TAMPERE UNIVERSITY
OF APPLIED SCIENCES

# DESIGNING AND IMPLEMENTING A ROBOT GRIPPER USING ADDITIVE MANUFACTURING

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# ABSTRACT

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Designing and implementing a Robot Gripper using additive manufacturing

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This Bachelor's thesis contains the designing and manufacturing of a new robot gripper for TAMK's open lab welding robot to have an alternative to the current gripper that is in use. The main goal was to manufacture as many parts as possible from additive manufacturing. The customer's requirements of the gripper were that it is able to pick up an 80 mm wide and 1 kg heavy object by also being lighter than the current gripper in use at the laboratory. The design process is based on the VDI 2221 guidelines which state the steps of the systematic approach to the development and design of technical systems and products created by the Association of German Engineers.

After acquiring the basic knowledge about this thesis, a clear statement about the scope and the marginal conditions of this work is provided. A requirements list then states all the demands and desires of the gripper before the reader finds a breakdown of the different functions and systems of the workpiece. A morphological box was created to collect ideas for the product which resulted in two possible design-solutions. The solution meeting the requirements best is further used to start designing a prototype. Once the prototype was tested and agreed on by the customer the designing of the final product started.

Calculations of the most critical parts are demonstrated and prove the safety of the construction. After finding the documentations about the safety features, the drive-system and the costs, the reader is given an insight of the manufacturing of the 3D-printed parts. The final version of the gripper was then tested and implemented into the open lab.

Key words: additive manufacturing, gripper, open lab, morphological box, 3D-printing

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**DECLARATION OF AUTHORSHIP**

I, Bastian Gerland, hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

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Tampere, 30.03.2017 ________________________

Bastian Gerland

## GLOSSARY

| | |
|---|---|
| 3D | Three-Dimensional |
| ABB | ASEA Brown Boveri |
| ABS | Acrylonitrile Butadiene Styrene |
| AM | Additive Manufacturing |
| CAD | Computer-Aided Design |
| DFAM | Design for Additive Manufacturing |
| DFMA | Design for Manufacture and Assembly |
| DOF | Degrees of Freedom |
| FDM | Fused Deposition Modelling |
| FEM | Finite Element Method |
| IRB | Industrial Robot |
| ISO | International Organization for Standardization |
| PLA | Polylactic Acid |
| STL | Stereo Lithography |
| TAMK | Tampereen ammattikorkeakoulu |
| VDI | Verein Deutscher Ingenieure (Association of German Engineers) |

Mathematical abbreviations

| | |
|---|---|
| *g* | Gram |
| *kg* | Kilogram |
| *m* | Meter |
| *mm* | Millimeter |
| *N* | Newton $[\frac{kg \times m}{s^2}]$ |
| *s* | Second |

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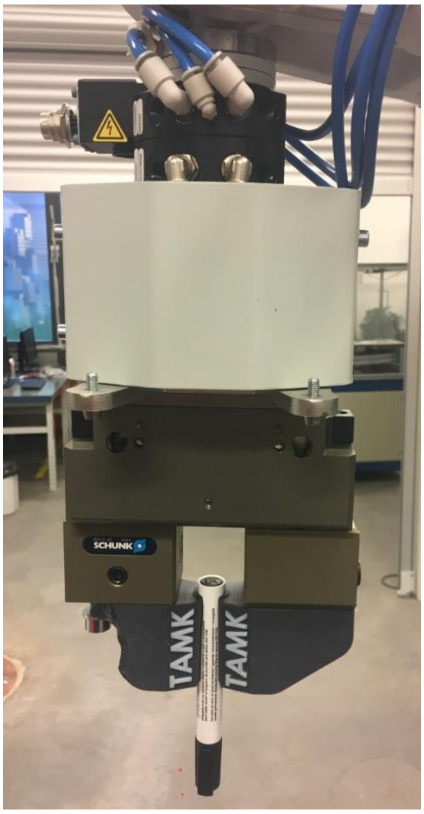
# 1 INTRODUCTION

This thesis project was developed to finalize the studies in the Mechanical and Production Engineering Degree Program at TAMK (Tampereen ammattikorkeakoulu) University of Applied Sciences. TAMK educates around 10.000 students in 50 degree programmes with a total of 730 staff members. These numbers make the higher education institution to one of Finland's biggest and most popular ones (Tampere University of Applied Sciences 2010).

One of the many laboratories' that TAMK has to offer is the mechanical engineering departments laboratory called the open lab. This research facility serves as the working environment for this project. Besides accommodating machinery, which offers the students to do structural strength tests and 3D-printing, it also holds a robot cell. The robot cell is equipped with an ABB (ASEA Brown Boveri) robot. The IRB (Industrial Robot) 2600 can be used for various tasks including welding, machine tending or Pick-and-Place. Juuso Huhtiniemi, laboratory lecturer at TAMK, is the customer of this work and requested a low cost, self-designed gripper for the IRB which is mainly produced by using additive manufacturing (AM), also called 3D-printing.

With the ongoing expansion of the AM business field many industries have been affected by this large growing production method. To keep up with the latest technology on the market, also the robot gripper industry has already introduced 3D-printing. One of the biggest robot components companies such as Schunk GmbH & Co. KG, has already gripper fingers on the market which are additively manufactured (Schunk: Additive manufactured Gripper… 2016). Now ABB Finland has requested a similar gripper solution from TAMK because the University of Applied Sciences has the necessary 3D-printers to manufacture a complex element like that. The company wants to see what is possible with this technology in this sector right now. The second reason for the design of this new gripper is that a more flexible gripper is needed at the laboratory. With this new version, the students will learn how to use the IRB in the robot cell.

The current gripper solution was designed by Juuso Huhtiniemi. As a result of short time resources during its production, the current gripper is rather a compromise that serves as a temporary solution and is not optimized for its purpose yet. The lack of time available forced the designer to improvise in the production process of this robot end effector. Therefore, only the two gripper fingers and the cover plate have been designed and additively manufactured whilst the rest of the gripper components were purchased external. All these parts were then assembled together and equipped with a pneumatic power source.




PICTURE 1. Current gripper solution

Having to order these very specific gripper parts from an external company makes the current solution a rather expensive one. Another disadvantage of the above shown solution is its weight. The metal pieces make the device very robust but at the same time extremely heavy. Overall the shown gripper has a total weight of 8 $kg$ with a maximum payload of the robot of 12 $kg$ (ABB Robotics: Data Sheet 2010). Given these facts, the gripper reduces the payload of the robot by roughly 67%. The aim of this work is to design a new gripper solution that is cheaper in production and lighter in weight; thus resulting in a more efficient use of the robot payload. To achieve this goal, all components that match the design rules of additive manufactured parts are 3D-printed, as long as the stability of the gripper is still given. Consequently, the including of external ordered parts is reduced to a minimum.

This thesis project orientates itself on the VDI (Verein Deutscher Ingenieure) guideline 2221. This systematic approach to the development and design of technical systems and products is based on four basic steps: clarification of the task, conceptual design, embodiment design and detail design. The design process leads the reader through these steps after the delivery of the basic theory that is needed to understand the major milestones of this work. Afterwards the documentation is found, followed by the implementation and testing of the final result.

Whilst working on the four steps of the VDI 2221, all the data resulting from them is documented. Examples of the documentations used in this thesis are a requirements list, a valuation table, a parts list and finally the CAD (Computer-aided Design) drawings of the result of the work. To prove the stability of the designed gripper, several calculations of the major parts are demonstrated.

# 2 THEORY

This chapter describes the basics of the theoretical background necessary to understand the work of this thesis. It covers the definition and description of the robotic arm itself, as well as the ones of the gripper. Besides informing the reader about the subsystems and classifications of the gripper, also an enlightenment about the current state of the art of this technology is given. After stating and describing the 3D-printing technology with its design rules, a view on the design process of this thesis work is given.

## 2.1 Industrial robots

The ISO (International Organization for Standardization) 8373:2012 defines an IRB as follows: "An automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications". There are also several other IRBs which are not covered by this definition though: many robots on the current market only serve a special purpose, for example machine tending. Considering this fact, they do not fall under the definition of multipurpose, hence do not fit in the above-mentioned definition of the ISO (Wilson 2015, 20).

IRBs, as mentioned in the definition, can be either stationary or mobile. Stationary robots, which cover all the 5- and 6-axes robots, are mounted and limited in their workroom. Mobile ones on the other hand can be moved on wheels, chains etc., meaning they have a much larger workroom and are more flexible in their usage (Wüst 2014, 101).

These manipulators serve a simple, yet efficient purpose: they are supposed to do their work faster, safer and more precise than humans can do it. Also, IRBs can do tasks which cannot be done by human hands, for instance lifting heavy objects. Therefore, the robots do not only allow manufacturers to accomplish tasks which humans cannot do but they also do it in a more efficient, hence more affordable way (Hesse & Malisa 2015, 36)

### 2.1.1 Classification

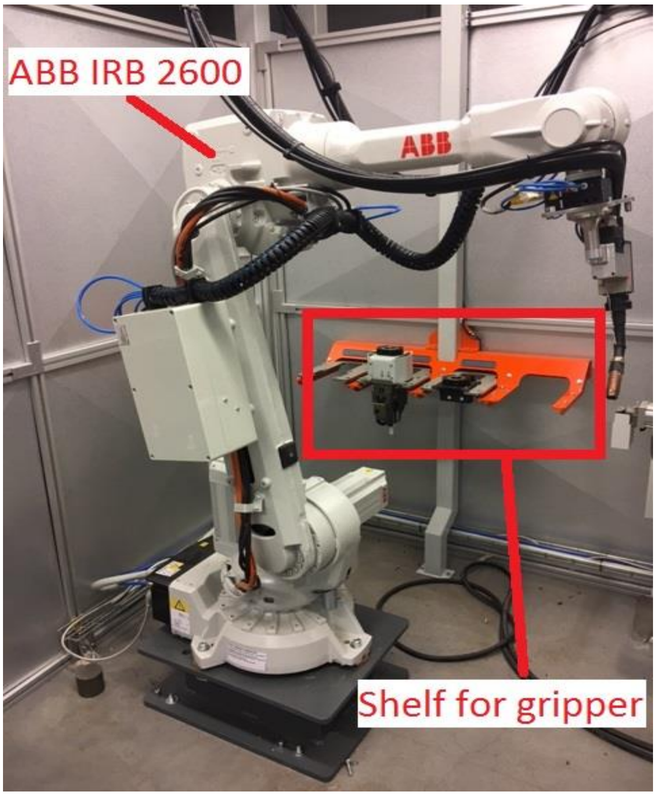
A lot has happened since the invention of the IRB in 1954. In the more than 60 years of development, the modern IRB nowadays can be classified into five different configurations: Articulated, SCARA (Selective Compliance Assembly Robot Arm), Cartesian, Parallel and Cylindrical. Each structure is defined by how the linear and/or rotary motions are linked to each other. By mixing these motions in different ways, every of the five classifications has a unique way of placing the robot structure in different positions. It is important to mention that the method of how the robot is mounted also has a significant impact on the working range (Wilson 2015, 21). Since the robot, which is being modified in this work, is an articulated arm, the other classifications are not taken into consideration as they are not part of the thesis.

The articulated arm is also known as “Unimate” because the structure is similar to the human arm. It most often has 6 DOF (Degrees of Freedom) resulting in a big hollow sphere shaped working room that makes this structure so flexible in use: welding, Pick-and-Place, measuring, assembling and brazing are only some of its applications (Hesse & Malisa 2015, 52). Each of the six joints are mounted on top of the previous joint which leads to the fact that it also must carry the weight of the previous joints resulting in an impact on the payload, speed and accuracy of the robot. Even though these kinds of structures are not rigid and the accuracy and repeatability is reliable on the axes, modern mechanics and the improvement of AC (Alternating Current) servo motors make the above-mentioned tasks possible and keep enhancing them (Wilson 2015, 24).

The six axes that most of these articulated arms have can be divided into primary axes and secondary axes. Primary axes are the axes number 1-3 which are used to position the robot from its basis. Both linear and rotary axes can be part of the primary ones. The secondary ones on the other hand are motion axes and only cause small movements. They normally serve for a change of the orientation of the gripper part. In most cases, only the rotatory axes are used as secondary ones (Hesse & Malisa 2015, 31).

