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Additive Manufactured Robot Grippers With Advanced Functionality

Sverre Steen

Master of Science in Mechanical Engineering
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Supervisor: Knut Sørby, IPK

Norwegian University of Science and Technology
Department of Production and Quality Engineering

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Kongsberg Automotive (KA) at Raufoss produce large quantities of injection molded metal parts for the automotive industry. Up to 36 parts are cast simultaneously and removed from the molds by a robot arm with pneumatic grippers, mounted on a structural frame containing all necessary substructures.

Robot gripper assemblies are relatively large, and consist of many parts, including air hoses, cables and sensors. Wear and snagging of hoses and cables is a challenge, and traditional routing of hoses and wires is always challenging. The room inside the opened injection mold is limited, requiring tight position control, and often relatively slow movements to avoid costly and time consuming tool collisions. Size and weight optimisation may allow shorter cycle times and reduce breakdowns.

In the BIA project NextForm, SINTEF Raufoss Manufacturing (SRM) and KA worked with advanced injection molding tools created by use of additive methods. The author and KA now investigates the use of additive manufacturing to build robot gripper frames and assemblies with extended functionality. My thesis will include the following:

- A study shall be conducted of the current gripper solution, and requirements for the grippers will be redefined. It shall be decided which features the grippers need, and how air hoses and electrical cables may be routed and connected to the gripper.
- • A new overall design of a gripper solution with the necessary functionality shall be developed. Topology optimization should be carried out, and it should be shown by simulations that the gripper satisfies the weight and strength requirements. The sustainability of the solution shall be discussed.
- • A prototype shall be built and tested. The prototype may consist of a combination of market available components and additively built parts.

The report should be edited as a research report with a summary, table of contents, conclusion, list of reference, list of litterature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also important that exact references are given to any external source used in the text.

Referring to http://www.ntnu.no/ivt/master-siv-ing for information on withdrawals, contracts, completion and submission.

Responsible lecturer/supervisor: Knut Sørby Supervisor at Kongsberg Automotive, Sture H. Sørlie

Preface and acknowledgments

This thesis is written as a part of the subject TPK4940. The workload should be equivalent to 30 study points. The purpose of this thesis is to develop a new design concept for robot grippers for use at Kongsberg Automotive, using additive manufacturing as a manufacturing method. The thesis is part of the research project Nextform. The work was carried out at Kongsberg Automotive Raufoss and NTNU in Trondheim.

I would like to thank the supervising professor Knut Sørby from the department of production and quality engineering at NTNU, and doctor Vegard Brøtan at SINTEF for help and ideas during my work.

I would also like to thank Sture H. Sørli, my supervisor at Kongsberg Automotive. He helped a lot, especially during the start of the project, defining the theoretical framework around the thesis. Thanks also to Tommy Rafteseth for great ideas. Trond Lindmoen's technical assistance was invaluable during the latter part of the project. Ole Steen has proofread the manuscript, and contributed with text clarifications.

Trondheim, Norway
24. June 2016

Sverre Steen

Abstract

Kongsberg Automotive produces injection molded parts. These are removed from the mold with a robot gripper. These robot grippers have grown larger as the complexity of the molds grew. This has increased the amount of collisions between the mold and the gripper. Kongsberg Automotive wants to find out if it is a possibility to use additive manufacturing to produce smaller and better grippers for their production lines.

During this thesis work a new design concept for robot grippers was developed. The purpose of this design is to reduce the production halts resulting from contact between the gripper assembly and its surrounding machinery, and to decrease the wear due to high moments of inertia imposing high loads on the assembly substructures. The design of the structural subunits is utilizing topology optimization. (Optistruct and Inspire by Altair)

This thesis is written in collaboration with Kongsberg Automotive, Raufoss. It has also developed and manufactured a prototype gripper that fits the injection molding tool and machinery used in production at Kongsberg Automotive, Raufoss. The gripper subassembly was manufactured using additive manufacturing of metal, utilizing powder bed fusion. The prototype is made from the aluminum alloy powder CL30AL, delivered by Concept Laser Co. specifically for use in additive manufacturing.

The design for the prototype was narrower than the currently used design, while fulfilling the demands to strength and stiffness. This gives the gripper sufficient room on all sides when it is inside the mold. It also has the quick change tool adapter build into the body of the part. It also has internal tubes for pressurized air to the pneumatic actuators. These significantly reduces the use of hoses which can snag on edges in the mold.

The Prototype produced showed some flaws and errors. This was a result from among other things internal stresses in the material during the build process. Many of these flaws could have been repaired by welding the cracks and patching the holes epoxy. Because of these errors there has not been enough time to test the prototype.

Sammendrag

Kongsberg Automotive på Raufoss produserer sprøytestøpte deler. Disse blir fjernet fra støpeformen med en robotgriper. Disse robotgriperene har vokst når formene har blitt mer komplekse. Dette har økt mengden kollisjoner mellom formen og griperen. Kongsberg Automotive ønsker å finne ut om det er mulig å benytte additiv tilvirkning for å produsere mindre og bedre gripere til sine produksjonslinjer.

I forløpet av denne masteroppgaven ble det utviklet et nytt designkonsept for robotgripere. Hensikten med dette designet er å redusere stopp i produksjonen på grunn av kontakt mellom griperen og andre maskinkomponenter, og å redusere slitasje forårsaket av unødvendig høye akselerasjonsbelastninger på griperkomponentene. Konstruksjonen er designet ved bruk av topologioptimalisering med programmene Optistruct og Inspire fra Altair.

Oppgaven er skrevet i samarbeid med Kongsberg Automotive, Raufoss. Det har også blitt utviklet en prototype av en griper som passer til et sprøytestøpingsverktøy som benyttes i produksjon hos Kongsberg Automotive, Raufoss. Denne griperen ble produsert ved hjelp av additiv tilvirkning i metal, med «powder bed Fusion» i en M2 additiv maskin fra Concept Laser. Prototypen er laget i aluminiumlegeringen CL30AL, produsert av Concept Laser spesifikt for additiv tilvirkning.

Designet til prototypen er smalere enn det designet som brukes i dag, samtidig som den oppfyller kravene til styrke og stivhet. Dette medfører at griperen har god plass på alle sider når den er inne i formen. Den har også verktøyadapteret bygget inn i selve delen. Prototypen har også innvendige rør til trykkluft fram til pnaumatikkaktuatorene. Disse tingene reduserer bruken av slanger betydelig. Dette er en fordel fordi slager kan hekte seg fast i kanter inne i formen.

Prototypen som ble produsert hadde noen feil. Dette var resultat av blant annet interne spenninger under byggeprosessen. Mange av disse feilene kunne ha blitt reparert ved å sveise sprekkene og lappe hullene med epoxy. Grunnet disse feilene har ikke prototypen rukket å bli testet.

Contents

Chapter 1

Introduction

The scope of this assignment is additive manufacturing technology and product development. The purpose of the assignment is to investigate the possibilities of improving existing robotic gripper design using additive manufacturing technology. If possible, Kongsberg Automotive Raufoss might save expenses generated from several different types of production halts in their production processes.

1.1 Background

Inherently good inventions and solutions may fail because the inventor or developer did not understand the user or their needs. It is paramount to gain insight in the problem before considering solutions. Tempting as it may be to solve the problem before it is fully defined, this will often reduce the variety of possible solutions.

1.1.1 The problem

Today's gripper assemblies represent a variety of different problems for Kongsberg Automotive and their casting machine operators. Among these, hoses and wires sometimes snag on edges, and the grippers occasionally collide with the molds or other machinery. To try to minimize these problems the speed of the robots is often reduced to suboptimal values. This causes reduced output from the machines. This situation might be improved or remedied if the gripper assemblies were smaller and lighter. The distance from the end of the robot arm to the tip of the grippers claws is often a limiting factor, See figure 1.1.

Figure 1.1: A gripper assembly between the two halves of the injection molding tool in the open position. The gripper is used to extract finished parts after they have been molded (Source: Sture Sørli, Kongsberg Automotive Raufoss, 2016)

1.1.2 The cost of the problem

The downtime from either damages by interference caused by the extraction robot arm or adjustment of the robots represent about 20 hours per week. This adds up to approximately 1000 hours each year. The downtime costs 860 NOK per hour in the affected department, plus loss of revenue due to products not being produced at approximately 2112 NOK. This adds up to about 2 million NOK per year. The gripper assemblies used today cost on average 60 000 NOK each. Thus if it is possible to reduce some of the downtime it might very well be highly cost effective

1.1.3 The user

Kongsberg Automotive Raufoss made the request for a new solution to improve the reliability of some of their production lines. If the product is well received it might have far more potential users.

1.1.4 Desired functionality

The user, Kongsberg Automotive, have expressed the desire for functionality they wish to be to implemented in a new gripper assembly design. These expectations are a result of their experience with the current gripper units, combined with visions of products planned for the future.

Narrower design

Some of the current gripper's speed vectors are limited by the gripper's constraining width. By making the new design narrower it might be possible to increase the speed and reduce the cycle time of the injection molding process.

Sensors

Sensors measuring acceleration, interference or other values for feedback to the robot's internal processor might increase speed and precision, and reduce the possibility of breakdowns. The feasibility of this depends highly on the available mechanical mounting possibilities. New gripper assemblies might reduce the future cost of implementing new sensors and other possible solutions.

Internal routing of pneumatic tubes and wires

All wires and tubing for sensors and pneumatic systems could be routed internally in the structure of the gripper assembly framework. One of the current problems is snagging of hoses and wires on edges in the robot's operating area. By rerouting this problem might be reduced substantially.

Hydraulic grippers

Kongsberg Automotive might convert from pneumatic to hydraulic grippers in the future. This is will facilitate the assembly of cast parts to simple assemblies directly after removal from the dies. This will necessitate greater clamping force than available with the pneumatic grippers used by today.

Weight

Today's robots attachments have an upper weight limit of 12kg and 6kg respectively. To be able to use a new gripper solution interchangeably the system's weight should be restricted to 6kg including the robot/ gripper interface and all pneumatic actuators.

1.1.5 Existing products

An existing product already on the market could possibly solve the problem at hand. We therefore conducted an internet search for existing gripping systems for industrial robots, including the interface between the robot and the gripper system.

The search mapped the specifications and functions of different robot/gripper interface couplings. The spreadsheet with the overview can be found in appendix B. A couple of the connectors could possibly reduce the total depth of the gripper assemblies compared to the current type. On the other hand, none of these alternatives had provisions for internal routing for cables and hoses at the same time in the size relevant for Kongsberg Automotive. Assemblies systems from the following manufacturers were considered: Wemo, ATI, Schunk, Grip, Destaco and SAS Automation. See figure 1.2.

(a) WEMO's robotic tool changer with a module for transmitting electronic signals. (Source: WEMO)

(b) Schunk's quick change tool adapter. (Source: Schunk GmbH)

(c) ATI's quick change tool adapter. (Source: ATI)

Figure 1.2: This is some of the robotic tool changer adapters available on the market

1.2 The direction chosen

In this thesis we aimed at making a carrying frame for the gripper assembly from scratch. We attempted to exploit all the benefits that additive manufacturing has to offer in terms of design restrictions. Some existing parts that inspired this path may be seen in figure 1.3 and 1.4

Figure 1.3: A connectiong node that have been optimized with topology optimization software and built using additive manufacturing.(Source: www.insidemetaladditivemanufacturing.com)

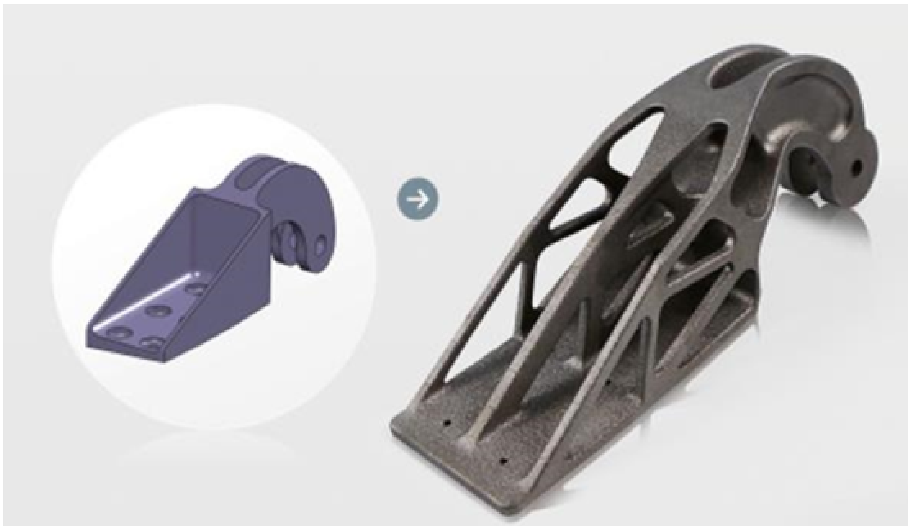


Figure 1.4: A hinge that has been optimized with topology optimization software and built using additiev menufacturing. (Source: EOS)

Chapter 2

Theory

The additive manufacturing part of this chapter is a summary of the author's specialization project fall 2015 [14].

2.1 Additive manufacturing

Describing some of the most used and most relevant additive production processes and their production materials, see ISO standard 17296. [1]

2.1.1 Processes

Additive manufacturing is a generic term of production methods in which the object is built up bit by bit by adding fluid or semi- fluid material. This differs from traditional production methods which are either subtractive or forming, removing material or changing the shape of the part [3]. The traditional production methods may be divided into the following main categories.

- Casting
- Forming (for example rolling or extruding)
- Cutting (for example milling or turning)
- Joining (for example welding or gluing)

Additive manufacturing differs from the traditional production methods. It allows the manufacture of more complex shapes and surfaces that might otherwise be difficult or impossible to produce. This is particularly true for internal structures and channels with shapes that traditional tools or casting forms is unable to shape. Many exclusive expressions and terms are used in additive manufacturing. Various companies producing additive production machines have registered different concepts and expressions as their trademarks. This means that there are many different terms describing for the same processes, making it difficult to gain an overview over the relevant methods and processes. ISO standard 17296 attempts to divide additive manufacturing into discreet categories. In this chapter we attempt to use the standardized descriptions when possible. [2]

Powder bed fusion

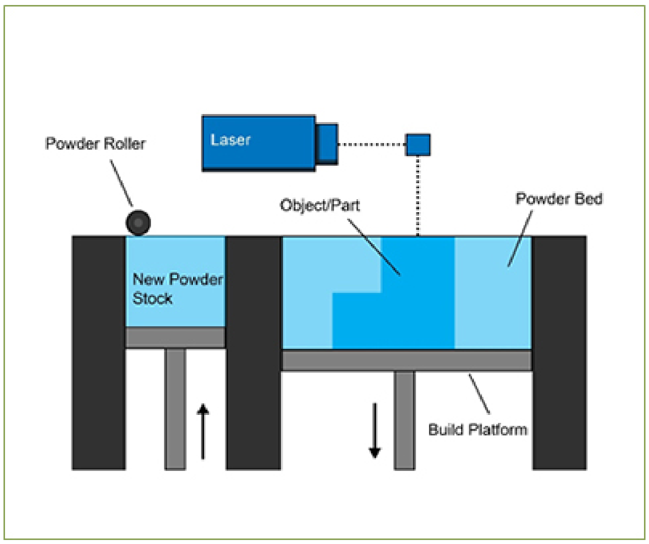


Figure 2.1: An example of powder bed fusion. (Source: Loughborough University)

This method involves fusing powder with a concentrated source of energy. The energy source may be a laser or an electron beam. The powdered material is sintered or fused more tightly together depending on the energy and temperature applied. This process is widely used to produce parts in metals or polymers.

Powdered substrate is distributed evenly and thinly on a table by a straightedge. This powder is then locally melted by a scanning energy source, passing over the bed of powder line by line. When one layer is melted in the pertinent areas a new layer of powder is distributed thinly over the already completed, and the process is repeated. The bed is then replenished layer by layer until the part has the required thickness vertically. (see figure 2.1)

Some materials require an inert atmosphere to avoid oxidation and to enhance forming of a contiguous part free of pores. This may be an inert gas for processes using lasers. Processes using electron beams are performed in a vacuum.

These processes usually provide a reasonable level of detail. [9]

Directed energy deposition

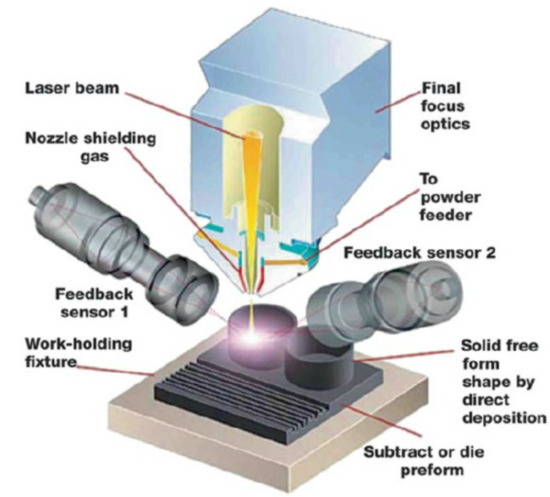


Figure 2.2: An example of a directed energy deposition process. (Source: www.Insidemetaladditivemanufacturing.com)

This process uses thermal energy to melt the material while it is being added. Some directed energy deposition equipment may resemble a welding robot (See figure 2.2).

Directed energy deposition is mainly used for metal products. It provides a coarser final product compared to powder bed fusion, but is cheaper and faster to perform. The requirements of the build materials is less strict. When powder is used, the grain size may be non- uniform. The building material may also be introduced in the machine in thread form, as with MIG welding. Most weldable materials may be used with this method.[9]

Vat photopolymerization

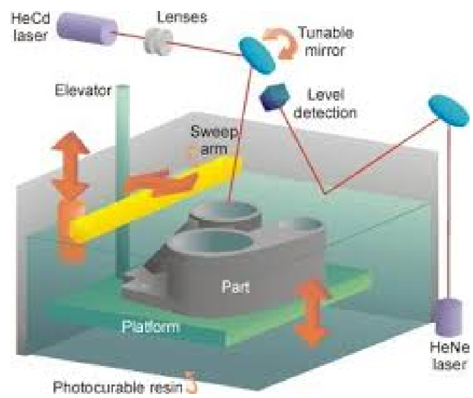


Figure 2.3: example of vat photopolymerisation. The part is being built in a container partially filled with liquid monomer. (Source: www.3dprinting.com)

This method utilizes curing of liquid monomer by UV radiation, using a focused and scanned light source. The monomer used is usually either epoxy, acrylic or vinyl-ether based. This is the oldest method of additive manufacturing, but also the one providing the highest level of detail. Some varieties of this method results in a partially cured product, requiring post-curing by heating in a separate oven.

