determine proper load when applied as a hand-tool.

4.3 Objective: Detect unpredictable obstacles

This objective goes into how the ACU would cope with unpredictable obstacles. This may be pointy crust, overhangs of crust between anodes with different height (appendix B) etc. "Crash detection" is a way to reframe it. The author did now consider the field of sensory for coping with the potential position errors of several centimeters between the obstacle and the predefined path, thus potentially hitting other parts of the tool where compliance is not considered or properly accounted for. The author was then looking for the ability to detect dangerous terrain variations and hostile cover-mass consistencies that might harm the ACU or the pot infrastructure.

4.3.1 Environment Probing

The main target in this probe was to identify and provide the physical features needed to test the product functions above. Primarily, this would involve featuring cover-mass surface-conditions with occasional crust-heaps. Initial testing would typically involve infliction of mechanical impulses, light impulses, make gestures or whatever stimuli necessary to validate functionality in the sensor solution. Testing at similar surface conditions would then be the natural next step, where the existing pallet prototype already provided much of the terrain-features as seen in the scenario in section 3.3.2.2. The pallet prototype could also be easily altered with very fast iterations in terms of amount of cover-mass, however, the conditions for testing variable hardness and prominence of crust should be improved.

Heat, luminosity, IR-radiation, HF-condensation etc. may all very much influence the sensor's survivability, but their relevance was considered by the author to be very product-solution dependent and should rather be highlighted as a part of a later objective. A more generic question was whether there was a possibility for common electronics to survive at (at least) decent operation conditions, or not. This will be addressed further in the later section on product probing of this objective.

4.3.1.1 The Crust

The crust representation was enhanced in this next iteration for crash detect, featuring more sharper edges and a rougher surface. This prototype was made from casting concrete at an angle. Its size was exaggerated to demonstrate crash at exceptional terrain conditions.

Figure 4.10 The casted concrete "crust" partly covered within the pallet prototype.

The crust was combined with the pallet prototype for a more complete representation of the front. Simple testing is featured within in the product probe.

4.3.2 Product Probing

Krotkov and his colleagues (Krotkov et al. 1999) prototyped and conducted field testing on a hazard detection system for lunar analog terrain. Although the sensory system was laser-based and applied on a rover, interesting, generic aspects of traversing varying terrain based on sensory, are discussed. They considered two different approaches to evaluate the terrain-hostility of the landscape.

The *capability approach* evaluated whether the elevation of the surface in front of the rover (represented in the rover's local coordinate frame) exceeded the rover's capabilities. Analogously, the ACU's end effector frame might be the reference for evaluating incoming terrain data versus the tool's capabilities, i.e. predefined restrictions in the tool's geometry, strength, elasticity etc.

The *signature approach* involved identifying signatures of different landscape formations that are invariant to the motions that occur when travelling over minor obstacles. The ACU would for this approach process incoming sensory data as certain tendencies of terrain-variations and compare it with characteristic shapes. Kotkov poined on three key limitations for the rover with this approach: the general difficulty of quantifying danger for a certain landscape profile, the significant increase in processing compared to the capability approach, and the risk of not covering all possible dangerous encounters with a designated signature. With that said, the author saw a clear potential in the signature approach with the assistance of machine learning algorithms and sound training of the ACU. Nevertheless, the more conservative, but simpler, capability approach was first used as inspiration in the further exploration of the tool's hazard-detection sensory.

4.3.2.1 The Pneumatic/Hydraulic Load-Cell

Adapting the principal of compression spring between the tool and the end effector, the tool could be pushed towards the cover-mass surface with an approximately linear load increase when the tool gets elevated by the surface from its planned path. Sensory at the springs should trigger an interrupt in the end effector's movement at the instant the springs get compressed beyond a critical limit. Applying sensory capable of registering the amount of compression is a solution option for *height calibration* functionality in the tool. This could be solved from applying hydraulic pressure sensing system with pistons parallel to the compression springs. This solution make the withdrawal of the electronics from the end effector to the ACU's base possible, limiting the hostile exposure to the sensor's electronics and the need for shielding. Inspired from the load-cell basics at ("Getting Started with Load Cells - Learn.sparkfun.com" 2017) an initial pneumatic load-sensing system was made from an absolute pressure sensor connected with a tube to a 2.5 mL syringe. Consistent increases in pressure values processed and read from an Arduino UNO ("Arduino - Home" 2017) proved a successful first attempt on registering loads with the sensor (the transducer) distanced from the mechanical impact, and thus the most hazardous areas.

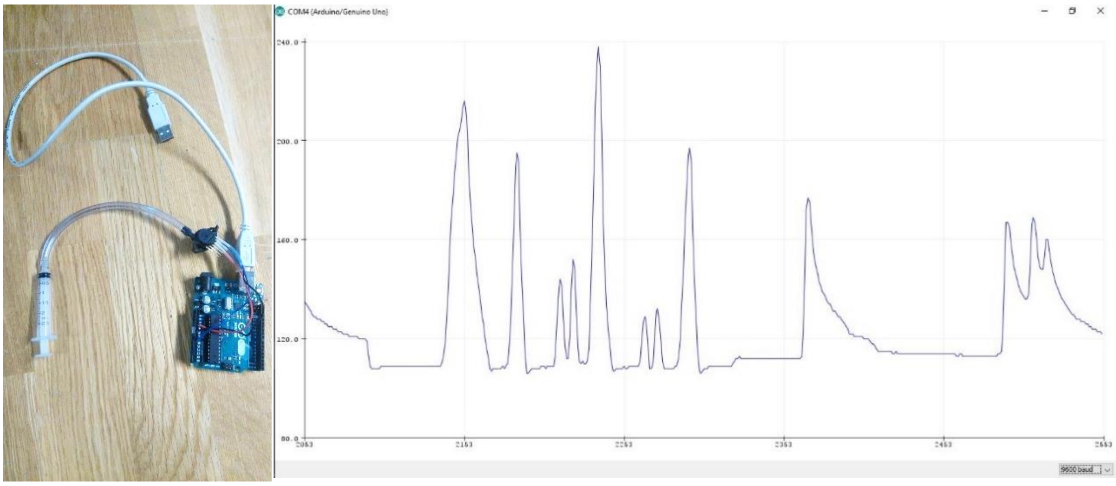

Figure 4.11 A simple pneumatic force-feedback system with a syringe, an absolute pressure sensor and an Arduino UNO ,reveals relatively rapid, prominent spikes at impact.

The initial testing proved rapid response when applying random impulses to the syringe. An accurate compression-distance acquisition was not required at this point, and crash-detection could be featured through only binary input if compliance in the tool gave enough delay before critical impact. There is only an absolute need for knowing the maximum pressure overload in the case of damage protection.

Applying pneumatics for such purposes were fast for demonstration but will be poor for implementation (Alciatore and Histand 2012). Hydraulics may be applicable. Reduction in the fluid's bulk modulus from environment influence should be avoided to maintain steady fluid properties (Theissen and Murrenhoff 2014) and will require a certain thermal shielding of the system in the tool and robot arm during operation.

4.3.3 Objective Summary

- Applying spring-functionality to the tool shows promise in terms of compliance at crust impact.
- Regarding sensory, pneumatics were applied as a proof-of-concept, but may be applicable where inaccurate force-feedback could prove sufficient. Hydraulics could provide rapid response due to the incompressibility (Alciatore and Histand 2012). Potential non-linearity-issues are not concerned.
- Prototyping unique solutions for this objective was at this point halted. Pursuing sensor solutions seemed first relevant after defining more of the operation and looking closer at potential control solutions (4.5).

4.4 Objective: Bring Cover-Mass to Cavities at the Rear End of Anodes

The previously probed objectives involved to a high extent of interaction between the tool and the cover-mass, which is also highly relevant for the current objective. The critical functionality required for *transporting cover-mass at distances up to 1.5 meters*, as enlisted in section 3.3.3, has therefore been neglected due to its obvious overlap with the functionality in the previous objectives and the functionality required in the current objective. However, additional functionality and challenges are posed for operations that are conducted all the way into the pot's center. This objective-section introduces testing of combined previous solutions, along with new individual product functions and relevant environment effects.

4.4.1 Environment Probing

What distinguished the operation environment for the ACU in this objective from the previous ones was the full immersion of its arm and the end effector into the pot. This would increase the exposure to potential sensor- and/or actuator-inhibiting effects, such as heat-radiation, dust, intense light from cavities etc. Demands regarding the ACU's workspace inside the pot (3.3.4) provide mechanical challenges that should be resolved. Changes in the pot center produce drastically diverse operation spaces for the ACU, caused by the relative height between opposing anodes. Along with prototyping and testing this effect, some initial heat and flame exposure solutions were introduced and tested together with components/materials from a tool-prototype.

4.4.1.1 The Anode-Age Scenarios

The ACU's end effector needs to reach and operate at the pot center, where not only static pot geometry sets limitations to maneuvering but also arbitrary height differences between the front and the rear anode (relative to the ACU) must be considered. Though being negligible slow, the anode heights are dynamic changes in the environment providing highly different environment scenarios. Different scenario-figures were developed to display how age difference between the front and rear anode may alter the ACU's operational space. Three important scenarios of two opposing anodes' relative height are shown in the three following figures.

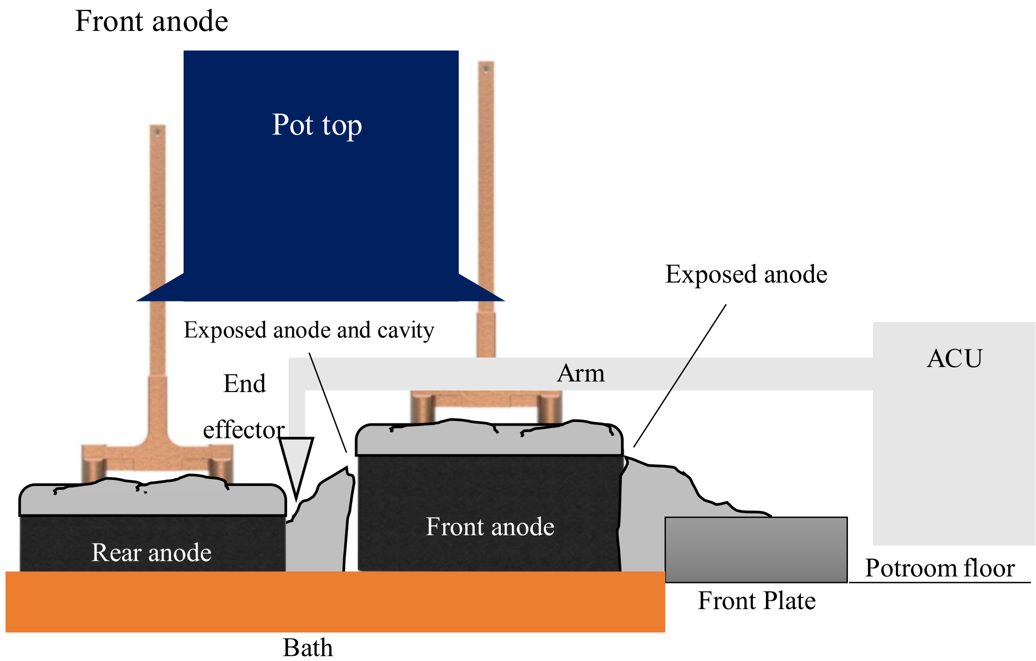

Figure 4.12 ACU operating in the pot center when the front anode is youngest.

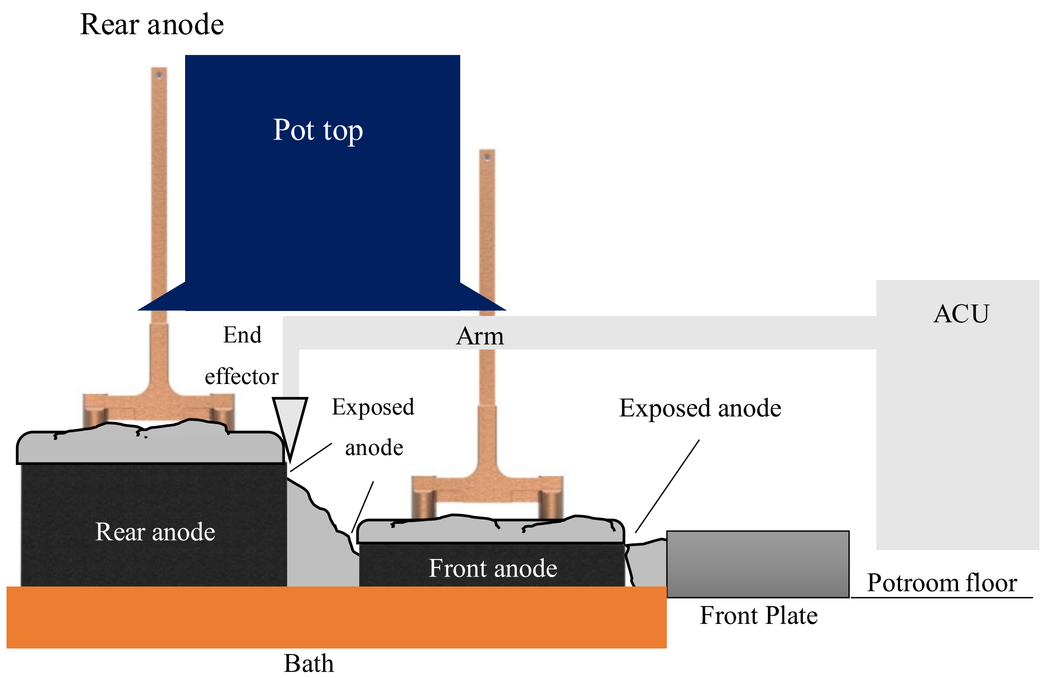

Figure 4.13 ACU operating in the pot center when the rear anode is youngest.

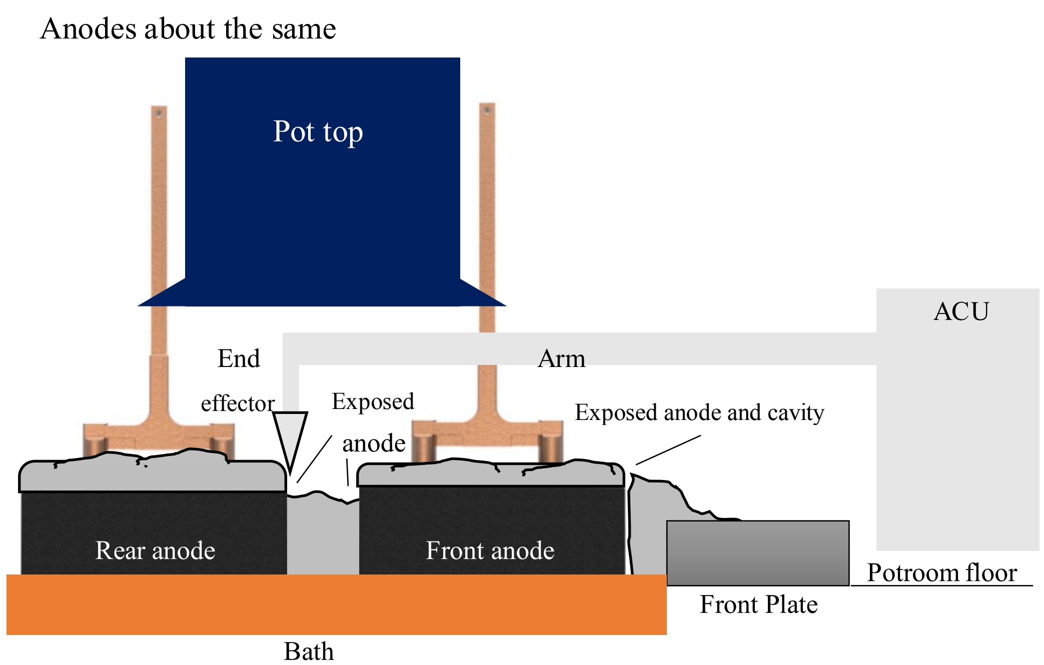

Figure 4.14 ACU operating in the pot center when the anodes are about the same age.

The ACU configuration used in the figures shows the assumed, maximum required reach of the end effector. Due to the lack of support in the center area, the cover-mass tends to sink and slip randomly, thus causing the cavities and anode exposures. Anode exposures and cavities are marked in the figures where they commonly appear. This is also where anode covering is crucial. The interesting revealing is to see the how the end effector and arm configuration must adapt to these different anode height scenarios. When the front anode is newest, there seem to be a need for the end effector tool to be placed or lowered considerably beneath the arm to get within reach of the surface, however reaching the dump was not a practical demand for anode covering success since these areas are less likely to influence or contribute to any anode exposures. Sufficiency may be achieved by only bringing cover-mass from the anode's top surface, however, utilizing cover-mass in the center area facilitates covering success, since there may be lacking moveable cover-mass on the top surface.

In a next iteration of prototyping the age-difference effect, a scaled model of an elevated front anode was made for testing an ACU concept (4.4.2.1) running the algorithm in section 4.5.2.1. The prototype elements were approximately scaled 1:10 of the original front plate and front anode, which were the key geometrical pot elements that should be represented. The prototype was very rapid, made from MDF and honey-comb cardboard. Geometric values from this prototype are the parameter inputs in the algorithm-code, and facilitates the proof-of-concept of a combined solution with the ACU and Arduino software ("Arduino - Home" 2017) running the algorithm. No extra crust and heat features were relevant for this initial test.

A fine layer of the cover-mass prototype was distributed on the anodes and the front plate, ready to get moved by the ACU. Two red wires where placed in the front anode's rear end and front to indicate cavities into the bath, which should be covered by the ACU.

Figure 4.15 A scaled prototype of the -age-difference effect between two opposing anodes. Measures were taken to resemble the actual geometries.

The test is discussed in detail in section 4.5.2.1.

4.4.1.2 The Torch

The ACU's immersion in the pot introduce intense heating to the mass-interacting parts of the tool during anode covering, but also to other hardware that may be exposed to everything from about 150 °C, to torching heat from gaseous flames at cavities in the crust. In (Winjum et al. In press), the author points on the convenience of revealing sufficiency in simple materials and technology when known, conservative solutions are likely to provide high costs and sophistication to perform testing in the initial phases of development. Revealing opportunities for using cheap and versatile prototyping materials and rapid production methods may be advantageous for additional and faster iterations on concepts. Performing a simple butane-torch test is one fast way to gain qualitative indications of simple materials' torch-resistance in the pot when low resolution prototypes are applied.

The torching-effect is here inflicted on different product articles using a butane-torch. The analysis by (Sharma, Sheoran, and Shakher 2012) on the axis-symmetric temperature profile in butane-torch flames reveals temperatures in the range well above 1000°C, depending on the fuel/air-mixture at combustion. The tests show temperature data in a 0-

12 cm range from the torch. It is then assumed a butane-torch test may represent expected, if not more, hostile torching conditions than the pot.

Tests were made with materials and components applied in the tool-prototype in the coming section 4.4.2.4. This involved single strips of natural rubber of different widths in relation to the rubber fingers tool prototype. Applying a flame-retardant welding curtain ("Welding Curtain, Dark Green" 2017) to shield MDF from direct flame exposure, was a way to explore the wood-fiber-based material's sufficiency for bracket or thermal shielding solutions for potential later tests in the pot. This was based on an interest to explore and generate knowledge for potential later early-stage projects related to such conditions. The curtain may also be a versatile solution for covering joints, sensory or mechanisms from dust and condenses, due to its ability to fold over long distances and follow potentially awkward reorientations from a manipulator.

Before applying any mechanical load, the rubber strips showed little to no visual degradation. However, their ends caught fire when aiming the torch at the specimens' tops at a 2-3 cm distance for about 10-15 second in the last test. The fire terminated immediately after the supply of energy to the specimen stopped. By clamping and straining the burned tip, the elasticity had increased drastically: However, the piece remained intact at strains up to 3-4 cm in the slim specimens shown in Figure 4.16. The wide specimen had distributed the energy better, providing more stiffness and integrity after the same test. A tensile strain-test was performed by hand-force on the torched, slim specimens, showing an expected 45-degree fracture in specimen's torched end. A similar test on an un-torched specimen did not lead to fracture. (Hosford 2005) points out the drastic decrease in shear modulus in elastomers at increasing temperature which is based on the work of (Engel 1981). ("Gummi Og Maskinteknikk" 2017) state pristine tensile strength, shear strength and fracture strain in their natural rubber, however its maximum working temperature is estimated to be around 90 °C. This is well-below what is expected in the pot. Nevertheless, applying a material-type this close to the applied material in the rake (chopped rubber tires) could be interesting to explore in the rubber fingers tool's configuration. As with the MDF, this may be an interesting finding related to the topic of exploring sufficiency-thresholds by testing simple materials in the pot.

Torching the curtain showed an excellent performance of absorbing energy and shield the underlaying MDF. As shown in Figure 4.17, the MDF was also torched directly for a approximately 30 seconds at a 4-5 cm distance with little but visual degredation on the exposed surface.

Based on these tests, the geometry of the rubber and its low maximum temperature makes it little likely to pose no degredation under direct contact with the cover-mass. It will therefore not be very interesting to see if it works overall over time. It is known it will not, however, observing when at at what particular action it will prove insufficient at qualitative, rapid testing may be a good benchmark for later.

Figure 4.16 Torch-testing rubber strips with respect to the rubber-fingers-tool test. The degradation is first prominent with applied load. Setup (top, right), burnt, wide specimen (top, left) and burnt and fracture strained slim specimens (bottom).

MDF shielded in a welding curtain, having no direct contact with the pot's terrain, was assumed to survive with little to no degradation. The curtain and the rubber proves clearly insufficient for long test-sessions in the pot, however to see the difference in degredation in the materials, between common anode covering and exposure to worst-case effects of torching, could be an interesting insight.

Figure 4.17 Torch-testing MDF with and without a flame-inhibiting welding curtain for cover. The curtain degrades fast during torching due to its excellent absorption of energy. Setup (top, left), Curtain-test (bottom, left), MDF-test (right).

4.4.2 Product Probing

The product probing of this objective is twofold. First, the author considers the required, tool-based functionality, and how it is common with functionality in section 4.2.2 and 4.3.2. Some of these solutions will now be combined. (Gerstenberg et al. 2015) suggests merging system components as soon as possible to tackle potential integration issues very early on. Findings from testing the combined-solution may be crucial for taking any of the sub-concepts further. The sub-components may be iterated later, individually. This is featured in section 4.4.2.2-4.4.2.4.

The need for operation in the pot's interior with a particularly demanding workspace for the ACU makes manipulator kinematics and functionality more relevant, and should be probed at this stage. A short derivation of industrial manipulator theory and benchmarks for the relevant functionality now follows.

A manipulator's mobility is ensured by the presence of joints (Siciliano et al. 2010), that are either revolute or prismatic. Each joint feature a single degree of freedom, where the prismatic joint creates relative translational motion between two links, while the revolute creates a relative rotational motion. Siciliano and his colleagues further classifies manipulators based on types and sequence of joints from their base to their end effector. They underline the *Cartesian* manipulators' good mechanical stiffness, which the common choice for straight motion in space, and with constant position accuracy throughout its entire workspace. Their workspace resembles that of a prism. Cylindrical and Spherical manipulators provide more options of end effector orientation (more dexterity (Siciliano and Khatib 2008)), however increasing the horizontal and radial stroke (prismatic joints) on the manipulators, respectively, will decrease the accuracy by the end effector. SCARA types are most commonly used for light, vertical lift and assembly operations, while the Anthropomorphic arm is the most commonly used geometry, with a wide range of applications due to their high dexterity.

Businesses are increasing in providing sustainable automation solutions for hazardous operation environments. KUKA offers the KR1000 Titan 6-axis manipulator for casting of liquid steel ("Foundry and Forging Industry, Automation | KUKA AG" 2017). Heat- and corrosion-resistant coating, dustproofing and other external shielding devices makes their manipulators a feasible option for anode covering. The author is in no doubt that existing robotics technology will offer viable product solutions to operate in the pot environment. However, such a comprehensive system needed for this operation specifically do not seem to be provided of-the-shelf. However, as pointed out in appendix A, the application of combined AGV-manipulator solutions is thought to increase drastically in in the few coming years (IFR 2017), thus more products is likely to be offered. Nevertheless, integration in a production plant system would always need some custom implementation.

The ACU must be extraordinary in the sense of accurately maneuvering and operating at a long reach when stationed on a mobile base. This requires significant stiffness, along with the previous precautions made in the tool-concept to achieve decent conditions for controlling the ACU during operation. The narrow access is an important factor that will affect the size and material stiffness required to show competent behavior in its entire workspace. High operational velocity and accelerations are not seen as critical criteria for design, at this point, and will likely be optimized with respect to effort, time-efficiency, cost and safety of the operation, later.

Even though a certain weight from the arm and cover-mass and crust interaction during operation would require considerable torque, implementing a hydraulic system seemed over-exaggerated. The need for a large system infrastructure, potential fluid leaks, noise, vibrations and maintenance are drawbacks that disfavor hydraulic solutions to electric in this case (Alciatore and Histand 2012). At this stage in the project, the corporate partner confirmed to the author that usage of an industrial manipulator in the potroom has been successful. The initial testing of this manipulator involved certain maneuvering of the manipulator that confirmed no noticeable influence on the electric motors from the high magnetic field induced by the massive leads in the pots. Alcoa sources suggests further that there should not be any application of magnetic-based analog devices in the ACU, due to their previous potroom experiences with failure of such devices. Any hall-effect based sensory for controlling purposes should be ruled out, favoring e.g. optic solutions for such tasks. The selection of motor will be mentioned for the respective concept.

The tool could desirably be designed to provide full functionality for anode covering at a fixed orientation, thus making the neglection of a wrist possible. In such case, an under-actuated robot (having less than six DoF) (Corke 2011) might be sufficient for operation. For selecting kinematic concepts, the geometric requirements set in section 3.3.4 along with the following design desires by the author, should be met:

- Solutions where electronics, sensory, actuators, joints etc. are distant from the hostile pot interior should be favored to decrease needed shielding.
- Solutions known to provide particularly good stiffness at long reaches and consistent behavior throughout its entire workspace should be favored.