### 2.1.2 Articulated arm ABB IRB 2600

In 2010 ABB introduced the IRB 2600 robot family (ABB IRB 2600 2010). It comes in three different versions, each equipped with a different range and payload. TAMK’s open lab is equipped with an ABB IRB 2600-12/1.85 (picture 2). This version of the robot has a payload of 12 $kg$ and a reach of 1,85 m (ABB Robotics: Data Sheet 2010).




PICTURE 2. Robot cell in the open lab with ABB IRB 2600 and shelf for the gripper

The design of this articulated arm has been optimized for its main applications: machine tending, material handling and arc welding (ABB IRB 2600 2010). Three main applications in addition to the fact that it can be mounted on the floor, wall, shelf, tilted or inverted make it a flexible option for many industries (ABB Robotics: Data Sheet 2010). This robot has 6 DOF and with respect to its sharp accuracy, short cycle times and large working range it increases the productivity and is also suitable for tasks like measuring or cutting (ABB Robotics: Data Sheet 2010). ABB equipped the robot with emergency stops and the latest safety technology on the market which make it also a very safe manipulator. An additional safety feature is the control panel that comes with the robot. With this device, the robot can be fully controlled without standing in its reach and risk to get injured whenever the robot is moving.

## 2.2 Gripper

The VDI 2740 defines the main task of the gripper as in creating, maintaining and releasing a connection between the object to be moved and the robot (Blatt 1 1995, 3). Grippers are subsystems of handling mechanisms which ensure the position and orientation when carrying an object. Prehension can be achieved in different kind of forms via impactive mechanical, pneumatic or magnetic gripper types. Even though there are multi-purpose grippers with a wide clamping range on the market nowadays, most commonly the gripping parts must be adapted to the shape of the object in order for the company to stay competitive. This allows the robot to work much faster and more precise (Monkman, Hesse, Steinmann & Schunk 2007, 2). Whenever choosing a gripper four parameters need to be taken into consideration to ensure a fit to its respective purpose: contact basis, gripping force, gripping time and clamping range (Wolf & Schunk 2016, 95).

### 2.2.1 Classification by gripping method

Robot grippers can and have been classified in many ways before in the past. For this work, the effectors are classified by their gripping method. Monkman et al. classified the grippers into four different methods which are shown in table 1 (2007, 19).

TABLE 1. Classification of grippers by method

| Gripping method | Non-penetrating | Penetrating |
|---|---|---|
| Impactive | Clamping jaws, chucks, collets | Pincers, pinch mechanisms |
| Ingressive | Brush elements, hooks | Needles, pins, hackles |
| Contigutive | Chemical adhesion (glues), surface tension forces | Thermal adhesion |
| Astrictive | Electrostatic adhesion | Magnetic; vacuum suction |

For impactive gripping there is the need of solid jaws to get the grasping force necessary to hold the object. This method of the mechanical gripper is the most used one in the industry and uses at least two jaws from two directions to produce the force by the impact against the surface of the object. When using the ingressive method, the object’s surface is being deformed, for example Velcro, or even penetrated down to a predefined depth by needles or pins. Contigutive gripping means touching and is working with direct contact but without impact between the object and the gripper in order to grip it. Astrictive grippers on the other hand do not necessarily need direct contact to move the objects because they use binding forces from a single direction for the transfer. This process is only possible with special materials: vacuum suction only works with non-porous and rigid materials, magnetic grippers can only lift ferrous materials and electrostatic adhesion works with light sheet materials (Monkman et al. 2007, 3, 5-6, 19, 61-63).

### 2.2.2 Grip-basics

In this chapter, the main basics of the grip itself are demonstrated. It is necessary to have an understanding of the prehension process to make further decisions in the design process of the gripper. It is of much importance to think of the consequences that the choice of gripper and its fingers will have. One of these is the amount of contact points with the grabbed item. The more contact points the finger has with the object the more friction surfaces are given. More friction surfaces lead to a lower possible gripping force because much of the objects weight is already held by the friction force.

Isaac Newton's law of interaction leads to another fact that has to be considered during the development: "Whenever one body exerts force upon a second body, the second body exerts an equal and opposite force against the first body". This leads to the fact that the prehension force is not affected by an increased number of gripper fingers (Monkman et al. 2007, 49). The amount of gripper fingers and therefore the resulting number of contact points have an impact on the calculations and the needed gripping force to move the object safely. This is demonstrated in the calculations of this thesis (chapter 6.2). It is important to mention that large active surfaces improve the retention stability hence a reduction in gripping forces is possible. An ultimate retention stability is achieved by maximizing the matching of the gripper and the object profile (Monkman et al. 2007, 21).

Grippers either work with force mating, shape mating or a mixture between both. Figure 1 by Wolf & Schunk demonstrates these kind of grippers (2016, 115). The chosen gripper defines how many contact points exist and how big the active surface is. To perform a handling process with the object, the forces created by the gripper have to be strong enough to compensate the gravitational force of the object in motion (2016, 115).

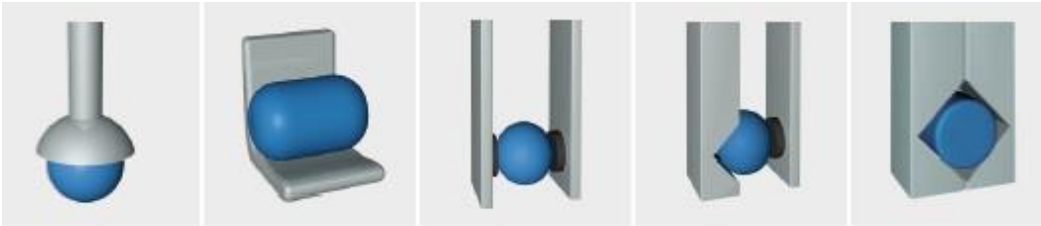


FIGURE 1. Mating of gripper and object

Attention should also be paid to how much free space is available to grab the object. A Pick-and-Place task where the gripper must move pieces from a box with a high object density for example faces problems in gripping around the piece to pick it up. A gripping strategy like that is called an external grip. To avoid problems like that, different grippers do an internal grip if the hollow object surface allows it. A combined grip where one finger grips from the inside and one from the outside is another alternative to that (Monkman et al. 2007, 40).

Also, the DOF of the workpiece need to be defined. The design of the gripper defines the rotational and translational axes which are not secured by the matching of forces. These DOF specify how the workpiece could move or fall if the frictional force is not high enough. It is important to mention that this problem cannot be solved with higher clamping force because it could cause damage of the gripper or the object (Monkman et al. 2007, 23).

### 2.2.3 State of the art

As mentioned above, nowadays it is recommendable and often even necessary to choose or design the gripper for a specific task and not to consider an all-rounder for several tasks at the same time. By doing so, companies save themselves a lot of time and money because the IRB can work much faster with a gripper that is designed for a special object or task. As machine automatization keeps growing globally, the shapes of the objects that need to be gripped are getting more and more complex. Consequently, more often grippers need to be designed for a single object to guarantee a safe movement without damaging it. In the 1980s, the first few firms noticed the problem that the standard grippers from KUKAs or ABBs robots for example were not going to fit the market in the future anymore, thus they started to specialize in the field of grippers. The aim back then and still today is to reduce the weight of the gripper and to make it faster by still increasing its strength. 30 years ago, the pneumatic grippers had a weight/force ratio of 1, whereas today they improved to a ratio of 2,5 (Wolf & Schunk 2016, 50-52).

Currently, a big milestone shaping the future gripper market, is the AM. In the year 2006, Robomotion was the first firm to introduce a gripper with additive manufactured gripper fingers. It was last year when Schunk GmbH & Co. KG launched their eGrip market where firms can design and order their specialised gripper fingers in 15minutes and get them printed in steel, plastic or aluminium. With this technique, companies can manufacture much more detailed and specialized shapes that were not possible before (Schunk eGrip 2016).

The company Robotiq recently introduced a gripper which had a big impact on the market. The 2-Finger adaptive robot gripper is compatible with all major IRBs, which makes it so desirable. Robotiqs 2-Finger adaptive gripper comes in two versions: a gripper stroke from 0-85 $mm$ or 0-140 $mm$. They are able to lift a payload of maximum 5 $kg$ with a gripping force of up to 235 $N$ and a tare weight of 1 $kg$. Installation and programming is simplified because of ready-made programming templates. These electric-driven end effectors with continuous gripping allow a safe maintaining grip without dropping the piece. Full control on fingers' position, speed and force allow a precise control of the items. As shown in figure 2, the usage of a parallel and encompassing grip enables a wide range of potential shapes to grip (Robotiq 2012, modified).

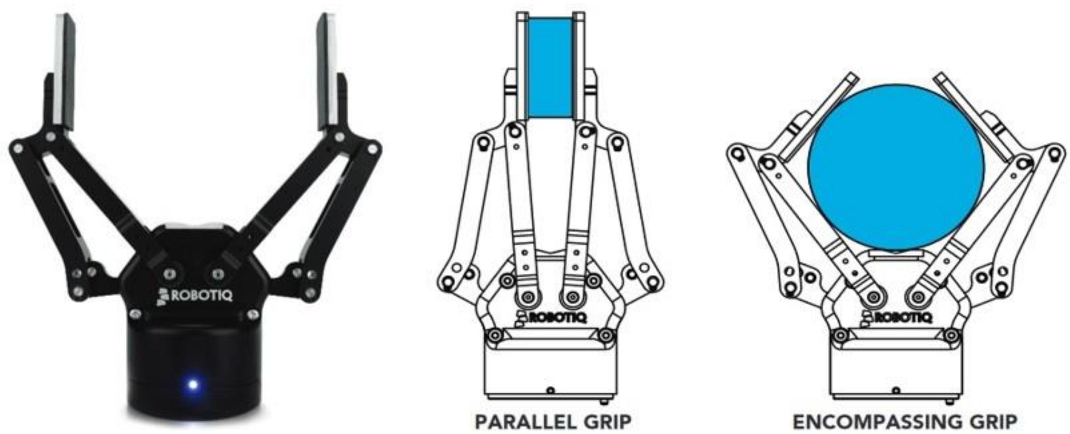



FIGURE 2. Parallel grip and encompassing grip of the 2-finger gripper

## 2.3 Additive manufacturing

AM has had a stabilized position on the market for years already, but it has only been recently that the technology has become affordable for the majority and it is experiencing a major growth ever since (Hausmann & Horne 2014, 1). The term *additive manufacturing* has only been introduced lately and has its origin in the term rapid prototyping. It describes the process when companies are creating a prototype in a rapid manner that serves as a basic model for further versions which are later commercialized. In the product development business sector this meant creating a physical work piece from digital software data (Gibson, Rosen & Stucker 2010, 1). The latest improvements of the 3D-printing technology though have led the manufacturers to notice that these products are now significantly closer to the final manufactured product. This fact has been one reason for changing the name of the manufacturing method. The other reason is the way 3D-printing works. By printing the 3D-model one layer at the time on top of each other the final physical product is created (Hausmann & Horne 2014, 1). The single layers are being added on top of each other. Therefore, the name *additive manufacturing* was born.

### 2.3.1 Process description

During the years, several 3D-printing concepts have been introduced to the AM industry and these form the market nowadays (table 2, Additively, modified).

TABLE 2. Additive manufacturing technologies

<table>
<tr><th>Materials</th><th colspan="5">Technologies</th></tr>
<tr><td></td><td colspan="2">Parts built by polymerization</td><td>Parts built by bonding agent</td><td colspan="2">Parts built by melting</td></tr>
<tr><td>Ceramic</td><td colspan="2" rowspan="3"></td><td rowspan="4">Binder Jetting (BJ)</td><td rowspan="2">Laser Melting (LM)</td><td></td></tr>
<tr><td>Metal</td><td>Electron Beam Melting (EBM)</td></tr>
<tr><td>Sand</td><td colspan="2"></td></tr>
<tr><td>Plastic</td><td>Stereolithography (SL)</td><td>Photopolymer Jetting (PJ)</td><td>Fused Deposition Modeling (FDM)</td><td>Laser Sintering (LS)</td></tr>
<tr><td>Wax</td><td colspan="2"></td><td></td><td>Material Jetting (MJ)</td><td></td></tr>
</table>

Even though all of these technologies differ from each other, they all follow the same procedure (figure 3, Gibson, Rosen & Stucker 2010, 43, modified) to go from the conceptual CAD drawings to the actual application of the 3D-printed piece (Fastermann 2013, 12).