An example is shown in figure 2.3. A vertically moving table inside the process tank is lowered until it is covered with a thin layer of liquid monomer, the viscous fluid evened out by a squeegee passing over it. The liquid is then selectively cured with a scanning UV laser or other scanning radiation source. The table is then lowered corresponding to the thickness of one layer, and the process repeated until the required thickness is achieved. [9]

This process was developed by 3D Systems in the US in 1986. It provided a very detailed surface, and many of these early machines are still in use. [10]

Due to the UV light sensitivity of the base material, the product is prone to brittleness over time if exposed to UV light, such as sunlight. This characteristic, combined with the good level of detail makes this method suitable for various prototypes where form is more important than the longterm mechanical properties.

Material extrusion

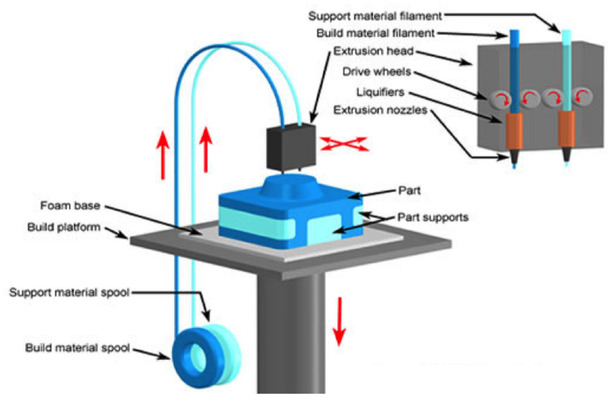


Figure 2.4: Material extrusion. (Source: www.Kul3d.com)

This method involves extruding a thin, melted string of material from a heated nozzle moving in the three linear axes. The material hardens when it cools and the part is built up gradually (see Figure 2.4).

Polymers with two different thermoplastic properties are often used in order to support the product mechanically during the build. ABS and PLA polymers are often used. One of the build materials may be removed with solvent after completion of the building process. [9]. Machines built on this principle have been developed for the amateur marked, using commonly available parts. [10].

Binder jetting

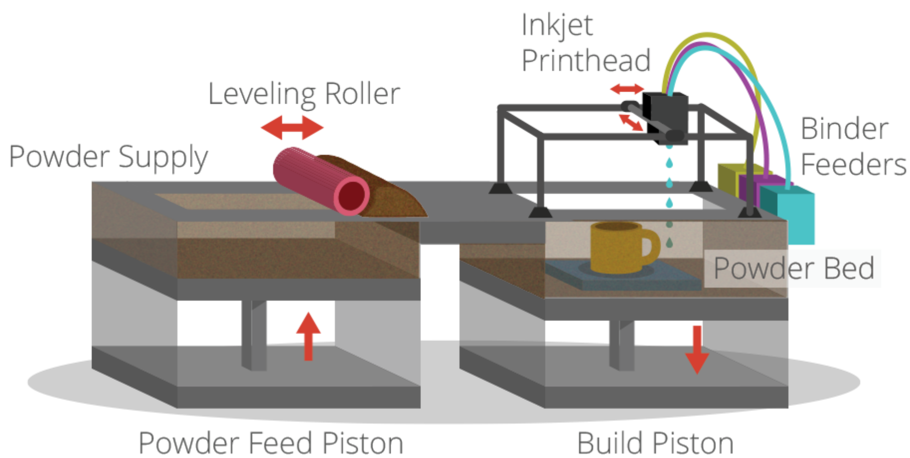


Figure 2.5: An example of a binder jetting process. (Source: www.3dprintingindustry.com)

In this method base powder is glued together by adding a hardening liquid binder. Base powder may be spread thinly over a table. A nozzle passes over the powder and adds binder selectively (see figure 2.5).

The base powder may be based on polymers, metal or ceramics. Using metal powder, the process may involve two steps. The powder part is built with a volatile binder. Secondly the structure is saturated with liquid metal at high temperatures, utilizing capillary action, evaporating the binder in the process. [9]

2.1.2 Advantages and disadvantages of additive manufacturing

Accuracy

Current additive manufacturing is not as accurate as traditional machining may achieve. The accuracy of the final product varies with the process, material and equipment used.

For powder bed fusion machines using lasers, the theoretical minimum wall thickness is determined by the width of the laser beam. Traditional cutting machine tools, on the other hand, have inherently no minimum wall thickness, utilizing subtractive processes. Other limitations restrict product design, e.g. when machining inner corners, being limited to the radius of the cutting tool. Machining in narrow pockets is also limited by the access opening. These machines often need a high number of different tools to achieve good accuracy and versatility. Additive machines normally require no special tools to obtain their highest degree of accuracy.[10]

Additive manufacturing machines are not yet manufactured in large, standardized series like traditional machines. Significant differences in accuracy between different machines exist, even with the same model from the same manufacturer. Knowledge of variation in product parameters due to environment, material and tool variables is still in its infancy.

To monitor tool and machine wear, as well as other variables, NTNU developed a method for measuring the accuracy of the construction plane of additive machines (Brøtan [5]).A test plate is built in the machine with round studs in specific positions. By measuring this standardized test plate on a coordinate- measuring machine, one may map the deviations from the original design, and correct machine parameters accordingly. [5]

Similar to traditional cast parts, additively made parts may need machining to reduce tolerances in certain areas. The part may include a bearing surface, or parts need to fit inside each other. It is important to think ahead when the part is designed, including clamping areas and reference point if later machining is required.

Build time

Traditional machining removes material faster than additive machines add, leading to the false conclusion that machining is the faster, more economical process. The truth is that this all depends on the complexity of the part. Some shapes and designs require a large number of different machining operations, tool changes and passes, adding up to long machining times. Some functionalities of assemblies must be made using a large number of different parts and materials. For these complex parts additive fabrication may best suited. [10]

A NASA subcontractor used additive manufacturing to manufacture an injection nozzle for a rocket motor. The original assembly consisted of 163 parts. Using additive manufacturing, the nozzle could be made as one, contiguous part. The reduced complexity led to a substantial increase in reliability and reduction of weight. [12]

Using additive manufacturing, complex parts are often easier and quicker to make than simple parts. It is the addition of material that takes time. A part with more cavities and more complicated truss- based structures often consumes less machine resources. The time needed to manufacture a part in a powder bed fusion machine may be estimated by adding the time required to melt the entire volume of the part, plus the time it takes to melt the contour, and the time required to disperse all the layers of powder outwards. [6]

A “hybrid production cell” may provide the best of both worlds. Using a CNC machine with cutting tools to produce simple geometries at high speed, and an additive subunit to produce the geometries that would otherwise be difficult or impossible for the CNC machine. A powder bed fusion machine may add material to a part previously machined from bar material by cutting action. The materials may be identical, similar to each other, or different. A bond or weld must be established between the machined and added components, posing some restrictions. A hybrid production cell like this may manufacture “almost anything”. [6]

Anisotropy

When a part is built up layer by layer, anisotropy may pose a problem. The material may not end up having the same mechanical properties in all directions. Using conventional production methods, anisotropy is less of a problem. This is often advantageous. Strength is more predictable, and the material is stronger.

Powder bed fusion is a method with low degree of anisotropy in the resulting product. The laser melts through the underlying, already fused layers in addition to the layer of powder, creating a reasonably uniform structure. [9]

2.1.3 Materials

The materials described in the following subchapter are some specific materials that might be considered for the current gripper project for Kongsberg Automotive, using available machines. These include the Concept Laser M2 Cusing machine at NTNU in Trondheim, a powder bed fusion machine manufacturing metal with good material properties. NTNU in Gjøvik has a EOS P395 powder bed fusion machine that works in different polymers. Tronrud engineering has an EOSINT M 280, and Promet has an SLM 280HL. Both these machines can produce titanium alloys.

Aluminum alloy CL30AL

This is an aluminium alloy powder distributed by Consept laser for use in their additive manufacturing machines, containing between 10.5 and 13.5 percent silicon. This alloy corresponds alsi12 (a). The alloy is used for lightweight constructions in the automotive and aerospace companies with high dynamic loads. [7]

Aluminum alloy LPW-6061

Corresponding to DIN 3.3214. This contains from 0.15 to 0.40 percent copper, 0.8 to 1.2 percent magnesium, 0.4 to 0.8 percent silicon. This is a fairly common aluminium alloy, widely used in automobile and aerospace industries because of its versatile mechanical properties. It is easy to work and weld. Well suited for additive processes, since this basically is a welding operation. This is used in NTNU’s M2 Cusing machine. This can be cured in different ways giving it different properties.

Maraging steel CL50WS

Distributed by Concept Laser. (Corresponding to LBC werkzeugstahl 1.2709) This is a steel containing 4.5 to 5.2 percent molybdenum, 17 to 19 percent nickel, 0.8 to

1.2 percent titanium and from 8.5 to 10 percent cobalt. An alloy used in tools for casting and forging that requires uniform cooling and heat transfer characteristics. It is also used for mechanical components. [7]

titanium alloy CL41TI-ELI

This is a titanium alloy containing 5.5 to 6.5 percent aluminium and 3.5 to 4.5 percent vanadium. It corresponds ASTM F136-02a (ELI Grade 23) This is an alloy used for components in aerospace, motor sports equipment and medical implants. Concept laser states in its data sheet that this titanium is well suited for parts with internal cooling channels. This could make it well suited for a robot gripper bracket with internal pipes of compressed air or hydraulic fluid.

Titanium is expensive to produce. This is partly due to the higher unit price but mostly because of the large consumption of argon during the additive build. [7]

Polymer PA12

This is a polyamide that may be produced in NTNU Gjøvik's EOS P395 machine. This is a polymer that is stiff and strong. It has very consistent mechanical properties over time. These properties are well suited for a robot gripper bracket. It is, however, debatable whether the tensile strength is high enough. When the tensile strength is too low the material's volume becomes too large for a given load. In our example the gripper should build as narrowly as possible. The material may be relevant for prototyping, as the cost and build time is significantly lower than for metals.

According to the data sheet, this material is suitable for fully functional finished products of plastics in the highest quality. Because of the good mechanical properties it is often used to substitute injection molded parts. It also has a durable finish that makes it suitable in assemblies with moving parts. [8]

2.2 Design thinking

Many authors have attempted to integrate the seemingly chaos of product development into an understandable system. "Design thinking" from Berkeley and the Danish university Tjalve, "Work Design Thinking" taught at Stanford. In this thesis, the latter has been used as a product development guide.

Design thinking is a methodology for maximizing the probability of successful innovation in research and development processes.[11]

2.2.1 The four rules of design thinking

To highlight some of the important aspects in design thinking philosophy, four rules have been defined by Christoph Meinel and Larry Leifer:

- *The Human Rule: All Design Activity Is Ultimately Social in Nature*

  To make a technical problem satisfy a human need, it is important to focus on the human element.[11]

- *The Ambiguity Rule: Design Thinkers Must Preserve Ambiguity*

  There is no chance for "chance discovery" if there are many constraints, and the fear of failing is at hand. Innovation demands experimentation at the limits of our ability to control events, and the freedom to see things differently.[11]

- *The Re-design Rule: All Design Is Re-design*

  The human needs have been the same for thousands of years. Through time there have been many solutions to these problems. It is important to understand how these needs have been adressed in the past. Then we can try to estimate how these needs can be met in the future. [11]

- *The Tangibility Rule: Making Ideas Tangible Always Facilitates Communication*

  This rule is about how prototypes is a good way of communicating and understanding ideas.[11]

2.2.2 Design thinking methodology

The design thinking methodology is based on alternatively expanding and reducing the problem and solution space. See figure 2.6. Before contemplating a solution, an understanding of the problem should be established as well and completely as possible. This implies interacting and empathizing with the user as well as possible, observing the user up close, not just to theorize and imagine what you think is their problem. Put yourself in their shoes, and try to see the problem from their point of view. [11]

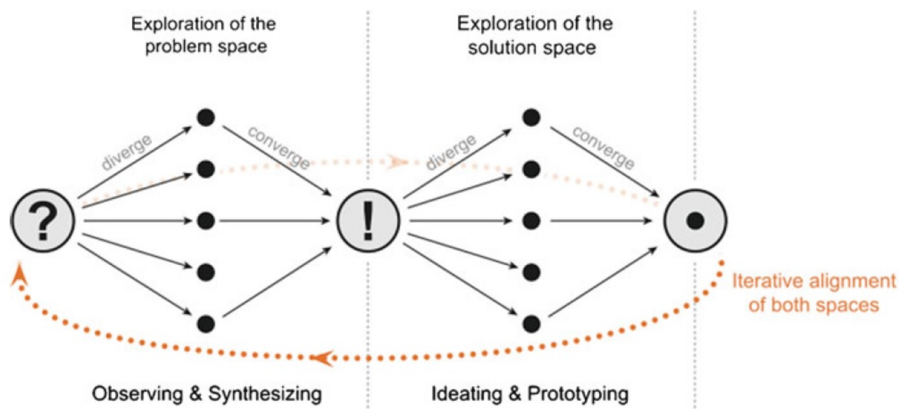


Figure 2.6: This figure illustrates the diverging and converging nature of the design thinking process. (Source:[11])

To explore the solution space, design thinking recommends that a great number of alternative ideas are explored in parallel, elaborating them with sketching and prototyping techniques. In this manner, ideas are being consciously transformed into tangible representations.[11]

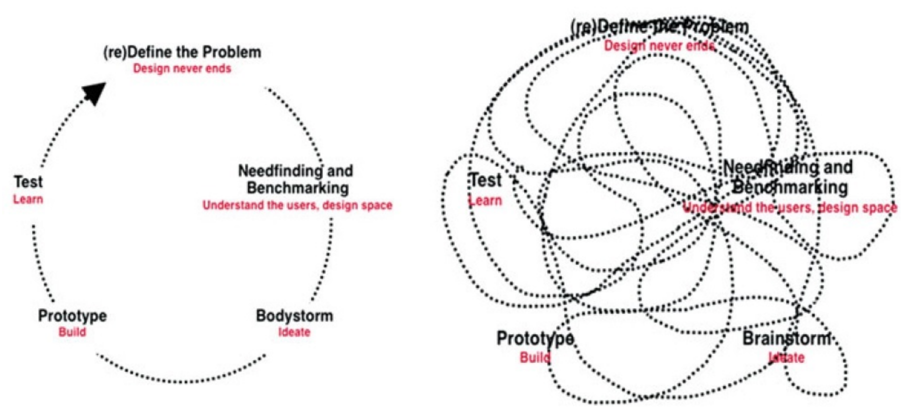


Figure 2.7: The left figure shows how design thinking works in theory. The right figure is closer to reality. (Source: [11])

Real life product development situations may seem chaotic. Experience shows that the end justifies the means. It Therefore is important to be flexible and adapt. See figure 2.7.

Chapter 3

Method

This is a step by step explanation of what was done to achieve the results in this thesis. These are presented in the next chapter named results.

3.1 Developing a product

After thorough research and getting to the root of the users problem it is time to start thinking about solutions. Which product can solve the problem in the best way possible. To get the absolute best product it is important to visit a lot of different ideas.

3.1.1 Brainstorming

Brainstorming is a good way of getting many possible ideas on the table. This is an important tool for maximizing the probability that a good solution is among those who are being considered. It is important to know the needs of the user and fully understand the problem before starting to think about solutions. If not, the foundation of all further work will be bad and future solutions is probably not as good as they could have been.

For Kongsberg Automotive's robot gripper problem many ideas was mentioned during an initial brainstorming process. In the following the most important are explained with simple sketches, see figure 3.1, 3.3, 3.9 and 3.6. for more see appendix A. Many of these solutions where similar. To narrow down the selection, the ideas were divided into categories based on their design:

- Traditional
- Traditional modular
- hexagon modular
- nontraditional

In the following these development lines will be summarized and evaluated:

Traditional

These solutions are modified versions of today's solution. Most of them may be manufactured with relatively low cost, and with traditional machining like CNC milling. See figures 3.1 and 3.2.The improvement possibilities are probably limited, and these are may not be best solutions in the performance category. They might be optimized further by using free form design and additive manufacturing.

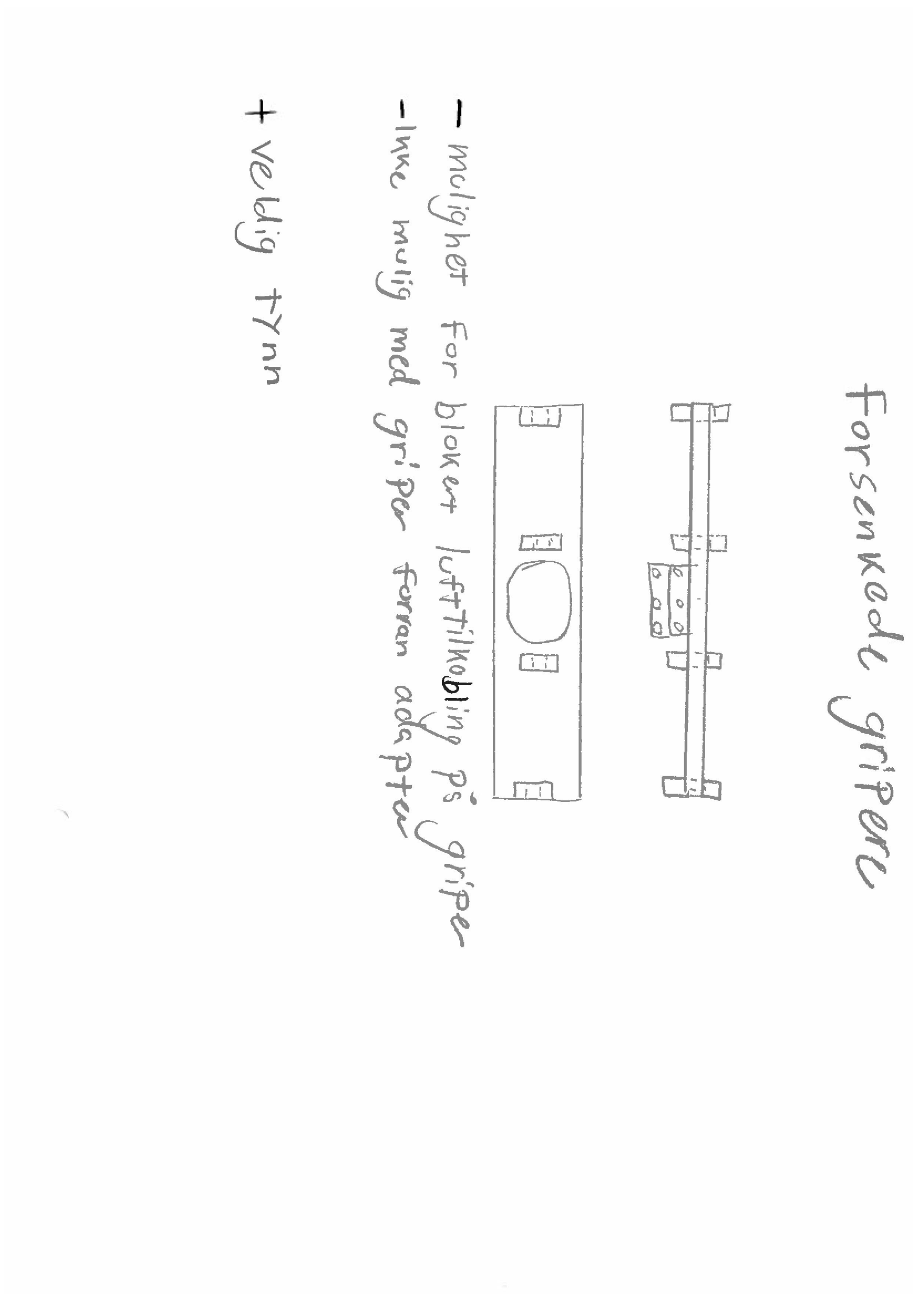


Figure 3.1: Solutions that are possible to manufacture with traditional techniques.