Through commercial benchmarking of industrial manipulators (“Homepage | KUKA AG” 2017), (“Industrial Robots for Smarter Automation” 2017), (“Robot Selector - Robotics - List Of Industrial Robots From ABB Robotics” 2017), two concepts matched the initial vision of exploring simplistic solutions.

Both concepts were thought to utilize the base’s mobility feature to move parallelly along the pot’s side, performing the anode covering operation inside the pot repetitively along that axis. The first concept idea was based on a prismatic joint lifting an arm in the vertical direction. The arm was telescopic, providing the needed reach within the area restriction set at the potroom floor, in front of the pot entrance. To decrease dusting into joints and drives, the telescopic solution was thought to be as enclosed as possible. The tool was in this case fixed to the arm of the telescopic joint to decrease the use of parts with relative movements within the pot. This concept is from now referred to as the Cartesian concept.

The second concept was a two-link. Altered with a parallelogram solution between its joints, comprising a closed-chain kinematics (Siciliano et al. 2010), would make it able to provide a long reach with high stiffness. Making the end effector joint passive, motors could be stationed at the mobile base. This way, the tool would be kept with fixed an orientation throughout the required operational space within the pot. This would fit well with the previously suggested tool-designs, but also introduce rotary bearings close to the end effector. With the requirement of high stiffness, link-weights tend to increase. This concept is from now referred to as the Two-link concept.

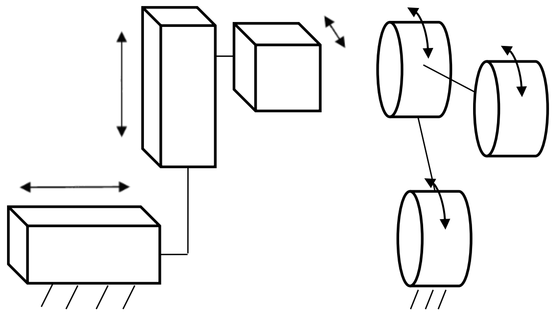

Figure 4.18 The classic Cartesian configuration of three prismatic joints (left). The Two-link configuration of three rotational joints (right).

A simplified representation of the link's dimensions and the kinematic concepts are displayed in Figure 4.19 below. The cross section view of the pot with the two concepts show suggested, sufficient joint orientations for the anode covering operation's most critical extreme end effector positions, located by the pot center and the front plate respectively.

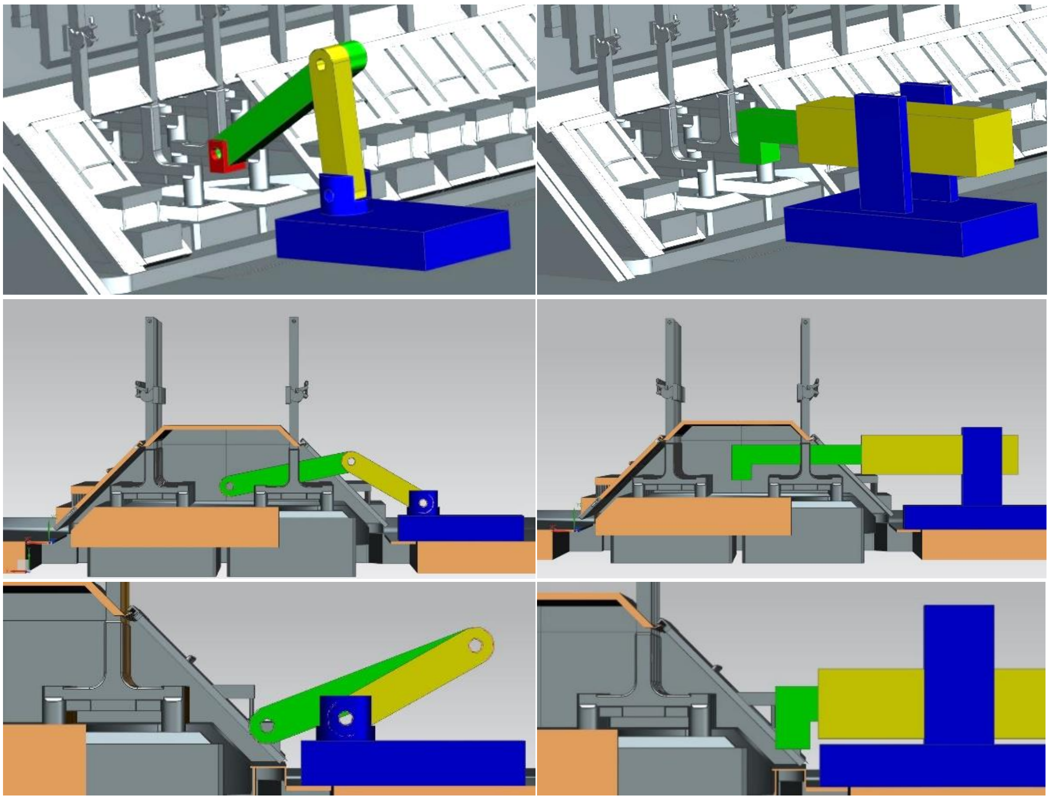

Figure 4.19 The Two-link concept (left) and Cartesian concept (right) on mobile bases (blue). They pose with their end effector (red on the Two-link) at relevant extreme-points for operations, such as the pot center (middle) and the front plate (bottom).

By looking at their pors and cons, the Cartesian concept would use prismatic joints that are more susceptible to dust and fragments interfering with its drive-mechanism, than enclosed rotary joints. This should be avoided to a highest extent to decrease the chance of malfunction. The Two-link concept has the drawback of possible singularity challenges when operating close to full reach. Siciliano and his colleagues explains the phenomenon of kinematic singularities in detail (Siciliano et al. 2010), (Siciliano and Khatib 2008). Shortly explained, it causes high velocities in the manipulator's rotary joints when trying to offer a sufficient pose to end effector movement near boundaries or where inverse kinematics reach discontinuities, such as when links align. The rapid joint reorientation might cause unpredictable and damaging movement in the arm. An example in the pot would be if the end effector is elevated in the pot's centre, and closely align the links. The elbow joint might then show unpredictable reorienting-behaviour, potentially crashing in the pot roof or down in the cover-mass (when the anode is young and at a certain height) if certain actions are not made in advance. The inverse kinematic solver should be designed to handle such problems, and a closed-kinematic chain in the elbow joint may provide mechanical stops to hinder unpredicted, damaging joint movements. Both concepts showed good potential for further development. Based on the fundamentally, simplistic control and good stiffness when operating at long reaches a scaled, physical prototype of the Cartesian concept was developed for the stepper algorithm testing in section 4.5.2.1. The design and building of the prototype is documented in the next sub-section.

4.4.2.1 The Planar Cartesian Manipulator with Telescopic, Horizontal Links

The foundation for approaching a custom Cartesian solution of the ACU was the desired stiffness and accuracy in the entire workspace, the possibility of few or no moving joints or actuators close to the end effector and simple kinematics. For this manipulator geometry, the tool would need to be placed below the ACU's arm to get access down, behind the front anode. Even so, the lowered end effector configuration must not prevent the ACU accessing the pot's center when the front anode is completely new, as shown in Figure 4.12 in section 4.4.1.1. The author then argued to materialize this concept as a scaled version of the ACU for algorithm testing purposes (4.5.2) and to further evaluate design based on a physical context. The latter highlights important aspects in robotics anatomy. The author wants insight on the challenges of providing a functional, compact design even in the early-stage, and later evaluate the pros and cons of such approach. This involves physically combining motors, gear and bearing solutions into one working unit, capable of physically testing operation concepts.

Establishing an initial overview of the robot structure and the working forces and torques, was done from sketching and simple free-body diagrams. This was used for dimensioning the different joints rapidly. All drives concerned with the AGV was not considered as relevant at this moment, and besides the references made on control theory in later discussions, it will not be featured any further in this thesis. The initial model from Figure 4.19 was the basis for further development of the concept.

The focus was then set on constructing a solution for the telescopic arm. A desired approach was to try keeping all motors outside the pot as much as possible to lower the hazardous exposure and potential need for further shielding of them and their supportive components.

The end effector would be fixed to the arm in this concept, containing potential sensory and/ hydraulics. The angled arm would provide the sufficient, low reach in the pot center. The upper part of the tool would be fixed to the end effector, with nothing moving but potential spring compression in the tool.

From the rapid force and torque calculations, a conservative estimate of sufficient bearing of the telescopic links was made, and set to hold about 30% of the links total length when the telescopic joint is fully open. It was desired to iterate further on a telescopic solution that was as enclose as possible, at least in those parts entering the pot during operation. This should hinder diffusion of sand, dust and condenses into the joint mechanics. It was also desired to simplify motor control in the prototype by lowering the number of motors needed. A solution for the telescope arm that would fully open and close with the help of one single actuator, was then chased. Through knowledge of mechanics and machine design, together with inspiration from commercial and research solutions, a tooth-belt drive solution actuated from the base looked promising. The tooth-belt would move the two links in a simultaneous or sequential order, depending on the friction forces in the bearing solutions of each link. The principle is illustrated in Figure 4.20. The A-bearings are static relative to one another. So are the B-bearings, which are fixed to the vertical joint. A are moving relative to B in the horizontal direction, and C may move relative to both A and B in the horizontal direction.

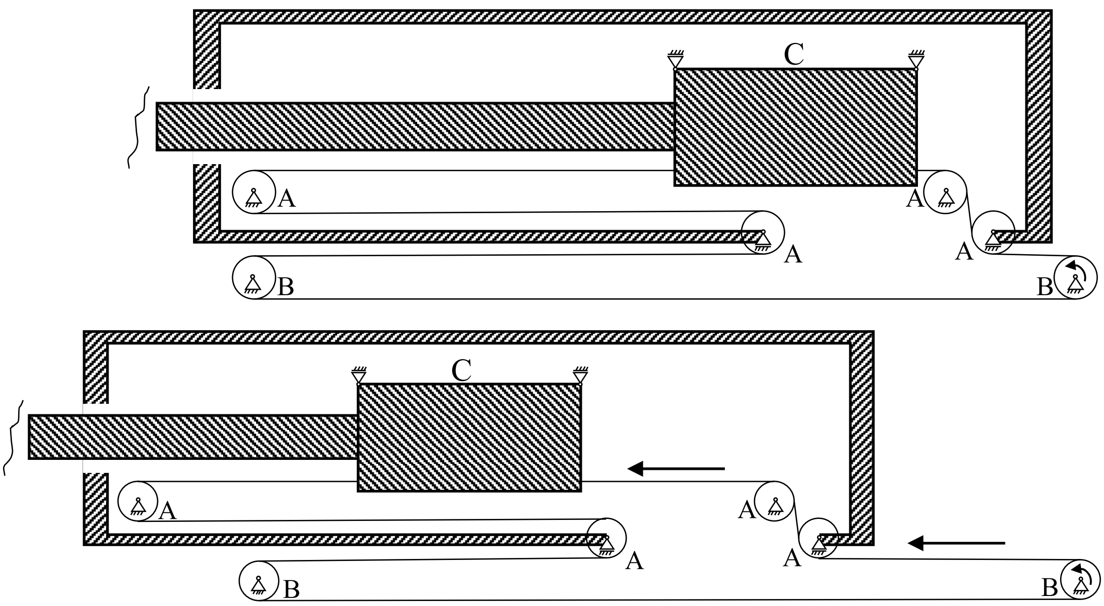

Figure 4.20 Principle of telescopic arm with a single tooth-belt drive. Timing pulleys in B are fixed to the vertical joint. The bearings in A may move horizontally relative to B. The bearing-block C may move horizontally relative to A and B. Torque is applied in B (right).

A rapid, physical prototype demonstrating the concept was made at the benefit of using simulation software. The prototype was made from MDF-links, screws simulating the timing pulleys and an arm-bracket (C) of LEGO clamped to a tooth-belt. The prototype confirmed the working principle of the concept in terms of DoF, by moving the arm-bracket by hand force. The prototype also let the author pay special attention to friction and looseness, and the importance of belt-tensioning in the further development.

Figure 4.21 Rapid prototype of the telescopic links moving relative to one-another. Screws work as sliding bearings in a slot on each side of the lower bearing.

At this stage, the author felt enough knowledge was acquired on the telescopic mechanism to proceed with the vertical drive, and how these two solutions may be combined and driven by motors. The gantry geometry shown in (Siciliano et al. 2010) inspired the author to chase a solution utilizing several load-bearing points with decent distance between one-another to withstand the torque from the telescope arm's weight and payload when being fully open. Torque around the manipulators yaw angle was neglected, and a scissor-lift solution ("Scissor Lift Jack Equations and Loading Calculator - Engineers Edge" 2017) should be sufficient. A prototype in MDF was first sketched on paper then geometry was drawn in CAD-software, featuring cross-bars on all four sides of two MDF frames with screws as load-bearing points. The many rotary and sliding connections made the issue of friction versus looseness ever more prominent in this prototype. This was the main learning and incentive for proceeding in the combined solution with what was available of proper bearings.

Figure 4.22 Scissor-lift prototype.

The next iteration was about designing a combined solution for the Cartesian concept. This should prove controllable, synchronous movement of the vertical and horizontal joints to demonstrate movement along arbitrary paths in the pot's cross sectional plane. The design process of this prototype was initiated by investigating and getting what was quickly accessible of components in the workshop, close to the dimensions and specs that was desired and required beforehand. Some key components such as timing belts and pulleys, motors and bearings, were crucial to get hands on before proceeding with the development of the design.

Especially in the case of bearings and pulleys the quality on what was accessible in the workshop varied a lot. Components of this kind would always be available at the closest hardware store. However, the tools of laser cutting and 3D-printing came in handy on producing, small, custom components compatible with the of the off-the-shelf components already acquired. The most high-end components were prioritized is places in the design where small clearances and little friction was particularly important to avoid, like in the telescopic mechanism. Good tooth-belt alternatives were not available among stores in Trondheim or with quick delivery, and the dimensions available in the workshop became driving dimensions for rest of the solution, along with the motors.

The decision on motors was based on finding a type not too big and heavy to unnecessarily scale up the produced parts of the robot, but powerful enough to handle the potential friction in the system and lifting the weight of the robot. Also, having the possibility to make rapid, iterative changes in motor control during code testing was another important feature. The workshop alternative closest to these desired features was a couple of bipolar stepper motors from MakeBlock ("42BYG Stepper Motor" 2017). Together with the stepper library in Arduino ("Arduino - StepperStep" 2017) they would provide a relatively simple way of initial control of the Cartesian concept (based on the authors knowledge). They should also be able to offer the needed torque when running at average-to-low speeds and sustain a holding torque at no speed (Alciatore and Histand 2012). The clear downside seen from the authors perspective was the uncertainty of torque needed to drive the system, due to the varying quality of the parts in the drive system, and that the stepper may 'glitch' steps when running close to maximum torque. Opposite to a servo, the stepper does not feature any position feedback (encoder) connected to the rotary shaft. The glitches in a stepper motor will not be recognized by any encoder, which will result in a permanent position error. The author still considered the stepper alternative to be the simplest of what was instantly available, and habile enough for the task of this prototype. However, for a higher resolution prototype featuring motors, mechanics and control software, the use of DC-motors with optical encoders is considered by the author as the best solution, and closest to what should be finally implemented.

The author now took the idea of the combined concept into CAD-software. This involved a lot of minor, frequent iterations in terms of dimensions, orientations and clearings between components. It was initiated with the design of the two parts making out the telescopic links, together with their bearing-solutions. This module would together with the tooth-belt dimensions available be driving dimensions in the further design of the outer body. The outer body was by far the most complex part to design. It should have stiffness to not comply during testing, thus making it as massive as possible. It was featuring slots for triangular bearings of the telescopic joint, slots for the upper bearings of the scissor lift mechanism, motor brackets, and sufficient space for the belts and belt-tensioners inside. The decision of the motors' placement was based on a set of things: weight-distribution, available space in the design, the belt-lengths and avoiding interfering with the scissor mechanism. Identifying and designing a sufficient rack and pinion principle for driving the scissor-lift was done simultaneously. Simple physical testing of the rack and pinion principle together with a stepper was done at this point to verify function and estimate the forces provided by the motor with no further gearing.

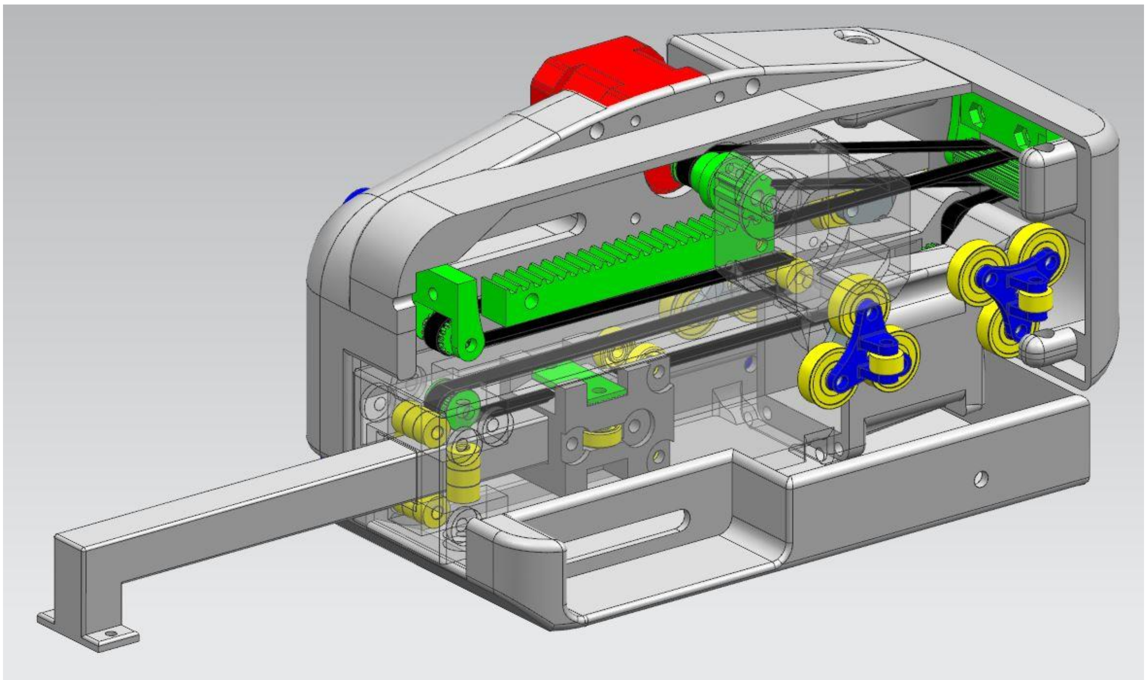

Figure 4.23 The Cartesian manipulator concept designed in CAD-software. The closest of the two outer body parts reveal the interior. Bearings of different qualities are shown in yellow; printed brackets in blue printed drive-related parts in green; motor in red; tooth-belts in black; bigger printed parts in grey. Screws nuts and rods are not shown. The belts were tensioned with screws and nuts.

The applied solution seen in Figure 4.23 seemed to suffice. All-components but the motors, the belts, the bearings, the scissor lift's arms and screws and nuts were 3D-printed in PLA using a Ultimaker 2+ ("Ultimaker 2+ Specifications | Ultimaker" 2017). The reason for the high volume of printed parts is the particularly small effort in producing the components, since other work on coding, electronics, documentation or prototyping other concepts may be done during printing. A drawback using 3D-printing over other production methods was the constant estimations of extra clearances, as the printed parts tend to swell with 0.2-0.3 mm (or even more) in certain directions. The geometry of the bigger components was deliberately designed for other manufacturing alternatives, such as milling, forming and/or welding, if scaled up and using proper materials. Milling may had been an alternative in this prototype. However, using the main body in the robot's upper section as an example, the huge material removal and several mountings of the same part would require certain changes in design to justify such a manufacturing approach. Applying even more effort on this would make the prototype's intentions diverge in terms of workload versus learning output.

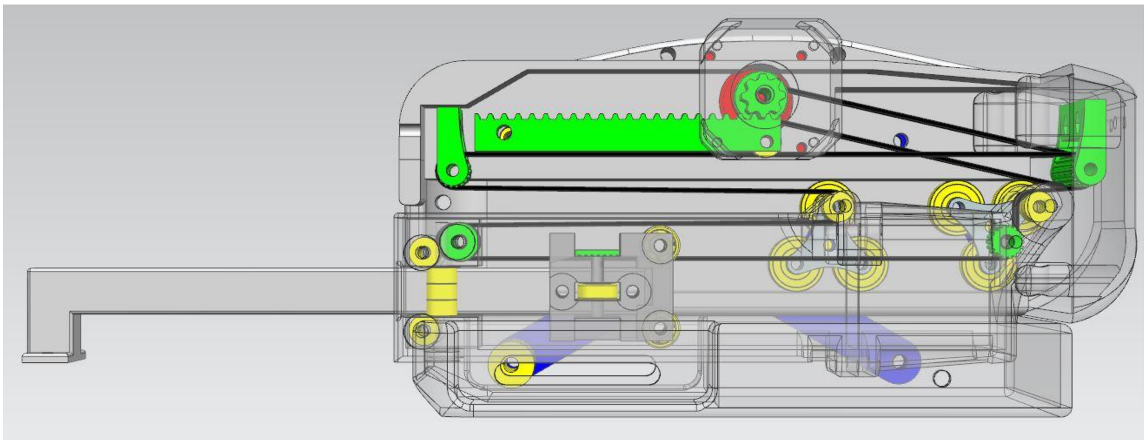

Figure 4.24 The Cartesian manipulator concept with a sideways section-view. Two tooth-belts were used to run the telescopic mechanism due to the positioning of the motors. The vertical joint was run through the rack and pinion mechanism. The rack had a rod connecting it to the outer-lying arms of the scissor-mechanism.

An important aspect of the design process was also to decide what and how parts should be split for assembly. There were examples where this was essential for building the prototype, however, the author wanted to keep the number of parts and bolt-connections to a minimum, and only split parts where it was necessary. One good example is the telescopic joint in the picture below, where the outer link needed to be split to assemble the inner link's bracket. Another reason to split certain components lies in the increased risk of failing prints when 3D printing large components. This was another good argument for splitting the main body in the robot's upper section.

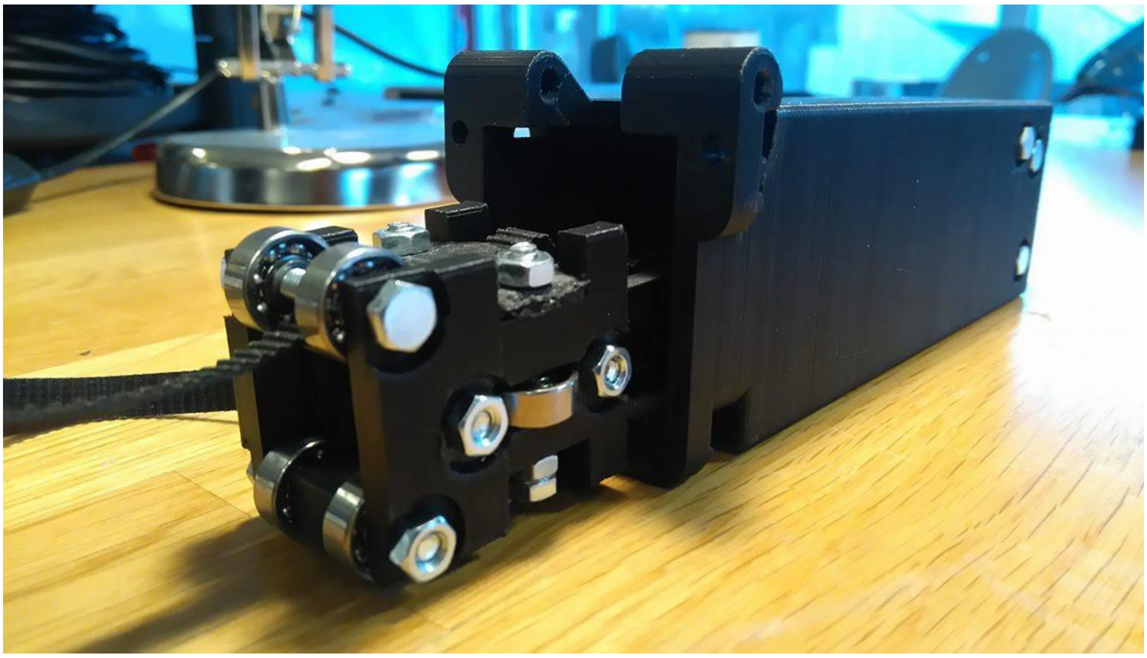

Figure 4.25 Assembled arm-bracket within the outer telescopic link.

The designing and building of this prototype are good examples on how one's qualitative knowledge of the concept and the different combined solutions increase drastically throughout the process. The learnings acquired prior the testing are significant for the understanding of such a system and its weak points. Building a working robot boosted the author's understanding of practical robotics generally, and the mechanical engineering of such system specifically.

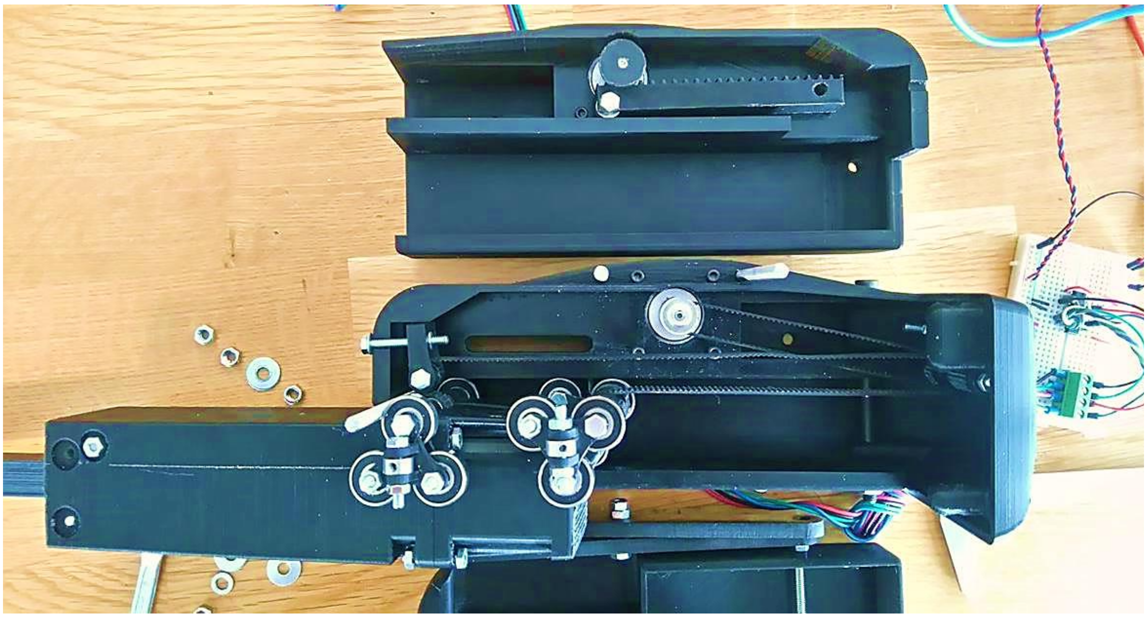

Figure 4.26 The Cartesian manipulator concept during assembly. A fully assembled telescopic joint restin in the outer-body with the belts tensioned is shown. The rack and pinion drive is also seen in the outer bod part at the top.