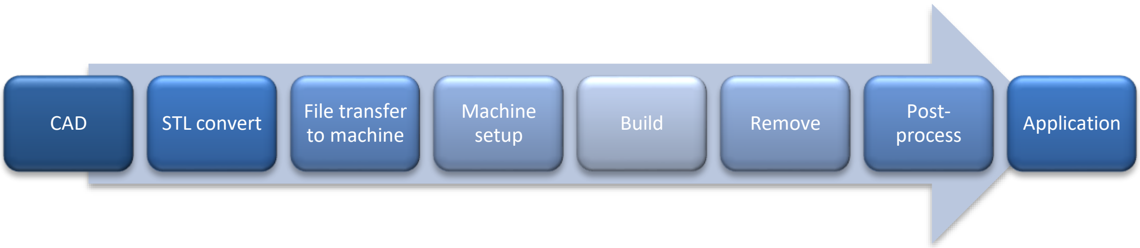



FIGURE 3. Additive manufacture process

The first step to every manufactured part is the 3D-CAD model. 3D-printing is also sometimes referred to as Digital Fabrication because the model first has to be created in a digital version (Fastermann 2013, 12). The model can be either designed in one of almost all the CAD programs available on the market or inserted via reverse engineering equipment, for instance laser scanning before converting it into a STL (Stereo Lithography) file (Gibson, Rosen & Stucker 2010, 4).

The STL format has become the standard of the industry and is supported by almost all AM machines (Hausmann & Horne 2014, 25). In this step the file converts the surface of the model into numerous small triangles. It describes the external closed surfaces and forms the basis for the calculation of the slices (Gibson, Rosen & Stucker 2010, 4). The smaller the triangles the more detailed the 3D-printed model. To ensure that all triangles point in the same direction and no errors occurred during the conversion, several repair software's are available which should be used to check the file before printing it (Fastermann 2013, 15). At this point the user can or even has to reposition the object to be able to print it. In some cases, even editing of the scale is necessary due to small shrinkage during the printing and drying process. Afterwards, in the next step of the printing process, the machine needs to be set up for the type of part that is supposed to be crafted. All this can be done in the repair software as well. Possible options that need to be set up can be material constraints, layer thickness and timings for example (Gibson, Rosen & Stucker 2010, 45). When the file seems printable in the repair software it needs to be transmitted to the AM machine.

Once the printer is set up correctly and the file is sent to the machine an automatic step takes place. The actual printing of the 3D-model is executed fully automatically by the AM machine and does not require any human supervision. When the printing is completed, the object has to be removed from the machine. Depending on the application that was used to manufacture the product this can either mean removing the model from the platform it was built on or cleaning up the secondary materials from the body that were used to stabilize the construction during the print (Gibson, Rosen & Stucker 2010, 46). The last step before using the printed part is the post-process editing. Models might require final cleaning, sandpapering or application of coatings. Certain skills are required for the removal and post-process editing to not damage the part and therefore lower the quality of the product. When the editing of the manufactured model is done without any damages it is ready to be used.

### 2.3.2 Design for additive manufacturing

In this chapter the DFAM (Design for additive manufacturing) rules are going to be introduced. Similar to the DFMA (Design for manufacture and assembly) rules they always need to be followed when creating a new concept in order to minimize manufacturing and assembly difficulties and especially costs (Gibson, Rosen & Stucker 2010, 284). The distinction between DFAM and DFMA is the fact that DFAM aim to take advantage of the unique AM possibilities whilst taking the technologies limitations into account to ensure manufacturability and safety (University of Cambridge). All characteristics to improve the component should be utilised during the design process. 3D-Printing frees the designer from the constraints of the usual manufacturing technologies and enables unique designs like lattice or crossbeam structure with great weight/force ratios (Stratasys Direct 2016).

When creating a new design, it should be considered that AM offers much more freedom when it comes to the complexity. Conventional manufacturing methods often limit the features of items because of the costs: the more unique the object and the more features it has, the higher the respective costs. These cost-limitations do almost not apply for AM because of the cheap material costs and the designers should use this freedom to a maximum when designing a new part (Stratasys Direct 2016). Also, restrictions like undercuts, uniform wall thickness and draft angles limit the designer in his work with conventional methods, but they all do not apply for AM. Starting to manufacture from the ground, doing it layer-by-layer and the breakaway supports make the restriction freedom possible (Stratasys Direct 2016).

Complex parts with the need of different material properties can now be manufactured with the AM technology. The FDM (Fused deposition modelling) process for example uses one nozzle for the support material and the other nozzles to inject different materials. This feature brings great new opportunities for instance when it comes to turbine blades (Gibson, Rosen & Stucker 2010, 295). Parts of the turbine blades that are being penetrated by high forces can be made of strong and resistant materials and the parts where the blade is not being penetrated so hard can be made of lighter materials to make the blade lighter overall.

AM also offers great opportunities to minimize parts of an object and to manufacture them all in one piece. This also enables the opportunity to print assembled parts that need to move with respect to another. It is further important that one must acknowledge clearance between the mating parts though to prevent them from fusing together (Gibson, Rosen & Stucker 2010, 288). Even though it is possible to create products all at once, there are some geometries that should be considered by breaking them apart as shown in figure 4 (Gibson, Rosen & Stucker 2010, 55). When printing the geometry all at once (left version) a lot of support material is needed. To save time and costs the parts could be manufactured separately (right version) and then be assembled later.

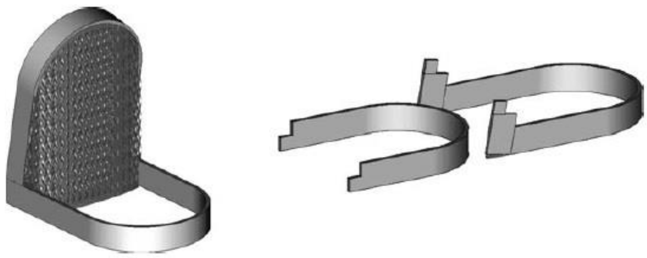
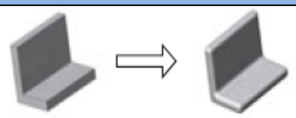
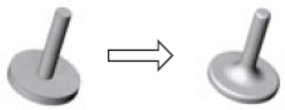
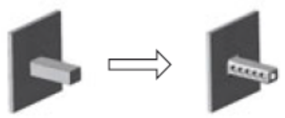
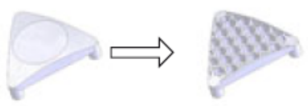


FIGURE 4. Approach of breaking up parts

When it comes to stability and yield strength the materials need to be paid attention to that can be worked with. Also, the wall thickness of the printed object needs to be taken into consideration (Fastermann 2013, 12). Designers need to find the perfect ratio between making the walls thick enough so that the object follows its requirements and at the same time saving material costs and product weight by including voids to the product (Lachmayer, Lippert & Fahlbusch 2016, 47). Given the fact that support material might be used, one should also consider that the printed object might need some cleaning and post-processing after the print. It is important that spots where support material might be used can be reached to clean them (Hausmann & Horne 2014, 39). Build support costs extra time and material and can be prevented when designing an object with angles lower than 45°, which is the maximum self-support angle (Stratasys Direct 2016). Additionally, it also has to be taken account of the limitation of production space. 3D-printed objects are mostly produced in one piece and not assembled from many parts. Therefore, the limitation of the 3D-printer size automatically limits the size of the product (Fastermann 2013, 4).

The designer must consider the different approaches of 3D-printed objects compared to conventional manufacturing. Even though conventional manufacturing and AM follow the same goals, their ways to achieve them is a different one. Breuninger, Becker, Wolf, Rommel & Verl summarized these differences in table 3 (2013, 114, modified).

TABLE 3. Suboptimal and ideal approaches of AM

| Suboptimal | Ideal | Explanation |
|---|---|---|
|  | | Approach: Give sharp edges rounding's if they do not serve a purpose. It saves material cost, has a better force flow and prevents injuries. |
|  | | Approach: Equip part connections with radii. This prevents tension maximums under stress. |
|  | | Approach: Design to save material. Save material in every place as long as the part still fits its stress requirements. |
|  | | Approach: Smooth transitions – Design for one-piece-construction. Attempt to avoid connection parts like screws or welding and make it one part if possible. |
|  | | Approach: Use of lightweight design. Save material cost and build time. For example, make use of honeycomb structure in big volumes. |
|  | | Approach: Integrate actuators or functional components in your design already. |
|  | | Approach: Avoid mass accumulation. Save material and build time with avoiding mass accumulation in intersections and joints. |

Another restriction that AM faces is the build orientation which can have a huge impact on the build time, strength and surface (Stratasys Direct 2016). Every part needs to be considered for itself and the build orientation depends on the objects purpose. By rearranging the build orientation one can save a lot of support material and thus make the parts surface smoother and the quality of the overall product better.

A disadvantage of this technology is that it faces some limitations in the design sector as well. It should be considered that there is a limitation of the materials that products can be printed out of. These limitations might lead to the fact that 3D-printing cannot even be regarded in the first place because the materials are not strong enough to fit yield strengths for example (Hausmann & Horne 2014, 39).

When the design of the object follows all of these restrictions and the quality and safety of it is still given, it is suitable for AM (Lachmayer, Lippert & Fahlbusch 2016, 46).

## 2.4 Design process

A product is not being designed in one big step but in many small ones. Each step has its own work content and a specific order during the development. This chronological sequence of individual steps is called a process (Feldhusen & Grote 2013, 11). The aim of a methodology is to impart the systematic design process in a product-neutral and general manner. When designing a new product, it is of much importance to choose the right methodology to do so (Naefe 2009, 2).

As mentioned in the introduction this thesis' design process is based on the German VDI 2221 guideline. A methodology like this one in combination with a project management approach helps to plan the development of the product.

### 2.4.1 VDI-guideline 2221

The VDI 2221 is the systematic approach to the development and design of technical systems and products. It was introduced in 1993 as a result of years of research in the development and construction process sector (Feldhusen & Grote 2013, 16).

Figure 5 (VDI 2209 2009, 9) describes the general design approach of the VDI 2221 and shows that normally a design practice is not made up in the first try. It is a series of tests and improvements throughout the process (Feldhusen & Grote 2013, 16).

The German guideline divides the design process in seven steps being worked on in four different phases: clarification of the task, conceptual design, embodiment design and detail design. Each step contains a form of documentation to present the results achieved in this period.