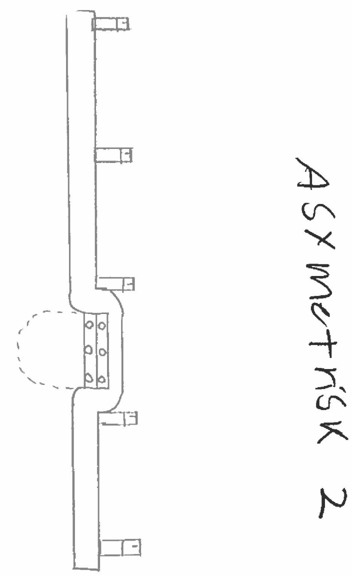


Figure 3.2: Solutions that are possible to manufacture with traditional techniques.

Traditional modular

This is a slightly different approach to the problem, based on creating a new gripper build principle. The solution is based a set of more or less standard parts that may be assembled differently for each task. Gripper assemblies for different molds may be made with the same set of parts. See figure 3.3 and 3.4. The modules involved may be manufactured with traditional techniques like milling and drilling.

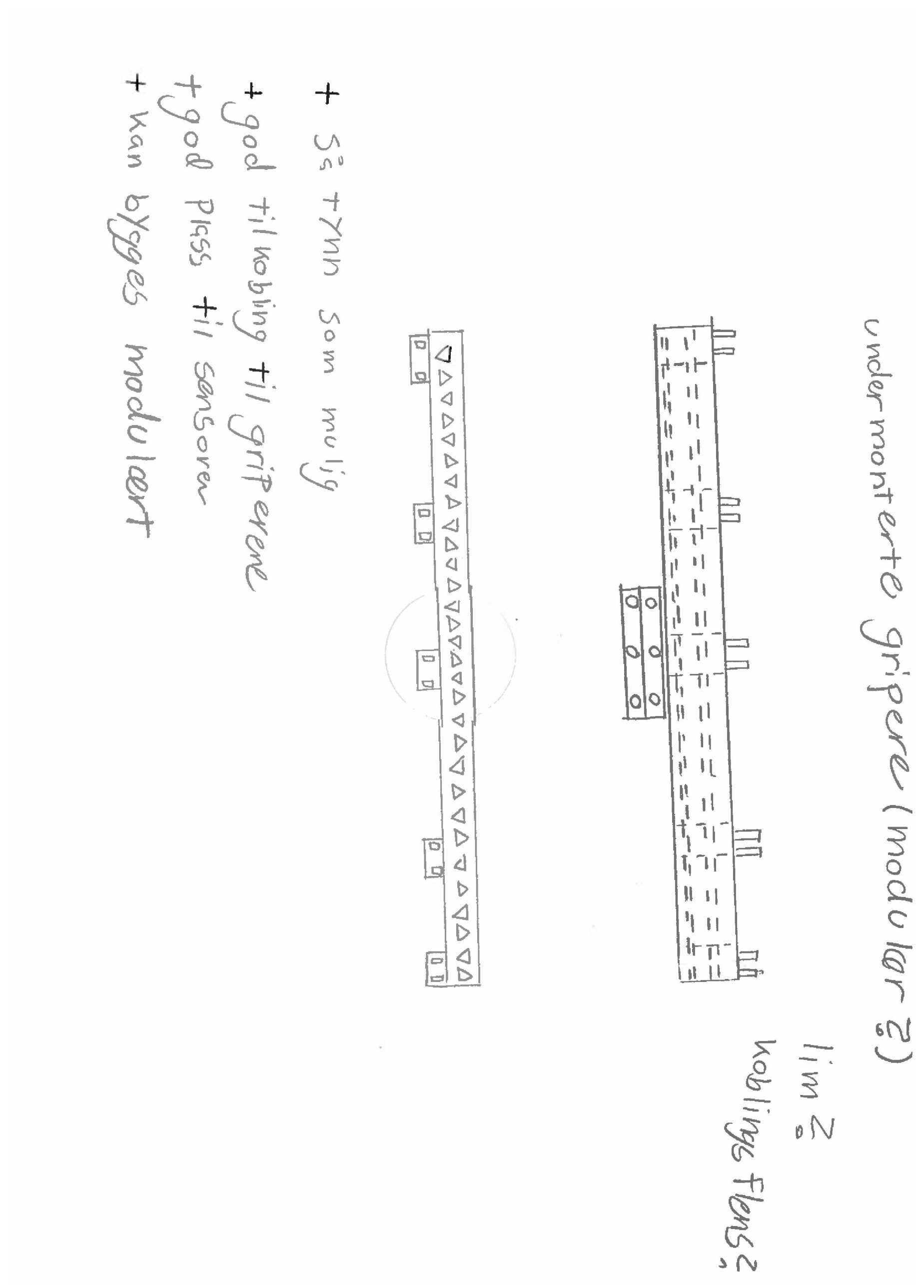


Figure 3.3: Modular solutions made with traditional manufacturing techniques.

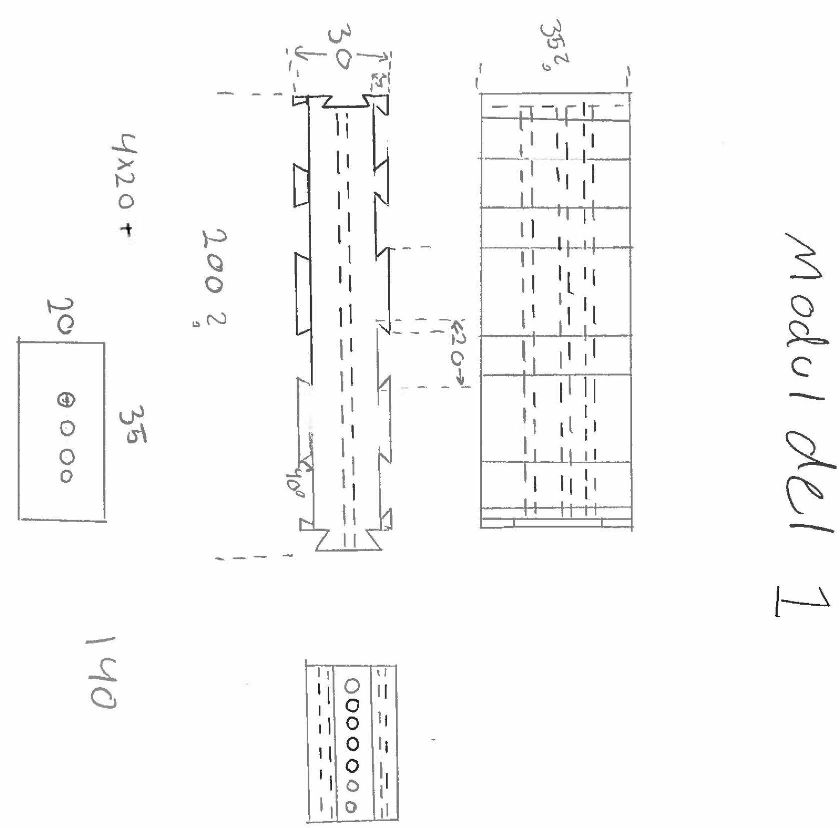
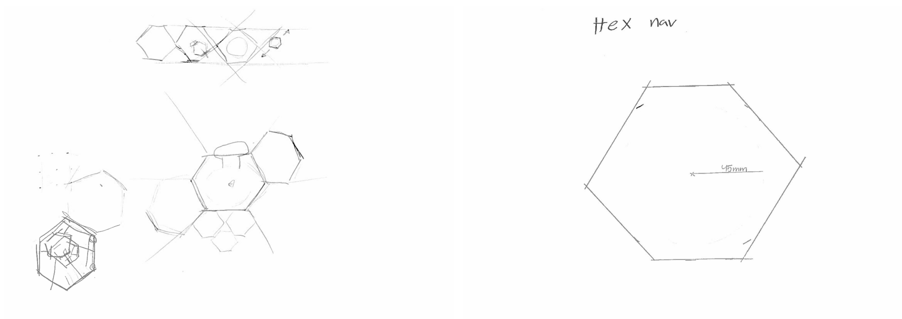


Figure 3.4: Modular solutions made with traditional manufacturing techniques.

Hexagonal modules

This solution is modular in the same way as the solution above, by having a set of parts that can be assembled in different ways. Here hexagonal building blocks are employed, creating a honeycomb grid pattern to cover the desired area. See figure 3.9.A hexagon pattern covers a large area with a minimum of material, reducing weight and improving stiffness per weight of the structure.



(a) (b)

Figure 3.5: Modular hexagon based solutions.

Nontraditional

This category includes solutions more difficult or impossible to produce with traditional machining equipment. Utilizing topology optimization software, shapes are automatically developed, based on available design volume, support points and forces. These solutions are often better suited for additive manufacturing than traditional cutting processes. The complex fluent shapes created are developed without hindsight to machinability in traditional manufacturing equipment. See figure 3.6 and 3.7.

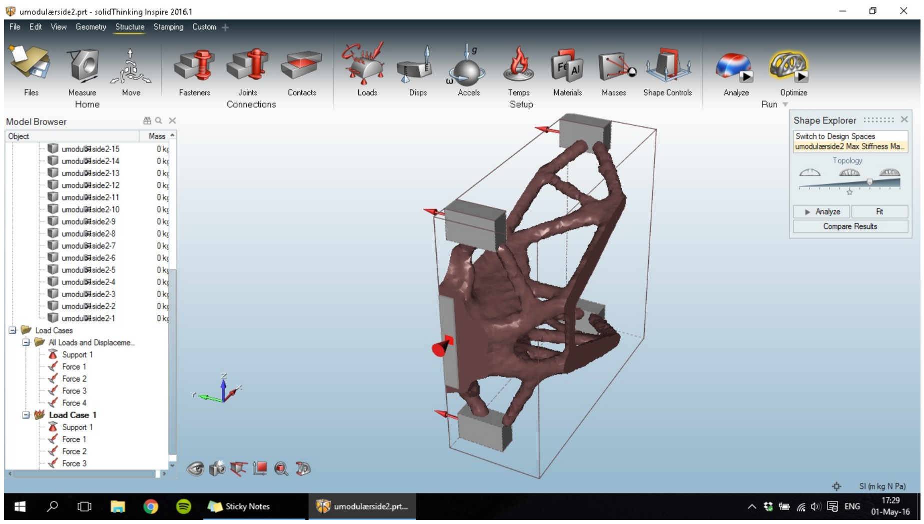


Figure 3.6: Solution examples that are intended to be produced by additive manufacturing.

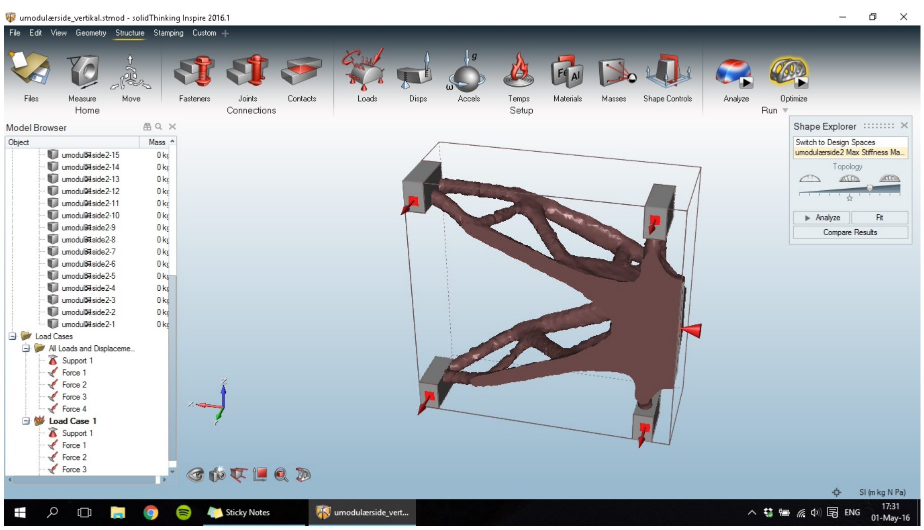


Figure 3.7: Solution examples that are intended to be produced by additive manufacturing.

3.1.2 Choosing the best ideas

After brainstorming and getting a large number of ideas and possibilities down on paper, it was time to start looking for the best idea among these. The end result might not be one of these propositions, but often a combination of multiple suggested ideas.

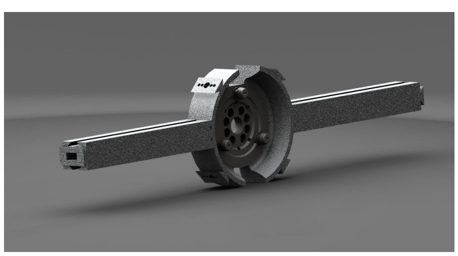
It is important to remember that this is a fluent, ever changing process. It is always possible to jump back and forth between the different stages, and if a new and better idea appears late in the process, or a solution does not work, the direction is altered based on the new knowledge. See figure 2.7 in the chapter: Theory.

During the development process, in a conversation with the author and Sture Sørli from Kongsberg Automotive's department for product development, it was decided to continue with the idea of a modular gripper system. The enticing factor was the ability to implement the solution on different production lines without the need for designing new parts every time. Also to be able to disassemble an old gripper system to reuse the parts on new systems. This gives more room for designing a system with more expensive parts because the parts will have a longer lifespan.

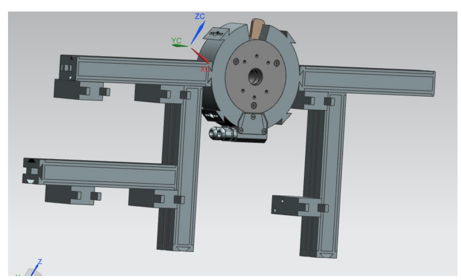
3.1.3 Further development

To get a better understanding of the previously developed designs and establish more detail solutions, details, the most promising ideas were developed further, using computer aided design tools (CAD). The tool used was NX 10, a high level CAD software package marketed by Siemens.

When the shapes where drawn we found several areas possible to improve. It gave a good basis for a new round of brainstorming and constructive criticism. See figures3.8 and 3.9.

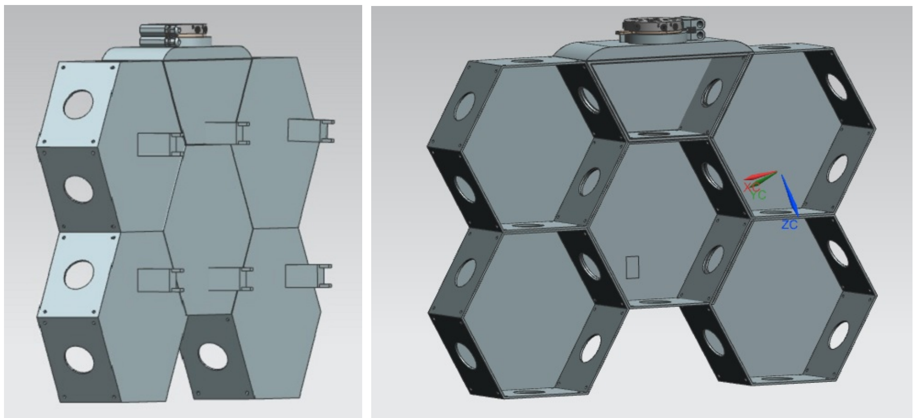


(a)



(b)

Figure 3.8: One of the ideas for a traditional, modular solution.



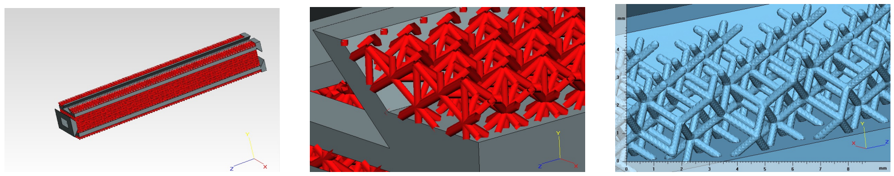
(a) (b)

Figure 3.9: Another solution that may be produced with traditional manufacturing methods in a modular, hexagon pattern.

3-Matic by Materialise

One way to improve stiffness to weight ratio is to use a design feature commonly called lattice structure. This is a grid type structure consisting of rods or beams that mainly are subject to pressure and tension loads, with reduced or no shear and torque loads. This is often referred to as a “truss structure” in two dimensions and “space frame” in three dimensions. The structural stability per weight unit is high if used correctly.

When large lattice structures are analysed numerically, exponentially large amount of computer resources are required. Designated software is preferred. A software system used to create and analyse lattice structures is 3-Matic by Materialise (www.materialise.com). This is a software developed specifically with additive manufacturing in mind. It incorporates multiple additive production specific functions, and 3-matic may be used create a wide variety of different lattice structures. It is also possible to create user defined unit cells to build a custom structure archive. NTNU Trondheim and NTNU Gjøvik have 2 floating licenses each of this software. We used it for some of the idea developments in this project, in an attempt to improve some of our solutions 3.10.



(a) Overview of a part.

(b) Enlarged image of the lattice structure

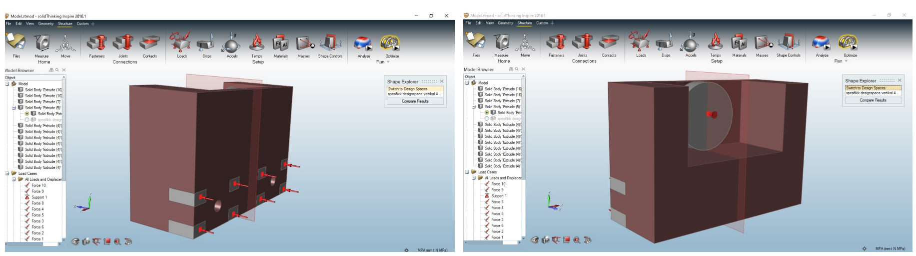
(c) The lattice structure has been converted to STL and merged with the solid walls. In this state it is ready for additive build.

Figure 3.10: These images show how 3-matic may create lightweight lattice structures.

3.2 Topology optimization

Topology optimization is a computer based method for creating a geometry, based on the loads it is subjected to. The optimization is based on iterative FEM analysis. The program runs many consecutive FEM analyses with minor alterations. Basically, the software keeps the version with the best result and optimises this further until the best solution is reached. For more information on topology optimization see reference number [4].