Initial testing included running the Arduino keyboard control script (appendix C). Running the horizontal drive proved that the outer link in the telescopic mechanism would always run first out and first in. The simple bearings at the outer link's very front had a lot more play than calculated (about 1 mm), however this did not seem to affect the functionality significantly, since the other bearing solutions were very solid. Solid was also the overall impression of the final robot, with the PLA providing significant stiffness even at only 25% fill density in some of the bigger parts, and sufficiently big dimensions for the bearing brackets to withstand payloads at testing with good margins. To even out the considerable downward force from the weight of the robot's upper section, a couple plain, tension springs was attached to the front and rear rods crossing the robot's lower section. These rods combined the two scissor lift sections at each side together, making the sections less likely to jam of flex individually due to friction. The springs applied linear force upwards in the scissor system, thus making the stepper hold torque in the vertical joint with considerable less effort.

The prototype work properly at decent speeds of what is estimated for the operation. The Cartesian prototype should be used next to test the path algorithm concept in section 4.5.2.1.

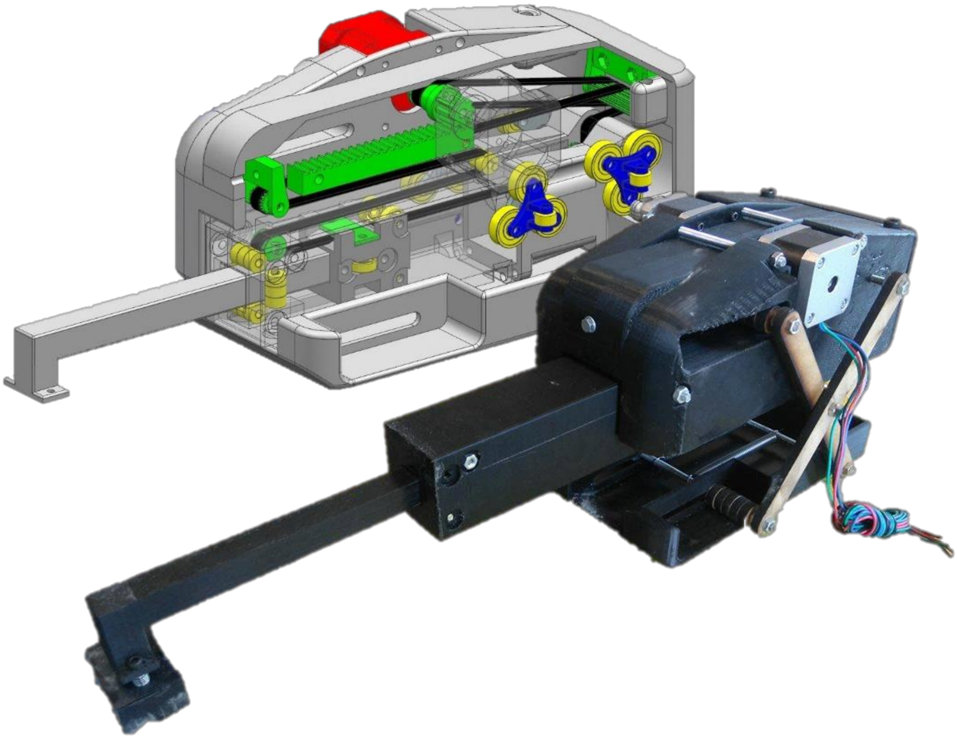

Figure 4.27 Modelled and functioning prototype. The functioning prototype pose with a full reach of its telescopic joint and with full height.

4.4.2.2 The Handheld Rubber Finger Tool with Pneumatic Load Sensor

As stated in 4.4.2, this objective crave much of the previously visited functionality of the tool. This section should be an opportunity to combine some of the previously visited solution into a handheld tool configuration. Related to the figures used in the environment prototype of anode-ages, the author chooses to proceed with the concept of rubber fingers featuring good tendencies both in terms of RCC and mass-moving capability. A new iteration of the pneumatic load-sensory concept using syringes, tubes and a pressure sensor is also applied for crash detection by the tool's static parts (above the rubber fingers). The syringes' pistons are fastened parallel to spring-tensioned bolt fits between impact-plates and the static tool-center. The impact-plates are meant to reveal sudden, unpredictable obstacles exceeding the rubber finger tool's geometric capability. This may involve crash-detection of crust heaps at the inclines, elevated above the path of the rubber. The rubber fingers tool is attached to a similar spring-solution for vertical direction, yielding impact-detection functionality. Roller bearings let the bolts travel into the tool-center when the springs are compressed. The tool-center simulates a custom end effector that is bolted to a 1.5 m shaft imitating the ACU's arm. The pressure sensor is located at the rear length of the shaft, wired to an Arduino UNO and connected to the end effector with a long tube. This end effector solution contains no electronics and has no movable parts but roller bearings. The concept is pushed due to its conservative approach with little or no usage of potential problematic solutions in the end effector, such as electronics, sensors, actuators etc. These may prove problematic due to the full immersion of the end effector in the hazardous environment, and the increased exposure and risk that goes with it.

The handheld functionality in this concept is to facilitate rapid testing of the end effector concept. This also involves evaluating the thought fixed orientation of the end effector during operation.

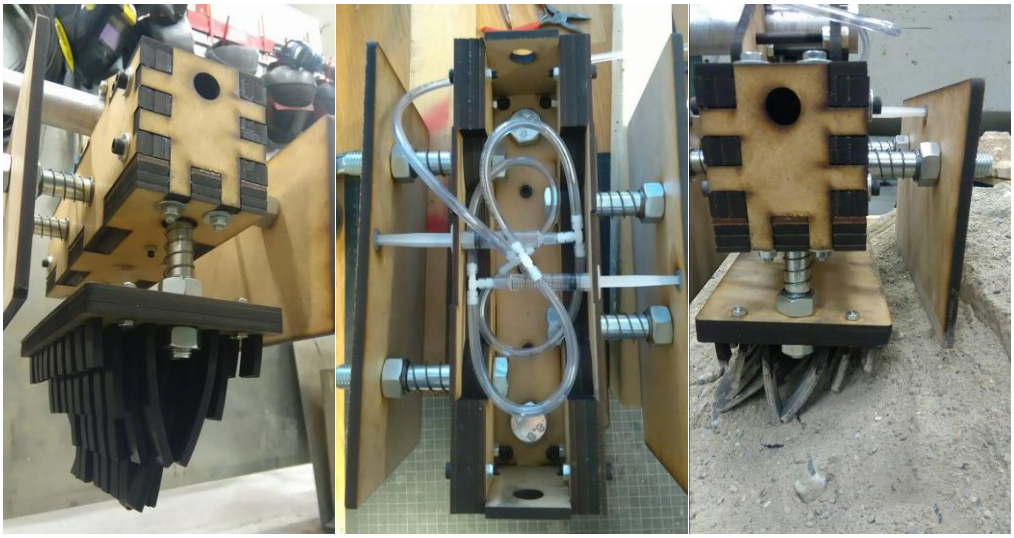

Figure 4.28 The handheld rubber fingers tool. The previously visited tool attached to a center-box (tool-center) for bolt-wandering when the pre-compressed springs gets further compressed (left). A common pneumatic system for two crash-impact plates, front and back, and the vertical impact from the surface interaction (middle). The tool was applied in the pallet prototype (right).

Testing of the handheld tool was conducted in the Anode Pallet prototype. By moving the tool with a constant orientation similar to the right picture in Figure 4.28 above, cover-mass was distributed in a predefined sequence.

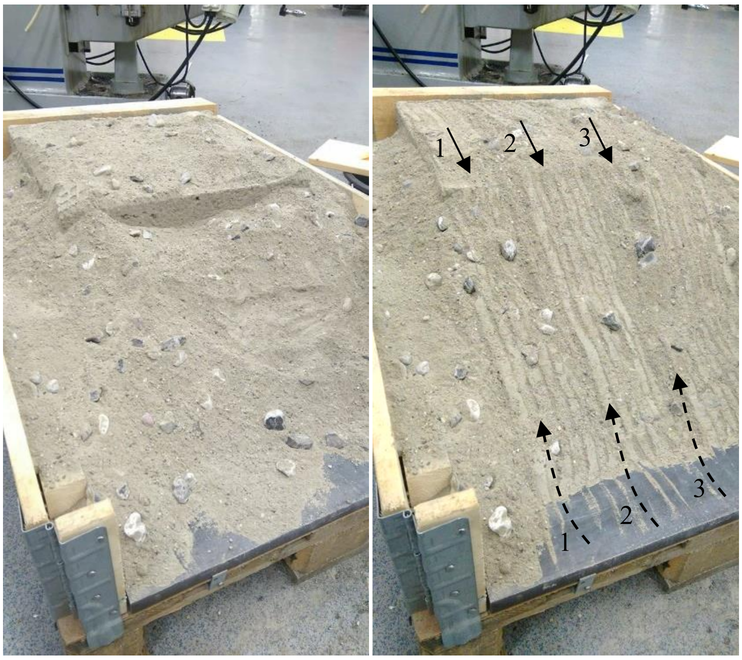

Figure 4.29 The test of the handheld rubber-fingers tool before (left), after (right). Arrows indicate the described test-sequence in the text.

The first test was aimed at a combination of the three previous objectives in section 0-□. Then, a test-scenario could be where the anode front was exposed with little to no mass on top the crust in front of the anode exposure. Cover-mass was spilled randomly on the front plate, along with a 2-3 cm layer of loose mass on top the anode. This is seen to the left in Figure 4.29. The sweeping-sequence was conservatively based on the assumption that little to no loose cover-mass would be accessible, and therefore the sequence was initiated with sweeping from the rear side of the anode prototype top towards the exposure. This way, what could be accessible of loose mass on the top would be swept over the exposure, and is indicated with solid arrows in Figure 4.29. The next action was to pull the tool back to the front plate through air, sweep the front plate towards the anode, then shovel cover-mass along the incline towards the anode's top front-edge, which is indicated with the dashed arrows in Figure 4.29. The combination of these action was conducted three times, in three parallel lanes, for a sufficient result.

Even though the test showed promising results for the tool concept in solving the first two objectives, there were several drawbacks. The concept with impact-plates did not work properly with the current bearing configuration and placement, constantly jamming at impact. This was due to significant play and friction in the bearings when experiencing torque through the impact-plate. A wider distribution of bearing points on each bolt should be applied if the concept was going further with this type of solution. The impact-plates felt over-dimensioned in area, and under-dimensioned in strength, and somewhat misplaced on the end effector.

Regarding the rubber fingers, they had been previously tested with the applied design and showed much the same sufficiency in moving mass. However, the test was now revealing that the grid of fingers should be even tighter. This would yield more desired stiffness to shovel the cover-mass. The fingers did also have an unfortunate tendency to pack cover-mass down in the terrain along the way. In a sense, this may be considered a waste of loose mass. The V-pattern of fingers seemed to intensify this, which made the author reconsider the design.

The amount of wandering-distance in the spring-tensioned bolt-fits seemed exaggerated and should also be scaled down. Feedback was received in the vertical load-cell, and the piston was properly withdrawn by the springs when no load was applied, however, the impacts were shifting due to the poor bearing solution.

The tool was tested next with a similar test-sequence standing on the opposite side of the pallet prototype. This was to simulate the action of anode covering the anode's rear side. The test was then started by shoveling from the top to the rear edge of the anode and beyond, then lowered to the slope, receiving a force feedback. The tool could not reach more than half-way down the slope, then it was withdrawn along the surface to cover the anode exposure. Due to the intentional symmetry in the tool, the test showed close to identical results in covering the exposure. This showed that anode covering may be conducted as a similar sequence at the anode's rear end. The clear drawback with this approach is the limited clearance between the robot arm and the cover-mass surface on the anode's top. Currently, this type of covering is conducted from the opposite side of the pot, applying a longer reach with the rake.

The next iteration will split the concept, and test new solutions or new configurations of what is already applied here, individually.

4.4.2.3 The Pliant Impact-Plate

The impact-plate design was changed with the newfound requirements of size, strength and torque. To also decrease the use of moveable joints and the risk of jamming bearings and collecting dust, an alternative to the spring-tensioned bolts was posed. As stated in the crash detection objective summery in section 4.3.3, continuing with new iterations of this concept would not be to pursue a solution for crash detection. However, the author saw this as an opportunity to experiment with this concept as an alternative RCC configuration. (Smith 2007) legitimize such experimentation as a way of exploring the limits of a concept without committing to how it may be applied, or indeed, whether it will be iterated further.

In this new solution, the surface for impact was reduced to a curved 6x24 cm surface. The piston-sleeve on the syringe was glued to a static MDF-bracket, whereas the spring-tensioned bolt-fits were replaced with plain, fastened compression springs, custom made to iteratively adjust the distance between the bracket and the impact-plate. The piston was not fixed, but pressed towards the impact-plate with spring-force to maintain contact. This way, the syringe's piston would receive consistent impulses from the impact-plate at arbitrary positions and directions of impact. Curved redesign should facilitate a better distribution of forces on the plate when hit in an oblique direction.

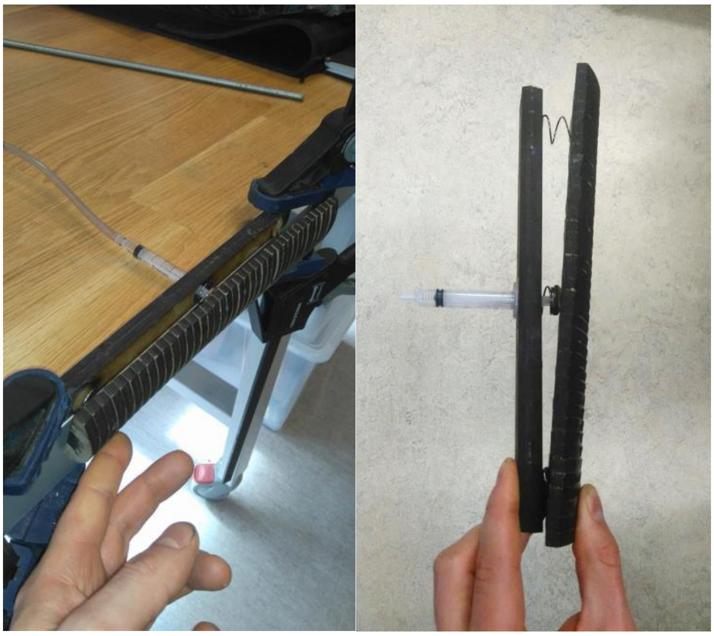

Figure 4.30 The pliable impact-plate.

The prototype was tested by fastening the bracket to a static object and register pneumatic pressure elevations on an Arduino UNO with the same pressure sensor setup as in section 4.3.2.1. This time, a smaller part of the syringe's volume was used, due to the decreased distance between the impact-plate and the bracket. This naturally led to smaller elevations in pressure values at impact, compared to the configuration in the handheld rubber tool, however the concise and sensitive registration of impulses as seen in the very first test in section 4.3.2.1, was evident. The contact-head at the end of the syringe's piston should be improved with a more curved shape of the same reasons as the impact-plate acquired its arc-shape. A next iteration should feature more friction between the piston and the impact-plate, as well as reorienting the springs as suggested by (Whitney and Rourke 1986) in their RCC solution. This should inhibit slipping when there are impacts below the syringe that introduce considerable torque in the impact-plate.

A notable, potential challenge may be the change in the springs' mechanical properties when they are exposed to considerable heat. However, ("High Temperature Alloy Spring" 2017) and a range of other spring manufacturers, offer e.g. custom Inconel springs with the possibility to operate at temperatures exceeding 550 °C with good corrosion resistance.

Overall, the solution seems promising for binary, tactile crash-detection, and only that function alone. It can only be used to sense *if* there is an impact, or not. Any attempt on registering accurate position values of the impact-plate for controlling purposes, using this concept, will basically be futile. This is because the sensor would not know whether there is a small, centered impact or a big impact on either of the plate's ends. Adding such functionality could be possible, but is not prioritized before a proper need is stated.

4.4.2.4 The Rubber Fingers Tool (further iteration)

As a first step in a new iteration of the Rubber Fingers tool was to reconfigure the number and geometry of fingers and the arrangement. Based on the torch and pallet tests the fingers should be somewhat bigger and stiffer. The author suggested clamping numerous fingers together to provide the local areas where the tool might flex. The width of the fingers was increased to 30 mm, and numerous layers of clamped finger-rows was applied to increase the stiffness in the tool's direction of movement during anode covering. The V-shape was scraped for the benefit of a hollow rectangular configuration as seen in Figure 4.32. This configuration was also a design for not yet visited topics that will be mentioned in section . The dissimilar orientation of the rubber fingers along the tool' side compared to its ends was intentional. The author wanted to experience the effort and stiffness difference between applying frontal and lateral forces during testing.

Figure 4.31 The rubber fingers tool. Featuring a tight grid of clamped rubber fingers. The clamping gives simpler design for assembly. The fingers are wider and shorter from last iteration for higher stiffness, and i terms with the findings from the torch test. A box in MDF is covered within the wrapped welding curtain.

Testing was performed inside several pots at Alcoa Mosjøen. Several qualitative tests and observations was conducted, starting out conservative with a front plate sweeping test. The tool should ideally have a fixed orientation with the rubber fingers orthogonal to the horizontal plane, as in the ACU concept. The initial tests involved front plate cleaning, before general cover-mass movement atop the anode carbon was conducted. Then several runs with the tool in a similar trajectory to the operation sequence evaluated in section 4.5.2.1 was done, featuring all previous objectives but 4.3. Finally, destructive test was made, such as holding the rubber still on the cover-mass surface and above cavities with intense flame exposure.

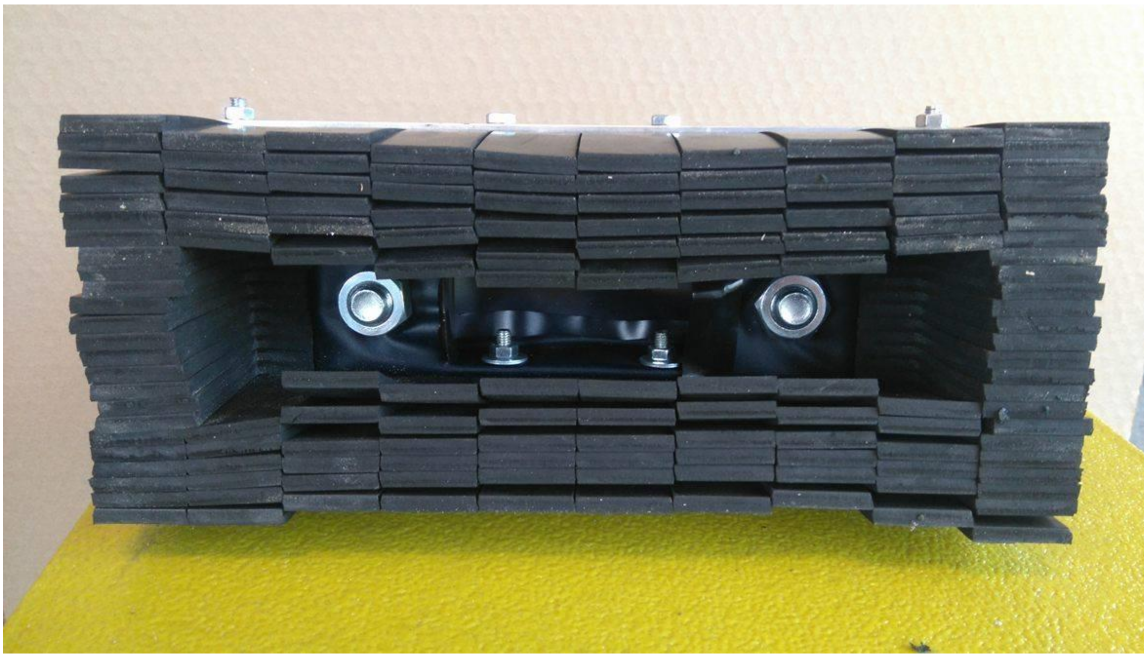

Figure 4.32 The rubber fingers tool seen from below.

Sweeping cover-mass into the pot from the front plate was performed with little effort and with excellent results. The tool shoveled cover-mass up the incline with somewhat less effort than with a regular rake. This was also commented by Alcoa process engineer and experience plant operator Kim Ronny Elstad who performed several raking procedures using the tool prototype. He stated that besides the tool's extra weight and the effort of holding it, he felt the effect from the intentional individual flexing between the rubber fingers. It made the tool flow better with the terrain with less effort; a physical demonstration of the passive compliance.

The author was however surprised by the considerable amount of movable cover-mass at new anodes, which made mass pile up fast and extensively when shoveling, applying heavy duties on the tool when kept within the same path of movement. Even though the tool performed well in moving cover-mass forward, it still tended to 'push' a considerable amount into the terrain. This shows too elastic features in the configuration of rubber. The extensive bending of the rubber fingers introduced downward forces intensified by the tool's weight during the testing.

Figure 4.33 The rubber fingers tool applied for anode covering during pot tests at the corporate partner. Dust and rubber-smoke is clearly seen in the picture to the right. The tool did however perform well with respect to its mechanical principle but still lacking a certain stiffness.

Regular covering also made gravel get stuck within the rubber fingers, as seen in Figure 4.34. This spread the fingers, thus decreasing a much-sought stiffness for shoveling. Shoveling sideways revealed less flexing in rubber fingers inward to the tool's center due to the increased second moment of area and seemed to be fully capable of moving cover-mass, however unfortunate spreading in the rubber was also occurring as gravel got stuck.

Figure 4.34 The rubber fingers tool seen from below. Only one iteration showed some degrading in the fingers and fine gravel getting stuck (left). After several runs of covering and intentional, destructive testing in open pot fires, the rubber fingers were shattered (right). A marked difference between front and back gives an indicator on the mechanical shear's impact when heated, as most load was applied in the front.

The degradation in the natural rubber during both normal and extreme cases of anode covering got very prominent. The rubber worked as a destructible sensor to indicate the rapid, severe temperature increase downward in the cover-mass layer. Estimated heat exposure had been based on the cover-mass' surface temperature generally, with occasional hovering over cavities as a critical case. The current raking does not commonly involve long periods where the rubber strip lingers in contact with the surface, and for good reason. New temperature measurements showed an instant surface-temperature increase from about 350 to about 500 °C by removing a 1-5 cm layer of cover-mass in the center area over the anode's carbon. It was interesting to see the different uneven melting of the rubber fingers. During testing, the tool had mostly been kept horizontal, however most forces seemed to have been applied in the front area. This clearly shows the practical, combined effect of heat and mechanical impact. The rate of degradation was significantly higher for this configuration with natural rubber than using the rake with tire rubber.

The MDF showed no sign of impact from the environment. The curtain covering it partially melted when held in the gaseous flames for 20-30 seconds when, meant as a destructible test.

The strength of this tool lays in the solution of separated segments (rubber fingers in this case) which features good qualities when receiving sudden impacts with less stress on the overall tool and effort for the ACU. (Siciliano and Khatib 2008) underlines that any active interaction control (the ACU controls the tool relative to the forces inflicted from interaction with the terrain) should be used in combination with some solution of passive compliance. It will introduce a much-wanted delay for the active compliance control to react to the overall load on the tool. The pot-testing clearly showed that an elastomer-tool solution would require a significant increase of the fingers size and thickness in terms of mechanical sufficiency, but also with a more heat-resistant elastomer with high durability, which after all is expected. Teflon might be a good alternative ("Gummi Og Maskinteknikk" 2017). However, if this function of passive compliance is preserved, an alternative where the elastic features is moved to a more heat-shielded area should be reevaluated. This means reviewing the spring tool design and look for opportunities to make the tool more suitable for the different objectives and pursue solutions where it initially did not suffice. These were related to front plate cleaning and imbalanced forces from the inconvenient spring orientations. A next iteration may be inspired from the "Push-Pull" shear pad RCC design by (Whitney and Rourke 1986), which might either be applied in the tool or within the ACU's arm.

4.4.3 Objective Summary

- The tool yields a passive compliance-features (Siciliano and Khatib 2008), yielding instant mechanical response. Siciliano & Khatib underline the value of applying some degree of passive compliance to decrease reaction forces on the ACU and maintain a reasonable operational speed without instant, fatal overloads.
- The tool's mechanical interaction is performed in a sufficient manner with a simplistic and cheap design. Its mechanical and configurative weakness were the lack of stiffness even at small finger lengths and the many layers of fingers accumulating gravel.
- Stiffer and more heat-resistant elastomers, such as Teflon, must be applied for pursuing a resembling concept to the rubber fingers tool.

- A new iteration on the crash-detecting impact-plates was made to inspire the author's solution-space regarding RCC. Based on the elastomers poor lifetime, the author advice reviewing the ideas from the spring-tool concept and possibly other RCC configuration alternatives (Smith 2007).
- Custom tool brackets for later pot testing may be sufficient using simple, cheap materials with rapid production methods, such as laser cut MDF and a flame protective welding curtain.
- The pot testing confirmed an insufficient amount of cover-mass in the pallet prototype during the workshop testing.