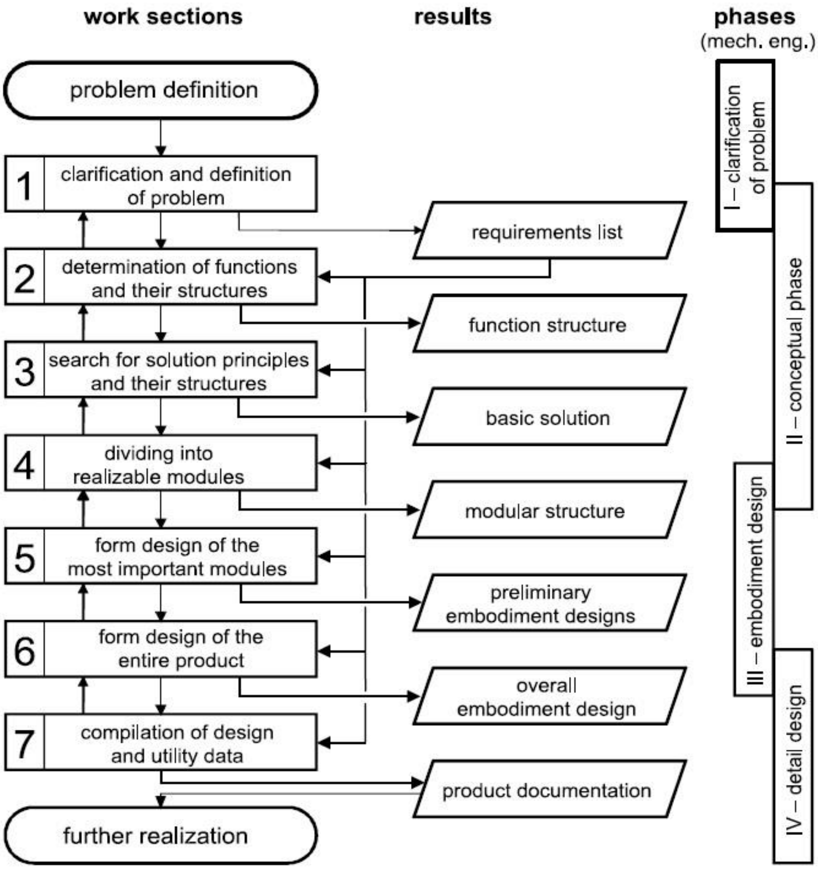



FIGURE 5. General design approach according to VDI 2221

To get to these conclusions, different methods need to be taken into consideration during the design approach. These supports, which are well documented in the literature concerning a design process, help the designer to make decisions, evaluate systems or find solutions for example. Normally the method fitting the situation the most to get to the best possible results gets selected. It is important to mention, that the VDI 2221 chosen for this thesis is not the only approach of a methodology of a design process but one of many.

# 3 CLARIFICATION OF THE TASK

The first phase of the VDI 2221 methodology is the clarification of the task. This period of work includes only the first of the seven design process steps: the clarification and definition of the problem. This is a necessary step to eliminate any possible misunderstanding with the customer. During this time the task is being defined hence clarified and specified (VDI 2221 1993, 10). Thus, a requirements list is documented which lists all the requirements and desires. It is important to mention that findings during the ongoing design process can lead to a change of the requirements list.

## 3.1 Scope

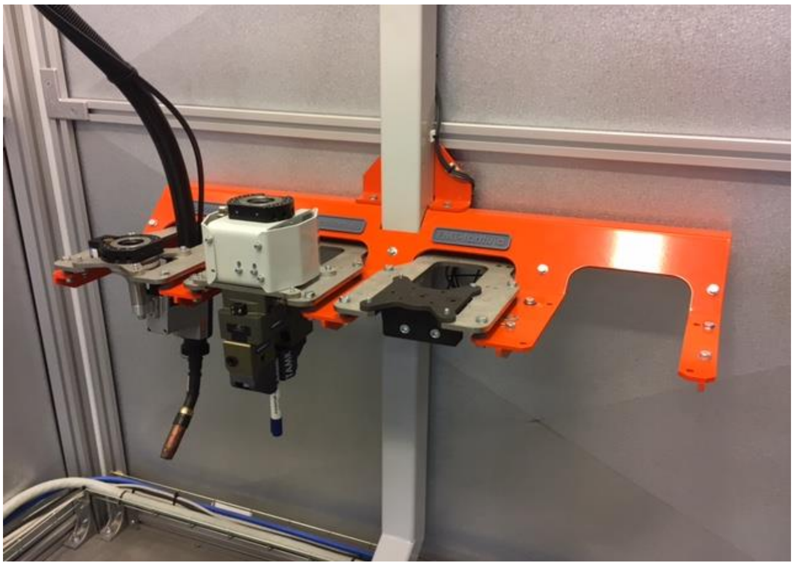
As mentioned in the introduction the thesis work consists of designing a new gripper for the ABB IRB 2600 in TAMK's open lab. Juuso Huhtiniemi is the customer of this project and defined the goals and purpose of the product.

ABB Finland is currently interested in a gripper solution that consists mainly out of 3D-printed parts. The company is interested in the possibilities of the technology and its recent developments in the field. TAMK has the necessary technology to fulfil a solution like that and hence was given the order. This gripper serves as a demonstration tool when customers visit TAMK's laboratory to show them the result of the research. Also, it is being used in class for students to learn the handling of the robot. The students do Pick-and-Place tasks with the gripper. The work consists of a second goal which is to design the gripper lighter than the current one. This would mean a higher productivity for the robot and a better use of the maximum payload. Another demand is that the gripper shall be cheaper than the current version. To achieve this, it is a requirement to get all parts, if possible, from AM as long as they fulfil the design rules and the safety requirements. Parts of the gripper that are not possible to 3D-print are ordered external.

It was agreed on with the customer that the end effector consists of an impactive two finger jaw and due to technical limitations of the equipment in the laboratory it has to be either electrical or pneumatic driven. Also, a decision concerning the gripping strategy has been made beforehand. As mentioned in chapter 2.2.2 there are three possible strategies: external, internal and a combined grip. An external grip can only be achieved if the space around the workpiece allows it. Since this gripper has enough gripping space and because an external grip is the most common one for impactive grippers, the external grip strategy was chosen. These decisions impact and limit the possible solutions for the gripping area. No further specifications of the design or the process itself were made hence the decisions about them are free of any further restrictions as long as it serves as a working solution. Integration of sensors is desired but not a necessary gadget if it fulfils the goal without sensing.

The task consists of the full design process of the gripper, beginning from the conceptual design all the way to printing and implementing it. To prove the functionality of the result the customer composed a goal for the gripper: it needs to be able to accomplish a Pick-and-Place operation with a 1 $kg$ heavy, 80 $mm$ wide object.

Since there are several different mountings for the ABB robot that can be switched at any time, the task also includes the design of a rack that fits in the shelf, which is located right next to the robot (picture 2 and 3). The rack serves as a base for dropping the gripper in the shelf when it is not needed and other mountings are attached on the robot. Picture 3 shows the space in the shelf that is reserved for this task of the project.



PICTURE 3. Shelf for installing the rack

The requirement for the rack is that it differs from the other 3 that are installed in this shelf. The reason for this is because only then it is ensured that the gripper is dropped in the right rack and not accidently in a rack and the position that was designed for another mounting.

### 3.2 Requirements

To clarify all the requirements of the product with the customer, these are listed in a list of requirements (table 4). This is a mandatory step when it comes to the clarification of the task. It is based on the claims of the customer and considers the design rules and specifications of the process. The claims are divided into requirements (=R), which the product must fulfil and desires (=D), which are tried to be implemented.

The list serves as the fundament of any further step in the design process. Further implementations of the gripper must not dissent with any of the listed requirements. If they do, the list has to be updated and the change has to be communicated and agreed on with the customer.

TABLE 4. List of requirements.

| Nr. | R/D | Approach | Details |
|---|---|---|---|
| 1. | Geometry | | |
| 1.1 | D | Gripper | The Gripper needs to be smaller than the current one |
| 1.2 | R | Jaw/Finger | Must be able to pick up at least an 80 $mm$ wide object |
| 1.3 | R | Flange | Needs to fit the flange of the ABB IRB 2600 to connect the gripper |
| 1.4 | R | Weight | New gripper is lighter than the current one |
| 1.5 | R | Rack | Design stable rack that is different from the current ones |
| 2. | Force | | |
| 2.1 | R | Gripping | Fingers need to be able to pick up at least a 1 $kg$ heavy object |
| 2.2 | R | Breakage | Neither finger nor object get damaged due to forces during the operation |
| 3. | Power | | |
| 3.1 | R | Drive | Power comes from an electrical or pneumatic drive |
| 4. | Manufacturing | | |
| 4.1 | R | AM | As many parts as possible are additively manufactured |
| 4.2 | R | External Parts | Parts that cannot be 3D-printed are ordered external |
| 4.3 | R | Quantity | During the thesis one gripper is being manufactured |
| 5. | Design | | |
| 5.1 | R | Design rules | The design process follows the DFAM |
| 5.2 | R | Gripping method | The Gripper consists of an impactive two finger jaw |

| | | | |
|---|---|---|---|
| 5.3 | D | Scaling | Design the gripper in a way that it is easy to scale down and make a smaller 3D-printed version out of it to use the same gripper for smaller robots |
| 6. | Materials | | |
| 6.1 | R | Force resistant | The material can resist the force peaks during the grasp operation |
| 7. | Safety | | |
| 7.1 | R | Injury | No one gets hurt due to damage of the gripper |
| 7.2 | D | Standards | All parts are designed due to international standards |
| 7.3 | D | Sensor | End effector is equipped with sensor-technology |
| 7.4 | R | Stability | Every part of the gripper is stable and does not break during the Pick-and-Place operation |
| 7.5 | D | Communication | The gripper can communicate with the robot |
| 8. | Use | | |
| 8.1 | D | Noise | Noise of the gripper is not unpleasant for humans |
| 8.2 | R | Function | Gripper has an "open" and "close" function |
| 8.3 | D | Range | Gripper is also able to pick up items of different sizes |
| 9. | Maintenance | | |
| 9.1 | D | Wear | The gripper is functioning at least two years |
| 9.2 | D | Replacement parts | Designed in a way so that replacement parts can easily be implemented if needed |
| 10. | Recycling | | |
| 10.1 | D | Environment | Only materials and external parts are used which are easy to recycle hence environmental friendly |
| 11. | Costs | | |
| 11.1 | R | Overall cost | The new gripper is cheaper than the current one |
| 12. | Schedule | | |
| 12.1 | R | End-product | The gripper is ready to use and tested for functionality by 31st of March 2017 |

# 4 CONCEPTUAL DESIGN

This chapter contains the second phase of the methodology. In the conceptual design phase, the next three steps of the design process take place: determination of functions and their structures, search for solution principles and their structures, dividing the gripper into realizable modules.

After defining the functions of a gripper and visualizing their structures the next step is to find solutions for these functions. This is done with the help of a morphological box. Once different solutions for all the functions of the gripper have been found in the morphological box, possible versions of the gripper are created. To decide for one of the possible solutions, these are rated economically and technically with the help of the VDI 2225 system. The design and choice of the gripper and its jaw depends on the work it is supposed to perform. Every gripper is dependent on technological requirements, the object to be moved, handling equipment factors and environmental parameters (Monkman et al. 2007, 63).

## 4.1 Defining systems and functions

First, the functions of the gripper need to be defined. This is a necessary step to evaluate what functions are needed to fulfil with requested solutions. Once they are identified, the functions can be connected to create the structure of the end effector. As shown in figure 6 (modified) the German VDI guidelines define the subsystems of a gripper in their 2740 regulations for robot grippers as follows: basic unit, drive system, kinematic system, control system and gripping area (Blatt 1 1995, 5).

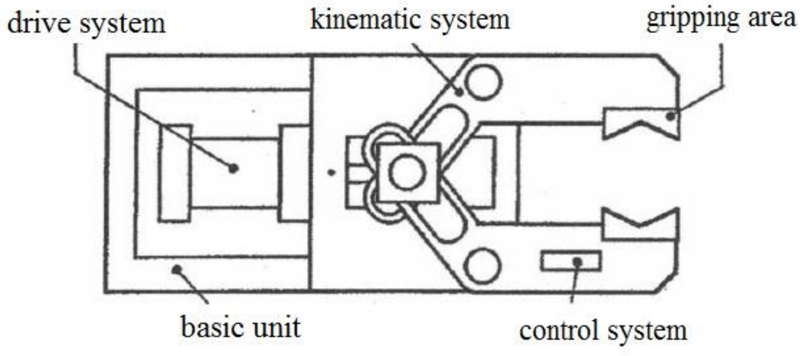



FIGURE 6. Subsystems of a gripper

*Basic unit:* This part serves as the rack of the gripper and connects it with the gripper guide gear of the robot. The unit transfers forces and torques between the gear and the gripper and thus has the following functions:

- rigid or flexible linkage between gripper and guide gear
- possibly opportunity to switch gripper
- transfer of energy and information between gripper and guide gear.

*Drive System:* It provides the end effector with the needed energy to open and close the gripper fingers and the force to hold the object during its movement. The energy can come from mechanical, pneumatic, hydraulic, magnetic or electric sources. Inside the drive system a transformation of the energy into mechanical energy takes place.