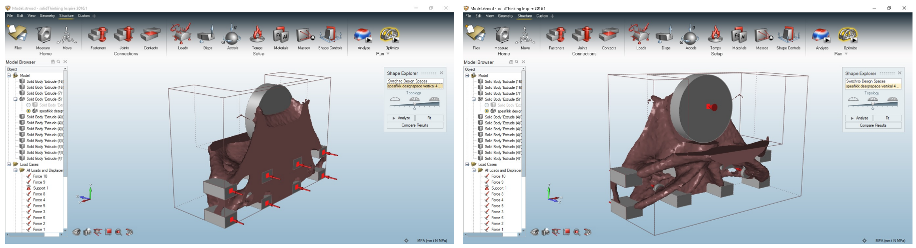
The topology software used in this thesis work is “Inspire” by Altair. Inspire is an intuitive interface window module into Optistruct. See figure 3.11 and 3.12. When Inspire interprets user input optimization problems, it exports the settings to Optistruct which runs the actual optimization. Inspire is an easy way to start experimenting with topology optimization but experienced users might eventually want to use Optistruct directly for better control of the optimization process.



(a)

(b)

Figure 3.11: A figure showing an example of Inspire setup.



(a) (b)

Figure 3.12: A figure showing an example of Inspire result.

3.3 Narrowing it down

As described in design thinking it is at this stage time to choose one of the solutions to continue the development work. After a meeting with Sture Sørli and Trond Lindmoen it was decided to continue work on the topology optimization based solution. The basis of this decision was that grippers made with this method will have a better performance than the modular solutions. They will have to be custom made for each injection molding tool. This is nevertheless a small part of the total development cost for each tool system. The production run for each tool is high. If a new gripper assembly can reduce downtime and increase the output it may well be worth the extra cost.

3.4 Final material

The choice of materials came down to either aluminium, steel or titanium. Some of the types of plastic may have a strength that are close to the values for aluminium, but high strength implies brittleness. The metals are much tougher.

It was important for Kongsberg Automotive that the grippers where reliable and durable. Titanium was a good candidate. It is strong and tough, but also difficult to work. In prototype work machinability is important, drilling some holes or milling a surface. For one of the adapters to pneumatic air hoses it was necessary to cut some internal threads. This would have been difficult in titanium.

Vegard Brøtan at SINTEF recommend steel. This could create a gripper with reduced volume in comparison with aluminum for a specific strength. Since the volume is the main contributor to build time and build cost in an additive manufacturing machine it would be more inexpensive to produce.

One aspect had not been previously reconsidered in detail. Kongsberg automotive pointed out that if (and when) the gripper crashes into the inside of the injection mold, it might cause damage to the mold surface. This problem would be significantly reduced with aluminium structures. The molds are costly and time consuming to repair so this was an important point. After this discussion we decided to aim for an aluminium structure.

3.5 Early prototype

After the design concept and choice of material it was time to make a functioning prototype for a specific injection molding tool. The tool chosen was for producing hollow 15mm diameter cylinders with a collar on one side. See figure 3.13 for an image of the part, and figure 3.14 for an image of the tool. These parts are used in one of Kongsberg Automotive's fluid connectors.

Figure 3.13: This it the part produced by the injection molding tool. This is the part that the gripper is going to extract.

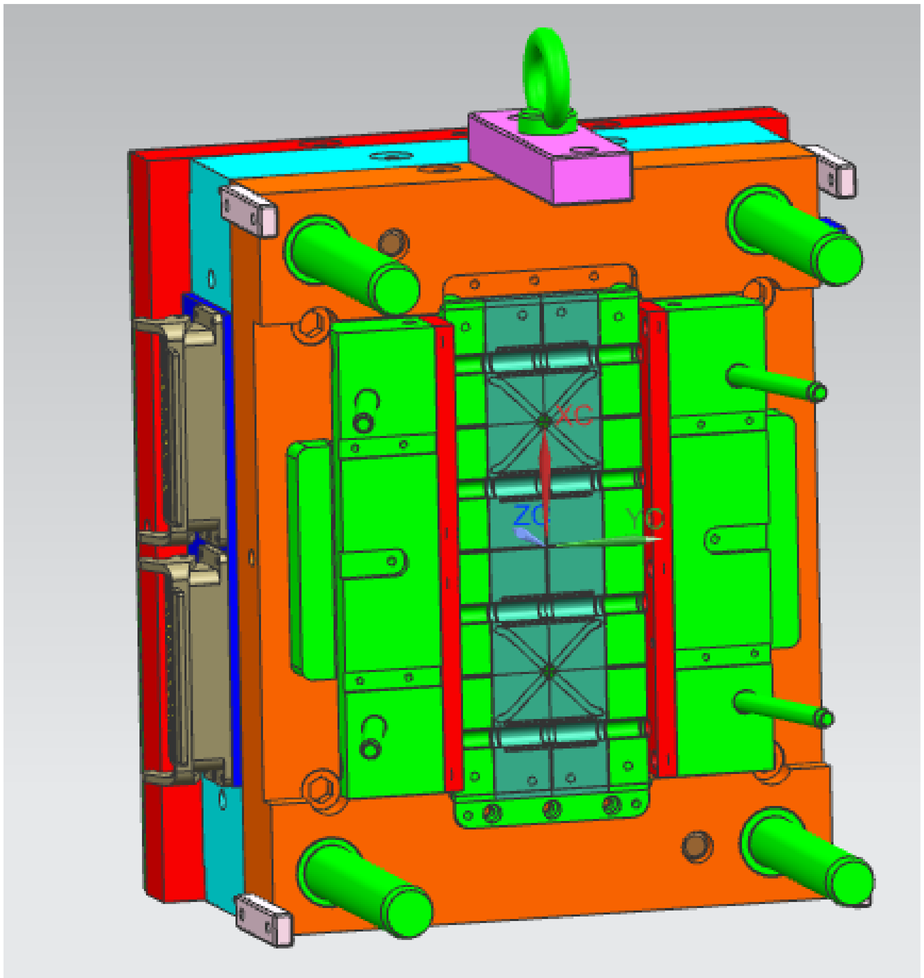


Figure 3.14: This is a CAD drawing of the inside of the injection molding tool, showing the environment in which the gripper operates. There are two rows of four parts, eight in total to extract from the mold. (Source: Sture Sørli, Kongsberg Automotive Raufoss)

By using Inspire, the first basic shapes of a functioning prototype was developed. See figures 3.15 and 3.16.

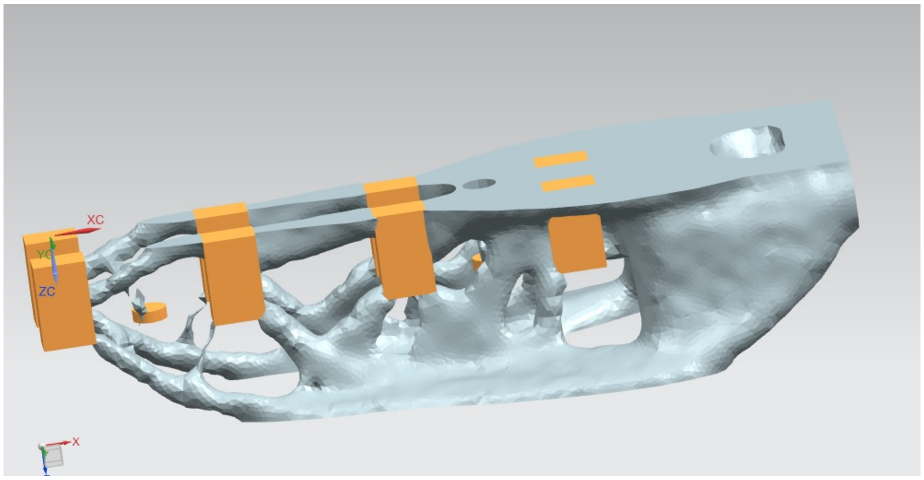


Figure 3.15: The resulting model from Inspire loaded into NX.

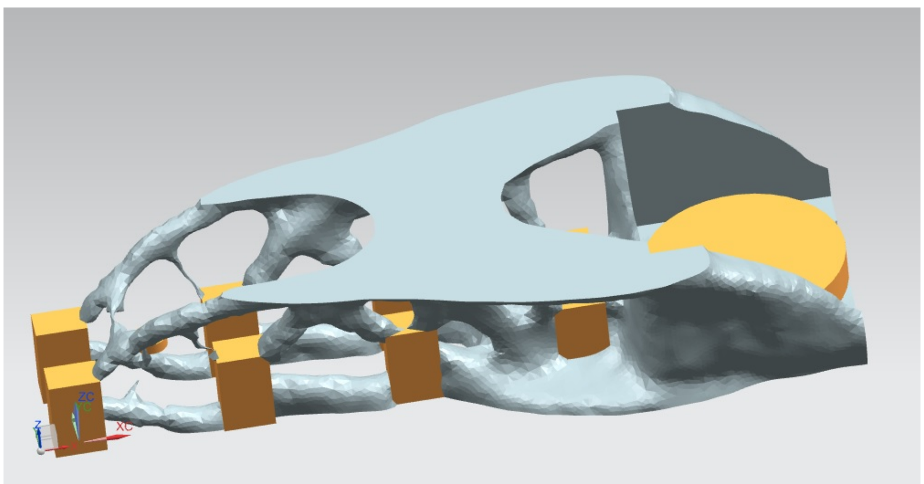


Figure 3.16: The resulting model from Inspire loaded into NX.

These solutions shown in figures 3.15 and 3.16 were simplified first runs, and had a low resolution surface. This was later improved, using the clean-up tools found in 3-matic. These tools worked well, and the surface of the part was considerably smoother.

A problem was encountered when transferring the part to NX. 3-matic has a exporting tool named cad-link. This enables the user to export the parts as “.step“or “.iges“ -files. These are commonly used CAD formats, and may be opened by NX. But when NX attempted to open these files they appeared as incomplete shells with large sections missing. Some time was spent trying to overcome this obstacle. Eventually we worked around the problem, and attempted to continue using the low resolution model. The result can be viewed in the figures 3.17 and 3.18.

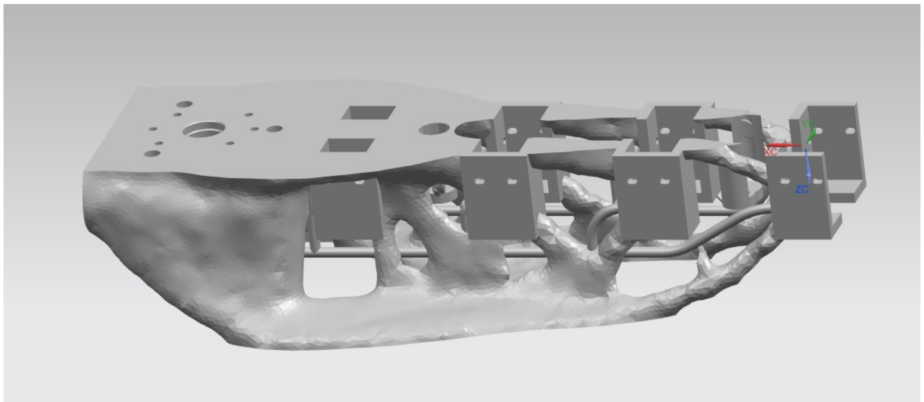


Figure 3.17: This figure shows the first draft of the part. The surface was still coarse from the topology optimization.

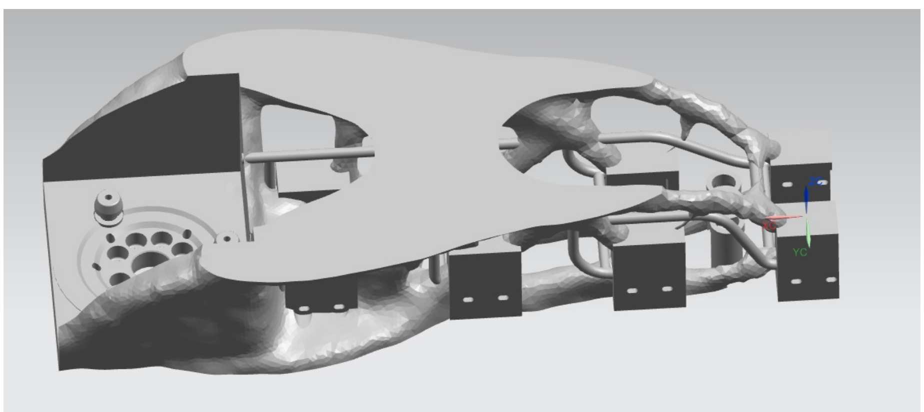


Figure 3.18: Backside of the first draft of the model. Still coarse surface from the topology optimization process.

After some work on this model it was decided that it was not good enough and that a new model should be drawn in NX using the optimized, but course model as a guide. This went reasonably well. Some of the proportions might have been imprecise, but a FEM analyses would reveal any stress points. These could then be altered or reinforced on the model. The first draft of the new model can be viewed in the figures 3.19 and 3.20.

The tool part of the WEMO adapter/ connector was integrated in the body of the gripper to reduce the depth of the assembly. See figure 3.21 for more information about the adapter. Channels and tubing for pneumatic pressure to the actuators were also included in the frame proper. This solution merges the adapter into the gripper since this eliminates the connection of the tubes to the adapter.

To eliminate as many hoses as possible it was decided to make an o-ring seal groove for the pneumatic actuators. This allows these to be installed without having to thread any hose into the connecting holes. See appendix B for more information on the actuators. See figure 3.22 for more information on the mounting of the actuators.

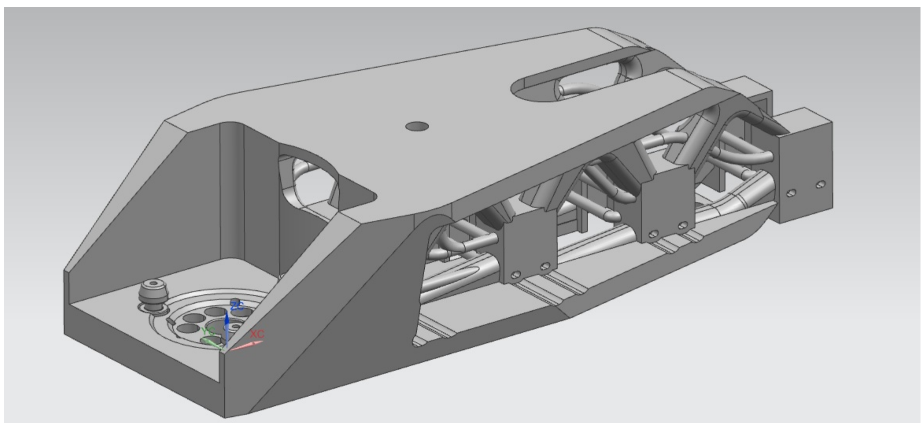


Figure 3.19: This is the model created from scratch using the topology optimized model as a guide.

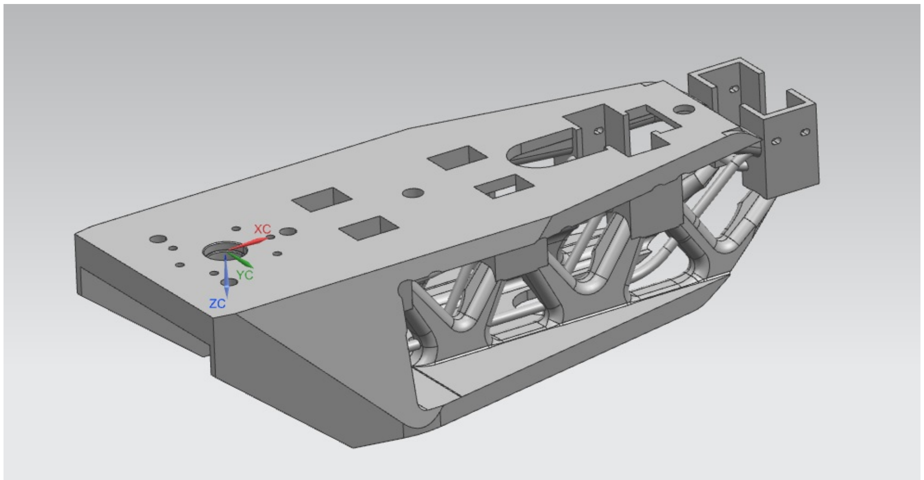
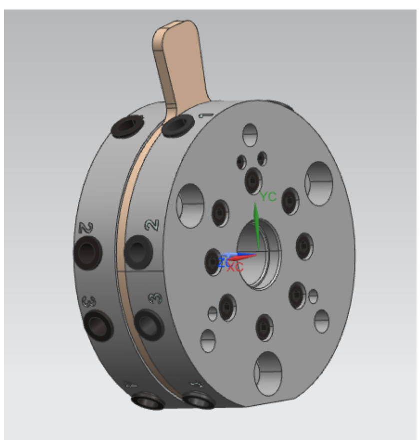
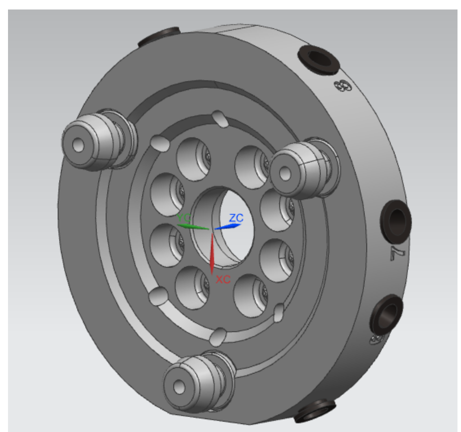


Figure 3.20: The rear side of the model created with the topology optimized figure as a guide



(a) Figure of the two halves of the adapter connected to each other. Pneumatic hoses connects to the black holes on the sides.