4.5 Objective: Generate Concept for End Effector Path Planning and Control During Anode Covering

This section goes deeper into how the ACU is going to operate to achieve the previous objectives in terms of movement and control. Thus, it is a first concept of simulating the overall operation. This include defining motions to the objectives of removing cover-mass from the front plate, cover up in front of the anode, and cover at the rear side of the anode. Interacting with the cover-mass is desirable, especially in the front of the anode where crust ridges will harden and linger, and thus facilitate more difficult covering conditions. It will be derived an approach of anode covering based on information from Alcoa, findings in the previous objectives and certain similar operations taken from autonomous soil-movement tasks.

Identification of cavities and exposed areas on the anode has been discussed in appendix A, where the authors weighted the possibilities of using thermal and vision sensory. These approaches showed good promise in evaluating the cover-mass surface's features of temperature and potential height variations in the terrain to define what would likely be a cavity or anode exposure, in 3D space. This would be based on applying vision equipment on the ACU. In the light of defining the ACU as an external, floor-based, mobile unit, together with Alcoa's strong desire of no altering or applying stationary equipment on or inside the pots, it must provide a sufficient field of view at the rear side of the anode on its own. Facilitating use of such exposed equipment at the pot's center would then be a potential new objective. This would have been a natural next step from the objective in section . With the downsides of using potentially expensive equipment with the higher risk of failure and malfunction in the hazardous pot interior, other strategies for establishing a foundation for trajectory planning was pursued.

By reviewing the environment probes in the previous objectives, there were three critical, geographical points of action that should be relevant for the ACU to achieve success. These were located at the pot's front plate where cover-mass should be removed (section 0), by the anode's front where cover-mass should be moved to hinder hardening and cover potential cracks and anode exposure (section 4.2), and at the anode's rear side where much of the similar actions to the anode's front should be performed (section □). By obtaining the information on the anodes' ages (the time since they were inserted in the pot), the ACU might get data on all anodes' heights within the pot it is located by. Since the anodes are static in all other directions than vertical, known pot geometry and height data may describe all anodes carbon top surfaces exact relative to the ambient, static environment. Given the ACU has identified its location in 3D-space relative to the pot's front plate, it will know the relative position to all the anodes' carbon surfaces within that pot. This is a great advantage for approaching geographical points where objectives should be solved. By also knowing the anode carbons' length and width (which are properties that might change due to oxidation and tearing on the carbon, but are either considered neglectable or irrelevant in this approach), the locations of the anode carbons' top front and back may be calculated. Again, these locations are known to be close to where cavity expansion and exposure are commonly occurring. When revisiting Figure 4.12 in section 4.4.1.1 where anode age scenarios were probed, a potential path (in the pot's cross sectional plane where inward and outward movement relative to the pot occurs) for the tool, is depicted in Figure 4.35.

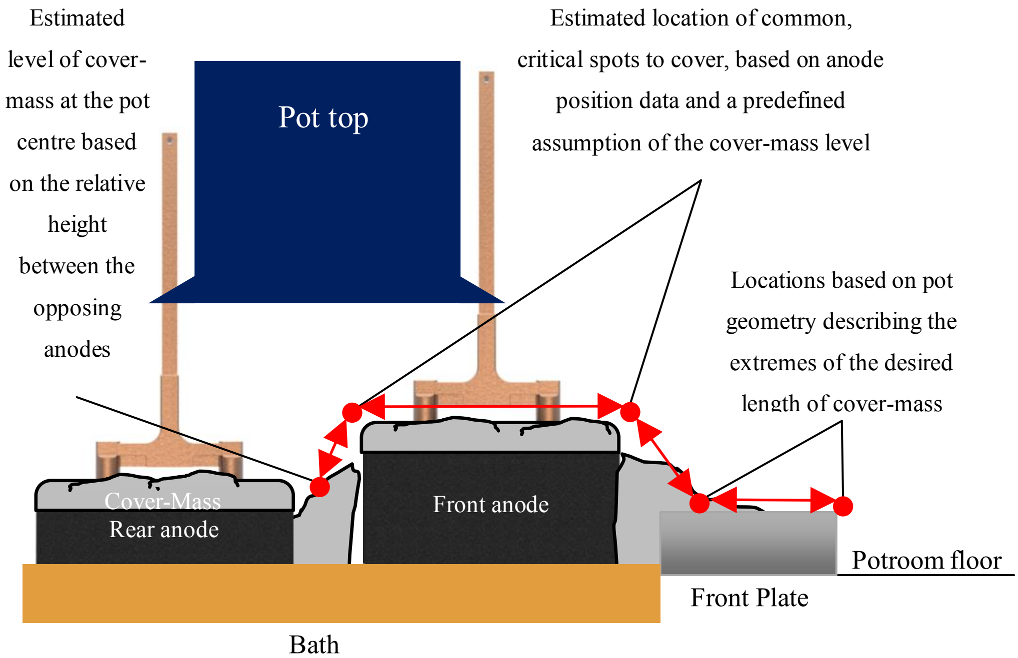

Figure 4.35 Potential path in the operational space based on pot geometry.

Probing-iterations takes this further in the sub-sections.

4.5.1 Environment Probing

The initial environment prototype for this objective should represent a downscaled prototype of the situation shown in Figure 4.35, fitting the 1:10 downscale in the Cartesian prototype. The setup from 4.4.1.1 was used. Testing is featured in section 4.5.2.1 with the following stepper algorithm.

4.5.2 Product Probing

4.5.2.1 Sweeping Along Path with Stepper Motor Control

This prototype is a proof of concept of sweeping cover-mass along a path based on constant geometric parameters of the anodes location and cover-mass buffer.

The code should provide arbitrary, linear movement for the end effector in the planar operational space. The anode covering operation was broken down into operation sections, where each section contained a sequence of movement intervals based on parameters of the desired movement in in the x and y direction. These parameters were distances between the predefined geometric point-parameters mainly, together with some calibration numbers added during testing. Each point was defined as x and y coordinates used for horizontal and vertical movement respectively. The transition from millimeters in the operational space to steps in the joint space was made empirically using linear interpolation and tuned from several iterations of running the joints individually a certain number of steps over certain distances. This effort gave decent accuracy from such a simple approach of solving the inverse kinematics (Siciliano et al. 2010).

The corner-stone in the algorithm lays within the "movement"-function (appendix C) with the number of motor steps in the x and y directions for the desired movement interval as inputs. The stepper in the dimension with the longest distance holds the predefined speed, while the stepper moving the shorter distance will move with a speed equal the fraction of the two distances. For instance, if a desired movement of (x,y) = (100,400), a loop with 400 increments will make the y-stepper move one step at every increment, while the x-stepper may not move until reaching an integer of steps. This will ultimately result in the x-stepper moving only once every fourth step relative to the y-stepper, making it a quarter slower. The movement will stop when the loop has reached its 400 increment, thus having the steppers move simultaneously with 100 and 400 steps in the x and y directions respectively.

Figure 4.36 The environment prototype for stepper algorithm testing. A pair of carbons were represented with their rear (left) and front (right) ends. The red wiring "cavities" were first revealed (top). The cavities were covered with available cover-mass, though the front plate were insufficiently cleaned (bottom).

The operation sequence start with a set of movements replicating the movement-pattern of tactile height sensing between the tool and the front plate. This is followed by a similar movement-pattern at the anode top to calibrate the approximated height of the cover-mass layer atop the anode. Next, the anode covering movements are run: sweeping towards the rear end; hover to the pot center; move down; return sweeping to the carbon's front; cleaning the front plate by shoveling inwards; sweep up on top; then return to home configuration. The sequences were tested and adjusted iteratively and added to the main code chronologically. Finally, the code ran as a complete sequence without much necessary calibrations. An example-run is shown in the video-link in appendix E.

The goal of the test was to observe the operation, particularly paying attention to mass movement execution, collision and ability to cover with varying amounts of mass. The operation sequence was run a high, unknown number of times where qualitative evaluations of the operation process and the hardware-prototypes were made iteratively.

The Cartesian robot did not show any prominent signs of insufficiency during the tests, but a few glitches between the belt and one of the printed pulleys. The pulley did clearly not provide the surface finish that was required to fit the belt teeth properly. Stepper-glitch errors first became very prominent in those cases when the robot accidently crashed and hit overload, as expected, however this was not a problem as soon as then mass layer height was calibrated for. The code did not provide any forward kinematics for translating the number of steps for a certain movement into a current position of millimeters by simple summation of traversed distances. This would have made a simple code even simpler in terms of intuitively tuning and changing parameters.

Important learning from this test was to confirm the functional implementation of code, robot and environment prototypes in an operation concept providing a very simple way of positioning the end effector close to the most important areas of the objectives and plan linear paths between them without any known need of sensory. The setup of prototypes worked further as a tool for discussing what the operation sequence had or lacked in sufficiency, concluding that the actual anode covering success with the current approach would be uncertain at the best. It is no secret that pure motion control strategies are prone to failure for robot-surface-interaction tasks (Siciliano and Khatib 2008), especially in dynamic interactions as this inertial case where varying cover-mass forces and mobility occur constantly. Obtaining an accurate description of the terrain needed for motion control to suffice on its own would be very hard, even with vision sensory to pre-plan sophisticated trajectories.

Concrete examples where problems arise for the motion control concept in this section may be when the end effector found itself wandering in air, where the path deviated from the cover-mass surface considerably, thus risking neglecting important covering. The ACU also had no way of regulating the amount of mass moved to actively bring cover-mass over crust edges rather than risking deposing most of the mass in front of the edge. Even though perfection is not attempted in the overall concept, a controlling concept for the cover-mass movement would be crucial. The need for this has been somewhat known from the start, however, important inspiration for suggesting and debating controlling concepts has surfaced throughout this probe. A discussion on further concepts for controlling mass movement and the suggestion of a simple open-loop proportional controller for tool-elevation versus horizontal load is featured in the next section.

4.5.2.2 Force and Motion Proportional Controller

From the learnings in the previous stepper control prototype, implementation of a controller for cover-mass movement should ensure physical contact between the tool and the cover-mass surface when it is *desired*. Experiences from the pot testing of the rubber fingers tool (section 4.4.2.4) showed that constant contact might neither be smart in terms of decreasing tool-life or necessary for the operation. The amount of cover-mass may suffice even with less cover-mass interaction. However, question as such on interaction-duration and trajectory timing plans was considered an operation optimization topic, and would be more relevant in a later stage in the development.

This concept focus on the controller’s ability to adjust itself to the terrain in a more continuous way, not by deflecting at crust edges only, but also “dig” for mass when it senses there is no contact between the tool and the surface. This might be sensed from distance, vision, force or other tactile sensory. Inspired by the force-sensory work in section 4.3 and research on hybrid force/motion control (Siciliano and Khatib 2008), a proportional controller for regulating tangential force with gains in the tool’s height combined with a motion controller with geometric references from pot data, was suggested.

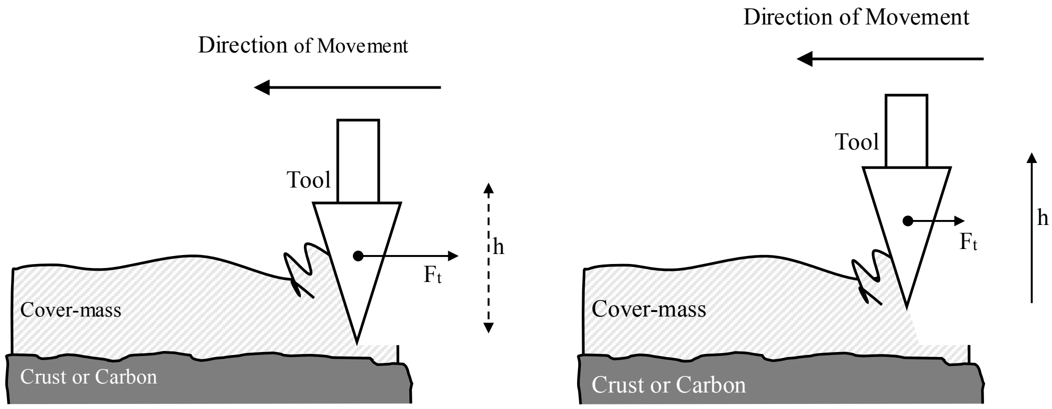

Figure 4.37 A proportional Force-controller senses the tangential force F_t. When F_t is increasing, the controller pulls the tool upwards (right) to achieve less load, and vice versa.

Figure 4.37 shows the principle of the elevation-control concept. When a sensed tangential force F_t on the tool deviates from a desired load, a proportional gain in height h will elevate or lower the tool to decrease or increase the sensed load respectively. In the case shown, a relief on the tool was desirable, as the amount of cover-mass builds up in front of the tool. This would also make the tool elevate when hitting crust. The force set-point would likely be decided empirically, and thus also an empiric tuning of the control parameters. However, some numeric approaches of parameter-identification with respect to automatization of excavation (Singh 1997), (Luengo, Singh, and Cannon 1998) and analytic force modelling of soil cutting (Reece 1964), (Terzaghi, Peck, and Mesri 1996), may be helpful in estimating force and control parameters.

In Luengo, Singh & Cannon's formulations of the forces applied on an automated excavator bucket, they reformulate the Fundamental Earth-moving Equation (FEE) by Reece, which describes soil-cutting in the horizontal plane, to apply for terrain slopes. This may be relatable to the cover-mass inclines on the anodes. They state forces in slopes are either over or under estimated in the absence of their reformulation of the equation. They suggest a combination of different alternative approaches to find model parameters efficiently since analytic solving is impossible due to the highly non-linear behavior.

The rapid, early-stage control concept in this thesis does not concern itself with applying any of these models. However, the author emphasizes the relevance of these findings for further simulations of control development.

Combined with the force controller, the author wished to preserve the strength from the previous control concept by applying a motion controller to keep the ACU's end effector from following the terrain out of the operation's desired domain. For instance, letting the tool follow the cover-mass surface into cavities is not desirable. A proportional controller was applied, where an extra gain is applied when the tool cross a predefined boundary above the anode. A two-dimensional simulation of a trapezoidal path representing an estimated cover-mass level from the front plate, above the anode's carbon and into the pot center, was modelled. The cross-sectional pot representation was generated from simulated pot data, and a random cover-mass layer was tied to the estimated cover-mass level. The pot system and the controllers was modelled in Simulink ("Simulink - Simulation and Model-Based Design" 2017), along with an artificial tangential force-sensor input.

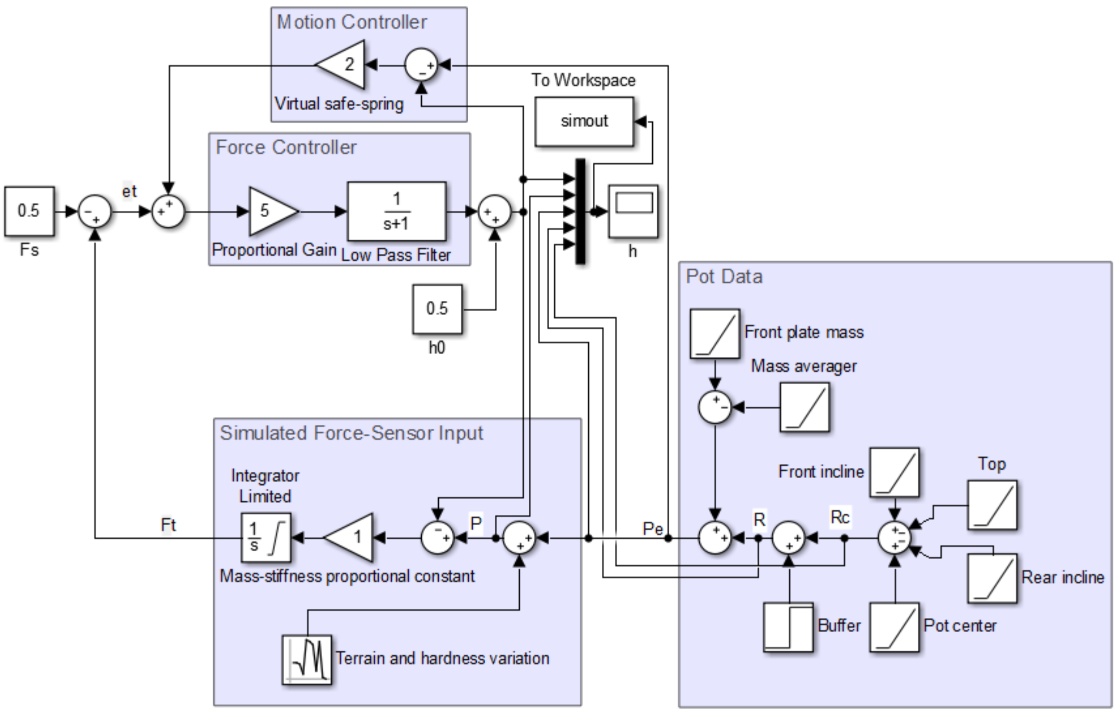

Figure 4.38 Simulink block diagram of the Force and Motion Proportional Controller.

In the simulation, the simulation-time was rather representing the pot's inward length axis (X) of an artificial metrics. This was to resemble the front plate, the front incline, the carbon top, the rear incline and the pot's center, from the origin respectively. The tool would move away from the origin with constant speed in the whole domain. The pot geometry was simulated using ramp functions which yielded the critical limit R_c for geometry location. Applying a buffer to the geometry gave the buffer limit R. The motion controller was tuned to avoid crossing this limit. An estimation of the assumed average (desired) level of cover-mass, P_e, was then added. Random noise was added to this average to represent the varying hardness and terrain experienced by the tool during surface-interaction. To represent force-accumulation in front of the tool, the deviation between the tool's height, h, and the terrain and hardness representation was multiplied with a terrain "stiffness" constant, then integrated. Figuratively, this should represent how for terrain above the tool-path in Figure 4.39 is swept into the "valleys" in the terrain below the tool. The common presence of loose cover-mass made this representation fairly realistic. Tuning the stiffness constant could be done empirically from mass properties and/or from calculation, such as the FEE. A low pass filter was applied to the force-controller to relieve the motors from responding to the highly frequent force-variations from the terrain. The motion controller was activated in the cases where small loads made the tool move below P_e. Its function resembles a virtual safe-spring, actively forcing the tool away from crossing the buffer limit.

In this simple simulation, the buffer limit and cover-mass layer estimate (besides the linear increase on the front plate) were simply proportionally shifted vertically, however more sophisticated estimation may of course apply.

A vertical force sensory input would be needed to control vertical impact, which, even though this would not be a necessary input to the controller at this stage. The tool-path followed P_e well. Decreasing the low pass filter's time constant will make the force controller more susceptible to sudden changes in the terrain stiffness, thus respond faster. The inertial forces in the ACU's arm makes this demanding for the motor. This underlines the value of implementing passive compliance functionality to avoid the need to actively control with such high response. The terrain-curve feature a random pattern of forces generated, however in future tests more realistic models may apply. One may want to assign different force parameters for different intervals on the path. The current control concept feature a constant force threshold and assumes a constant velocity in the operational space, which is not likely to be a good choice at implementation. On the front plate, a fitting force threshold for achieving the cover-mass removal may differ from what is sufficient force control on the anode carbon top. Consequently, the terrain hardness on the front plate is poorly modelled in this concept, however this could be easily changed.

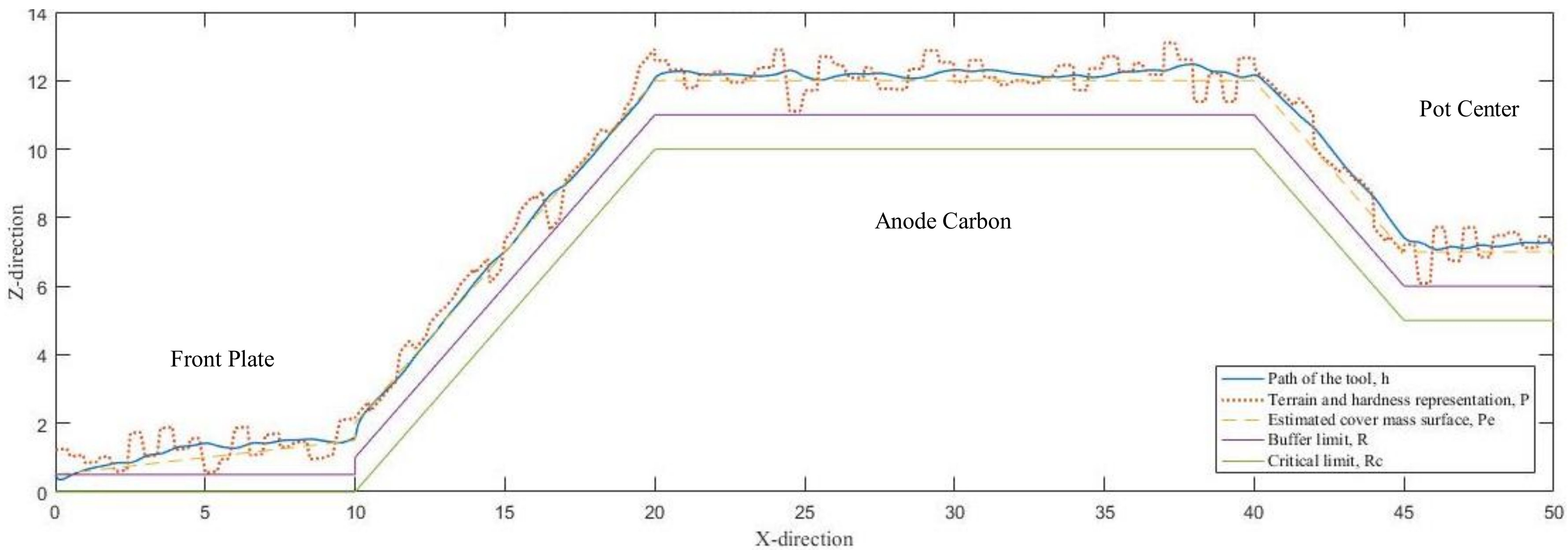

Figure 4.39 Simulink simulation of the Force and Motion Proportional Controller on cover-mass movement with a tool.

More sudden, frequent and drastic changes in the terrain may happen at the slopes compared to the front plate or anode carbon top. A slower movement in these areas would likely be more convenient.

4.5.3 Objective Summary

- Applying trajectory control exclusively seems insufficient in terms of sufficiently bringing cover-mass to potential cavities.
- Derivations from the FEE may be relevant for pursuing an analytic model for estimating force parameters in future simulations. Much relevant knowledge for the corporate partner may be obtained from the research-field of autonomous excavation.
- Different set-point parameters of force and velocity should change depending on location along the path.
- Other alternatives of simulating the terrain's stiffness should be tested, compared and evaluated.
- The legitimacy of a two-dimensional model of the movement of cover-mass should be the reviewed in further simulations, since realistically, prominent shear forces by the tool's ends are likely to apply.
- Vertical force sensory may perform position calibration between the tool and the front plate to verify the relative distance between the tool and the anodes, and for performing a mass level control atop the anode to correct/adjust the estimated buffer level of cover-mass, thus knowing where to start the operation in the vertical position domain.
- A combination of passive compliance and active force and motion control seems to be the most critical set of functions to achieve the overall objective of this thesis, sufficiently.
- The function of passive compliance does not necessarily have to be a part of the tool-design rather than closer to the ACU's base. However, implementing it close to the interaction may be beneficial for lowering the inertial forces. Force-sensory may on the other hand rather be moved to joints closer to the base.

5 Discussion

The concept detailing of the project has been a flexible way of moving between the most central objectives for achieving sufficient, autonomous anode covering, considered by the author. The high response to move between objectives and disciplines has been essential to give a broad picture of the solution space, but more importantly to understand what is a sensible anode covering operation. Due to the thesis' development approach providing iterative evaluations of the concepts, a lot of discussion is conducted locally within the different probes. The reader is encouraged to review the objective summaries before resuming this section. Important discussions are also featured in the product probes, particularly in section 4.4.2 and 4.5.2.

5.1 Findings in Concept Detailing and Further Considerations

The initial objectives were first prioritized due to their essential part in the AS-IS operation, which helped the author comprehend the importance of interaction to avoid further growing of crust-edges. Thus, concepts providing passive compliance in the ACU's tool emerged. This is a robotics topic mostly applied in the field of human-robot-interaction as a matter of safety, but also for co-operation. The concepts related to the end effector tool all featured some form of compliance, but at the same time, strived to suffice stiffness to move cover-mass. Achieving this balance has emerged as a critical function for interaction with the cover-mass surface, however is heavily biased toward the achievements of active compliance control in the ACU. The need for passive compliance has never been doubted as a solution to handle instant impacts on the ACU's tool, but should be designed with relation to controller design, and vice versa. This strong disciplinary correlation was an important learning for the author to establish a priority of further considerations from the project.

Where elastomers showed very good promise in performing excellent work on removing mass from the front plate (4.1.3), other solutions should be reviewed to perform this relatively simple objective. This is based on the rubber fingers tool being the subject to several iterations and a pot test where it did not suffice in several ways (4.4.2.4). The rubber-solution did however bring with it interesting uniformly elastic features. This may be interesting in terms of obtaining a more desirable distribution of the elastic forces in a compliance-solution, than what was achieved with the spring-tool.

The physical demonstration of a very simple, and achievable, trajectory concept (4.5.2.1) was a clear momentum booster in terms of defining a working concept for the anode covering operation. The demonstration did however also prove the assumed insufficiency of motion control alone, thus a Hybrid Force/Motion Control strategy was suggested. Then the ACU would still need to operate within boundaries of a pre-planned path, however moving cover-mass by controlling a tangential force input through elevation gains to a predefined force-value. A combination of vertical and tangential force inputs may be relevant to control height properly. Figuring out how applied forces behave on the tool is still a topic that should be considered with some certainty if cover-mass interaction applies. The tool's geometry and interaction will have grate impact on this, as one can derive from the analytic model of the FEE by (Reece 1964) and the altered model for soil-cutting in slopes by (Luengo, Singh, and Cannon 1998). Another aspect where the tool's geometry may have considerable impact is related to the legitimacy of a two-dimensional model of the tool moving cover-mass. Prominent shear forces at the tool's ends are likely to apply. Changes in the ACU's dexterity, e.g. featuring reorientation of the tool during cover-mass movement will of course also influence how the operation is modelled.