*Kinematic System:* The system serves as a converter of movements and forces between the gripping area and the drive system. There are many different kinematic systems to transform the drive motion of the prime mover into movements of the gripping jaw during the opening, closing and holding phase.

*Control system:* All elements that receive, adjust, strengthen, evaluate or forward information about the status of the gripper, parameter of the task and the gripping object are part of the control system. The sensor information is used to regulate or adjust the prehension force.

*Gripping area:* The part of the end effector that touches the object to be handled and transfers the gripping force to the objects surface is called the gripping area. The area of the gripper that touches the object is called active surface. The part of the object that touches the gripper is called passive surface. The larger the active surface, the smaller the pressure on the object surface (VDI 2740 Blatt 1 1995, 5).

After the functions of the gripper parts have been identified, a function structure needs to be created. For this task, it is necessary to look at the main purpose of the workpiece. In this case, it is the prehension of an object. Now that the primary task is known, the next step is to look at the secondary tasks. Figure 7 (Monkman et al. 2007, 36) visualizes these secondary tasks in a process. When the process is known, all possible information concerning the manipulation procedure for the further design process need to be considered. (Naefe & Luderich 2016, 154-156).

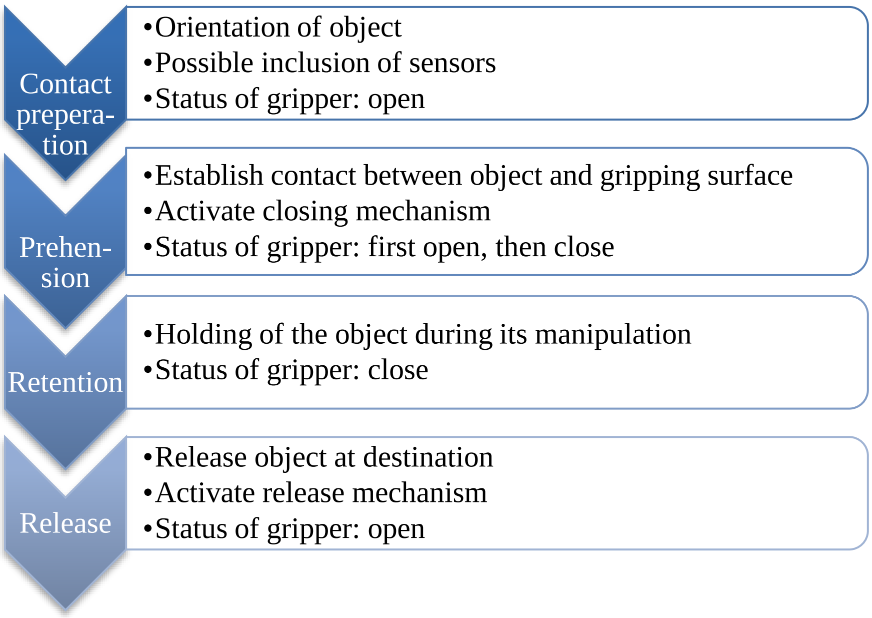



FIGURE 7. Function structure of a gripper

After the subsystems have been pointed out, the different flows during a grasp need to be visualized. Figure 8 (Monkman et al. 2007, 75) shows the structure of a gripper drive chain for one gripping operation. As shown in this figure, the force flow, energy flow and possible information flow between the pieces are the most important aspects needing to be taken into consideration.

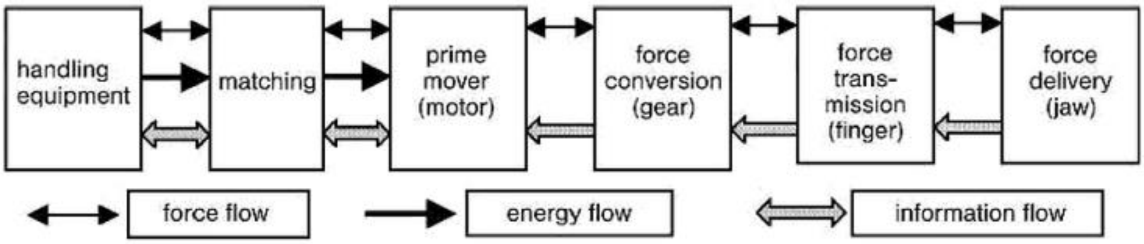



FIGURE 8. Gripper drive chain structure including flows

## 4.2 Solution finding

This is where the third step of the design process starts: search for solutions with the help of brainstorming. For every function that has been defined in chapter 4.1 one or more solutions need to be found that later might be chosen for the project. There are various theoretical methods defined in the lecture that assist during the design process. For this project, possible solutions are found with the help of the morphological analyses. The results of the analyses are visualised in a morphological box (table 5), an order scheme that helps to organize and match the solutions that have been found to every single function (Naefe & Luderich 2016, 180).

TABLE 5. Morphological box

| Subsystem | Solution 1 | Solution 2 | Solution 3 | Solution 4 | Solution 5 |
|---|---|---|---|---|---|
| **Basic Unit** | △ ◆ SCHUNK standard flange | - | - | - | - |
| **Drive System** | Electrical: Stepper motor | Electrical: Servo motor △ | Electrical: linear motor | Pneumatic: Double-acting cylinder ◆ | Pneumatic: Single-acting cylinder |
| **Kinematic System** | Spindle drive △ | Rack and pinion drive | Direct drive from motor | Toggle lever ◆ | - |
| **Control System** | No sensor ◆ | Contactless sensor △ | Contact sensor | - | - |
| **Gripper jaw movement** | Parallel motion ◆ | Circular motion △ | - | - | - |
| **Gripping area** | Shape force-mating | Shape and friction mating ◆ | Pure friction mating △ | - | - |

△ = Variant 1; ◆ = Variant 2

## 4.3 Completing solutions

By logically adding together different features of a mechanical gripper, two realistic versions of the end effector are the result of the morphological analyses, which are summarized in figure 9 and 10. The listed advantages and disadvantages of the variants help assessing them (chapter 4.4) and to identify the variant that fits the situation best.

**Variant 1:**

- SCHUNK standard flange
- Electrical drive – Servo Motor
- Spindle drive
- Contactless Sensor
- Circular Motion
- Pure friction Mating

FIGURE 9. First result from morphological box

Advantages:

- Electrical Servo drive is very precise
- Knows where the object is located because of sensors
- Force control via sensors

Disadvantages:

- Electrical drives are not very strong
- Circular Motion limits the size of the object drastically
- Electrical Motor are expensive
- Inefficient energy consumption, power is needed throughout the whole prehension process

**Variant 2:**

- SCHUNK standard flange
- Pneumatic drive – double acting cylinder
- Toggle lever
- No inbuilt Sensor
- Parallel Motion
- Shape and friction mating

FIGURE 10. Second result from morphological box

Advantages:

- Strong and cheap pneumatic drive
- Parallel Motion allows various object sizes
- Shape and friction mating allows lower forces
- Efficient energy consumption, power is only needed for opening and closing, but not during the prehension process

Disadvantages:

- Can only do an open and close operation
- No information about locating the object

### 4.4 Assessing with economical and technical view

Following the identification of possible solutions for the gripper, the technical and economical valuation of these is the next step to find out which one is more suitable. Table 6 shows this valuation with the requirements of the created requirements list (table 4). Each of the requirements are given a factor between 0…1 which states the importance of it (0 = not important…1 = very important). The variants are than rated in each requirement with a number from 0 to 4 where:

0 = unsatisfactory; 1 = barely acceptable; 2 = adequate; 3 = good; 4 = very good, ideal.

TABLE 6. Technical/Economical assessing

| Aspect | Requirement | Factor | Variant 1 △ | | Variant 2 ◆ | | Ideal | |
|---|---|---|---|---|---|---|---|---|
| | | | Points | Sum | Points | Sum | Points | Sum |
| Technical | Force | 0,25 | 2 | 0,5 | 4 | 1 | 4 | 1 |
| | Easy to use | 0,05 | 2 | 0,1 | 3 | 0,15 | 4 | 0,2 |
| | Intelligence | 0,1 | 4 | 0,4 | 0 | 0 | 4 | 0,4 |
| | Range | 0,1 | 2 | 0,2 | 4 | 0,4 | 4 | 0,4 |
| | Stability | 0,15 | 2 | 0,3 | 3 | 0,45 | 4 | 0,6 |
| | Closing Mechanism | 0,1 | 3 | 0,3 | 1 | 0,1 | 4 | 0,4 |
| | Environment | 0,05 | 1 | 0,05 | 3 | 0,15 | 4 | 0,2 |
| Economical | Cost of Production | 0,1 | 2 | 0,2 | 3 | 0,3 | 4 | 0,4 |
| | Operating costs | 0,1 | 1 | 0,1 | 4 | 0,4 | 4 | 0,4 |
| ∑ | | 1 | | 2,15 | | 2,95 | | 4 |
| Value fitting | | | | **0,54** | | **0,74** | | 1 |

The valuation shows that the second variant fits this project the most. The cheaper and stronger pneumatic drive in combination with the flexible parallel motion of the grippers fit the ideal solution 20% better than the first variant. This means that variant 2 is chosen to be worked on in the continuous steps. Variant 1 is no longer subject of the design process.

# 5 EMBODIMENT DESIGN

In the third phase of the design process, steps five and six take place. Each of the modules are designed separately to reach the final goal of this phase: design the entire product.

The design has been split into the four functions that have been identified in chapter 4.1. The control system unit was left out because it is not implanted in this gripper as a result of the morphological analyses. A structural plan was created to get an overview of the parts that need to be designed (figure 11).

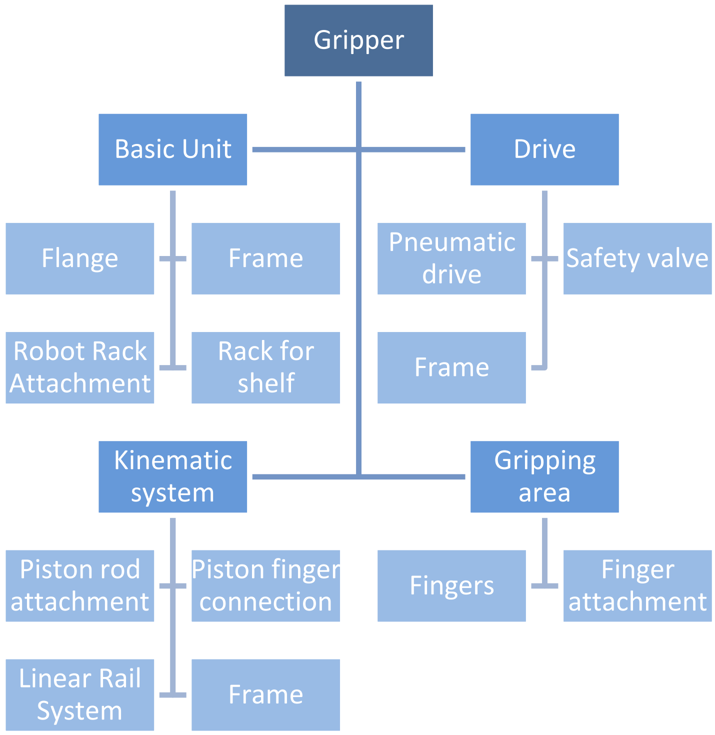



FIGURE 11. Structural plan of the gripper

As mentioned above, a design process does not happen in one step, it is a constant process of going back and forth between the steps until all possible errors are eliminated and the most suitable solutions are found. It is of that reason, that the first step of this phase is the creation of a prototype. The created design for the prototype is then additively manufactured and examined. All the information and improvements that have been identified from this prototype are then implemented in the final product. Possible errors that are found are eliminated and fixed in the end version of the gripper.