(b) Figure of the tool half of the adapter

Figure 3.21: Inspire setup. (Source: WEMO)

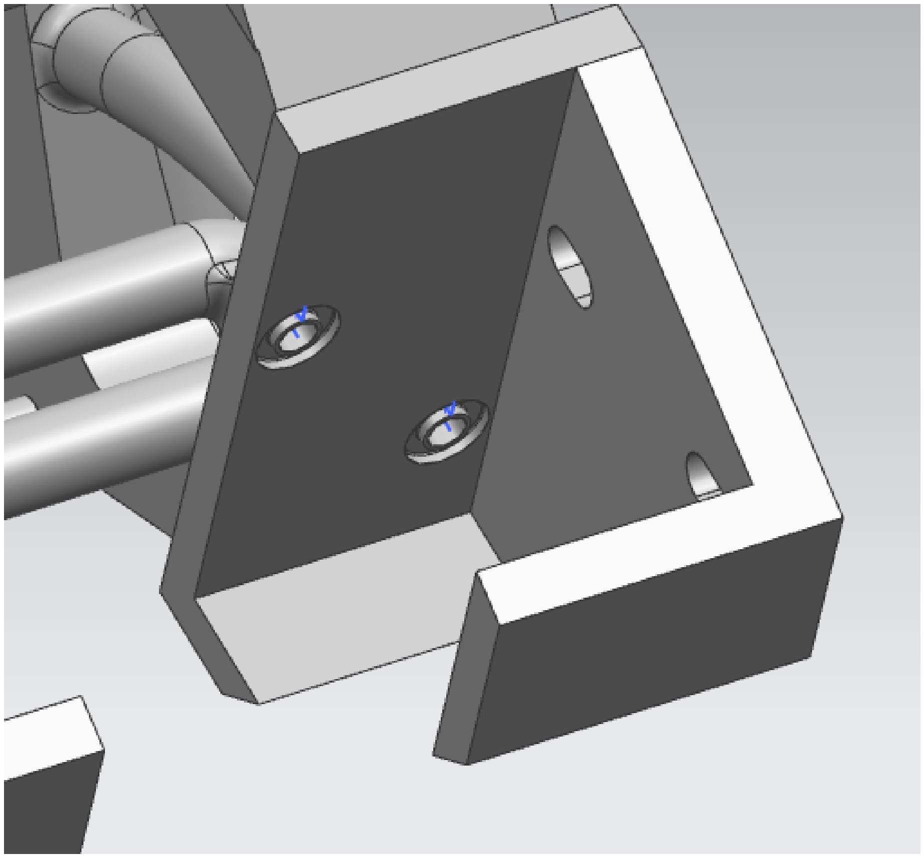


Figure 3.22: This figure shows in detail the connecting surface between the gripper and the pneumatic actuator. An o-ring is going to sit in the indentation, and seals against a flat surface on the actuator.

After further input from Sture and Trond at Kongsberg Automotive, some alterations and additions were made. More room was made behind the suction cups for the flues. These each have an air hose attached to the rear end. The hose should be able to move freely as the suction cup springs back. The model was also opened up in the back to make room for the rack on the back of the robot. See figure 3.23 and 3.24. The resulting changes may be seen in figure 3.25.

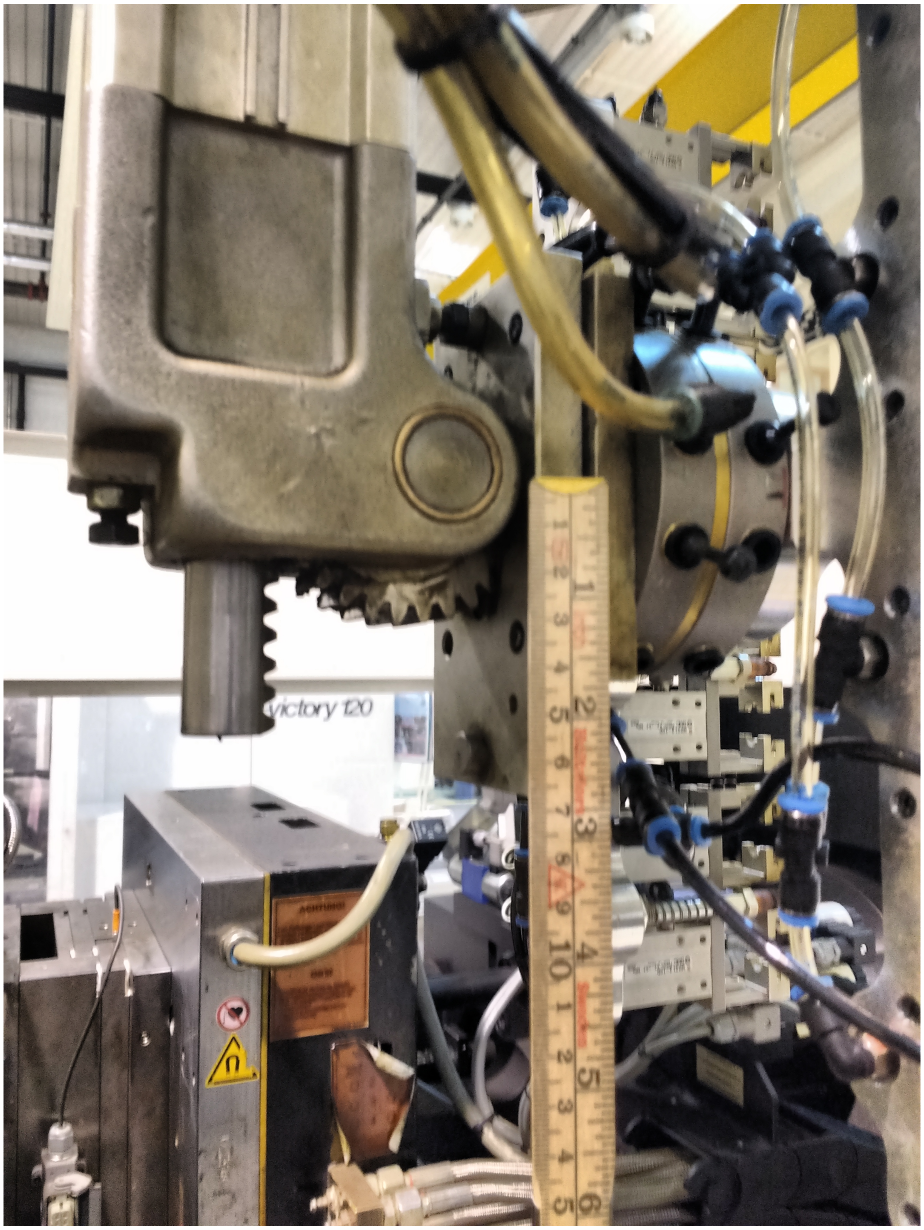


Figure 3.23: This figure shows the part of the robot arm attaching to the adapter on the gripper, as well as the rack.

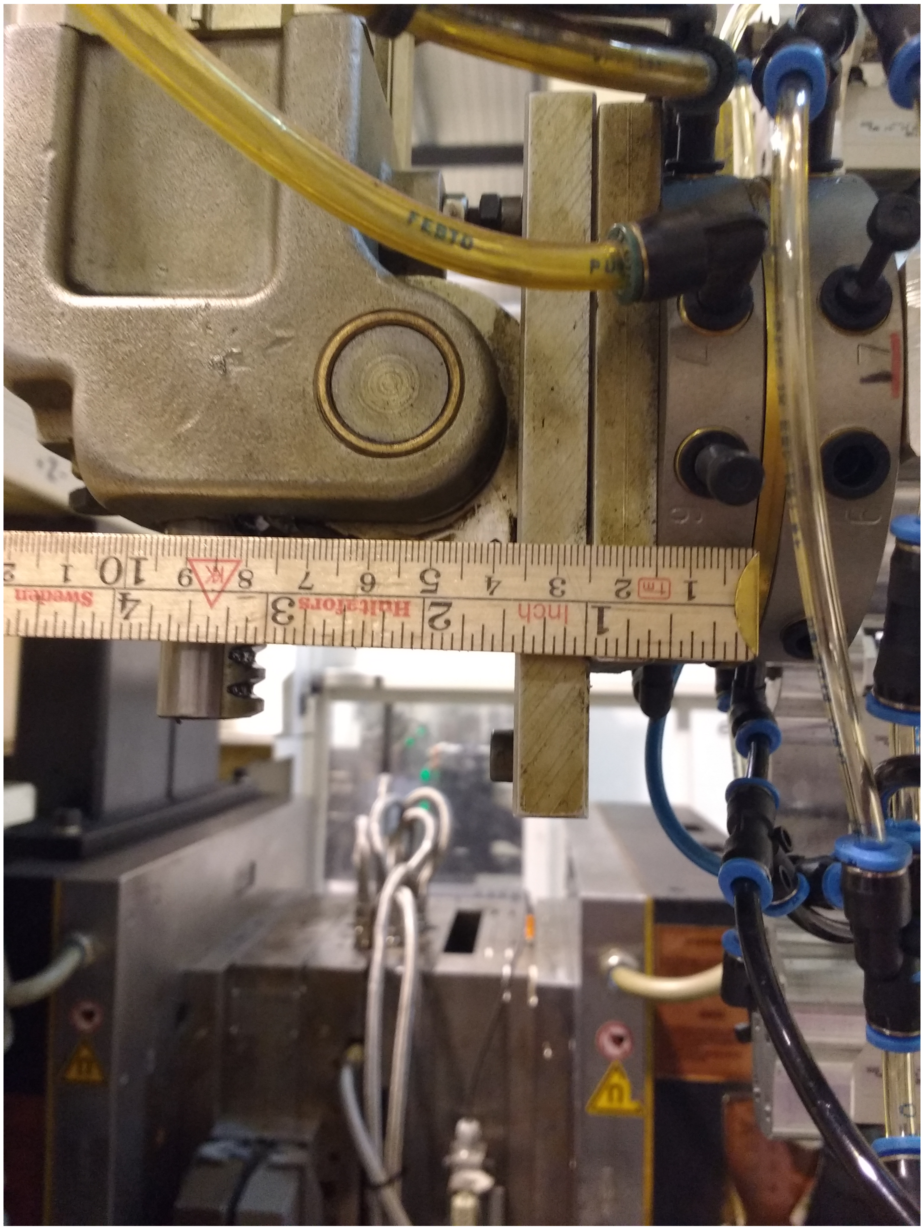


Figure 3.24: This figure shows how the robot attaches to the quick connect adapter on the right.

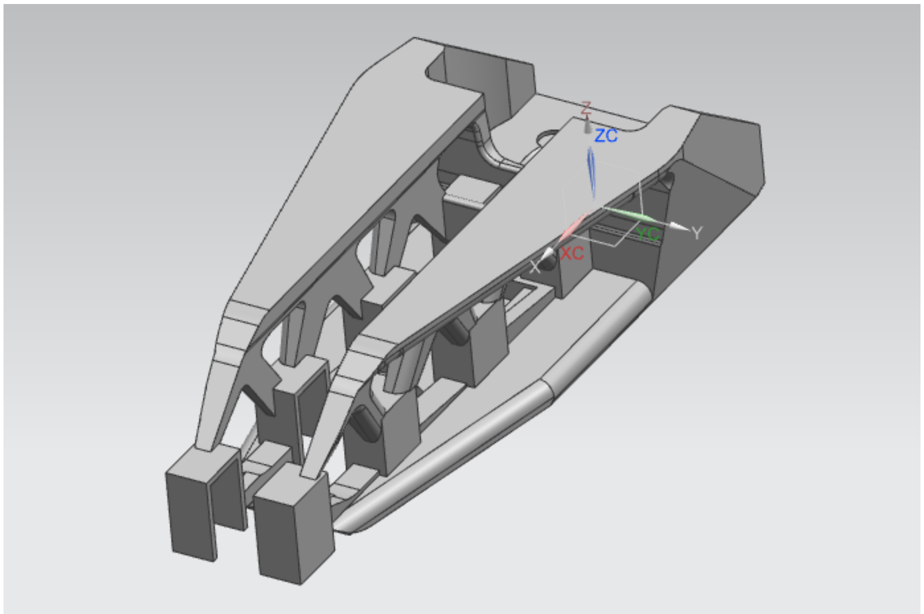


Figure 3.25: This figure shows how the back of the model was opened up to accommodate uninterrupted movement of the suction cups and the rack on the robot.

3.6 FEM analysis

One way to test the strength and stiffness of a geometic shape is to use FEM (final element method) analysis. This is a computer based method for viewing the effects of different loads on a structure or geometry. In this thesis “ANSYS Structural” was used. This is a user friendly simulation software package that contain different modules. These are designated varying physical situations. Some analyse fluid flow, some are to be used for structural loads as the one used in this chase.

The results of these analyses were the basis of some minor changes to the model, and were used to check that late changes to the model did not weaken the part unnecessary. See figure 3.26.The forces applied in this simulation was 10N to each of the eight pneumatic actuators, and to a fixed support at the adapter surface. This simulation was the background for a minor change. See figure 3.27.

A new analysis was conducted. See figure 3.28. This result was improved, indicated by reduced deformations in the figure. The exaggerations of the deformations are proportional in the two simulations.

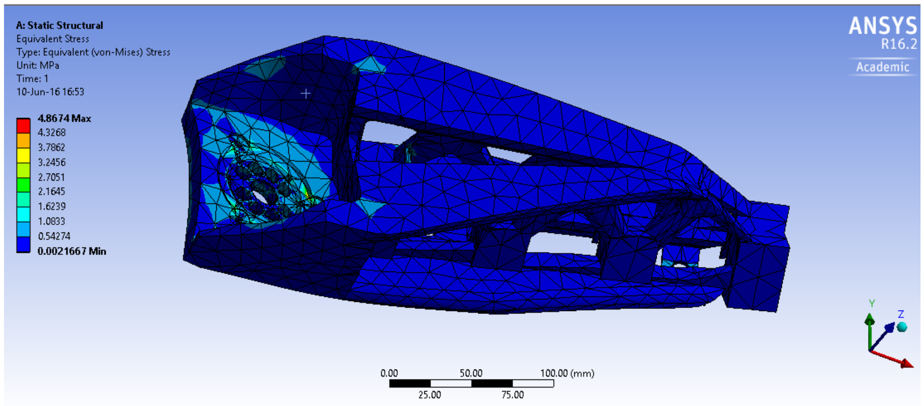


Figure 3.26: This figure shows (exaggerated) how the current part will deform under load. In this model some structural details, like the pipes, have been removed to reduce the complexity of the simulation to get within the complexity limit set by ANSYS for their academic license.

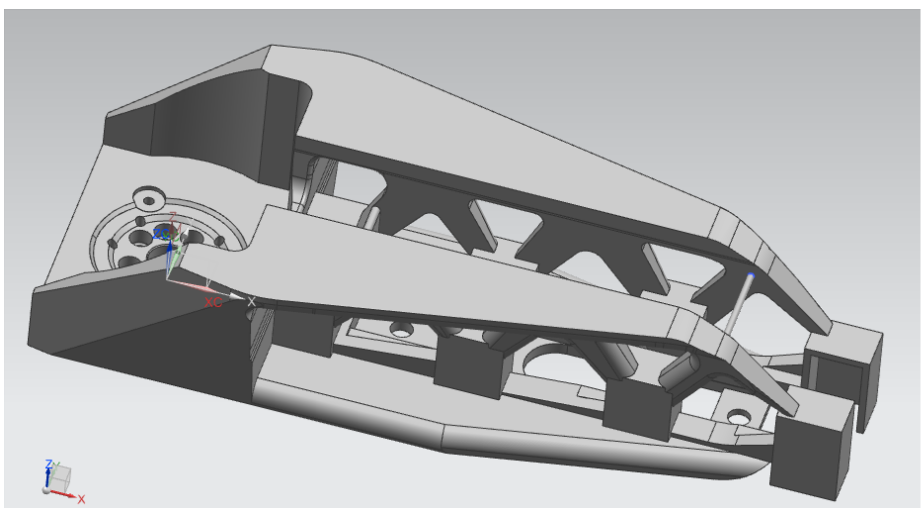


Figure 3.27: A rod was added to the model after reviewing the analysis shown in 3.26.

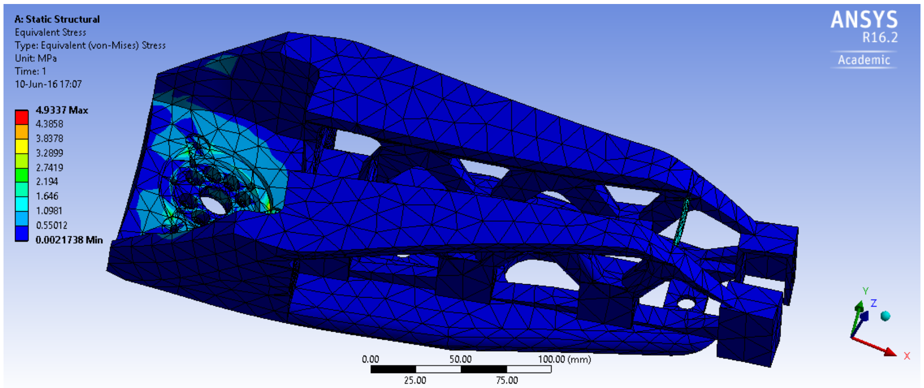


Figure 3.28: This figure shows how the addition of a rod altered the deformation of the model from 3.26. The deformation in this image is also exaggerated.

3.7 Production methods

This topology optimized design is usually well suited for additive manufacturing, as was our plan from the start of the project. There however several different methods of additive manufacturing that could create a satisfactory result. The process and the material are partially linked because of the limited number of available materials for each process. Powder bed fusion and directed energy deposition may both produce parts in similar steel alloys. We had already decided to make the gripper in aluminium, the challenge was which process to choose. Because of the time constraints in this thesis, the choice fell on the Concept Laser M2 cusing machine in NTNU in Trondheim. This also gives the added advantage to be able to observe the process directly, and be more involved in the build process.

3.8 Final revision of the model

The model would have to fit the build volume of this machine, with maximum dimensions 250mm x 250mm x 280mm in the x, y and z directions where the z-axis is vertical. This volume needs to include a build plate. The function of this plate is to anchor the part and support structure, and to maintain the rigidity of the part while it is being built. The plate is made of the same material as the part, in order to fuse as well as possible. In our case it would have to be 30mm thick. The machine operators also insist on a safety margin around the build plate. The usable build volume then is reduced to 245mm x 245mm x 220. The thickness of the build plate is subtracted twice, as it limits the travel both on the top and the bottom of the prism formed build volume. The size of the build needed some adjustments to fit, probably without reducing the stiffness or strength significantly. The final model can be seen in figure 4.1 and 4.2.

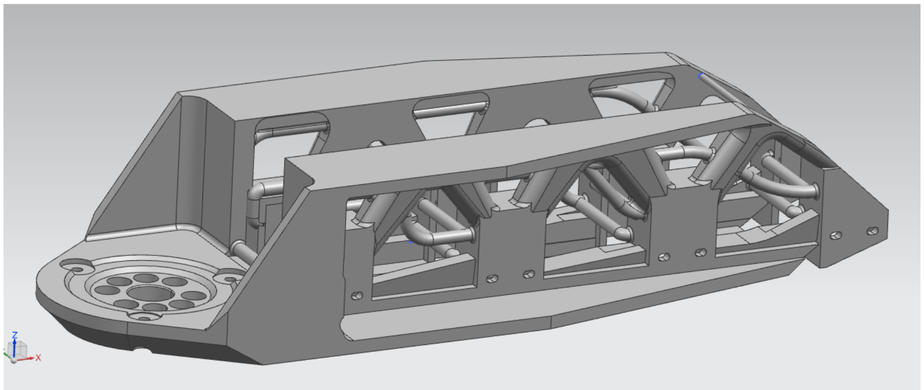


Figure 3.29: This figure shows how the length of the part has been reduced to fit in the build volume of NTNU's additive manufacturing machine.