Dexterity has also been a prominent concept aspect. Tool-frames following the terrain may be desirable in terms of designing control and passive compliance solutions. Considering the arm and end effector in the custom concept in section 4.4.2.1, it was designed for simplicity. However, the ACU's inability to roll and pitch the end effector may comprise some very fundamental errors. When the mobile base gets tilted from gravel and uneven areas on the floor, orientation errors will linger. Tilt-sensory in the base, along with trajectory control, could even out for the position deviations from the planned path. Even though the orientation-errors may be neglectable for moving cover-mass, the transformation-matrix of tool's reoriented geometry must be calculated from the tilt-sensory and be accounted for, to avoid obstacles. On a general basis, the author would suggest the corporate partner to keep their doors open on the topic of dexterity and let the operation and control algorithm drive that decision.

The pitch problem may be neglected from proper tracking control in the case with the two-link manipulator (Meng et al. 2016). The pitch problem will remain for the Cartesian unconditionally, and may provide uneven wear and tear in the tool, which was experienced in the handheld rubber-finger tool's pot test in section 4.4.2.4. An uncontrollable tilt of the tool may also cause unpredictable heat and force impacts which may shorten the tool's life and impairing control, ultimately increasing the cost and maintenance and lower the quality and performance.

Severe cases of incline in the base may be caused by e.g. huge crust bulks, heaps of gravel or an elevation difference between the concrete floor and the iron grate. However, the author does not consider these deviations in the base's orientation to be very prominent frequently. Simulations of the trajectory and force control of the ACU should give good indications on the extent of the problem. In cases where huge tilts are registered in the base, the AGV should make a new attempt on positioning itself in front of the pot and report an error and abort the current operation if the problem persists. This is like the mission-aborts that should be executed in the ACU's program if an extraordinary error occurs within the pot (appendix C).

In terms of the ACU's kinematics, the Cartesian concept somewhat escalated in size due to the applied parts. The approach for landing on the design is thoroughly explained in section 4.4.2.1. A compact solution in terms of mechanics and simplistic in terms of control were the motivating factors for experimenting with this concept in the early-stage. The author is however convinced that the corporate partner may come to term with a supplier on a fitting robot configuration. The author considers the following special features for a mobile manipulator operating from the potroom floor, to be among the most relevant:

- A long reach with compatible shoulder geometry to avoid crashing with the pot entrance's upper ledge.
- Singularity control close to its workspace's boundaries, such as in the pot center or the pot's front plate.
- Mechanical stiffness to operate properly at the long reach with varying induced loads.

Regarding material applied in the concepts, these have solely been subject to operation functions, such as the rubbers ability to move cover-mass and comply to crust. Identifying sufficiency and insufficiency in simple, cheap materials applicable for rapid prototypes has rather been the focus than aiming for state-of-the-art solutions and materials. The motivation behind this lays in the question of 'how much knowledge may be acquired with as little effort as possible'? More testing within the pot should be highly relevant in the iterations of further development, and some qualitative limits (as those found in section 4.4.2.4) of known prototyping materials, could be valuable from a developer's perspective.

Bringing mass to the pot through deposition has been debated, but not found critically important in the concept generation of this thesis, however might be desirable in later iterations of the ACU. The duct-space in the rubber fingers tool's bottom (Figure 4.32) was intended to show where potential cover-mass may be deposed, during the showcase with the corporate partner. A resembling design of the tool should be able to accurately shovel deposed mass in all directions of the horizontal plane. A concept with a feeding-screw in the ACU's arm was an interesting idea for cover-mass deposition, but not followed up. This would be particularly interesting in the two-link concept where no sliding telescopic joints are needed. A tall tank with a feeding mechanism could supply the feeding-screw in the arm with cover-mass through a flex pipe attached to the arms-rear end.

Figure 5.1 The Cartesian concept together with Even Jørs' concept-unit for cover-handling operations together on an AGV.

5.2 Thoughts on the Development Process

The author wished to embrace the whole problem in its complexity to begin with. Starting out with a broad, interdisciplinary approach was desirable, since changes within a certain product objective or new disciplinary insight might have drastically altered the solutions, requirements, tasks or even other objectives. This was to facilitate the converging towards a unified solution, where as many of the relevant functions of the complex, automated product has been visited or discussed, as possible within the project's time-frame. This was partly at the benefit of generating and screening a wide spectrum of opportunities for a specific, predefined tasks, as (Ulrich and Eppinger 2012), (Leifer and Steinert 2011).

Accelerating between design-build-test cycles of different objectives when finding it relevant, has rather been prioritized. The author saw the overall objective in this thesis to be too comprehensive and shrouded in uncertainty to define a clear operation or task-sequence for the product to begin with. Thus, defining the tasks became a natural part of the development process, where prototypes of product functions were tested versus relevant environment effects with respect to loosely defined objectives. This provided not only knowledge on the product parts' functional sufficiency, but also continuous understanding on how the environment-interacting could be managed and tasks defined.

As the thesis' approach is encouraging to constantly chase potential effects in the environment that may affect the product's functions, the pursuit for defining an operation demanded more basic testing. Thus, the cover-mass surface was very representative of what felt as relevant environment effects for testing. To the author's understanding, managing surface-interaction autonomously was most critical for the ACU to achieve success. Other obvious effects, such as heat and magnetism may very much affect a functioning ACU, however these aspects resembled more optimization parameters as development progressed. The author thinks the reason to this, is the broad interdisciplinary approach in the project. Prioritizing to touch several objectives rather than focusing in one area, as the most efficient way to understand the system and operation of the ACU as a system, is not regretted.

For this thesis, the following research questions has been asked:

- **How can we generate relevant early-stage design concepts in multidisciplinary comprehensive projects with high uncertainty of applicability of the product's solution(s) and task(s)?**
- **How can we facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development?**

While the first question has been highlighted more within this thesis and will be concluded in the following summary, the latter question became the research question of the author's publication (Winjum et al. In press) during the work on this thesis. Its concluding comments are stated there (appendix G).

6 Concluding Summary

This thesis is focused in the very initial phases of product development (the Fuzzy Front End) when approaching the concept and task detailing of a fully autonomous unit for anode covering operations in an aluminum electrolysis plant. The thesis is built-on and inspired by established principles of flexibility in the development and the approach of (Winjum et al. In press).

An amplified focus on the environment in the form of prototypes were essential to continuously reflect on the aluminum smelting pot's interior conditions. This greatly assisted defining an operation concept for the ACU, and revealed interesting findings on qualitative thresholds for pot operation through testing a tool-prototype with simple materials in the pot.

A multidisciplinary "vigilance", in the sense of approaching problems with different disciplinary perspectives and solutions concurrently, was essential for effective generation of competent solutions of complex product systems. The ACU is a good example.

The corporate partner should from the work of this thesis be able to decide what aspects to focus on in the further development of automated anode covering. The thesis provides qualitative specifications of what should be assumed fundamental for elaborating the suggested operation concept. Thus, defining a clear operation description and technical list of demands should be done in direct conversation with the corporate partner. Concurrent work on control simulations is also considered an essential next step, which naturally depend on defining the operation pattern, and vice versa.

Particularly important is clarifying the frequency of surface-interaction needed from the ACU. Further research on the works on autonomous soil-cutting may be rewarding inspiration. The author also suggests that trajectory planning based on pot geometry, with a force-controller for cover-mass interaction, is a solid first step in defining a sufficient operation pattern. Operation around the anode carbon's front and rear ends should be prioritized, since these are considered the most frequent problem areas along with the objective of cleaning the front plate. Deciding the need to pursue functionality for external mass-deposition via the ACU, will be clearer from further operation planning. This function has yet to be deemed critical in the ACU's initial concept by the author. Proceeding with development of concepts for force and trajectory control are undoubtedly important in case of surface-interaction. In such case, a combination of active compliance embedded in the controller with passive compliance close to the tool should assist in handling the varying terrain consistency. Force sensory should be applied for the compliance control, however may be designed into the manipulators bearing-solutions, away from the pot interior and closer to its base.

From the author's perspective, manipulator requirements are mainly regarding a sufficient workspace. Making the ACU survive the hazardous effects is considered optimization measures to be taken at a later stage in development. No effects are assumed as substantial for not operating adequately, applying state-of-the-art technology. A custom Cartesian concept was explored, featuring inspirational, simple functions particularly related to the workspace challenges. However, with a business perspective, a custom solution is not likely to be the best choice, where of-the-shelf anthropomorphic arms are likely to suffice. The following qualities should in such case be minded:

- A reach to the pot center (at least), with compatible shoulder geometry to avoid crashing with the pot entrance's upper ledge.
- Singularity control close to workspace boundaries, such as in the pot center or the pot's front plate.
- Mechanical stiffness to operate properly at the long reach with varying induced loads.

Such manipulators will also provide higher dexterity needed to properly calibrate orientation-error from the pot floor on the mobile base, than what is suggested in the concept in this thesis.

6.1 Concluding Statement from the Corporate Partner

The author wish to conclude the thesis with the following statement from the corporate partner regarding the presented work from this thesis:

"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 futuristic 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."

Live Spurkland

Alcoa Mosjøen

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APPENDIX A: The Authors Initial Reflections on Automatization of Anode Covering

Based on the conclusions in the pre-master work, the ACU should perform its actions with a base externally to the pot, possibly a manipulator platform based onto an automated guided vehicle (AGV). Commercial concepts of such robot-synthesis, also for large workspaces and high-load operations, are a reality (Spohn 2017), and will be seen in an increasing variety of applications (IFR 2017).

When first approaching a pot where anode covering should be performed, the ACU should have a clear idea of where it is located relative to the pot's external, geometric boundaries. This is highlighted in section 3.2.1. This is the foundation for calculating physical references between the environment and the ACU, which lays the foundation for interaction. Besides interacting for the sake of the operation, accurate position and orientation references are crucial to avoid potential crash and damage to the ACU during operation, and to limit the scene needed to be processed by the ACU's computer. The removal of pot covers is assumed to have been already managed. Based on this, the author considers the ACU to already have knowledge of its base's location relative to the pot as a part of the preceding pot cover-handling. However, small deviations may appear. Sensory should then confirm the boundaries to the unit's desirable operational space. First objective will then be to **identify boundaries**, and next to **set boundaries for the operational space** in terms with the pot's geometry and the ACU's *workspace* (Siciliano et al. 2010). The unit should now have isolated a relevant, limited scene for processing and maneuvering. Automated machinery is fundamentally dependent on strict rules to operate properly, and solid work on these two first objectives may prove extremely important for success in a functioning, fully-automated prototype, in such a complex environment.

From the isolated scene, the ACU should next **determine whether there is a need to act or not**. In the pre-master work, we judged camera-vision to be a strong input of decision-making data. In section 6.1 in appendix H this was discussed. It was pointed out that the best way of approaching this objective would depend on testing the quality and speed of data acquisition for RGB images, 3D point clouds, and thermal images of the scene, primarily. Testing processing time of the three different technologies (online/offline solutions) depending on relevant algorithms for identifying covering need would then be important. However, given that some technology or installment able to predict the need of action prior to the handling of the pot covers, determining whether there is a need to cover the anodes, such functionality may prove redundant for the ACU. It is conducted research on measuring temperature deviations locally between the pot covers and interior-exterior pot environments to reveal exposure before pot cover handling is conducted by students in the product development course TMM4280 Fuzzy Front End at NTNU.

Given there is found a need for anode covering, **obstacles and key-references within the operational space must be found**. Besides the constraints at the operational space's boundaries and layer of cover-mass and crust on top the anodes, the anode yokes are obstacles one would like to avoid. The project report showed a variety of sensory options to not only accurately calibrate relative position to the yokes (intestinally for crash control, but also utilize the yokes as "location beacons" for the anodes that need to be covered. If the unit knows the exact location of the anode's carbon, the a 3D-scanned scene can ideally be matched to reference of an ideal level of mass. The inward, horizontal distance towards obstacles in the pot interior, such as the yokes and the alumina feeders, are static relative to e.g the front-plate. Data on the current heights of the anodes should also be possible to generate, since this is controlled in the plant. Such obstacles may then be considered as geometry with known locations once the ACU first relate with a certain pose relative to the pot's exterior. By utilizing such known location data, we may also calculate avoiding the alumina feeding holes below the crust breaker next to the alumina feeder in the algorithm of anode covering (described among the error scenarios in appendix B).

Initiating covering of potential cavities and anode exposures within the defined operation space is a natural next step. This could be done with a high variety of speed, accuracy and chance of success. It is likely to pose natural compromises between cost and sophistication in our solution, and quality of operation. Ways to operate is highly diverse. For instance, one may choose to avoid a certain area around the yoke and bombard the scene with mass and iteratively check the need, or can pursue a more delicate approach, where the unit would consequently need a 3D perception of where there is too little or "too much" cover-mass. Finding critical areas of interest is also discussed in section 6.1 in appendix H, and emphasizes the potential in 3D scanning of the scene's topography to identify these areas. The mass-bombardment would call for a very simple solution, but on the other hand, potentially yield high amounts of unwanted over-covering and solidification with the lack of direct interaction with the surface.

In the case of identifying cavities and exposures very locally inside the pot, it would be necessary to **acquire and quality-control sensor data on where mass is needed (and possibly where it is redundant)**. This might involve acquiring sensor input from several locations and angles, stitching it together into a dataset sufficient to work with. The location-data gives an estimation of where the ACU needs to be, to either get or deliver cover-mass. **Analyzing the data for suggesting points to get or deliver mass** is needed, followed by **trajectory planning** for the ACU's travel between these points. This involves an algorithm for the ACU's pattern of motion depending on where cover-mass is needed. The ACU should know what cover-mass to use and what is (likely to be) available, ideally finding useful areas of redundant mass, use the alumina feeder, or feed mass from an external depot. Depending on this, trajectories can be generated. The known obstacles in the operational space, i.e constraints in the geometric path followed by the end effector is referred to as *kinematic constraints* by (Siciliano and Khatib 2008). *Constrained motion* is what occurs in the case when the end effector interact with stiff surfaces, such as hitting crust. These constraints would obviously have to be accounted for by the ACU, either in physical design, control or both. The operation should finish with a verification of the executed operation, determining if there is still a need for anode covering. If insufficient, the prior actions should be rerun or an error report should be filed before proceeding. In the case of success, the ACU may move straight to the next operation.

Less intricate operation patterns may be conducted if settling on not evaluate and identify every potential crack or anode exposure, as potentially with the mass-bombardment approach. The covering does not necessarily have to be of a surgical character, however must be considered sufficient relative to the standards of the corporate partner.

APPENDIX B: Scenarios of Anode Covering with Profound Errors

Scenario: Extreme cavities

Cavities on the side of anodes may occur, particularly in the cases where young and old anodes stand next to one another. If this occur when neighboring anodes are about the same height, it is almost always a consequence of extreme errors in the initial covering at anode change. These extremes are shown in picture y, and are considered alarmingly bad. Based on input from Alcoa, *the ACU should under such conditions report the error and proceed to the next operation*. Any attempt of AS-IS anode covering is in this case futile. The threshold for considering such a case as a significant error is related to sensory and data processing, and will not be evaluated further in this thesis.

Scenario: Gas pockets

When sensing open flame from a cavity, the unit shall identify the cavity as a gas pocket. These pockets of gas are usually not covered, due to the trapped gas that could re-burst from the covering mass shortly after. Addressing them as such is dependent on sensory and data processing, and will not be evaluated further in this thesis. Following today's standard of covering, *no covering of cavities with open flame shall be performed*.

Scenario: Considerable height difference between neighboring anodes

The ACU may import data on the real-time height difference between two neighboring anodes, based on the anode changing schedule and anode lowering frequency. At critical height difference, cover-mass will not be wasted trying to cover in between since the old anode is about to be changed, and all overlaying mass will fall and get spilled only after a few days, if that. The threshold for this is related to logistics, and will not be evaluated further in this thesis. Regardless, following today's standard of anode covering, *no covering between anodes with a considerable height difference shall be performed*.

The AS-IS procedure of anode covering accept this type of exposure on the three oldest anodes within the same pot. This is a compromise between the effort of covering and wasting alumina, since they are about to be replaced within just a few days, and the increased amount of unwanted exposure of the sides of the new anodes.

Scenario: Over-covering

In the unlikely, but very unfortunate, event of over-covering the anode has accidentally been covered too conservatively when first installed, leaving redundant mass often close to the yoke or sidewalls in the pot interior for solidification. In the extreme case in the figure below, the yoke's shoulders have been completely submerged during the initial anode covering, which again has solidified, thus troubling the yoke's recycling process significantly. Such scenario is currently revealed visually by the worker, and might be identified by the ACU from mass location sensory as 3D scan or force-feedback calibration in the ACU's end effector. Nevertheless, this is a grave deviation in anode covering routines, and like the above scenarios, the ACU should file an error report, however regular objectives as the front plate cleaning and handling the mass on the front incline may be attempted.

APPENDIX C: Code for Stepper Motor Control – Arduino

Stepper Keyboard Control

```
/* Coded in the Arduino IDE applying the built-in Stepper library
   ("Arduino - Stepper" 2017)
   Stepper Motor Control - keyboard input */


#include <Stepper.h>

int val = 0; // incomming serial value from keyboard

const int stepsPerRevolution = 200;  /* for these stepper
with 1.8 degree resolution,
one full rottation contains 200 steps.*/

// initialize the stepper library on pins 4 through 7 for
the horizontal drive stepper (x direction):
Stepper xStepper(stepsPerRevolution, 4, 5, 6, 7);

// initialize the stepper library on pins 8 through 11 for
the vertical drive stepper (y direction):
Stepper yStepper(stepsPerRevolution, 8, 9, 10, 11);

void setup() {

  // set the speed at 20 rpm (maximum):
  xStepper.setSpeed(30);
  yStepper.setSpeed(30);

  // initialize the serial port:
  Serial.begin(9600);
}

void loop() {

  if (Serial.available()) // if serial value is available{
  val = Serial.read();// then read the serial value
  Serial.println(val);
  if (val == 'a'){ //if value input is equals to a
  xStepper.step(1);

  }
  if (val == 'd'){ //if value input is equals to d
  xStepper.step(-1);

  }
  if (val == 'w'){ //if value input is equals to w
  yStepper.step(1);
```

```
  }
  if (val == 's'){ //if value input is equals to s
  yStepper.step(-1);

  }
  else{
  //  xStepper.step(0);
  // yStepper.step(0);
  }
}
```

Covering Sequence

```
/*
 Stepper Motor Control - Covering Sequence

 This program drives two bipolar stepper motor.
 The motor is attached to digital pins 4 - 7 and 8 - 11
 of the Arduino.
 */

#include <Stepper.h>

const int stepsPerRevolution = 200;  /* for these stepper
with 1.8 degree resolution,
one full rottation contains 200 steps.*/

// initialize the stepper library on pins 4 through 7 for
the horizontal drive stepper (x direction):
Stepper xStepper(stepsPerRevolution, 4, 5, 6, 7);

// initialize the stepper library on pins 8 through 11 for
the vertical drive stepper (y direction):
Stepper yStepper(stepsPerRevolution, 8, 9, 10, 11);

void setup() {

  // set the speed at 20 rpm (maximum):
  xStepper.setSpeed(30);
  yStepper.setSpeed(30);

  // initialize the serial port:
  Serial.begin(9600);
}
```

```
void loop() {

// The home position is where the vertical joint is fully
down and horizntal joint fully withdrawn
//
/* 1) Run front plate calibration function
 *     Parameters:
 *     x and y values of front plate position
 *     (where the bottom of the tool tool shall hit).
 */
  frontPlateCalib(10, 13);
  delay(500);

/* 2) Run mid anode calibration function
 *     Parameters:
 *     x and y values of anode's upper midpoint position
 *     (where the bottom of the tool shall hit).
 *     x and y values of front plate position
 *     (where the bottom of the tool shall hit).
 */
  midAnodeCalib(150, 25, 10, 13);
  delay(500);

/* 3) Run sweeping function. The actual covering of the
anodes.
 *     Parameters:
 *     x and y values of anode's upper midpoint position
 *     (where the bottom of the tool shall hit).
 *     x and y values of front plate position
 *     (where the bottom of the tool tool shall hit).
 *     x and y values of pot center position
 *     (where the bottom of the tool shall hit).
 */
  sweeping(150, 25, 10, 13, 150);
  delay(500);

/* 4) Return the manipulator to it home position
 *     Parameters:
 *     x and y values of anode's upper midpoint position
 *     (where the bottom of the tool shall hit).
 *     x and y values of front plate position
 *     (where the bottom of the tool tool shall hit).
 *     x and y values of pot center position
 *     (where the bottom of the tool shall hit).
 */
  return2home(150, 25, 10, 13, 150);
  delay(500);

  delay(5000);
}
```

```
/*------------------------------------------------------------
 * ---------------------------FUNCTIONS-----------------------
 * -----------------------------------------------------------
 */

/* CALIBRATION ON FRONT PLATE MOVEMENT
 * front plate pos relative to end effector pos at origin,
as inputs.
 */
void frontPlateCalib(float xFrontPlate, float yFrontPlate){
  movement(mmX2steps(0), mmY2steps(-20-yFrontPlate));
  delay(200);
  movement(mmX2steps(-10-xFrontPlate), mmY2steps(0));
  delay(500);
  movement(mmX2steps(0), mmY2steps(20));
  movement(mmX2steps(0), mmY2steps(-5));
  movement(mmX2steps(0), mmY2steps(5));
  movement(mmX2steps(10), mmY2steps(-20));
}

/* CALIBRATION ON ANODE MID-POS ESTIMATE
 * anode top midpoint pos relative to end effector pos at
origin, as inputs
 */
void midAnodeCalib(float xMidAnode, float yMidAnode, float
xFrontPlate, float yFrontPlate){
  movement(mmX2steps(-xMidAnode-10), mmY2steps(10-
(yMidAnode-yFrontPlate)));
  delay(200);
  movement(mmX2steps(0), mmY2steps(10));
  movement(mmX2steps(0), mmY2steps(-5));
  movement(mmX2steps(0), mmY2steps(5));
  movement(mmX2steps(0), mmY2steps(-5));
  movement(mmX2steps(0), mmY2steps(3));
}

/* SWEEPING (ANODE COVERING)
 * anode top midpoint pos relative to end effector pos at
origin, as inputs
 */
void midAnodeCalib(float xMidAnode, float yMidAnode, float
xFrontPlate, float yFrontPlate){
  movement(mmX2steps(-xMidAnode-10), mmY2steps(10-
(yMidAnode-yFrontPlate)));
  delay(200);
  movement(mmX2steps(0), mmY2steps(10));
  movement(mmX2steps(0), mmY2steps(-5));
  movement(mmX2steps(0), mmY2steps(5));
  movement(mmX2steps(0), mmY2steps(-5));
```

```
  movement(mmX2steps(0), mmY2steps(3));
}

/* CONVERT MILLIMETERS ON THE HORIZONTAL AXIS TO STEPS
 * millimeters as input
 */
float mmX2steps(float mmX){
  return (1990/(260-20))*mmX;
}

/* CONVERT MILLIMETERS ON THE VERTICAL AXIS TO STEPS
 * millimeters as input
 */
float mmY2steps(float mmY){
  return (300/(110-65))*mmY;
}

/* MOVEMENT OF BOTH STEPPERS
 * This function is the general function for moving both the
stepper a certain amount of steps.
 * The sign of the parameter values indicates the
directions.
 */
void movement (float xNumOfSteps, float yNumOfSteps){

  float xStepInc = 0.0;
  float yStepInc = 0.0;
  float xStepPos = 0.0;
  float yStepPos = 0.0;

  if (abs(xNumOfSteps)>abs(yNumOfSteps)){
    xStepInc = xNumOfSteps/abs(xNumOfSteps);
    yStepInc = yNumOfSteps/abs(xNumOfSteps);

    for(int i=0; i<abs(xNumOfSteps); i++){

      xStepPos += xStepInc;
      yStepPos += yStepInc;

      xStepper.step(xStepPos);
      yStepper.step(yStepPos);

      if(yStepPos >= 1){
      yStepPos -= 1.0;
      }
      if(yStepPos <= -1){
      yStepPos += 1.0;
      }
      xStepPos = 0.0;
    }
```

```
  }
  else{
    xStepInc = xNumOfSteps/abs(yNumOfSteps);
    yStepInc = yNumOfSteps/abs(yNumOfSteps);

    for(int i=0; i<abs(yNumOfSteps); i++){

      xStepPos += xStepInc;
      yStepPos += yStepInc;

      xStepper.step(xStepPos);
      yStepper.step(yStepPos);

      if(xStepPos >= 1){
      xStepPos -= 1.0;
      }
      if(xStepPos <= -1){
      xStepPos += 1.0;
      }
      yStepPos = 0.0;
    }
  }
}
```

APPENDIX D: Code for Pneumatic Load Sensing – Arduino

Pneumatic Load-Sensor Input

```
/* Code for the Pneumatic/Hydraulic Load-Cell
   sensor input.
*/

int pressurePin = A0;
int pressure = 0;
int V_out = 0;
int V_s = 1024;

void setup() {
  Serial.begin(9600);
  pinMode(A0, INPUT);
}

void loop() {
   V_out = analogRead(A0);
   //Serial.print("Raw value: ");
   //Serial.println(V_out);
   pressure = map(V_out,0,1015,0,250) + 250*0.04 +2;
   Serial.print("Pressure: ");
   Serial.print(pressure);
   Serial.println(" kPa");
   delay(50);
}
```

APPENDIX E: Video Link

https://drive.google.com/open?id=0B6ZDGjva9HY0QWNFeVRqM3FsdDA

APPENDIX F: 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 aktiviteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.

Signaturer: *Ansvarlig veileder: Martin Steinert* — Jardar Winjum, Even Jørs — *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			

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

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	

NTNU HMS	Risikovurdering	Utarbeidet av HMS-avd.	Nummer HMSRV2601	Dato 22.03.2011
		Godkjent av Rektor		Erstatter 01.12.2006

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
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.

NTNU HMS	Risikovurdering	Utarbeidet av HMS-avd.	Nummer HMSRV2601	Dato 22.03.2011
		Godkjent av Rektor		Erstatter 01.12.2006

									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

NTUU				
NTNU	Risikovurdering	Utarbeidet av	Nummer	Dato
HMS		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

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.