### 5.1 Prototype

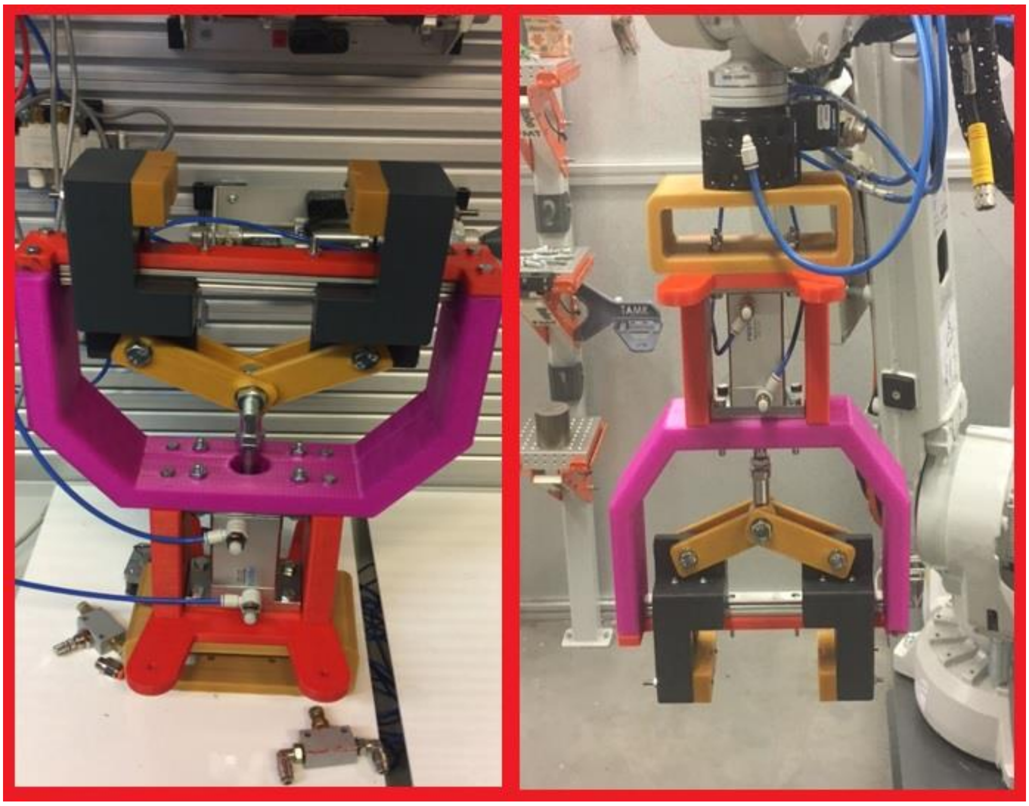
The prototype is designed to test the first created solution. Since one of the requirements is that this version of the gripper is lighter than the current one all parts are first printed in PLA (Polylactic Acid) plastic. The prototypes purpose is then to look at the stability of the parts and if possible outline the parts that are not stable enough for the construction in plastic and need to be printed with metal.

All the ideas coming out of the morphological analyses are realized in this design. It is a pneumatic driven, 2-Finger-Parallel jaw gripper which translates the motion from the piston via a toggle lever. The flange part, the pneumatic drive, a piston attachment, the linear bearing and the attachments like screws, ball bearings, shafts and circlips are ordered externally. None of these items are possible to be manufactured via 3D-printing. The whole base frame for the design, the two gripper fingers and their attachments, the rack-holding and the connection between the piston and the fingers instead are all 3D-printed. Once the solution is agreed on by the customer, the external parts are ordered and the printing of the additively manufactured parts begins (see chapter 7). After the ordered parts arrived and all the other parts were manufactured, the product was assembled and tested for function, strength, fittings and stability.

Picture 4 shows the testing phase of the gripper. Before installing it to the robot the general function was tested in the pneumatic laboratory of TAMK. After it succeeded this test, it is installed to the robot and tested there for further functionalities. Below are the most important discoveries from the installation and testing of the prototype listed:

- it is noticed, that there has been a miscalculation concerning the base-frame on the very bottom, where the rail is installed on. The outer two beams are designed too wide so that it is impossible to slide the two fingers on them. There is a change in the design in the final product to fix this situation
- some of the wholes turned out to be printed too small. This is a result of some of the disadvantages that were mentioned in chapter 2.3.1 as in the tolerance and shrinkage of the material during the print. These holes are scaled a little bigger in the final version to fix this problem
- the DFAM rules were purposely not used in the prototype but are being used in the final product

- slight bending-deformations were noticed in the top frame piece that is connected to the flange because of the weight of the gripper. Support beams are installed in the final product to prevent the piece from breaking while the gripper is in use. All other parts were stable so it was decided that PLA plastic is an acceptable choice of material
- covers are implemented in the final version for openings of the gripper to reduce the risk of injuries
- the prototype was printed in random colours that were available at the time which is going to be changed in the final product. The final product is printed with dark grey and black PLA material
- the prototype is functioning and is able to do a full and safe prehension so the design can be implemented in the final product



PICTURE 4. Prototype testing in pneumatic laboratory (left) and on robot (right)

## 5.2 Basic unit

### 5.2.1 Flange

Due to the very complex design and its amount of small detailed parts inside it is decided that the flange unit is not possible to 3D-print. For that reason, a work-piece is purchased.

The requirements for the flange unit are that it needs to fit the connection piece of the ABB robot, handle the weight of the gripper and the prehension object and have pneumatic connections to provide the air for the cylinder.

After analysing different manufacturers offers for flange units it is decided to purchase one from Schunk (figure 12, Schunk 2017, modified). This flange unit can handle an object of 25 $kg$. It is a universal attachment for several robots from almost all the big manufacturers including ABB's robots. It is characterized by its low weight combined with the capability of lifting high weight objects. The flange (figure 13, #1) is equipped with 8 G1/8" pneumatic connections to power the air to the cylinder through the safety valve.

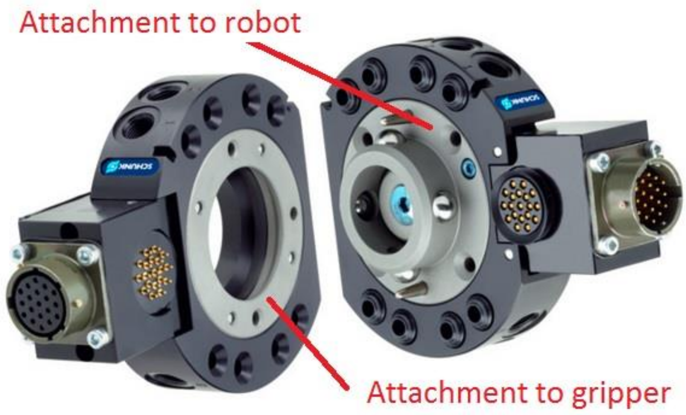



FIGURE 12. Schunk's flange unit

Schunk's Pneumatic flange unit SWA-021-000-000 – Data (Schunk 2017):

- Weight: 300 $g$
- Pneumatic connection: G1/8"
- Operating pressure: 4.5...6.9 $bar$
- according to DIN ISO 9409

There are 4 pre-installed holes in the flange. Four M6 screws attach the gripper to this flange. The screws need to be able to hold the weight of the whole gripper without the flange itself. This calculation represents the number 1 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{(F_{WG} - P1.1)\times g_a}{4} = \frac{(4\ kg - 0{,}3\ kg)\times 9{,}81\ \frac{m}{s^2}}{4} = 9{,}07\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_{WG}$ = Weight-Force gripper
- $F_s$ = Screw-Force
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force a 8.8 screw with the size of M4 is needed. M6 ≥ M4

### 5.2.2 Frame

The upper frame (figure 13, #2) of the gripper is the first piece that is additively manufactured. The purpose of this piece is the connection of the flange that is attached to the robot and the rest of the gripper. Also, the side of the frame serves as the surface for the installation of the Schunk safety valve, which is introduced in chapter 5.3.2. As mentioned in the chapter above, the design in the prototype needed some support to hold the weight of the gripper. For that reason, two v-shaped poles in the middle now support the structure. These give it more stability when it comes to the bending forces and for the torques that occur when the gripper is held in a horizontal motion and all the weight is put on the end of the gripper. On top of the object is a small piece with a long-shaped hole in it installed. Through this hole the pneumatic tubes are going to be installed so that they stick to the construction and do not lay loose in the air and might get stuck at some point. Four screws each are attaching the flange, the robot rack attachment and the Schunk safety valve to the frame to secure a safe grip.

This and all the other additively manufactured parts were decided to be printed in PLA plastic. A comparison of PLA and ABS (Acrylonitrile Butadiene Styrene) plastic can be found in the appendices. The prototype showed that this material is stable enough to resist all the forces and guarantee a safe structure of the gripper. It is not needed to print anything with the metal printer. This step would have had a severe impact on the weight of the gripper. PLA is chosen because it is possible to print more detailed structures with it than ABS and it has a smoother surface. It is also easier to print with PLA plastic and it is eco-friendlier. Another advantage is the fewer percentage of shrinkage of material after the print. This means a more accurate version of the final print. One disadvantage of it is that it can deform in higher temperature surroundings but this case does not occur for the gripper.

### 5.2.3 Robot rack attachment

The rack attachment (figure 13, #3) serves as the base for the gripper to be dropped on when it is positioned in the self-designed shelf. This piece is also 3D-printed which is why unusual curves and edges have been added to match the DFAM rules. No sever changes have been made to the design in the final product compared to the one used in the prototype. It consists of four beams that each contain a hole in them where M5 screws are attached. These screws serve as blockers when the gripper is dropped into the shelf as they are placed in the designated holes in the shelf so that it has a secure grip and does not fall off.

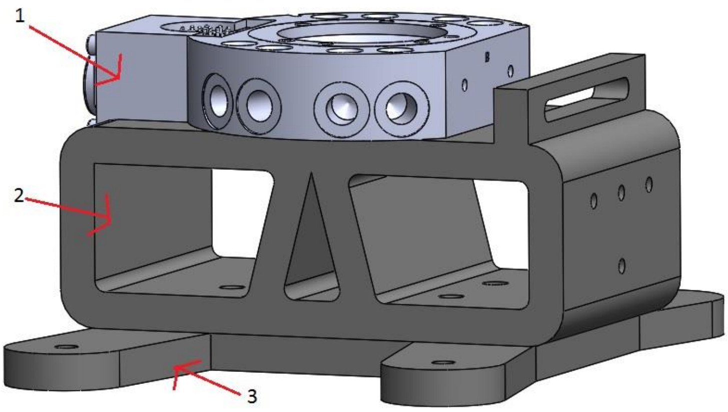



FIGURE 13. Basic unit

### 5.2.4 Rack for shelf

The outside design of the rack had to follow the marginal conditions of the designated shelf (see picture 3) that it is placed in. These marginal conditions are defined by pre-installed drilling holes that connect the rack with the shelf later and other pre-installed screws in the shelf. The inside marginal conditions are defined by the connecting holes in the attachment piece of the gripper and the general marginal conditions of the gripper so that it would fit inside the rack. The aim is to design a big and strong enough work-piece where the robot can drop the gripper in when it is not needed. Also, the matching holes for the attachment piece of the gripper are designed differently than from the other robot attachments to prevent confusion. This way, every robot attachment has its own designated rack in the shelf were it only can be placed in. The occurring forces and the shape of the rack fitted the DFAM so that this workpiece is also additively manufactured.

As mentioned earlier, an object that is 3D-printed is always limited in its size by the size of the 3D-printer. The rack is too big for both, the Ultimaker and the Prenta Duo XL 3D-printers, that is why this workpiece was split in half (figure 14, #1). It is held together by a self-designed connection piece that is also 3D-printed (figure 14, #2). This assembly is connected with four M6 screws.