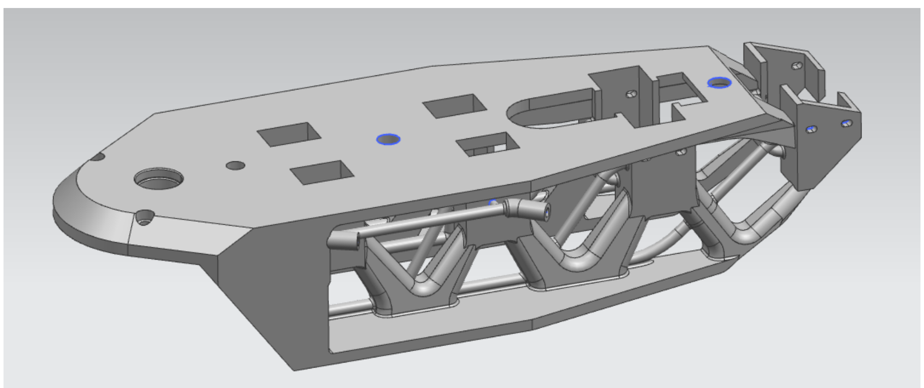


Figure 3.30: This figure shows how the length and outer size of the part has been reduced to fit in the build volume of NTNU's additive manufacturing machine.

3.9 Prototyping

Prototyping is a large component of design thinking. Errors and problems should be identified and remedied as early as possible. A minimum of time should be spent on work that is discarded later in the process. For the process to be as efficient as possible the first prototypes need to be quick to make, and to modify. This way more iterations are made, and more problems are discovered, in less time.[11]

Before creating the prototype in metal, there we made a small prototype in scale 1:3. This prototype revealed no obvious flaws or errors, but gave us a tactile understanding of how the part is going to look. This prototype was built using vat photo polymerization. This gives a good surface quality, which is important for a scaled down part.

After the scaled model the process of building the full size metal part started. The build time was estimated to 170 hours. This should have been a straight forward process.

The build was started on a Friday afternoon. On Monday morning some discrepancies in the build were discovered. The build was aborted. The part may be seen in the figure 3.31 and 3.32.

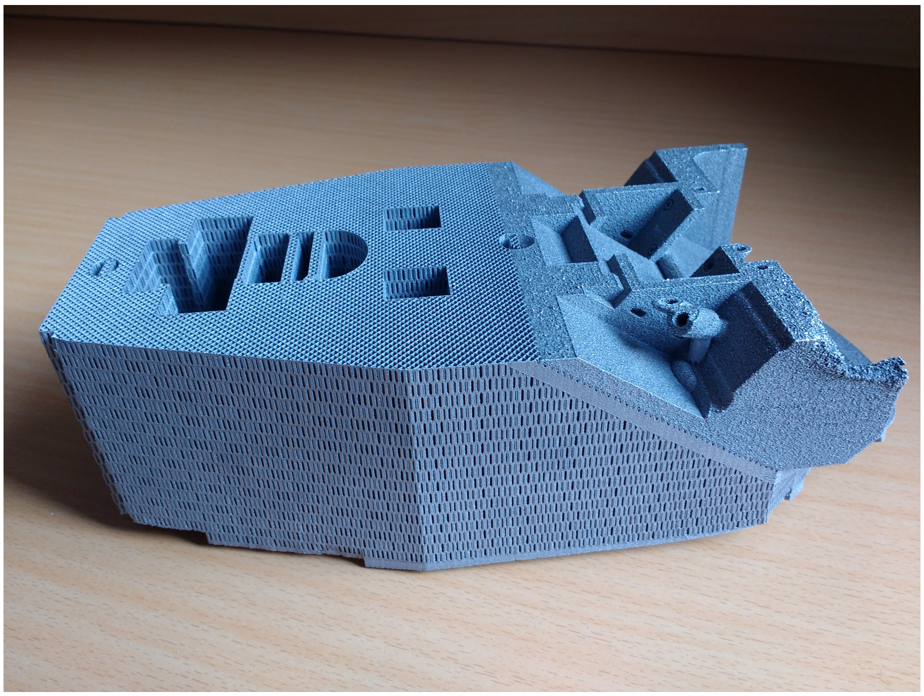


Figure 3.31: The aborted aluminium build

The build parameters were thought to be slightly off. These parameters vary significantly from build to build, and are established partly using experience and intuition. The power feed was suspected to be too low. This caused a pit to start growing into the part. When the part was removed it was also discovered that the it had deformed slightly, and some of the support structures had separated from the build plate.

For the next build the density of the support structure was increased which should help prevent excessive deformation

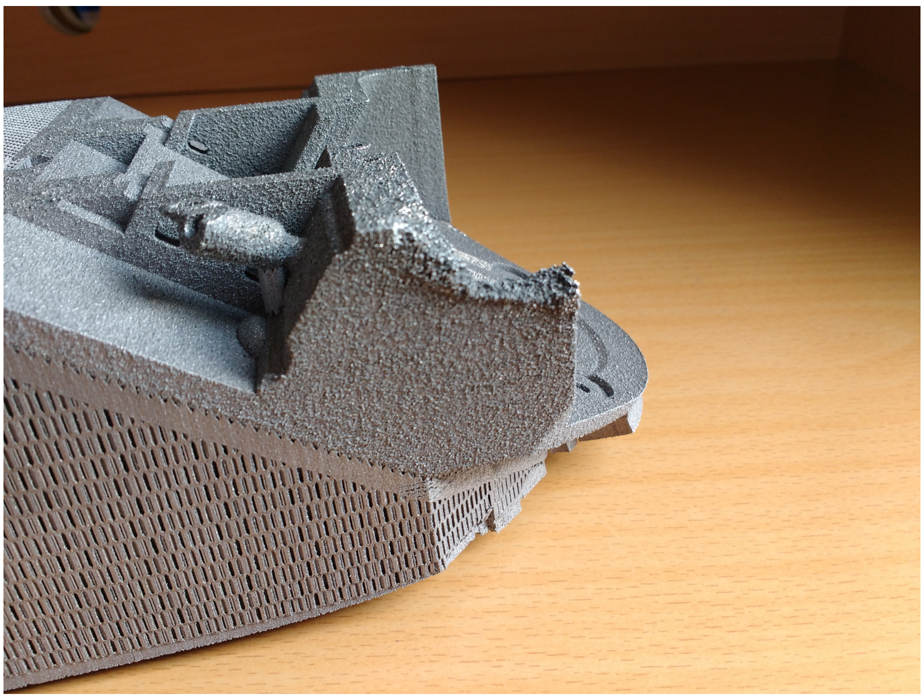


Figure 3.32: Close up of the section where a pit grew into the part from lack of powder.

Chapter 4

Results

4.1 Design Concept

Kongsberg Automotive Raufoss requested a design concept that could be the basis for multiple grippers for different injection molding tools. Our design concept is in this case interpreted as a method for designing new grippers. Every gripper design will be different depending on the limiting factors. These may be the shape of the injection molding tool, the shape and function of the robot, the tools attached to the gripper, and the forces the gripper is subjected to.

This thesis is using topology optimization in combination with FEM analysis software to create the design. This design concept will be referred to as topology optimized grippers.

The result from the topology optimization may be used directly after a cleanup in a suitable design software package. In our case the resulting topology was used as a guide to arrive at a basic set of shapes and dimensions, and the final design was made using manual input to the design software system. See chapter 3 for more information on the topology optimization process.

In our case the final design is then produced in aluminium by additive manufacturing. One of the requirements from Kongsberg Automotive was that the material of the gripper assembly should be softer than the material of the injection mold. It might still be possible to use softer steels, other aluminium alloys or polymers, or even to equip the frame with softer "bumpers" to avoid collision damage. If the design was too large, it may be split it into multiple parts and then joined by conventional techniques.

4.2 Gripper

The model that was created for this project is seen in the figures 4.1 and 4.2. For more detail the model of the final prototype is presented with this thesis on zip file in DAIM. The part has a volume of 0.507dm3. With a density of the aluminium alloy of 2.712kg/dm3 the resulting mass is about 1.3750kg. This is without pneumatic actuators, gripper fingers and the robot part of the gripper adapter.

The FEM analysis of the final gripper may be seen in figure 4.3 and 4.4.This analysis shows the stress distribution of the assembly subjected to a load of 10 Newton on each pneumatic actuator, the adapter surface being defined as a fixed support. We have not measured the actual forces the gripper is subjected to, they were said to be “pretty small”. The important part was to make the gripper as stiff as possible per unit weight. The yield point of the aluminium alloy used as given in the data sheet is between 170 and 220 MPa. (CL30AL [7]).

The maximum stress in this simulation was 5.8 MPa. According to tests carried out at NTNU the aluminium built additively showed characteristics as described by the manufacturer [13].

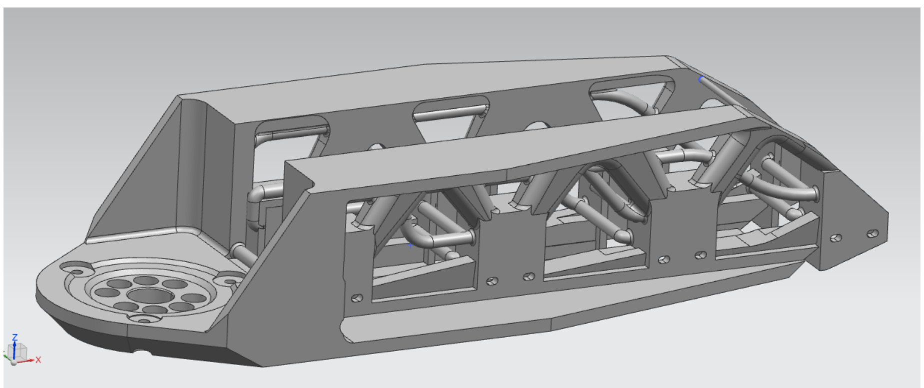


Figure 4.1: This figure shows the rear view of the model for the final prototype.

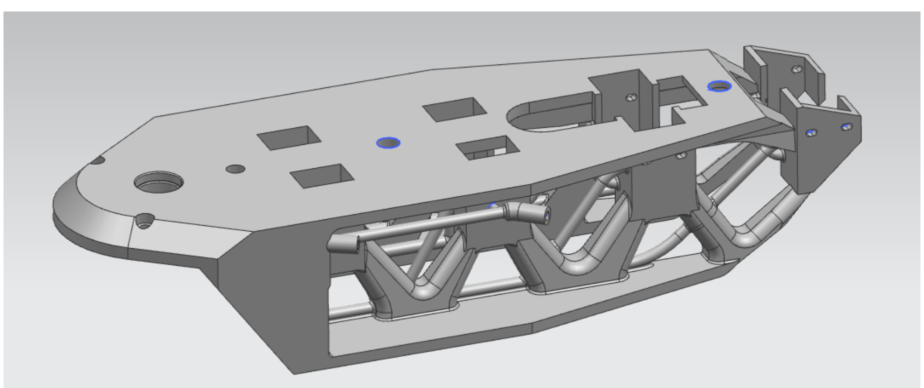


Figure 4.2: Same, front view.

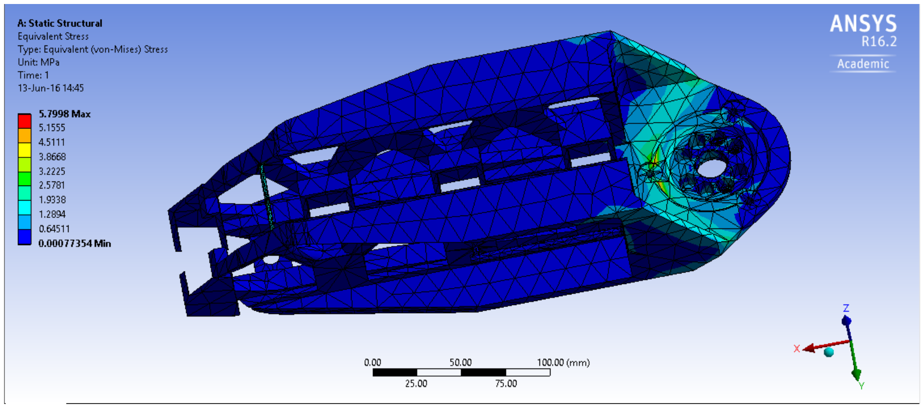


Figure 4.3: FEM analysis result of the final product with a load of 10 Newton on each pneumatic actuator.

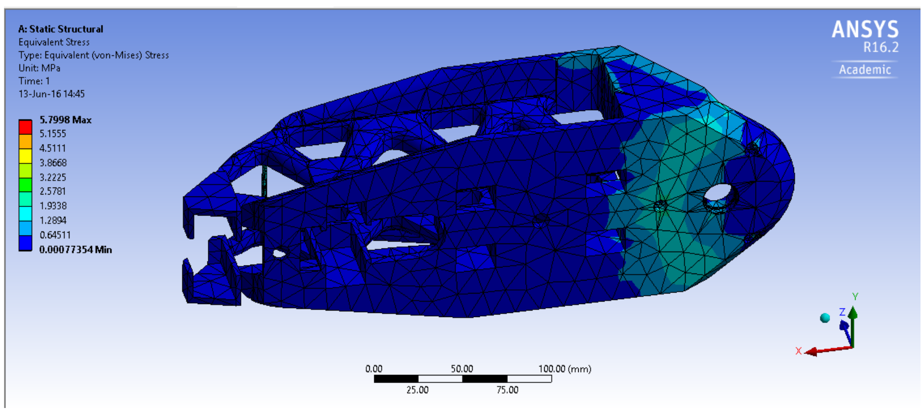


Figure 4.4: FEM analysis result with a load of 10 Newton on each actuator.

4.3 Prototype

Photos of the physical prototype can be seen in figures 4.5, 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11

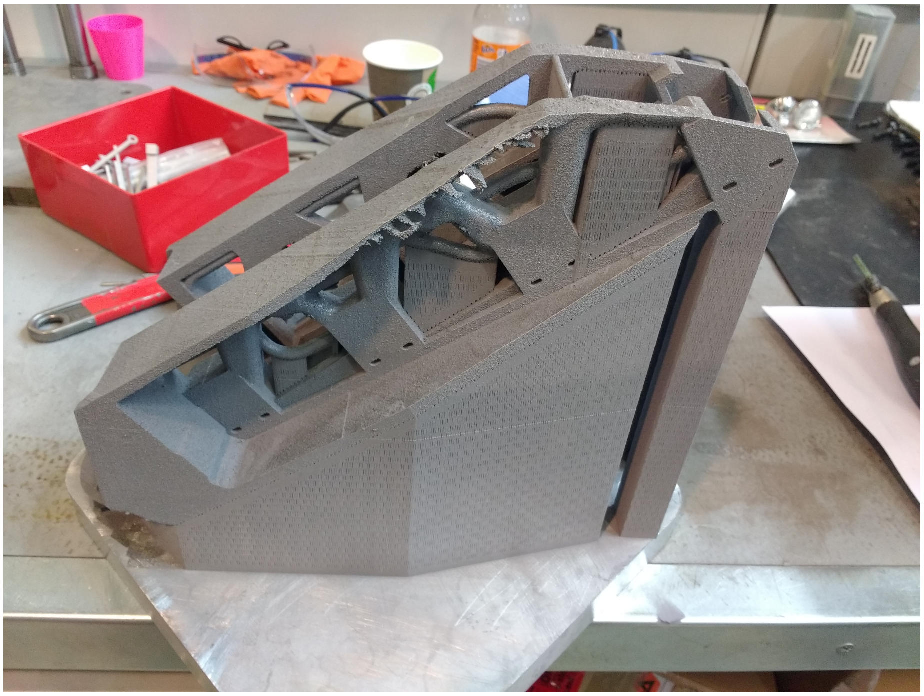


Figure 4.5: This figure shows an overview of the prototype as it was built with support structure and still anchored to the build plate.

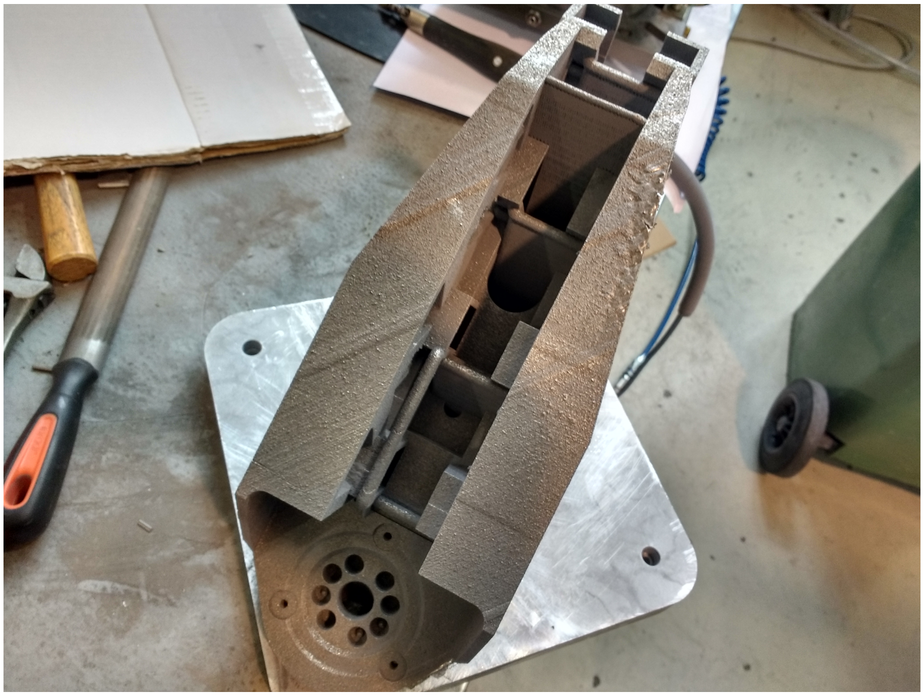


Figure 4.6: Rear view

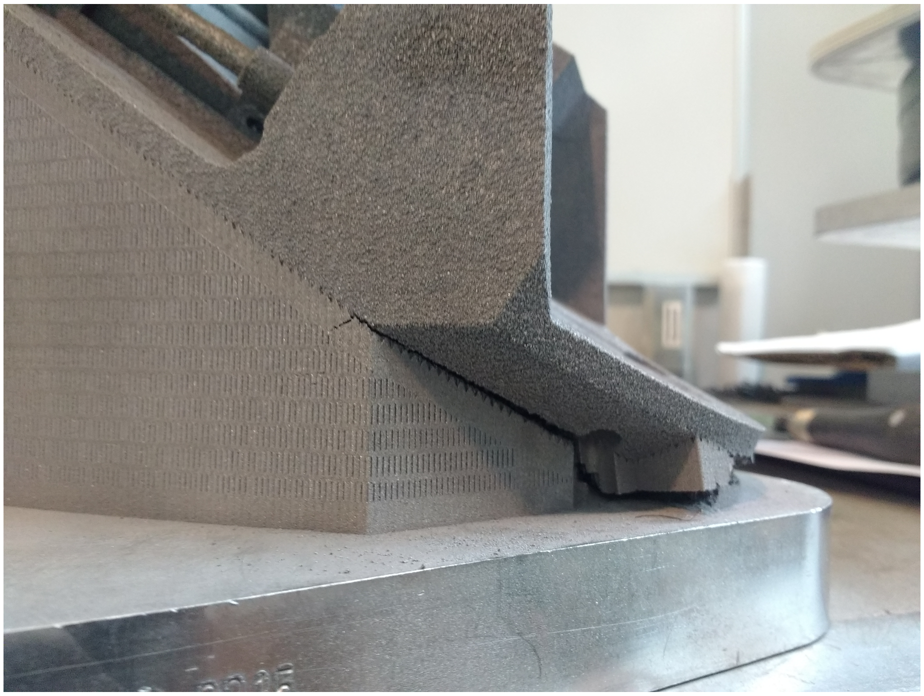


Figure 4.7: The internal stresses from the build caused the prototype to partially separate from the build plate and deform slightly.