NTNU	Risikomatrise	utarbeidet av	Nummer	Dato
HMS/KS		HMS-avd.	HMSRV2604	08.03.2010
		godkjent av		Erstatter
		Rektor		09.02.2010

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 G: A Heuristic Approach for Early-Stage Product Development in Extreme Environments (Winjum et al. In press)

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A Heuristic Approach for Early-Stage Product Development in Extreme Environments

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***Abstract*— This article considers a heuristic approach for developing products for extreme environments. The authors propose a set of heuristics for exploring environment and product features throughout the design probing process. The proposed strategy is exemplified through several cases, with special emphasis placed on a project that considers developing new products for aluminium electrolysis shop floor environments. These heuristics are presented as an approach for dealing with large amounts of uncertainty in an early-stage product development setting.**

Keywords—engineering design; probing; early-stage product development; environment prototypes; product prototypes;

I. Introduction

Rooted in the early stages of product development, this paper discusses a heuristic approach for early-stage product development for extreme environments; i.e., a delimited space with a combination of external, physical conditions, exceeding the limits of the standard environment conditions, that influence the growth, development, behavior and operational life of products. How we choose to design, build and test may be influenced by the different extreme environmental aspects—extreme parameter values, parameter variations and relations between parameters. Handling the challenges related to these aspects, and the difficulty of setting initial requirements when working under such harsh conditions, have been motivation for the approach to be discussed below. The strategy involves probing both the environment and the product throughout the concept development phase. Probing is referred to as an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, then subsequently, converging, as the prototype concept is evaluated.

How can we facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development?

From an overall objective for the project, we apply probing to elaborate on objectives, thus increasing the level of detail toward a concept solution. The approach takes a critical look at revealing causality during testing, and suggests applying environment parameters one-by-one. This should allow designers to identify root causes of environmental effects.

In this paper, we will use contextual examples from concept development of an unmanned unit performing anode covering in an aluminium electrolysis plant environment processing raw aluminium-oxide into aluminium. This case is used as both an example for the different aspects of extreme environment and for exemplifying probing of both the environment and the product. In the electrolysis process, large carbon anodes are placed in electrolysis pots at high temperatures. Inside the electrolysis pots, the anodes are covered with an alumina/sand/gravel mixture (from here referred to as “cover mass”) for thermal insulation of the electrolyte bath and to prevent unwanted oxidation of the anode that will occur if exposed to the surrounding air over time (Fig. 1). The carbon is slowly sunk into the electrolyte bath by the attached, current-leading yokes, which are made from copper.

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30.

II. Aspects of Extreme Environments

Environment is defined by [1] as the combination of external, physical conditions that affect and influence the growth, development, behavior, and survival of organisms. If one put products in the role of the organisms, much of the definition applies. Gomez [2] relates extreme environments to inhospitable conditions for life, describing it as a habitat characterized by harsh environmental conditions, beyond the optimal range for the development of humans; for example, pH 2 or 11, -20°C or 113°C, saturating salt concentrations, high radiation, and 200 bar pressure, among others. Cressler [3] describes the extreme environment his transistor and electronics systems must cope with as surroundings lying outside the domain of conventional commercial or military specifications. In what Schrage [4] refers to as ‘Spec-driven’ engineering, this would probably be a rather convenient description.

From these definitions, we define an **extreme environment** as a delimited space with a combination of external, physical features, deviating substantially from the standard environment that influence the growth, development, behavior and survival of products. Typically, these standard environment conditions are set to an indoor workspace with common values, say, staying around 25 °C and 1 atm of pressure, etc.

Fig. 1. Two anodes covered in mass, but with excessive tearing in front after long air-exposure. The front plate is shown in the bottom of the picture, and the current-leading yokes ascend from the mass, on top the anodes. Picture courtesy of Alcoa Mosjøen.

To achieve sound product functionality under harsh operational conditions, and to understand how to maintain this, it is important to acquire what is accessible of relevant environment data. This would typically be measurement data of the different **environment parameters**, e.g. temperature, luminosity, pressure, humidity etc. Cressler [3] exemplifies typical influencing parameters in his studies of electronics for lunar missions as extremely low temperatures (e.g. -269°C or colder), very high temperatures (e.g. 300°C or warmer), very large and/or cyclic temperature swings (e.g., -230°C +120°C night to day, as found on the lunar surface), and ionizing radiation (e.g., aurora). These are examples of conditions ranging between two extremes. [3] also explicitly points out the fluctuation as a challenge in itself.

We identify three aspects of extreme environments that should be taken into consideration in the process of early stage product development. First, the **extreme values**—the extreme values of a specific environment parameter. Second, the **variation**—how values vary in both time and space. Third, **relations between parameters and resulting effects**—how different parameters interact and create effects that influence the behavior of products.

A. Extreme Values in the Environments

One can think of an extreme value of a parameter as a substantial deviation from a predefined environmental, technological or physical standard. This extreme value is often the basis for an early characterization of the extreme environment. The extreme value is important when looking at how the extreme environment will influence the product capabilities. The standard represents the norm which is perceived convenient for a respective development project. It could then make sense to relate the extreme environment to a related a priori-known environment, e.g. a marine environment as the standard in relation to an arctic, marine environment as the extreme. Hence, while shifting the focus toward the extremes—i.e., what separates this particular environment from the (known) standard, representing the focus herein. Pahl & Beitz' [5] term of 'overall function of the product' does not usually concern itself with the environment at all—this being extreme or not. However, by identifying discrepancies between standard and extreme environments early on, this represents the first step of understanding of the potential challenges and how it will impact the design as progress is made.

B. Variation in Environment Parameters

By variation in environment parameters we mean the spread of measured values. This might be generally high dispersion in the measurements of a parameter, or when there are prominent deviations between a parameter's mean value and its extreme value. Variation may both be time and space dependent. High variation then makes us ask questions on what context we are going to design for. Designing for the extreme value or mean value of a parameter might seem insufficient. Then testing the behavior of product and environment within the range of limit values is an approach that is further discussed below.

There are several examples of variability in environment parameters in the case of an aluminium electrolysis pot. One key parameter is temperature, where cavities in the cover mass radiate heat from the bath up to temperatures between 600-900°C, sometimes including flames from burning gas. Where these cavities are, how big and how many, vary significantly. IN most cases the anodes are properly covered, thus leaving an average surface temperature of the cover mass at about 200-350°C. This is an example of a major deviation between the mean and extreme conditions within the same environment. It is also likely to have a high variation of measured thermal values due to the variety of the cavities.

An example of an extreme value with low variation is the presence of a 250 Gauss magnetic field caused by the strong, but steady electric current through the pot. This parameter could then be tested for only this value, as opposed to testing for a range of values for high variation parameters.

C. Relations Between Parameters and Resulting Effects

By relations between parameters and resulting effects, we consider the co-occurrence of multiple environment parameters and their resulting effects that might influence the product solution. These effects may obviously differ from solution to solution, and between the product and humans. One example is Palmer & Croasdale [6] who suggests danger and discomfort for human beings in the artic as the combined effect of wind and low temperatures by an analytic wind-chill index [7], which again can be linked to heat transfer models that calculate the likelihood of frostbite. Heat transfer between the air and a human body is plainly complex, and involves factors such as whether one is primarily concerned with an exposed face or with cooling of the whole body. There are also dynamic effects: cooling is most rapid at the beginning of exposure since the skin blood vessels have not had time to contract. This shows how the effect (chilling) sprung from the combination of parameters (low temperature and wind), and how this effect may change as the body (or a product for that matter) adapt its behavior.

The human body could pose as an analogy to complex products where the same phenomenon of effects from combined parameters would apply. All kinds of situations where certain parameters are prominent, certain effects from combining the respective parameters may be prominent. Some examples are applications of E-glass/epoxy composites, where the properties are altered from combined parameters of load, moisture and temperature [8], or the combined influence of temperature and pressure for water vapor transport through textiles at high altitudes [9]. How one divides the environment into separate tests of parameter effects, and thereafter recombine parameters to determine effects from parameter combinations, is explained further in section III.E.

III. Elaborate on Objectives Through Probing Both Product and Environment

A. The Approach of Probing both Product and Environment

Gerstenberg et al. [10], describe a design probe as a prototype where new knowledge is created and tested by deduction, induction and abduction (Fig. 2). In principle, it is an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, thus stimulating creativeness. Subsequently, convergence occurs as one evaluate the prototype concepts [11].

The concept of probing has earlier been applied as a way of iteratively discovering and changing functional requirements by developing prototypes built on existing functional requirements until a satisfying solution is found [12]. This way, the development team has a dynamic approach towards the design criteria. This is similar to what Schrage [4] describes as 'prototype-driven' development, as a contradiction to 'spec-driven' development. In the latter, prototypes are designed according to predefined specifications. The approach in this article adapts the 'prototype-driven' development form the aspects of divergent and convergent thinking around both the product and the environment wherein it operates.

Design probing is an iterative prototyping of solutions for proving functionality, thus arriving at the best local optimum within the explored solution-space, according to [12]. Similarly, an iterative prototyping of test environments involves creating or utilizing different environments featuring (a set of) common functionalities. The different environments are equivalent to the product's solution-space. As for the product, one may evaluate an environment prototype the same way, and then build on the knowledge for later iterations; hence, revealing parameter relations as the environment prototypes gets more complex.

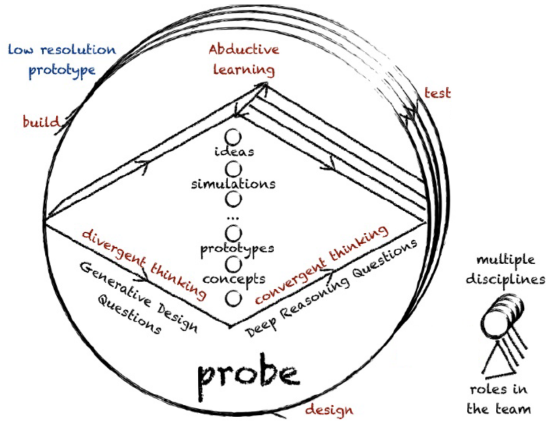

Fig. 2. Probing cycle, adopted from [5].

An example of unclear causations can be found within an aluminium electrolysis pot. The anode covering mass has a certain hardening rate, and one could find the frequency of needed covering to avoid total hardening by looking at the hardness versus the time that the mass lays untouched. From this information alone one might think the mass is hardening over time, due to for instance air-exposure. However, as one acquires more knowledge of the conditions, the pot's air temperature, the thickness of the mass layer and the content of the mass, all do influence the hardening rate. Eliminating the effects of these parameters would cease the hardening, thus eliminating the assumed relation between hardening and exposure time. Failing to uncover root causes may lead to false or incomplete understanding of the environment, which in term may negatively influence the value of the developed solutions.

Having an explicit focus on probing the test environment as a prototype on the same terms as the product prototype, should help the development team test relevant product functions versus relevant effects from the environment. A general rule for developing new knowledge or understanding is to avoid introducing more than one change at the time. This is true for both prototypes and environments. The reason for not changing more than one parameter at the time is to isolate effects that come from specific changes. In the case of extreme environments, extracting the influential parameters into a respective environment prototype by testing their effects separately should establish a clear relation between environment parameter and product behavior. After gaining control over the individual parameters, the design team can start combining them to investigate potential new effects and responses.

The incentive for the approach of probing both environment and product is providing continuous awareness of, and learning about, the environment throughout the development process. This resonates well with the dynamic requirements in probing as new discoveries about the environment is likely to affect and change our view on the product and its objectives. The learnings acquired from environment prototyping is mostly about confirming or debunking our (pre)assumptions of what the critical functions of the product should be, and how our product will impact the environment. Therefore, striving to expose

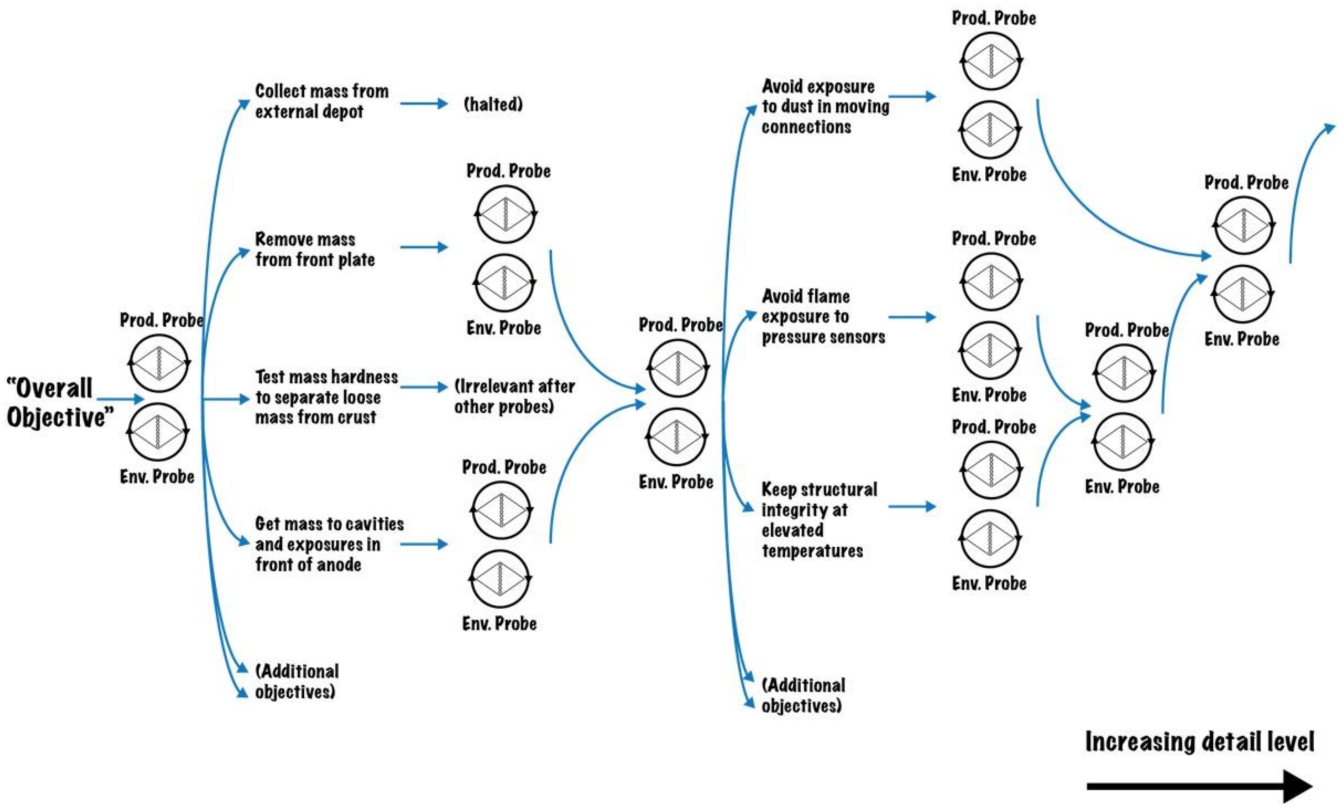

Fig. 3. Example from the 'elaborating objectives' of the the anode covering unit. Probing product and envronment for different objectives generates knowledge to elaborate further objectives and functions as a way of detailing our concept. As the detail level increases, product functions and relevant environment effects for different objectives are combined in new probing cycles.

causes by stepwise testing and adding parameters, and converge towards the actual environment, is essential.

B. Establish the Overall Objective

Initially, the product developer's focus should be on establishing the overall objective. This objective may not necessarily be directly determined by the product's operating environment. For instance, much of the core functionality of both soft- and hardware of smart clothing for arctic environments could be evaluated under more regular conditions [13], as indoors, to demonstrate functionality, e.g. equipped clothing and electronics.

The overall objective is similar to what Pahl & Beitz [5] refer to as the overall function. The reason *objective* is used instead of function is to reduce solution-bias when working toward objectives rather than defining functions—even though the latter term is common. This is especially true in early stage product development where the focus lies on staying open minded in terms of what the end-product might be. Pahl & Beitz then further evaluate the complexity of the overall function. By complexity they mean the transparency of the relationship between inputs and outputs of a product. They break the overall function down into less complex sub-functions to describe the functionality less ambiguously and facilitate the subsequent search for solutions. They call this establishment of additional sub-functions a "function structure", and has commonly a main flow to focus our attention of development. In this article, the analogy to establish such a function structure lies in the *elaboration of objectives*.

The overall function is according to Pahl & Beitz governed by initial requirements. However, for extreme environments we may concern ourselves with high variation in the environment parameters and obscure parameter relations, which makes it harder to define clear requirements to begin with. A more dynamic way of setting these requirements is using probing. One can elaborate on one's objectives through probing, rather than establishing a structure that is prone to continuous change from new understanding of the interaction between the product and environment.

C. The First Product/Environment Probe and Utilizing Existing Prototypes

Getting an initial understanding of the objective (and potential challenges) through interaction, benchmarking and gaining general information about the operating conditions. The initial interaction with the environment may be viewed as a first environment probe. This may be a physical interaction with the actual environment, or something just resembling it. We are then utilizing existing conditions for acquiring knowledge.

An existing product prototype in such a setting might be a previous version of the product, or simple tools or goods helping to recreate aspects relevant to the overall objective. For automatization of anode covering in our aluminium electrolysis plant case, this existing product prototype is typically the current

Fig. 4. Probing rake and pot environment. Picture courtesy of Alcoa Mosjøen.

raking-tool for shoveling mass. By testing the rake, and the raking operation in the pot in person, we physically interact with an existing product prototype and environment prototype (in this case the actual environment). Seeking out realistic environments early is a good opportunity to get invaluable information from experts and experienced personnel.

Based on the work of Gerstenberg et al. and Kriesi et al. [10, 12], we note that a central part of the learning process of prototyping comes from building the prototypes—to observe the different components come together and understand their relationships. After the first probe, it may be sufficient to recreate/build parts of the features for some tests when comparing time and effort to the potential learning output. As you then elaborate on your objectives, the utilization of 'existing prototypes'—something that resembles the functionality you want to achieve, is an important tool to learn fast during probing. For products, this might be high-end existing products, such as industrial robots or computers, or low-end hand tools. An existing environment might be a landscape with certain features relevant to the real test environment, such as a crater landscape hosting lunar analog terrain in the rover example.

D. Elaborate Objectives Through Probing

The process of 'elaborating the overall objective through both probing the product and the environment' is best explained through exemplification (Fig. 3). In the case of automation of anode covering in aluminium electrolysis plant ovens (as described in section I), the overall objective would be to "cover potential cavities or anode exposures". Full automation and mobility of the unit performing this covering is desired, and the concept system rapidly becomes complicated. Thorough background research on the facility was done, gaining input from technical personnel, and technology analysis, before new objectives were set for the early-stage concept generation phases. These objectives were: 1) Acquire available mass; 2) Move mass to potential cavities or anode exposures; and 3) Cover potential cavities or anode exposures.

Note that the initial probe involved visiting the actual environment and testing the raking procedure in the production facilities, as mentioned in section III.C. From this initial probe on the electrolysis pot environment (real environment) and rake-tool (existing product) (see Fig.4), further objectives could be elaborated. Here, the designers first diverged by asking themselves what can be learned from this opportunity of interaction, before converging by using the insights from testing.

Establishing the objective on acquiring mass was particularly important. However, the mass accessibility is an uncertain aspect of the environment due to the uneven hardening in the pot and busy infrastructure outside. Other newfound objectives (e.g. the 'remove mass from front plate' and 'get mass to cavities and exposures in front of anode') were also crucial to the overall objective, and had certain functions that unified well with a mass acquisition objective of transporting existing, loose mass along the mass surface. Further elaborating on the objective of mass acquisition from outside the pot was then put on halt.

The designers had now progressed to objectives concerning direct interaction between the cover mass surface and an automated unit. The next design probe concerned recreating the cover mass material, specifically mechanical properties. A product prototype could then be introduced with the task of distributing the material on a surface. The actual cover mass contains condensed toxins, unsuited for a regular workshop or working-space. Prototyping a resembling mass for testing mass-movement functionality in our objective was necessary, due to the hazardous. The other incentive was, as previously argued, to materialize the designers' idea of the environment (the mass) and evaluate it, thus 'calibrating' the designers' understanding of the environment. Various product prototypes were then tested for moving mass. Probing how to move mass up in front of an anode led to a test of the purely mechanical function of moving mass in that manner. An environment prototype based on dimensions and resembling topography of the anode-front was then built. Firm, bulk materials beneath the loose mass was an important effect in the environment prototype, resembling uneven hard crust. A combined environment prototype of the mentioned probes is shown in Fig. 5.

After building an environment prototype (Fig. 5), the designers could then test different product prototypes in the environment prototype. A combination of several product functions tied to these objectives are shown in Fig. 6. One of these combinations involved damage protection and calibration objectives. The designers originally did not perceive these as relevant before initial solutions for mass-moving tools were tested. These solutions were respectively built on the 'clean plate' and 'move mass' objectives.

Fig. 5. Prototyping (aspects of) the anode covering environment.

Given the overall objective, and that electronics (including actuators) and moving parts are particularly vulnerable to the heat and dust, the designers had up to this point considered the solution space to be mostly mechanical. From testing, basic electronics and microcontrollers, such as an Arduino board [14] controlling blinking LEDs and small servo motors temporarily malfunctioned when stationed by the pot's entrance. Solutions where these elements could be withdrawn from the extreme environment, or less exposed, have been favored. Further emerging objectives might be 'avoid exposure to dust at moving connections'; 'avoid flame exposure to pressure-sensors'; 'attain structural integrity at elevated temperature' etc.

This example highlights how some objectives may be temporarily halted, because some other objective is more crucial to explore further (much like Pahl & Beitz's 'main flow'), or it might simply be proved irrelevant by other probes. How one can combine probing of product prototypes and environment effects relating to certain objectives one-by-one is shown in the right-hand part of Fig. 3.

E. Heuristics on Learning From Environment Probing

It is first when combining parameters and see their resulting effects that one understands what is truly causing the behavior between the product and the extreme environment. Decomposing the extreme environment first should facilitate this insight. We then have experience with testing product versus single environment effects, interacting on several levels of combined functionality. This way, it is easier to reveal what is causing different (unexpected) behaviors when parameters are combined. Continuous evaluation, both of product and environment probing, from relevant stakeholders should be included throughout the process. This is especially important for the environment probing, since it is likely to be the most difficult to evaluate for the developers.

Ultimately, testing in the real environment is needed to uncover discrepancies between the environment prototype and the real environment. This should both work as verification of understanding and estimates of the environment, as well as reveal potential relations of parameters and their true effect.

IV. Future Considerations

When designing for extreme environments, a very common question is whether the product's materials and technology is sufficient to cope with the conditions or not. As mentioned in section II, extreme environment is likely to pose more challenges than the extreme parameter values do alone. What is sufficient under very varying values and types of parameters is hard to say when also relevant data is hard to acquire. Utilizing good product benchmarks is then important to have some beacons in the solution-space. For example, if rubber is known to do its job well when sweeping cover mass, but it also has a short lifespan, then making solutions based on simply changing the rubber throughout operation might be a more wanted solution than finding more expensive alternatives. In other cases, we do not have this luxury, or the stakes of insufficiency is simply too high to go for anything but the "best".

In his work on researching fundamentally adaptable electronics, Cressler [3] points on the "warm box" solution for lunar rovers, a common approach of shielding prone technology from the environment (in this case from cryogenic conditions), as crude at best. He points on how this "warm box" design-approach critically limits the designer's ability to create a truly distributed system for such rovers, resulting in excessive point-to-point wiring, increasing system weight and complexity, lack of modularity, and an overall reduction in system reliability. We see how these drawbacks also apply to heat and magnetic shielding of electronics and actuators brought into an aluminium electrolysis pot. However, a consideration of stakes and accessibility should of course be taken when evaluating sufficiency of material and technology. Failure on the moon is likely to have way higher stakes than failure in an automated unit in an aluminium plant in the unfortunate case of insufficient or malfunctioning machinery. Based on this, we consider the level of coping technology and material to not necessarily correlate with the environment's hostility alone, as this will depend on stakes and accessibility.

In the case of high variation for certain parameter values, it is more convenient to uncover a certain threshold of what we can expect to be sufficient of material and technology—especially if the material or technology needed to withstand the extreme value has a way higher cost, restriction or sophistication than materials or technology required for more nominal conditions. Having possibility to tune these conditions in environment

Fig. 6. Product prototype for ultimately performing anode covering autonomously. Several solutions for different functions are here combined.

prototypes could be a good facilitation for maneuvering toward the respective 'sufficiency threshold'.

V. Conclusion

In this paper, we describe an approach for early stage product development in the context of extreme environments. It emphasizes our finding that environments should be prototyped with a similar approach as products before testing environment and product together. The prototypes of both products and environments are generated with specific environment parameters or product functionality in mind. Knowledge on product behavior is developed through testing solution principles versus single environment parameters and their corresponding effects. When we then later combine parameters for testing, we may assume a potentially new product behavior to be tied to the relation between the parameters and their new effect. We then already have experience with the individual parameter effects and the respective product behavior, to make such an assumption. Eventually, testing in the real (or close to real) environment is crucial for validating our assumptions regarding the environment and the testing.

We base our approach of probing (iterations of divergent and convergent solution thinking) the product and environment together where environment parameters affect product functionality. 'Existing prototypes' may be used, but focus has to be placed on the right factors that are causing product behavior. The way we choose to test, the materials and the prototype's resolution, may all be influenced by the different extreme environment aspects—extreme parameter values, variation in parameter values and relation between parameters.

It may be hard or not necessary to set strict, initial requirements for our product concept, due to the extreme environment aspects stated above. We suggest an approach to work towards objectives, and elaborate them through probing both the product and the environment. This way new objectives may naturally evolve as some may become redundant along the way, while keeping the critical functionality of the product in mind.