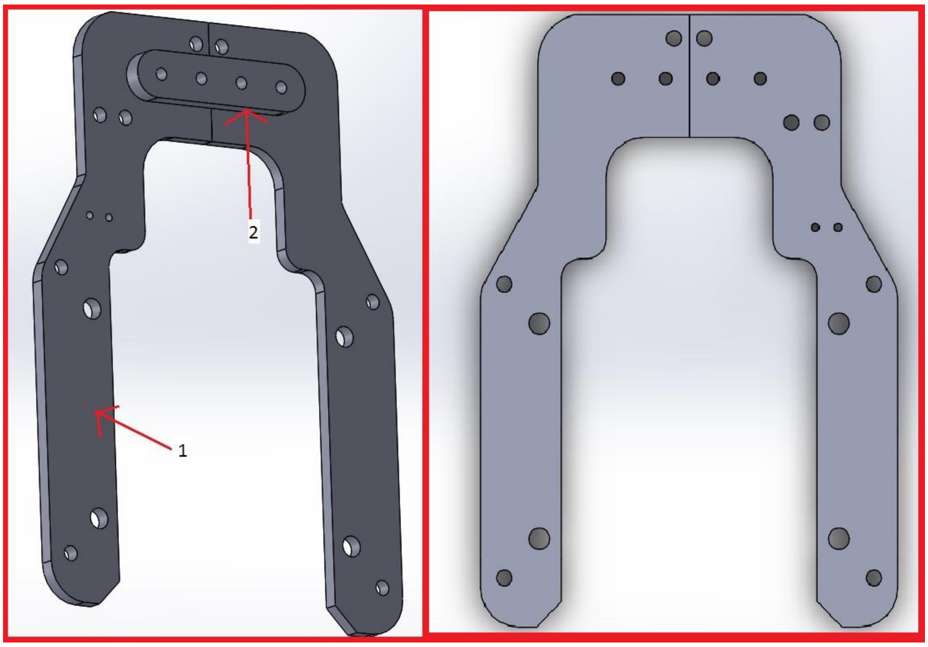



FIGURE 14. Rack for shelf back view (left) and top view (right)

## 5.3 Drive system

### 5.3.1 Pneumatic actuator

As a result of the morphological analyses and the following evaluation of the two versions that came out of it, it was agreed on that the system is powered by a pneumatic double-acting cylinder. To know what size the pneumatic cylinder needs to have to provide enough power to do the prehension without damaging the object, a few calculations needed to be made beforehand. These calculations can be found in the appendices. Due to its results the following cylinder was chosen for this project (figure 15, #4).

Festo ADN-32-40-A-P-A – Data (Festo 2017):

- Piston rod diameter: 32 $mm$
- Stroke: 40 $mm$
- External Thread: M10x1,25

- Conforms to Standard: ISO 21287
- Operating pressure: 0.6...10 *bar*
- Opening Force at 6 *bar*: 483 *N* = $Q_{op}$
- Closing Force at 6 *bar*: 415 *N* = $Q_{cp}$
- Pneumatic connection: G1/8"
- Weight: 301 $g$

The calculations show that the maximum weight of the object that the gripper can do a prehension with is 1,62 $kg$. The cylinder can be opened and closed by the control panel of the robot. Pushing the open/close buttons on the panel results in an airflow through the system that opens and closes the gripper.

To attach the pneumatic actuator to the system a cylinder mounting from Festo is installed (figure 15, #2). The mounting is especially designed for cylinders of this size. There is one attached on top and one on the bottom to ensure a tight attachment without any possible movements of the cylinder. Four screws are connected to the actuator itself and another four are implemented to the gripper frame.
Festo flange mounting FNC-32 – Data (Festo 2017):

- Weight: 221 $g$
- Conforms to Standard: ISO 15552

The bottom four screws hold together the upper part of the gripper and the lower part of the gripper beginning with the main-frame. It means that they have to hold the whole weight of the bottom part of the gripper. They are supported by an additional four screws that connect the main-frame with the frame that is surrounding the cylinder. This calculation represents the number 6 and 7 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{(F_{WG} - P1.1 - P2.3 - P1.2 - P1.3 - 2\times P2.2 - P2.1 - P2.6)\times g_a}{8}$$

$$= \frac{[(4 - 0{,}3 - 0{,}1 - 0{,}35 - 0{,}12 - 2\times 0{,}22 - 0{,}3 - 0{,}38\ )\times kg]\times 9{,}81\ \frac{m}{s^2}}{8} = 2{,}46\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_{WG}$ = Weight-Force gripper

- $F_s$ = Screw-Force
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. For the connection between the main-frame and the cylinder frame a M5 size screw was chosen. M5 ≥ M4. The holes in the FNC attachment were already pre-manufactured and thus a M6 was chosen. M6 ≥ M4.

### 5.3.2 Safety valve

To save the prehension-object from falling or getting damaged in case of a pressure drop a safety valve is installed (figure 15, #1). The valve prevents the air from escaping the cylinder when the pressure drops and keeps the jaws together hence the prehension act going. This installation saves not only the object from getting damaged, but also prevents the object on falling on a foot or any other body part of the person controlling the robot at the time. The safety valve is installed with four screws on the side of the most upper frame of the gripper.

Schunk's safety valve SDV-P 04 – Data (Schunk 2017)

- Weight: 100 *g*
- Operating pressure: 2…10 *bar*
- Pneumatic connection: G1/8"

### 5.3.3 Frame

The frame (figure 15, #3) surrounds the cylinder and the FNC cylinder attachments and connects the bottom of the gripper with the top part. The front opening is covered by a plate which has the writing "TAMK" engraved in it. This exact cover is the reason that the rack attachment piece and this frame have now been split up into two pieces. In the prototype, they were printed as one piece but now that this cover has been added, a smooth and save print is not given any more if the piece would still be one. The reason for that is that too much support material would have been needed and there is no perfect printing direction of the piece. By splitting up the pieces into two different parts they both can be printed very easy and with almost no support material.

Openings on the side have been added so that a nut can tighten the screws that connect this frame with the bigger main-frame from underneath. To save material two big holes have been added to the design that match the circular design of the whole gripper. Similar to the most upper frame that connects the gripper with the flange, also to this frame a small piece with a long-shaped hole in it has been added to the back of it. This hole has the same purpose: the pneumatic tubes are going to be pulled through this hole so that they are not loose and they stick to the construction. This frame is a great example of the possibilities of DFAM. The design shows very rare curves and holes in it, which no other manufacturing method would be able to produce in only one step.

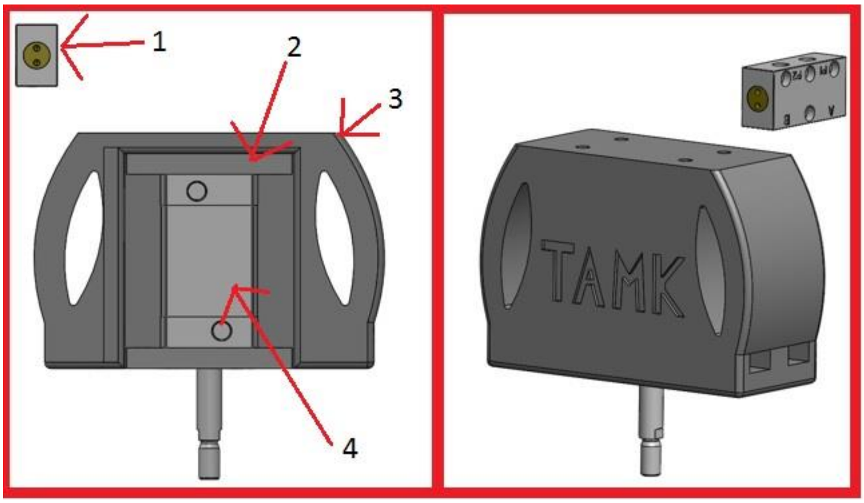



FIGURE 15. Drive system. Back view (left) and side view (right)

## 5.4 Kinematic system

### 5.4.1 Piston rod attachment

To convert the movement from the cylinder to the gripper a toggle lever in combination with a linear rail system is used. The best fit for this kind of systems is a rod eye attachment (figure 17, #1). The rod eye is fixed to the end of the piston and converts the forces through a shaft that is connected through the eye. The company Festo manufactures these kinds of attachments and the rod eye in this system is ordered from them to fit the cylinder, which is also from Festo.

Festo rod eye SGS-M10x1,25 – Data (Festo 2017):

- Weight: 87 *g*
- Size: M10x1,25

### 5.4.2 Piston finger connection

Two self-designed connection pieces (figure 17, #2) connect the shaft in the piston rod eye with each of the two fingers of the gripper. They serve as a converter from the vertical into a horizontal motion. The connection pieces are each equipped with two holes in them: one for the shaft that goes through the rod eye and one for the shaft (figure 17, #6) that goes through the finger. To be able to convert the movement from the piston from a vertical into a horizontal motion each hole in the connection pieces is equipped with a ball bearing (figure 17, #9) where the shafts go through. The top ball bearing has a 10 $mm$ inner-diameter and the bottom one a 8 $mm$ inner-diameter. The shafts have the same diameters so that the ball bearings can fit around them.

Because of tolerances and shrinkage (see chapter 7) of the AM method that is being used for these pieces, the holes are each sized 0,4 $mm$ bigger than the outer-diameter of the ball bearings so that they can fit inside the holes.

To ensure that the ball bearings do not glide of the shaft during the usage, they are saved with circlips (figure 17, #10) which are clamped around a groove in the shaft. The circlips are all according to DIN-471 and were chosen by the size of the shaft. The 10 $mm$ shaft is saved with a DIN 471 – 10 x 1 circlip on each side and the two 8 $mm$ shafts are saved with DIN 471 – 8 x 0,8 circlips on each side.

### 5.4.3 Linear rail system

For the rail aluminium was chosen as material over steel. It is strong enough to handle the light forces that appear during the prehension force but saves almost 60% of the weight compared to a steel version. Only the raceways where the rail touches the sliders are made of stainless steel X46Cr13. A length of the rail of 220 $mm$ is needed to ensure a safe prehension with enough tolerances for the sliders on the sides. The rail (figure 17, #8) has holes in it to attach it to the frame-base. Both rail and sliders are mounted from the top.

Four screws connect the rail with the frame-base and hold the weight of it. This calculation represents the number 11 in the visualization of the screw connections (appendix 7).

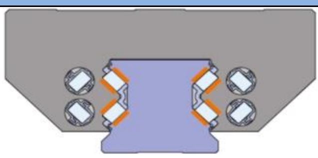
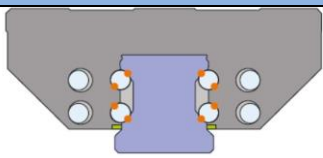
$$F_s = \frac{P3.7 \times g_a}{4} = \frac{0,056\ kg \times 9,81\ \frac{m}{s^2}}{4} = 0,14\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_s$ = Screw-Force
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. The holes in the rail were already pre-manufactured and thus a M4 was chosen. M4 ≥ M4.

Two sliders (figure 17, #7) are attached to the rail to convert the movement of the piston rod. The fingers are later mounted around the sliders to use the movement coming from the piston for the prehension. When it comes to sliders there are two possible solutions for the movement: rolls or balls. Table 7 (Ludwig Meister 2017) shows the comparison between these two and helps making the decision which one fits the system better. For this system, it was important that the movement is transformed in a very light way with the friction reduced to a minimum.

TABLE 7. Properties of rolling bodies

| **Rolling body** | **Roll** | **Ball** |
|---|---|---|
| Visualization |  |  |
| Properties/ Used for | -high loads<br>-high rigidity<br>-high accuracy | -high speed<br>-high acceleration<br>-good friction conditions |

Considering table 7, for this project balls were chosen as the rolling body for the sliders of the linear rail system. The balls can handle the high acceleration caused by the piston rod better than the rolls. Also, the friction conditions are better with this scenario. Properties of the rolls as in high loads or high rigidity are not needed at this point since the system is not handling any real high forces.