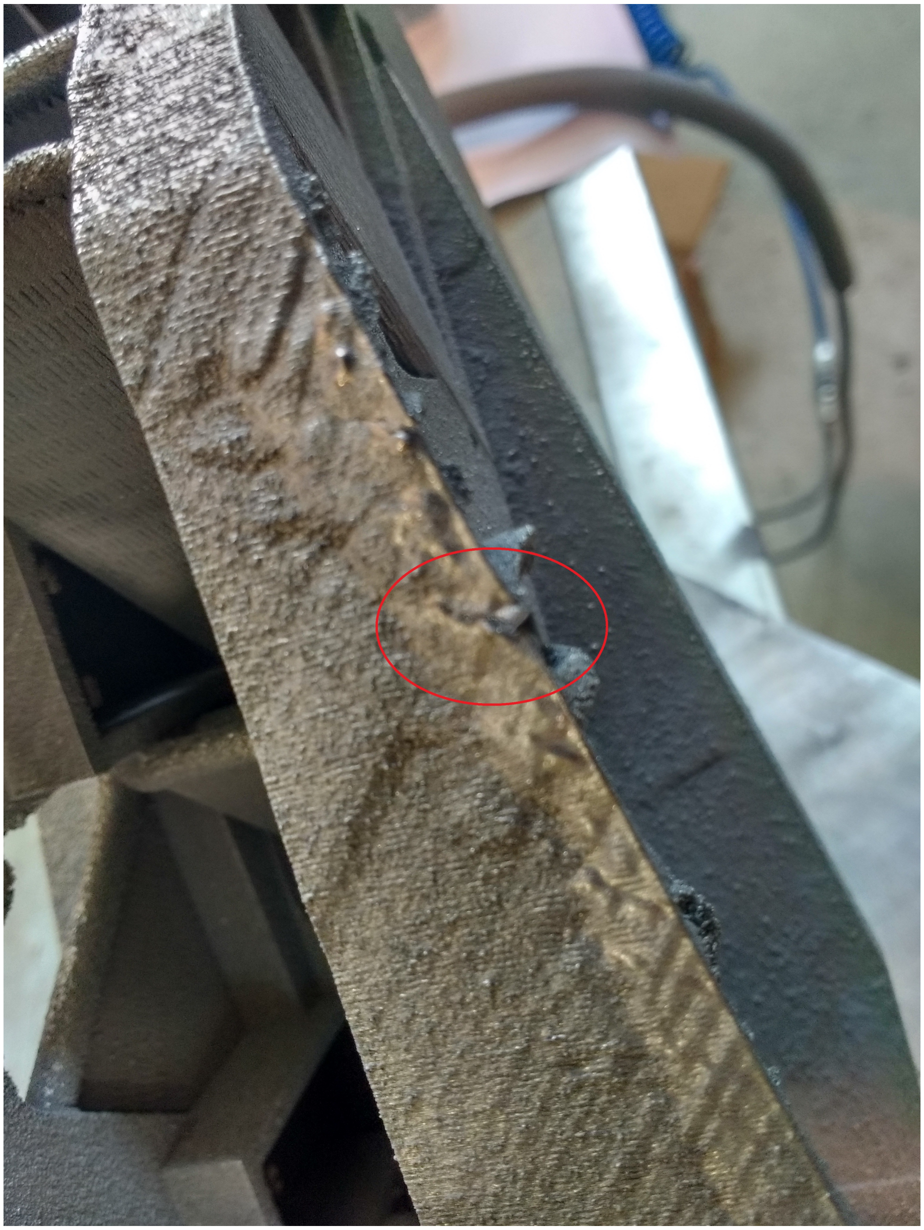


Figure 4.8: Surface roughness and a crack. (circled)

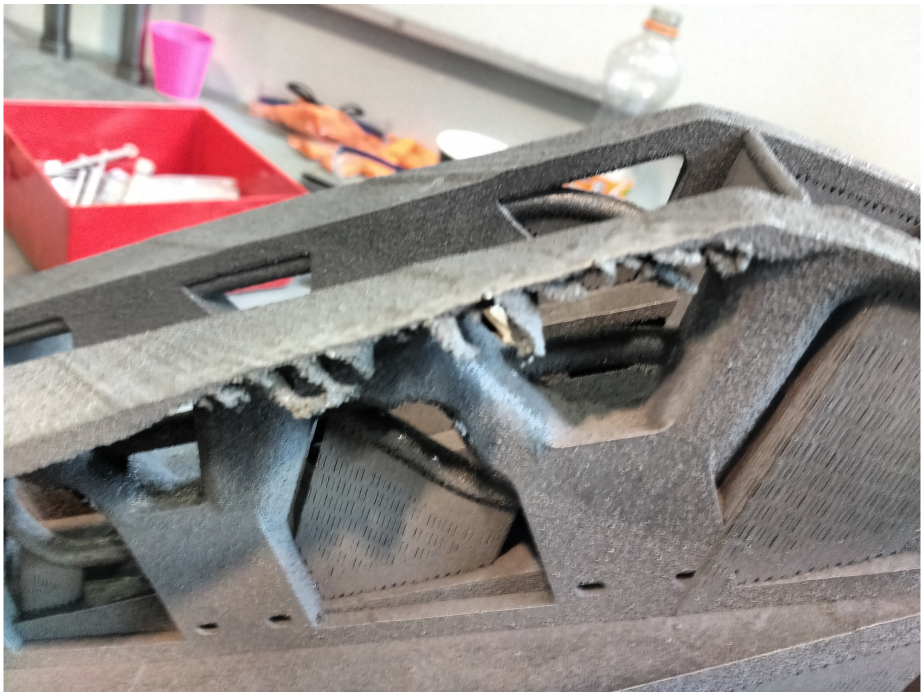


Figure 4.9: One surface facing downwards was heavily deformed.

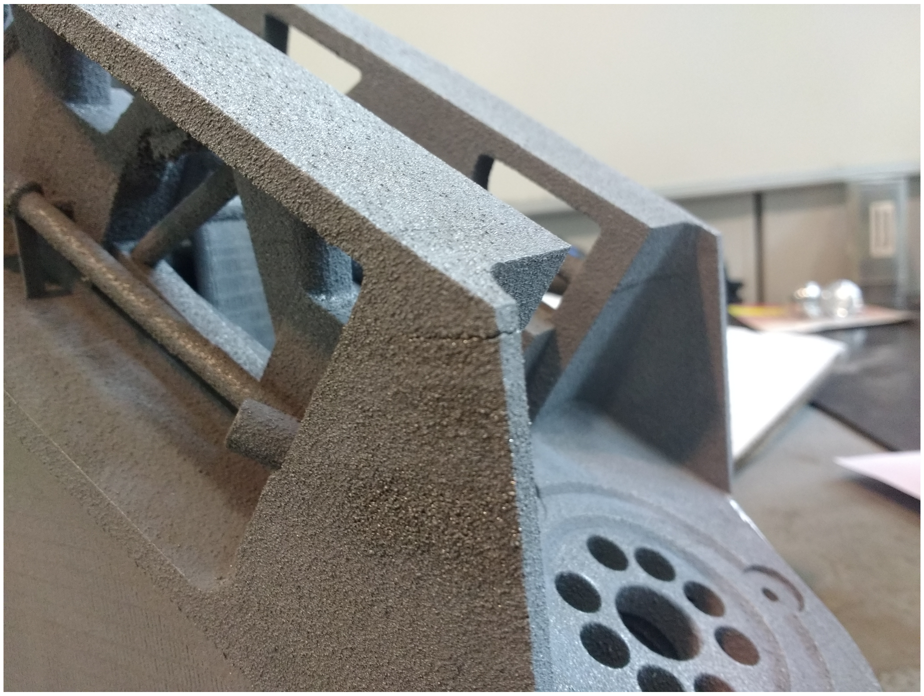


Figure 4.10: A crack formed by internal stresses caused by the build process.

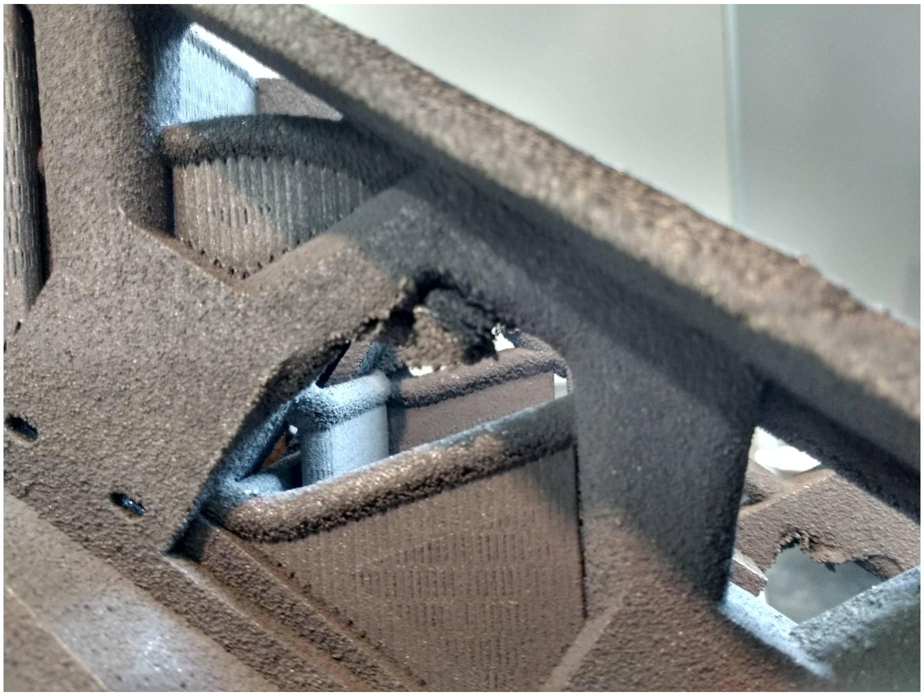


Figure 4.11: Deformation of the prototype.

Chapter 5

Discussion

5.1 Analysis of the chosen design

Kongsberg automotive requested a new design that could be implemented for different grippers. This new design should be superior to the old gripper design in multiple ways. See old design concept in figure 1.1. The new design should reduce the amount of collisions between the robot and the tool, and reduce the frequency and amount of downtime in the production line. The design concept developed in the work associated with this thesis has the possibility to accomplish these objectives. The possibility of air hoses being caught on edges in the mold and ripped of is reduced significantly as a result of hoses being replaced by tubes. The new gripper prototype is also narrower in the direction where it previously was a tight fit. This might help to reduce the chance of collisions. So all in all the purpose of the thesis has been reached.

Since the adapter have been moved away from the center of the forces, the quick change adapter is subjected to more torque. The adapter did not fit between the pneumatic actuators, this was required to reduce the thickness of the gripper. The benefits were considered to outweighed the drawbacks, but this is an expected but challenging side of the concept.

This gripper is not specifically designed to work with any type of sensors. Mounting points were not integrated in the design, but might be added at a later stage.

It is believed that the maintainability of this solution is as good as the currently used grippers. It uses the same pneumatic actuators and adapters. The reliability is possibly increased due to the reduced use of hoses. The reliability of the o-rings in the quick change adapter might wear faster depending on the surface roughness inside the connecting holes. All accessory parts are commercially available, and the pneumatic actuators and suction cups are unchanged. Prolonged testing might gain new knowledge and uncover unexpected problems, strengths and weaknesses.

5.2 Building the prototype

It was expected that building such a large, intricate part in aluminium would be challenging. The aluminium built in the m2 cusing machine at NTNU Trondheim tends to warp and deform more than steel. The intensity of the laser is partially responsible for this. NTNU's machine has a 200W laser. According to Vegard Brøtan the machines with 400W lasers and higher produce better results in aluminium. This is related to aluminium's great heat conducting abilities. Building the prototype in steel might have been less problematic, but also not as didactic.

The prototype might be repaired to by welding the cracks and patch up the hole in the internal tube. Some milling of rough surfaces might also be required, as the surface of the quick change adapter.

5.3 Experience

Product development is better suited for teams than single persons. This is not because the workload is too big, but the benefit of being two people to exchange and develop ideas is large. Two people working together can create more than their separate works put together.

There is a possibility that the product does not work as expected. It may not fit inside the mold, or collide in some unforeseen way. This possibility could be reduced if we had been made a full size plastic prototype and tested this in the injection mold.

There is a possibility that the seal of the o-rings between the pneumatic actuators and the gripper are going to leak. The interface surface and fit of the pneumatic actuators to the gripper could have been tested on smaller parts before the entire gripper was sent to production. These are things that I would have done if I had more time.

The product development process went reasonably well. However, with a bit more effort in the early stages of the project would have given more time for testing of the final prototype.

There were more problems than anticipated during the additive build. The large assembly with the resulting long building time and high cost prevented further development of the building process and sequence.

The things learned during this build process might reduce problems in the future. Among the things we learned was how the support structure affects the part while it is being built, and we got an indication on what kind, and where, support structures are needed.

5.4 Further work

Since there was some problems producing the prototype and the flaws it had when it was built, it was not enough time to test the prototype as first planned. Therefore i would suggest for the continuation of this work thorough testing of the gripper prototype constructed in this thesis work. Information gathered could be used to make new grippers for different injection molding tools. Perhaps a more complex tool might be promising. Sensors or other accessory devices might be included in the design of later gripper systems.

5.5 Conclution

Kongsberg Automotive Raufoss wanted to use additive manufacturing to create grippers with advanced functionality. The conclusion in this thesis is that this is possible, and might be highly cost effective.

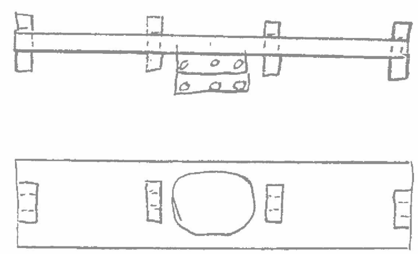
The grippers made using this design concept are built specifically for each injection molding tool. This makes them a great candidate for this kind of automated manufacturing process. As more experience is gathered, additive manufacturing will likely establish itself in this industry.

On the other hand, simple and uncomplicated injection molding tools might not benefit from this technology, as traditionally manufactured systems are well established and cause few problems.

Appendix A

Appendix A: sketches

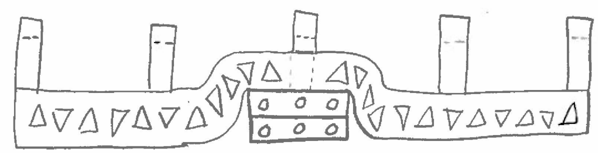
Forsenkede gripere



- mulighet for blokert lufttilkobling på griper
- Ikke mulig med griper forran adapter

+ veldig tynn

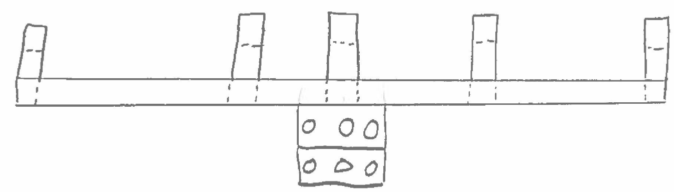
Hvis griper er foran adapter
forsenket griper med optimal stivhet
og plass til sensorer



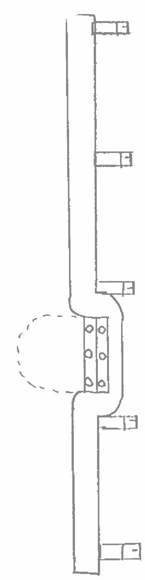
+ tynnere enn orginal med tilsvarende tykkelse av orginalplate
10 mm?

+ Plass til invendige foringer

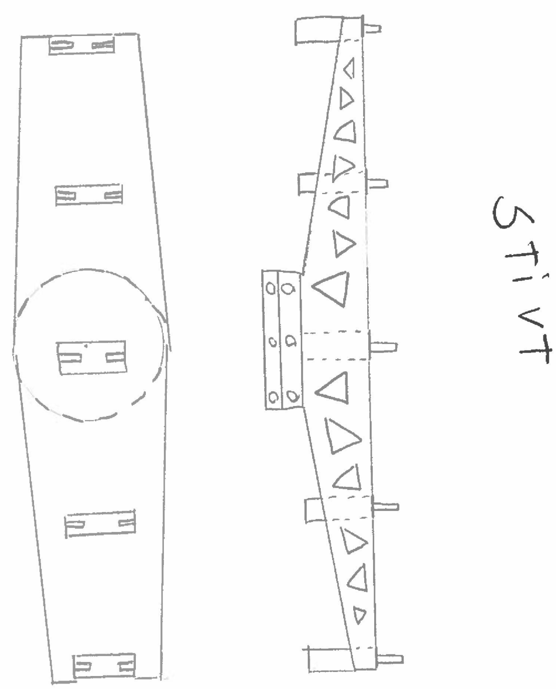
Hvis griper er foran adapter
forsenkede gripere



+ tynnere tilsvarende tykkelse av orginal Plate
+ Plass til sensorer på fram siden av plate
+ Ikke begrensende for robot bevegelse



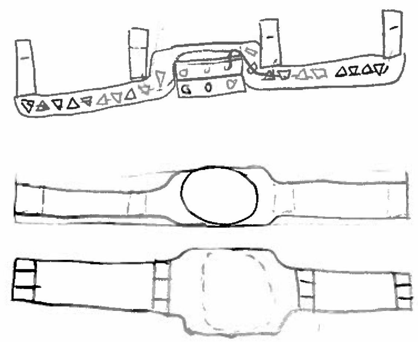
ASYmetrisk 2


Stivt

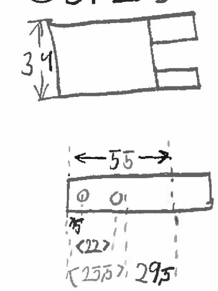
M2, byggevolum
10"x10"x11"
254 x 254 x 280

adapter:
diameter 94 mm
tykkelse 33 mm

TYPE: forsenket adapter



Griper:
GDP1?