Acknowledgment

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APPENDIX H: Pre-Master Project Thesis

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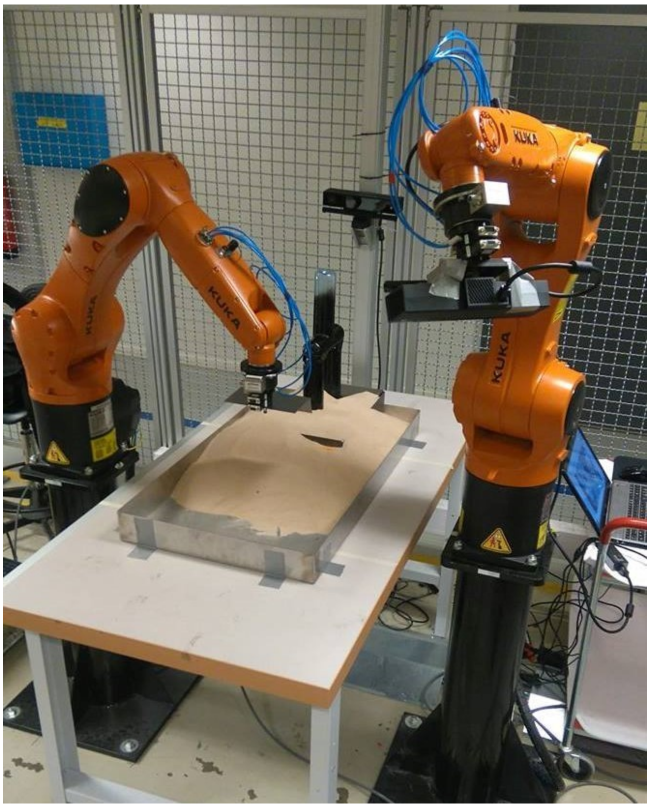

Process Automatization Concepts in Extreme Environments Such as Aluminium Electrolysis

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.

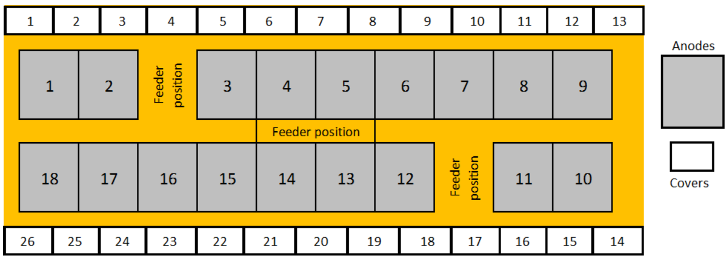


Figure 4: Cross section of pot at Alcoa Mosjøen

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.

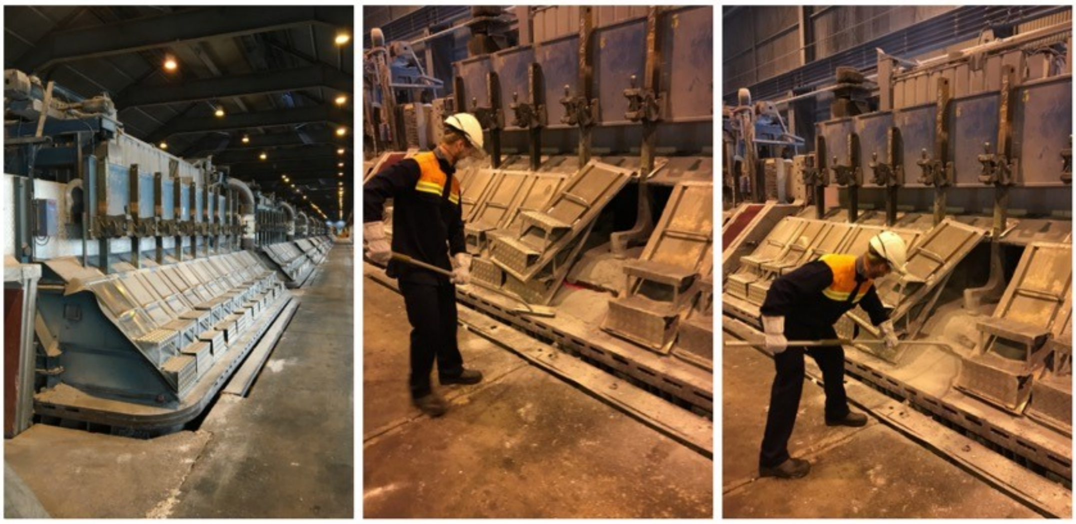


Figure 5: Picture far left displaying a row of melting pots at Alcoa Mosjøen. Last two pictures illustrate an exposed anode being manually covered with cover mass by an operator.

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.

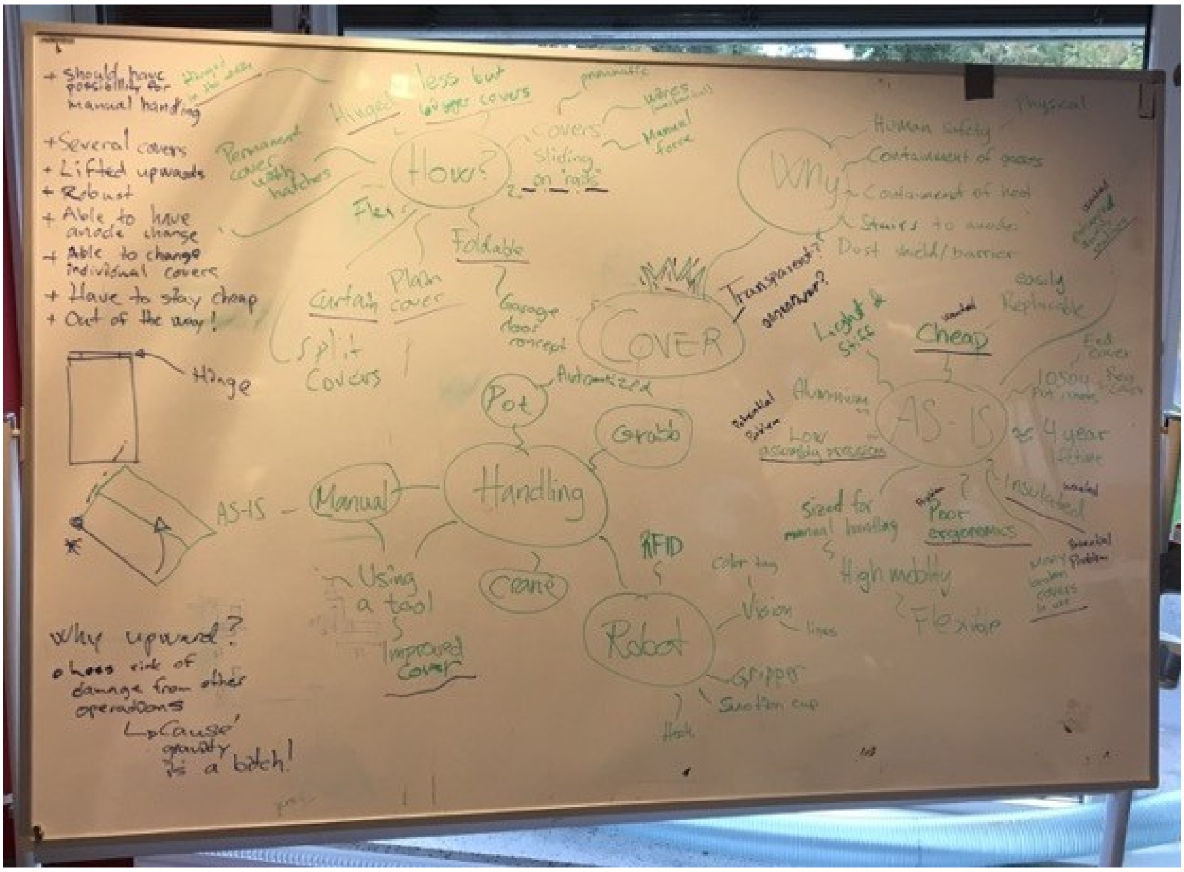


Figure 7: Whiteboard mind map from the brainstorming pot cover and pot cover handling ideation session

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

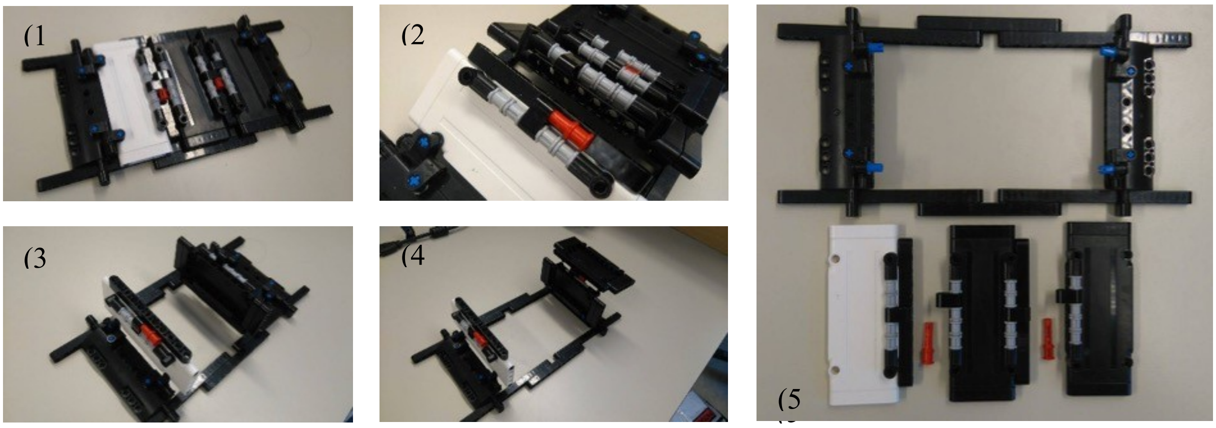


Figure 8: Lego mock-up of hinged pot covers. Numbers 1-5 are related to the description in the text.

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.

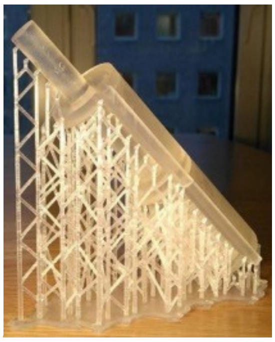


Figure 10: Cross-sectional hinge-pin prototype produced with VAT Photopolymerization. The prototype is made for physical evaluation of the prototype's structure. Here with support still attached.

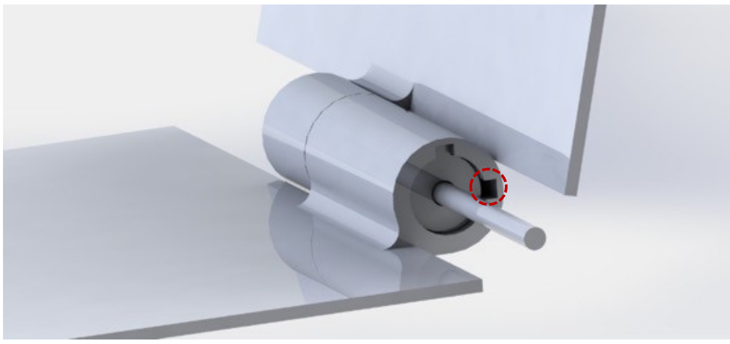


Figure 9: Rapid hinge pin assembly. When the pot cover surfaces lay parallell to one another, the spring experience a 90 degree torsionional force. By pulling the pin shaft, the wedge on the pin's front section can slide into the free slot space marked with the red circle, thus releasing the covers from 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.

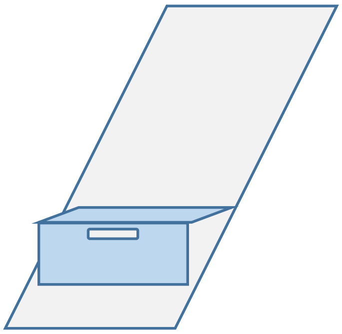


Figure 11: Rough sketch of the minimalistic pot cover concept. The handle and one of the steps are removed, and slots in the step is added for grabbing and moving the pot cover.

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.

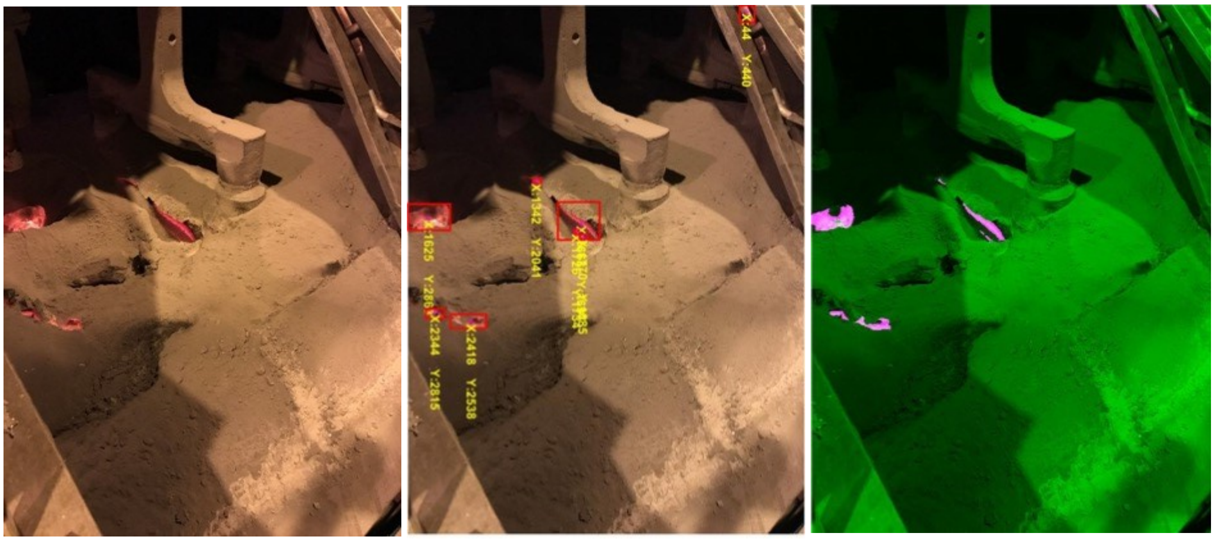


Figure 13: Left: Original pot image imported to MATLAB. Middle: Centred pixel location of the detected red areas. Right: Original and binary image fused to visualize detected areas.

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.

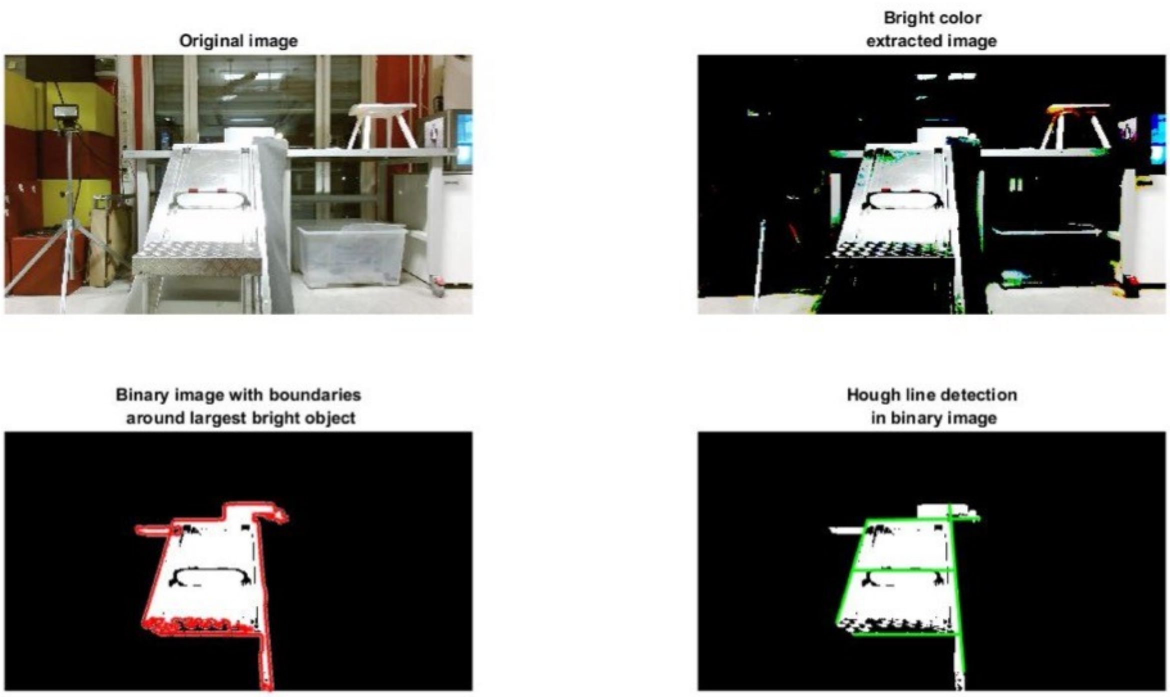


Figure 15: Contour and Hough lines related to the biggest, bright object in an imported image in MATLAB.

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

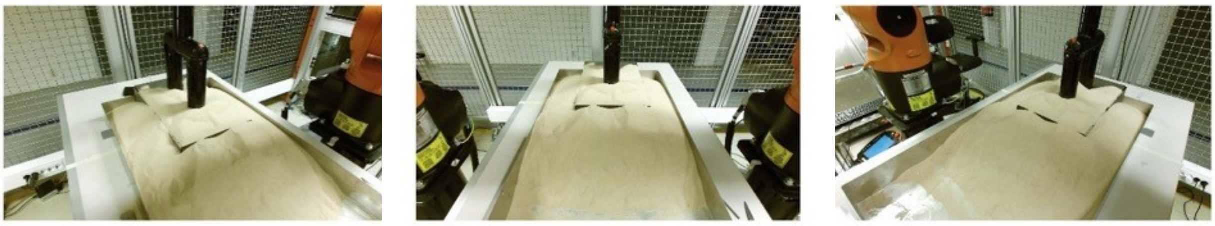


Figure 16: Anode covering mock-up. Centred view and +-35° side views from Kinect.

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.

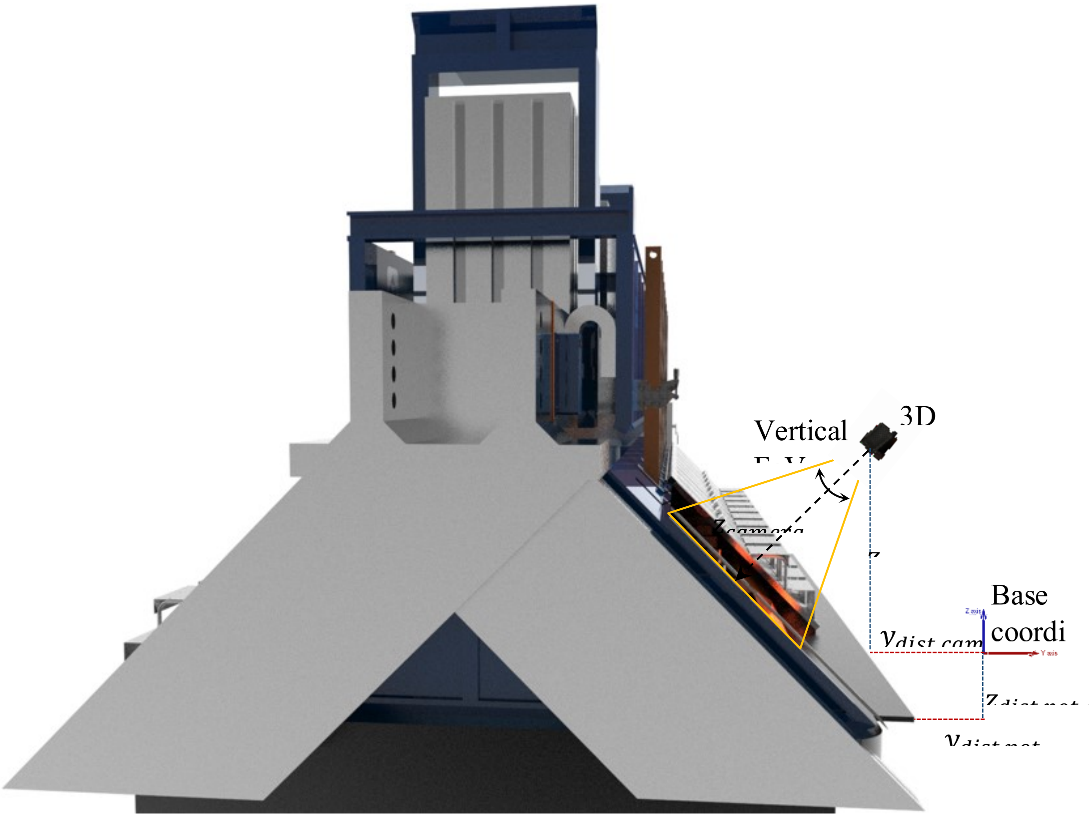


Figure 17: Optimal pose of camera relative to its base of operation, which again has a known position relative to the pots edge. The vertical FoV should be calibrated tangent to the pot opening, and the camera should be within the optimal performance range relative to the reflective surface.

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.

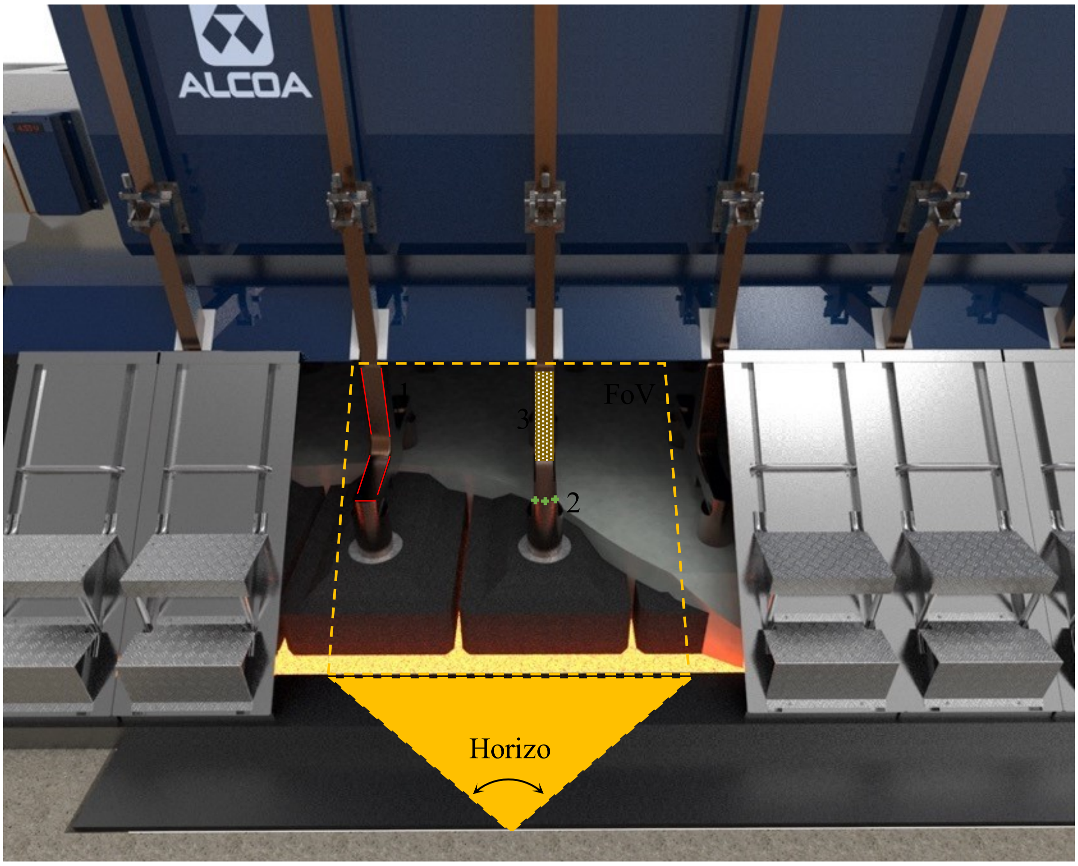


Figure 19: The field of camera view from the front of the pot. 1. Lines detected on yokes as labels for reference geometry. 2. Corners detected on yokes as labels for reference geometry. 3. The scanned yoke as PC, later fitted to a reference PC.

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.

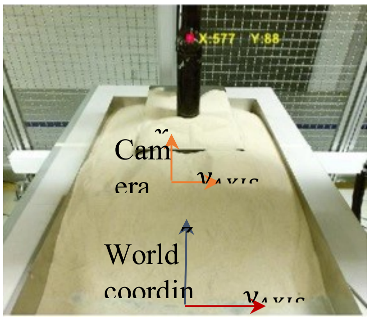


Figure 18: Red label on mock-up found in the forward oriented FoV with the red area detection algorithm in section 5.2.1.2.

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.

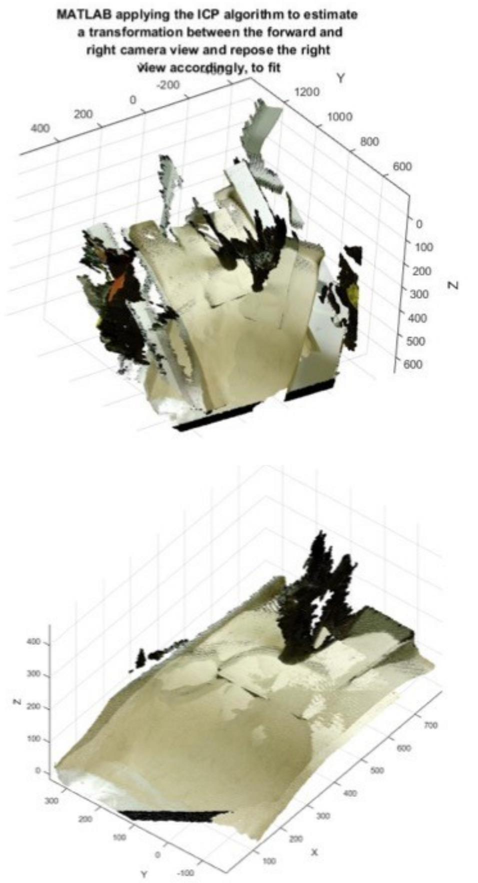


Figure 20: The upper merge is performed by the ICP function in MATLAB on raw cloud scans. In the lower merge, the scans are first transformed with a known transformation according to the robot arms joint angles to our familiar world coordinate system. The PCs are then roughly aligned and most of irrelevant 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.

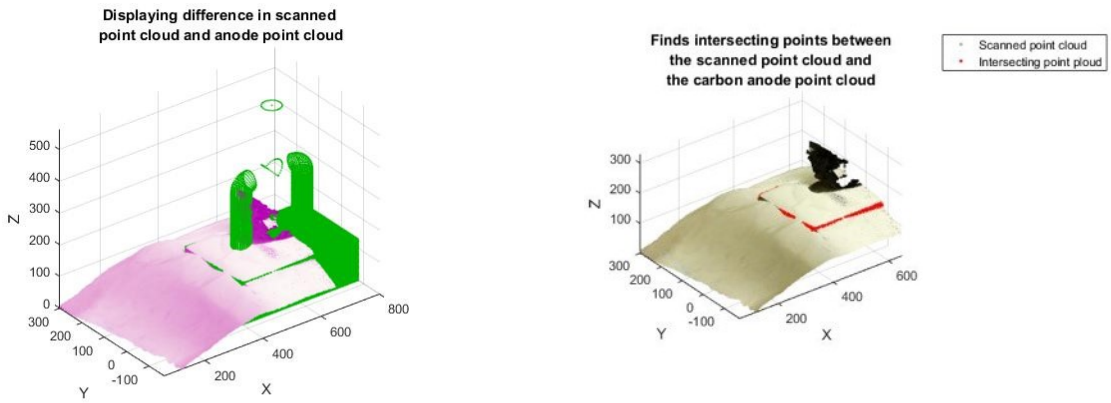


Figure 22: Scanned PC and reference anode PC intersected. The intersected areas could be isolated into separate PCs as shown in red to the right. Axes in mm.

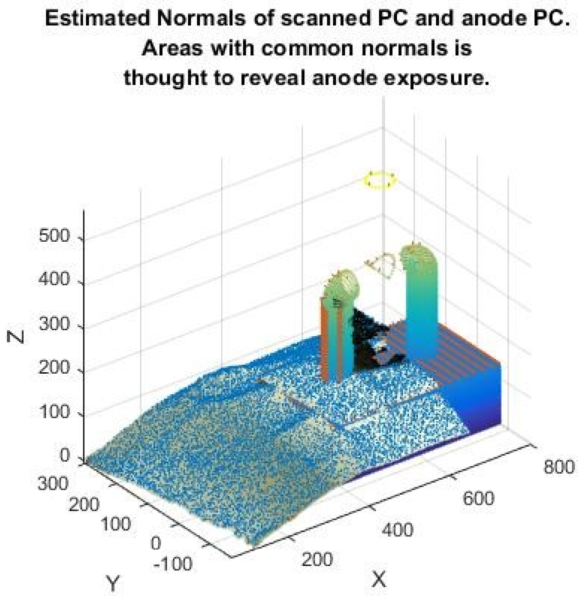


Figure 21: Display of normal vectors of both the scanned PC and the reference anode PC.

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

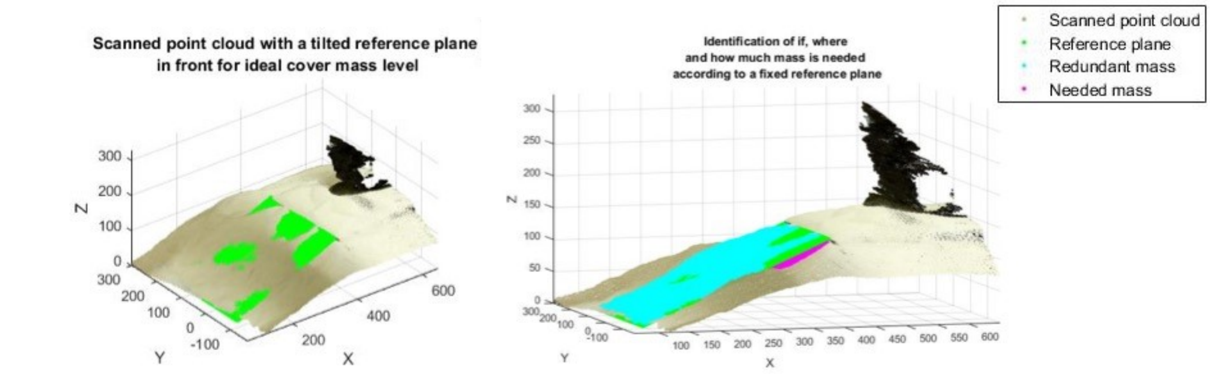
When the scanned PC is satisfyingly aligned as reference geometry, here a PC of the mock-up anode, we can compare the PCs normal vectors. Areas of vectors in the clouds with common location and direction could indicate common surfaces. If the scan has a common surface with the anode reference PC, it 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.



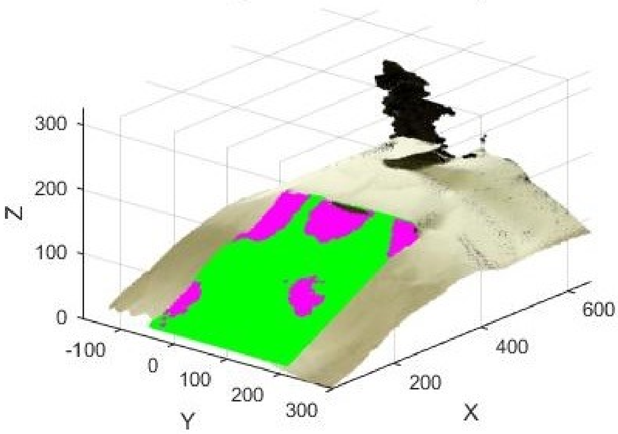


Figure 23: Cyan PC of redundant mass and magenta PC of needed mass. Isolation of these PCs is depending on the green reference plane's intersection of the scanned PC.

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.

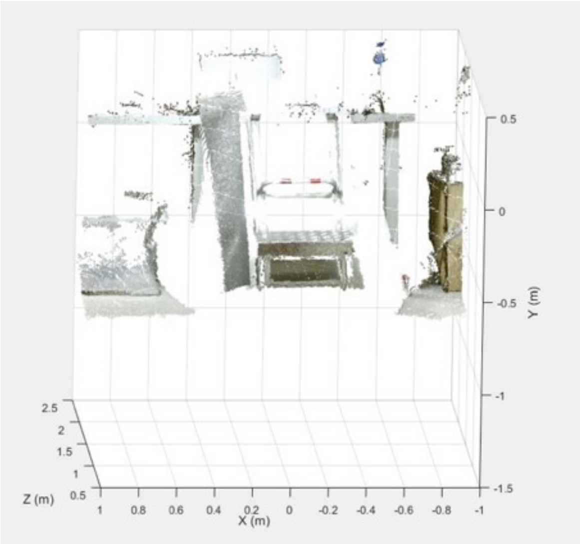


Figure 24: Points with specific colours could identify yokes, cracks or anode exposure.

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.

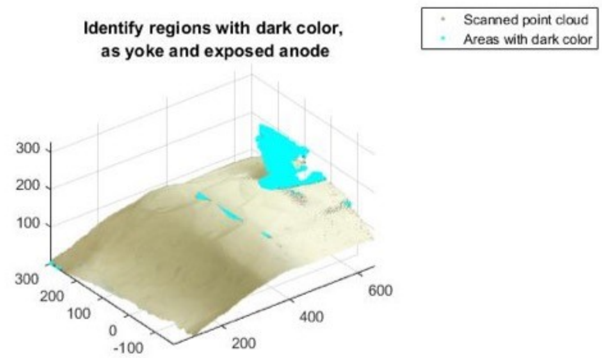


Figure 25: Pot cover 3D point scan with Microsoft Kinect. The image is taken from a PC stream to MATLAB.

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

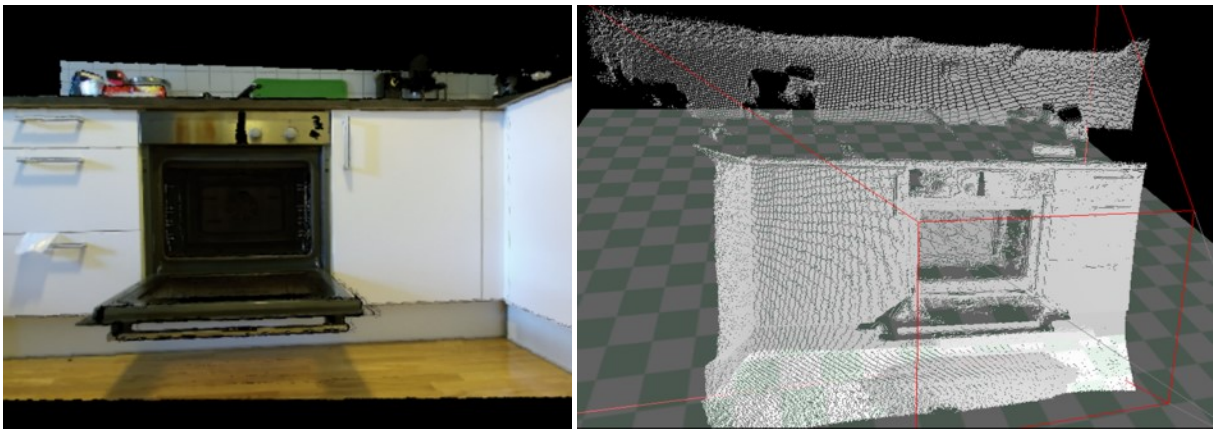


Figure 26: Microsoft Kinect placed in front of an open baking oven preheated to 250 °C. One can clearly see depth point readings from the heated interior of the oven.

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.

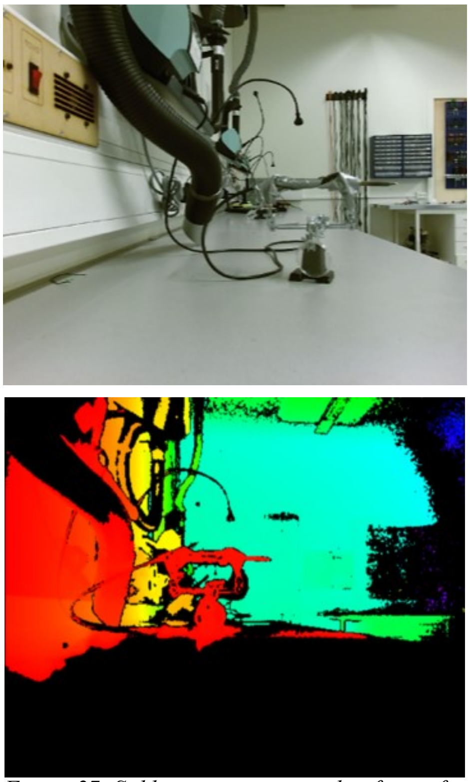


Figure 27: Soldering iron mounted in front of Microsoft Kinect and heated to 450 °C (top). Point cloud stream is shown with red indicating close distance and blue far off (bottom). The 450 °C tip of the iron is not neglected by the Kinect. Neglected areas are black.

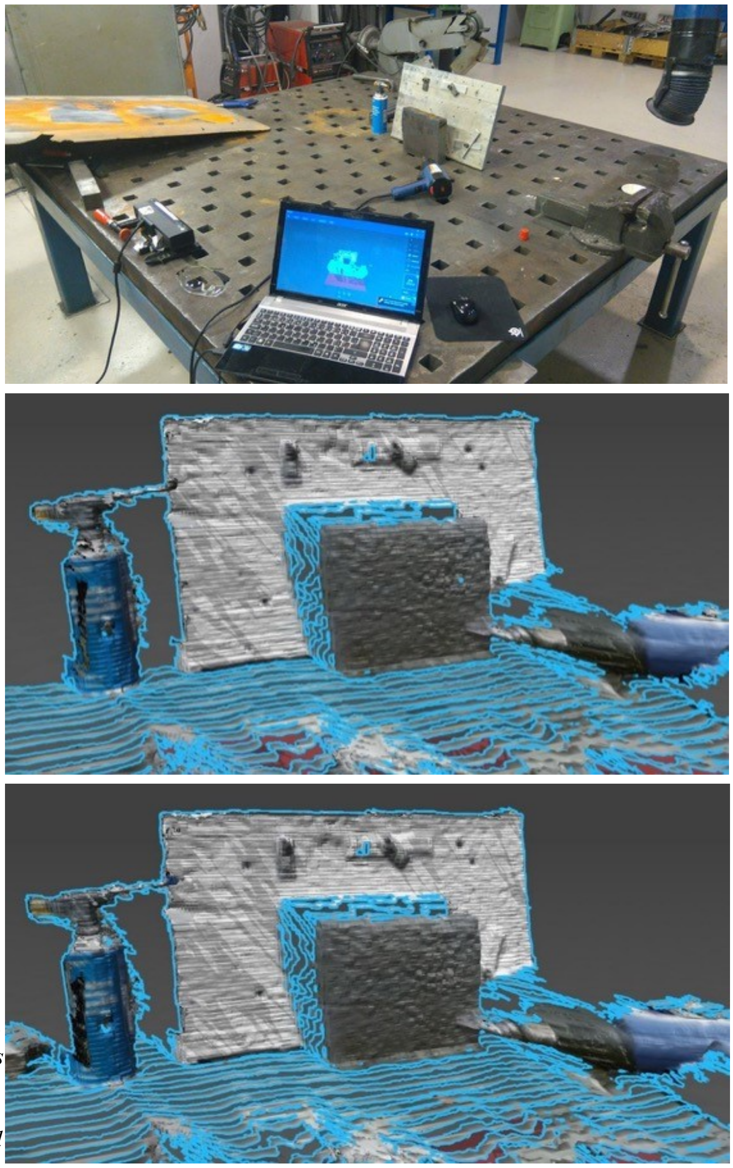


Figure 28: Test setup (top) for visualizing the difference between PC scan of surfaces at room-temperature (middle) and with a torch and warm-gun in front of, and pointing towards, the surfaces during the scan (bottom). Heated temperature is unknown. No critical distortion or neglection of points are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

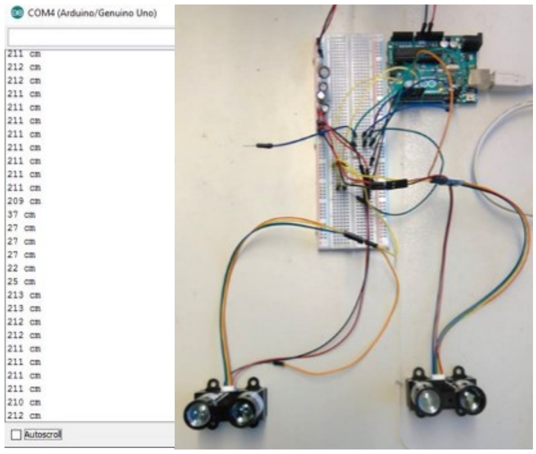


Figure 29: Two LIDAR Lite V3 hooked up to an Arduino Uno microcontroller for testing. Readings from one of the LIDARs when a flat surface is swiped above it is shown in the Arduino serial window to the left.

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

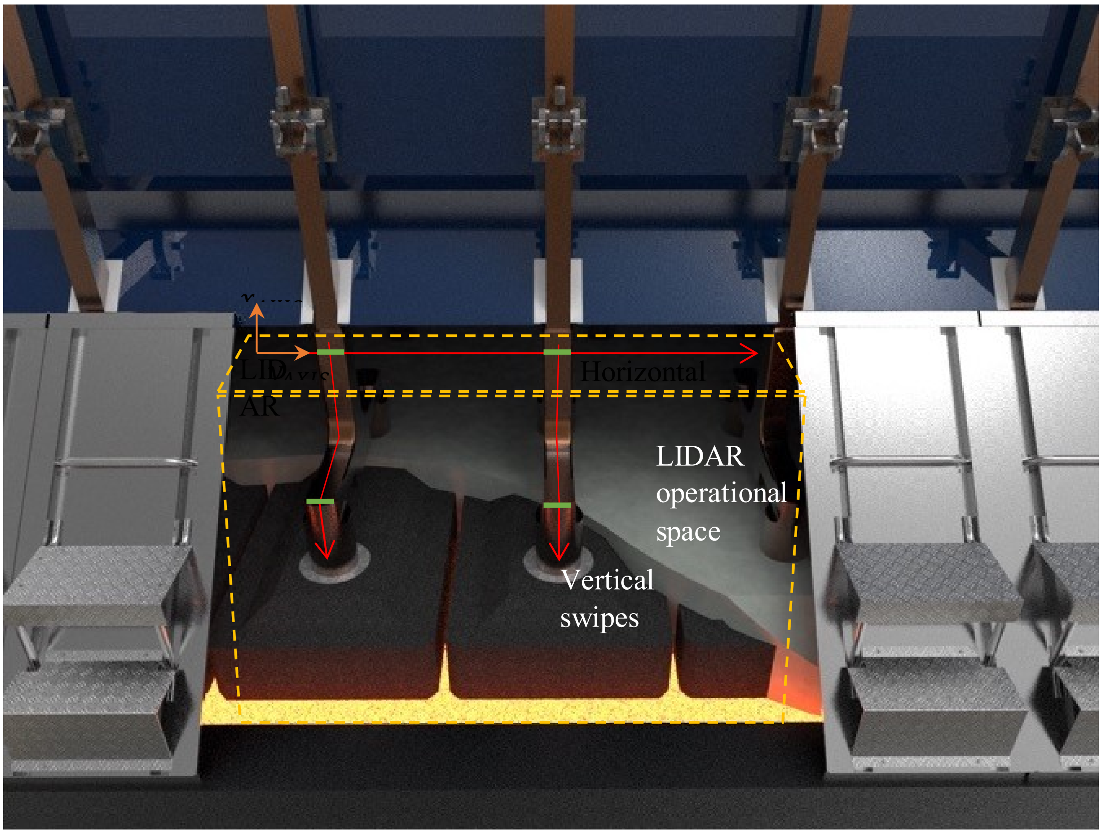


Figure 30: Yoke identification with LIDAR. First a horizontal sweep is made from the LIDAR origin, finding the rods (upper green labels). Next the LIDAR does vertical swipes accordingly, finding the yoke buts i.e. height of the yokes (lower green labels). From this we can get an accurate location of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

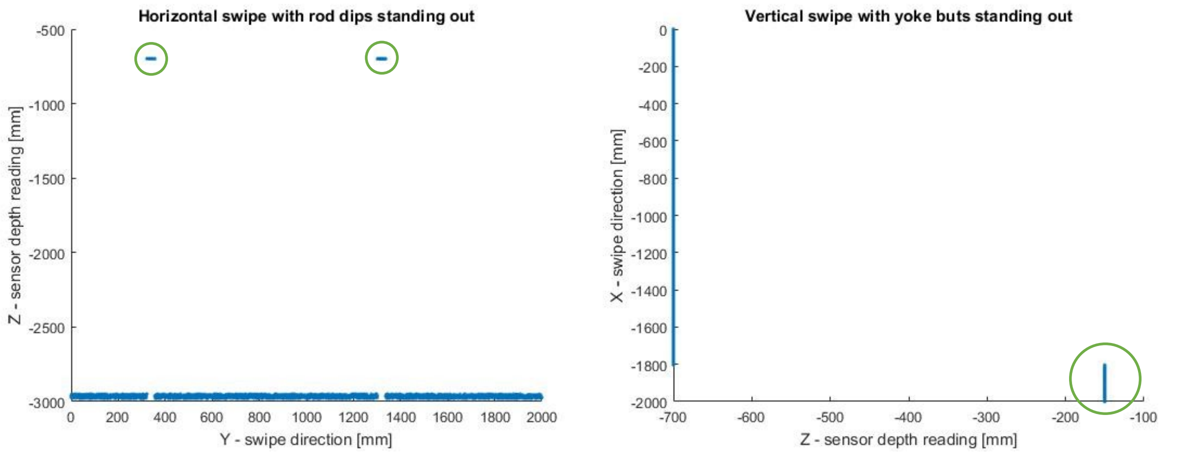


Figure 31: Yoke characteristics standing out in horizontal and vertical swipes. The readings we are looking for are marked with green circles. The blue lines are point depth readings. LIDAR origin at [X,Y,Z] = [0,0,0]. This figure is only an illustration, not based on actual data.

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.

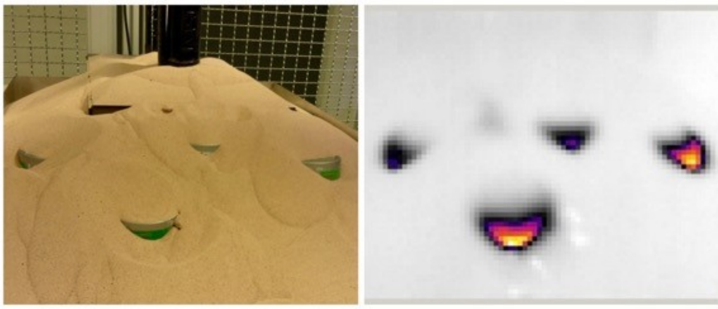


Figure 37: FLIR visual results from mock up test of anode air exposure

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.

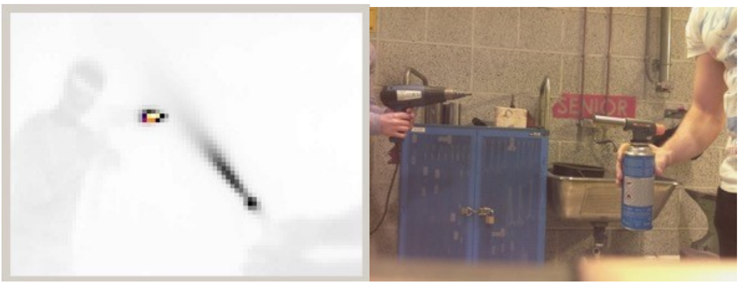


Figure 32: FLIR sensitivity test

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.

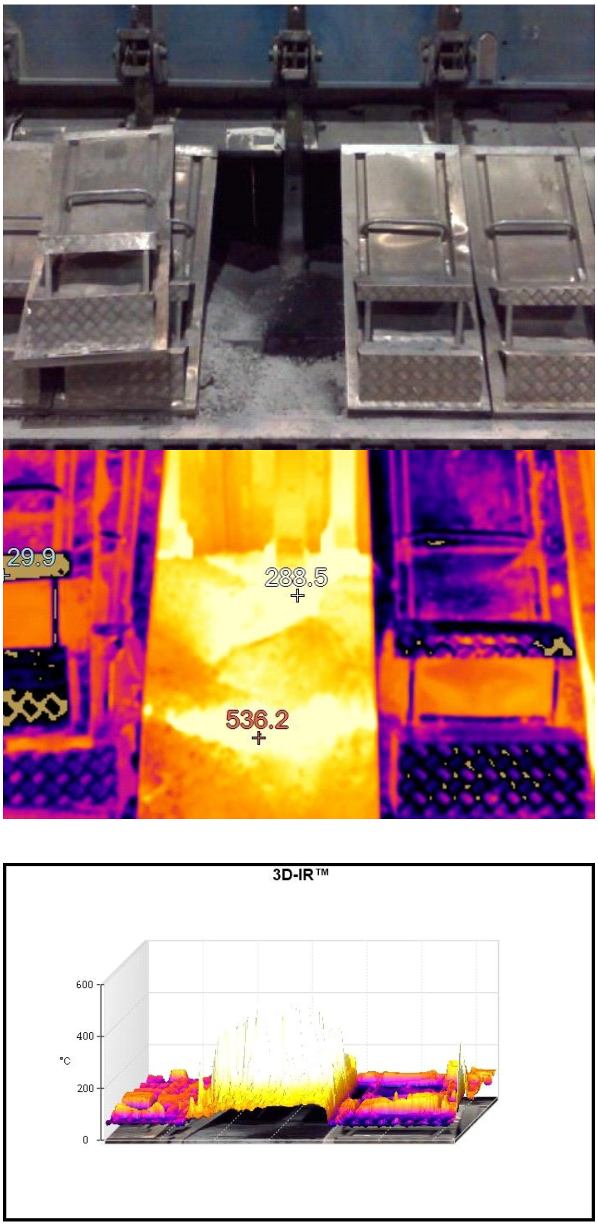


Figure 33: Fluke's SmartView post-processor. Maximum (red), Minimum and image centre temperatures are shown in the thermal image (middle). SmartView features 3D image plot of temperatures to evaluate the whole image visually by an operator.

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:

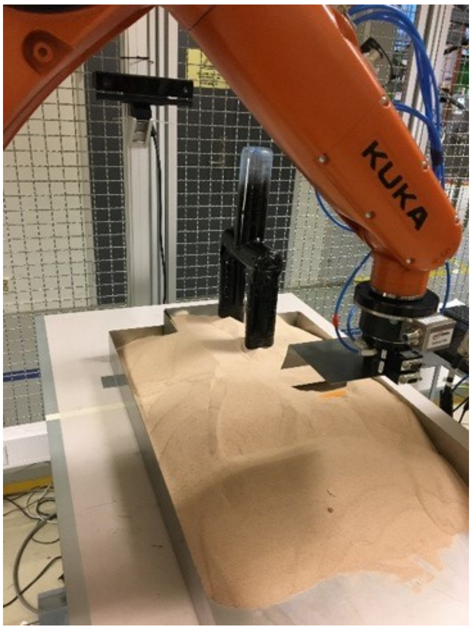


Figure 34: Demonstartion ofcover mass distribution with KUKA Agilus KR6 R900 sixx manipulator.

- 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.

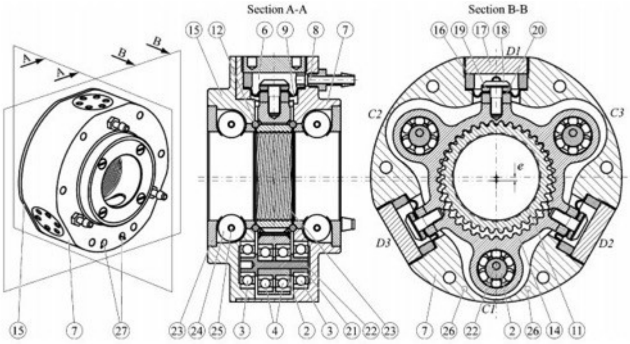


Figure 35: Isometric view and two cross sections of the pneumatic stepper motor. In section B-B we see the three chamber ports, the off-centred gearhead and the motor-shaft. This figure should only support the description in this thesis. Therefore, the numbers in the figure can be ignored.

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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