~~Lab 2~~

~~2 samtidig på 1~~

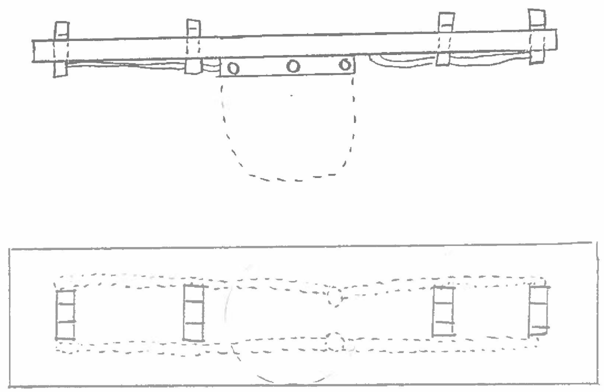
Tykkelse gevinst = avstand fra bak ende av griper til starten av "tenner" 40 mm?

+ gode koblingsmuligheter for gripere
+ veldig tynn

– Ikke mulig med griper foran adapter

adapter som del av strukturen

(alternative føringer)



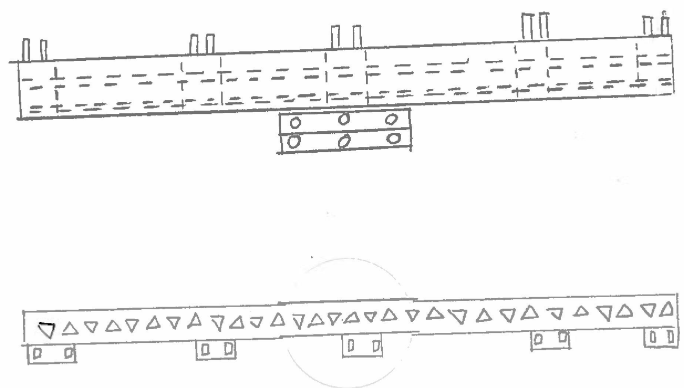
+ veldig tynn

− Vanskelig å produsere

undermonterte gripere (modulær?)

lim?

koblings flens?

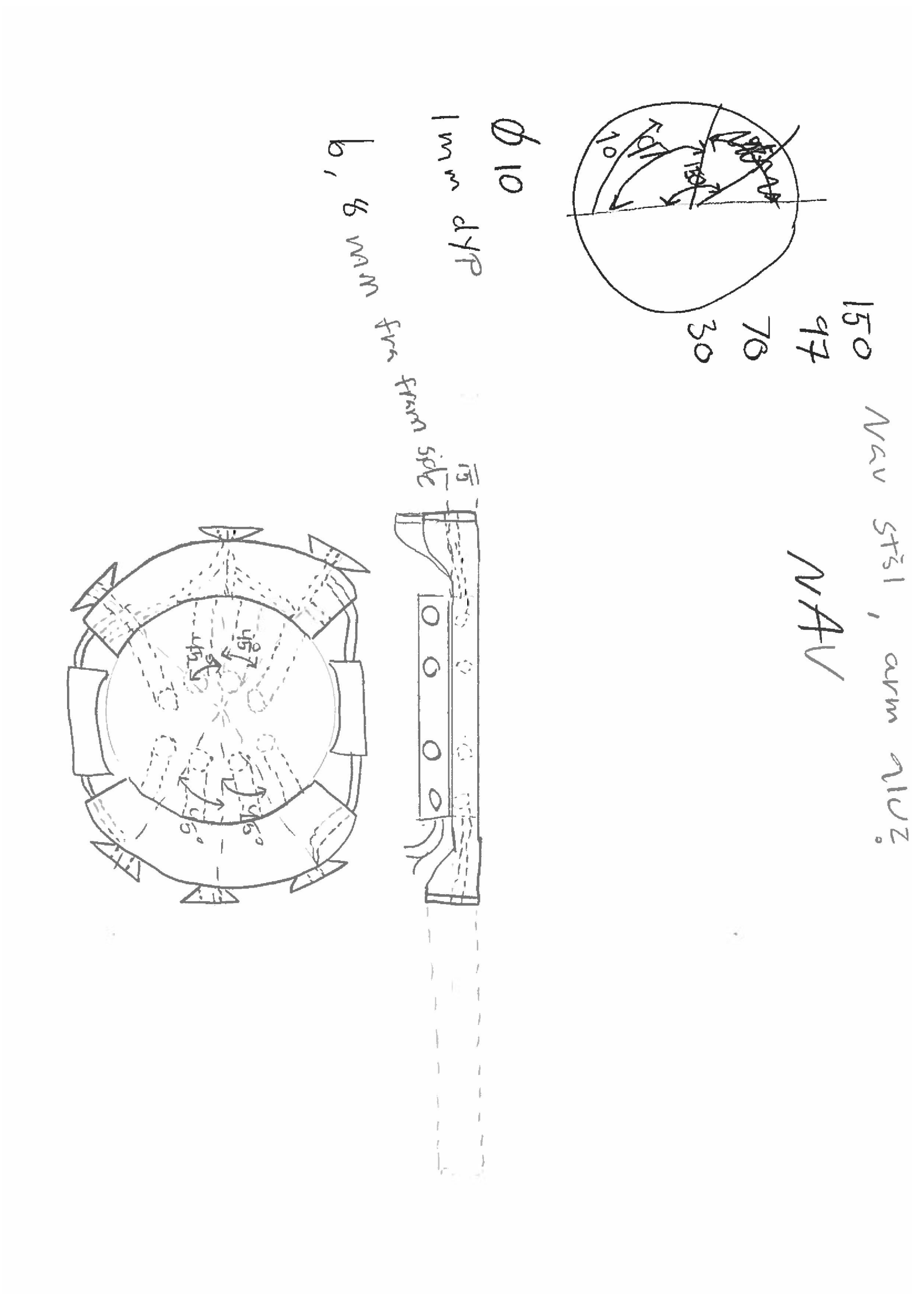


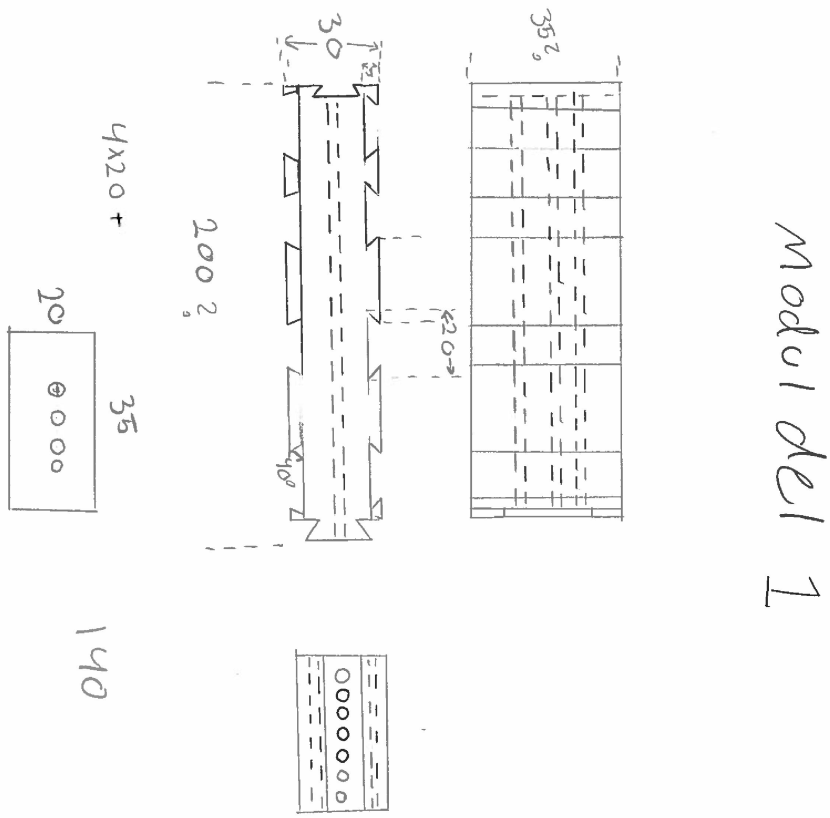
+ så tynn som mulig

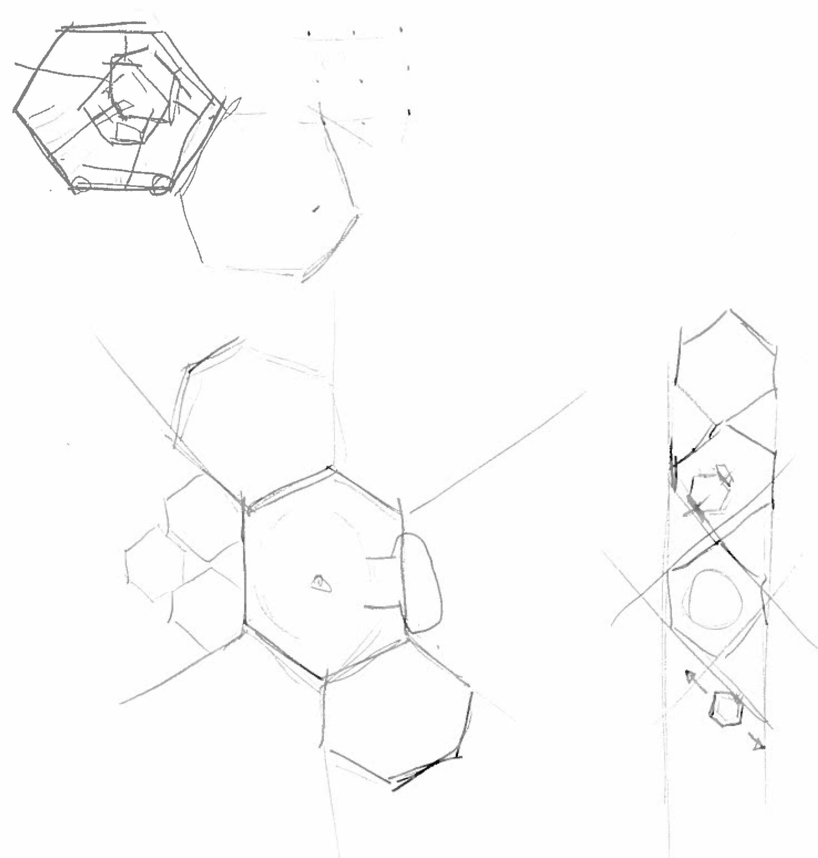
+ god tilkobling til griperene

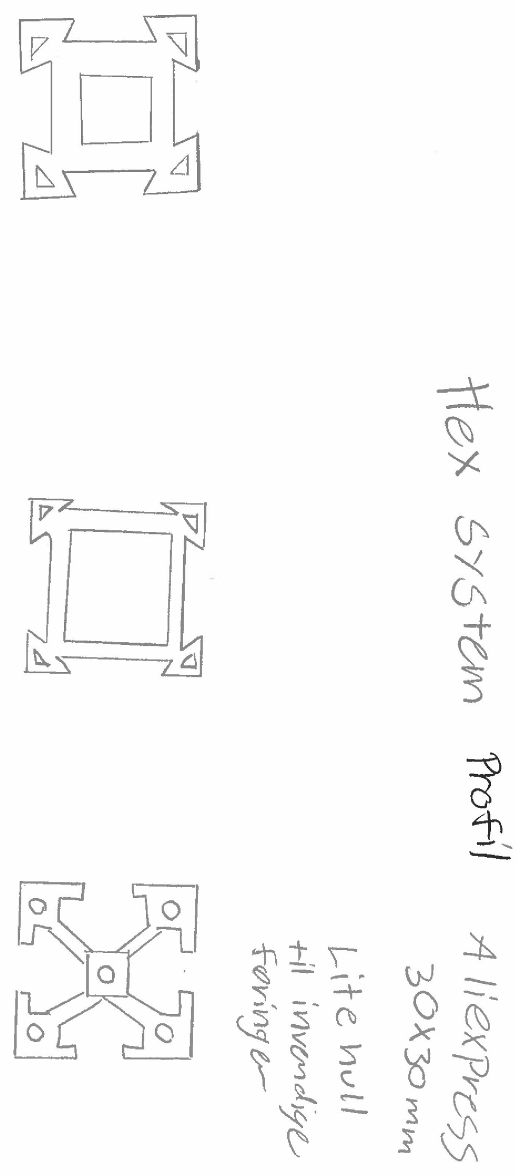
+ god plass til sensoren

+ kan bygges modulært


150
97
70
30
Nav stål, arm glue?
NAV
Ø 10
1mm dyp
b, 8 mm fra fram side


Modul del 1
35?
20
30
3
40°
200?
4x20 +
35
20
140




Hex system Profil
Aliexpress
30x30 mm
Lite hull
til innvendige
føringer

Appendix B

Appendix B: misc.

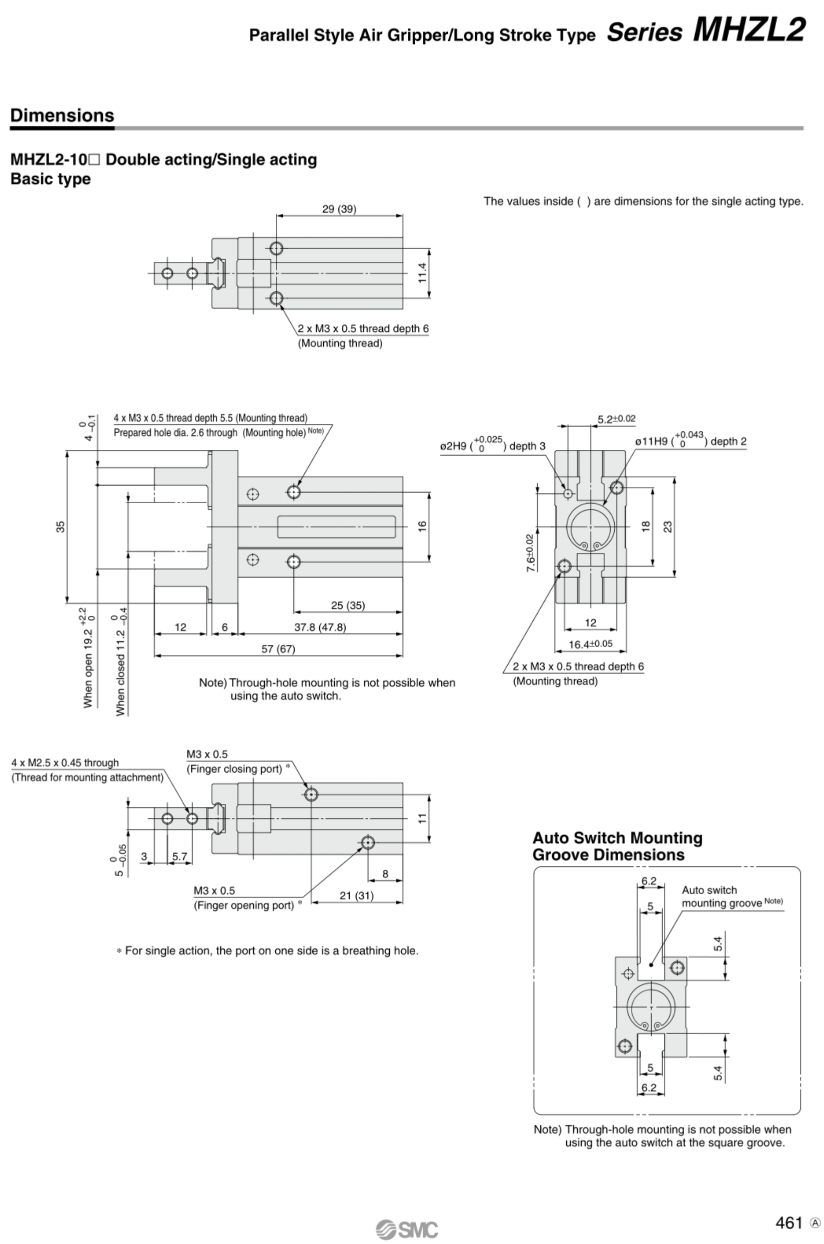


Figure B.1: Pneumatic actuator from SMC used by Kongsberg Automotive(source: SMC parts catalog)

	A	B	C	D	E	F	G
1		WEMO	ATI	Schunk	Grip	Destaco	SAS Automation
2	Navn	WGS quick-lock midi	MC-16R Euro	HWS	SWS050	QC/TP-30	QSR/QST 90-8
3	koblingstype	Manuell	Manuell	Manuell	Manuell	Manuell	Manuell
4	Antall elektriske koblinger (modul)	15 pin d-sub	* 26 pin/Ethernet	32	12	15 pin D-sub	19 pin
5	Antall innebygde pnaumatiske koblinger	6	4	10	4	4	8
6	Trykkområde for trykkluftkoblinger	-1 - 6 bar			-1 - 8 bar	3-7 bar	
7	Tykkelse (fra robot til griper)	34mm	47,6mm	-	30mm	39,7mm	36mm
8	Vekt	0,685 kg	0,735 kg	0,22 kg	0,41kg	0.34 kg	0,546 kg
9	Lastkapasitet	400N, 100Nm, 50Nm (push/pull, rotation, bending	16 kg	8 kg	14 kg	13 kg	11,25 kg
10	Hydraulikkoverføringsmodul	nei	Ja*	ja	nei	nei	nei
11							
12	* Kun en modul av gangen						

Figure B.2: This is a spreadsheet made while researching different tool changing adapters.

Bibliography

[1] ISO 17296-1. Additive manufacturing - General principles - Part 1: Terminology.

[2] (2015a). ISO 17296-2. Additive manufacturing - General principles - Part 2: Overview of process categories and feedstock. Technical report, International Standards Organization, Geneve.

[3] (2015b). ISO 17296-3. Additive manufacturing - General principles - Part 3: Main Characteristics and corresponding test methods. Technical report, International Standards Organization, Geneve.

[4] Bendsøe, M. P. and Sigmund, O. (2003). *Topology, optimization : theory, methods, and applications*. Springer, Berlin.

[5] Brøtan, V. (2014). A new method for determining and improving the accuracy of a powder bed additive manufacturing machine. *The International Journal of Advanced Manufacturing Technology*, 74(9-12):1187–1195.

[6] Brøtan, V. (2015). *Additive Manufacturing for High Value Metal Production in an Optimized Hybrid Manufacturing Cell*. PhD thesis, NTNU.

[7] Concept Laser (2015). http://www.conceptlaserinc.com/materials/.

[8] EOS. http://www.eos.info/material-p.

[9] Gebhardt, A. (2011). *Understanding Additive Manufacturing - Rapid Prototyping, Rapid Tooling, Rapid Manufacturing - Knovel*. Hanser Publishers.

[10] Gibson, I., Rosen, D., and Stucker, B. (2015). *Additive Manufacturing Technologies*. Springer New York, New York, NY.

[11] Meinel, C., Leifer, L., and Plattner, H., editors (2011). *Design Thinking*. Springer Berlin Heidelberg, Berlin, Heidelberg.

[12] Northon, K. (2014). Sparks Fly as NASA Pushes the Limits of 3-D Printing Technology. http://www.nasa.gov/press/2014/august/sparks-fly-as-nasa-pushes-the-limits-of-3-d-printing-technology/#.VkHinvkvfIV.

[13] Rønneberg, T. (2016). *Characterization of Aluminium Components Produced by Additive Manufacturing*. PhD thesis.

[14] Steen, S. (2015). *Additiv produksjon av lettvektstruktur*. PhD thesis, NTNU.