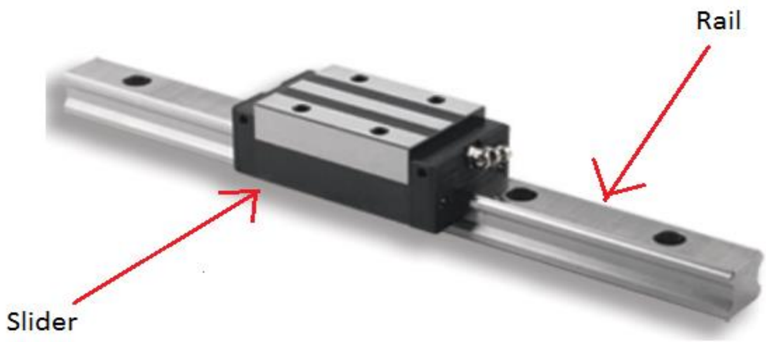



FIGURE 16. Linear bearing

Rollco Rail A15-220 and GNS15 Sliders – Data (Rollco 2017):

- Conforms to Standard: DIN 645-1
- Weight of 2 Sliders: 160 *g*
- Weight of Rail: 126 *g*

### 5.4.4 Frame

This frame consists of three parts: the mainframe itself, the frame cover and the frame-base, which is attached from the bottom. The mainframe (figure 17, #3) is the biggest part of this self-designed gripper. It connects the cylinder with the rail and serves as a base for the whole kinematic system itself. The design is slightly different than the one from the prototype: to have a unique look and to follow the DFAM rules curved beams with holes in them to save material are built in this frame. This kind of design matches the look of the rest of the gripper and is also impossible to manufacture with other kind of manufacturing methods. The mainframe now has curved edges that not only fit the shortened frame-base at the bottom but also saves material costs.

Two frame covers (figure 17, #4), one on each side, are added to the design. They serve as a protection against any kind of injuries from the moving piston, which is the main risk when it comes to possible injuries. They have multiple small openings in them so that viewers can see what kind of processes are happening in the inside but not, for example, put their fingers between any pieces and get hurt. Two screws, one on each side, connect each of the two covers with the main-frame. This calculation represents the number 8 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{2\times P3.6\times g_a}{2} = P3.6\times g_a = 0{,}0542\ kg\ \times 9{,}81\ \ \frac{m}{s^2} = 0{,}53\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_s$ = Screw-Force
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. For this connection, a M6 size screw was chosen. M6 ≥ M4.

The frame-base (figure 17, #5) closes the frame from the bottom and serves as a surface for the rail to be placed on. As mentioned earlier, the frame-base was too wide on the sides in the prototype. Because of that, they have been shortened in the final version. The I-shaped beam has six holes for screws installed in it: two screws attach it to the mainframe and another four connect the rail to the I-beam. The two screws that attach it to the mainframe have to hold the weight of the rail, the sliders, the fingers and their attachments, the frame-base and take the force that is caused by the piston. This calculation represents the number 10 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{[(P3.3 + 2\times P3.4 + 2\times P4.1 +\ 2\times P4.2 + P3.7)\times\ g_a] + F_B}{2}$$
$$= \frac{\left[(0{,}126 + 2\times 0{,}08 + 2\times 0{,}178 +\ 2\times 0{,}0188 + 0{,}056\ )kg\times\ 9{,}81\ \frac{m}{s^2}\right] + 268{,}74\ N}{2}$$
$$= 137{,}98\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_s$ = Screw-Force
- $F_B$ = Force from piston movement (see chapter 6.2.2)
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. For this connection, a M5 size screw was chosen. M5 ≥ M4.

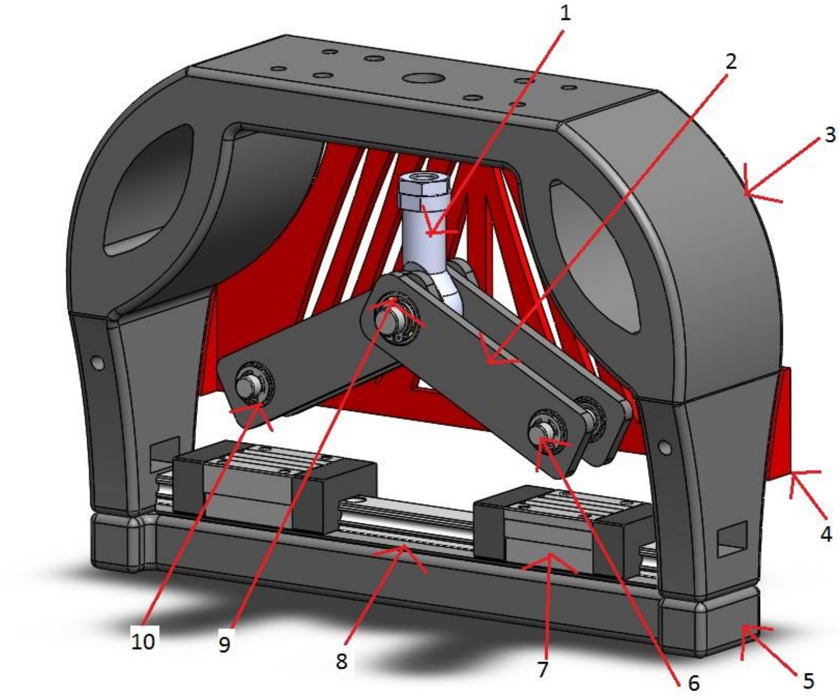



FIGURE 17. Kinematic system without front cover-plate

## 5.5 Gripping area

### 5.5.1 Fingers

The fingers (figure 18, #1) are designed in a way that they are attached around the sliders on the rail. For this, an opening is installed in the centre of the finger for it to fit around the sliders, the rail and the screws and nuts that are attached on the rail. On top of every finger is an opening for the 8 $mm$ shaft which connects the fingers via the connection pieces to the cylinder. The vertical motion of the cylinder now results in a horizontal motion of the fingers on the rail. With this technique, the finger-jaw can be opened when the cylinder pushes out and closed when it pulls in. Each finger is connected by four screws to each slider. The screws on each finger have to handle half of the force that is resulting from the piston movement. This calculation represents the number 9 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{F_B}{2 \times 4} = \frac{268{,}74\ N}{8} = 33{,}59\ N$$

- $F_B$ = Force from piston movement (see appendix 3)
- $F_s$ = Screw-Force

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. The holes in the sliders were already pre-manufactured and thus a M4 was chosen. M4 ≥ M4.

### 5.5.2 Finger attachment

The gripper is designed in a way that it can easily handle objects of different shapes and sizes. For this, adjustable finger attachments were designed to be simply installed or re-installed to the finger. The attachments can just be designed via a CAD software to fit the object that needs to be handled, 3D-printed and then be fixed to the finger with two screws without much work, time effort or complicated adjustments to the finger. The two screws need to hold the weight of the finger attachment itself. This calculation represents the number 12 in the visualization of the screw connections (appendix 7).

$$F_s = \frac{P4.3 \times g_a}{2} = \frac{0{,}042\ kg \times 9{,}81\ \frac{m}{s^2}}{2} = 0{,}22\ N$$

- $P$ = Part number according to part list (appendix 6)
- $F_s$ = Screw-Force
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$

According to table 8-13 in appendix 2 for this force an 8.8 screw with the size of M4 is needed. For this connection, a M5 size screw was chosen. M5 ≥ M4.

The first finger attachment (figure 18, #2) was designed in a way that it would fulfil the requirements of the customer. It can handle a cubic-shaped object with an 80 $mm$ width. The first attachment has a clamping range of 36-95 $mm$. The second finger attachment (figure 18, #3) is a lot longer which results in an actual touching of the two fingers. It is because of that reason that very small pieces can be handled also. This attachment has a clamping range of 0-59 $mm$. Both finger attachments include a circular profile in the middle in case a cylinder-shaped object needs to be handled.

As mentioned in the theory, when designing a gripper the DOF of the workpiece need to be taken into consideration. With these finger attachments, the cubic shaped objects have

2 DOF when they are being handled. The object could fall vertically and it could also be spun in a vertical motion. These motions are not blocked through the finger jaw. All other movements are blocked and saved and give the object a save position when it is gripped.

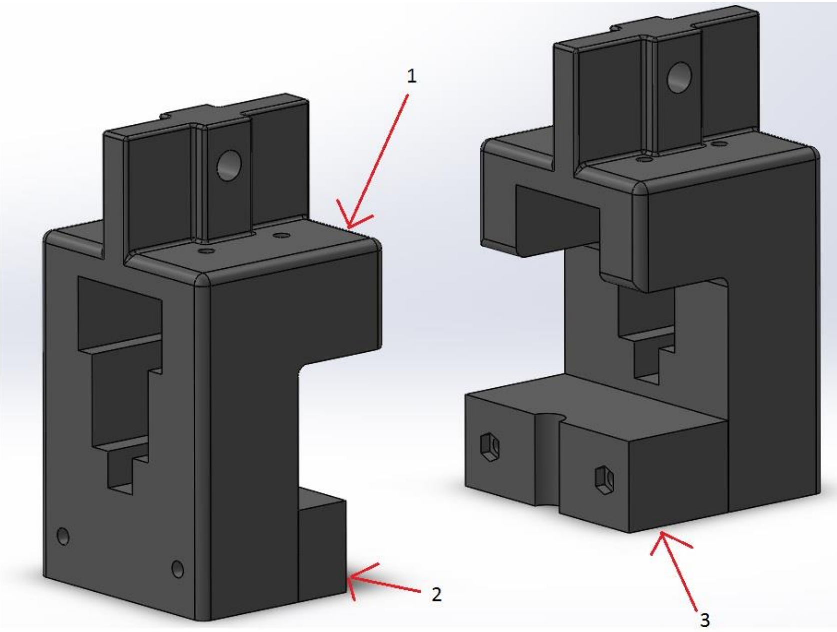



FIGURE 18. Gripping area. Finger with attachment 1 (left) and attachment 2 (right)

# 6 COMPLETION OF WORK

The fourth and last phase includes the final step of the design process: the compilation of the complete design and the documentation. In this chapter a final look at the completed gripper is given, calculations of the most critical parts are demonstrated and further information about the pneumatic plan, safety engineering and the overall costs of the gripper are explained.

## 6.1 Presentation of complete design

After the design process has been declared detailed, this chapter introduces the complete design of the gripper (figure 19). The gripper is also being compared to the old one in use to prove the points of the requirements list.

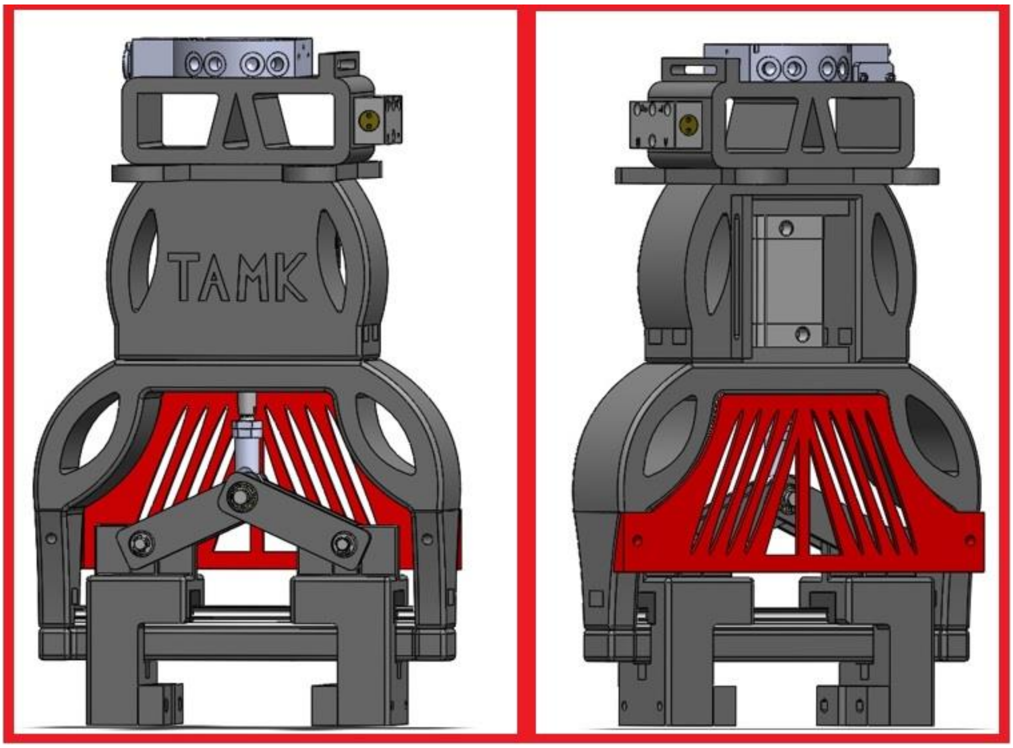



FIGURE 19. Front view without front cover plate (left) and back view (right)

Differing from the prototype, the final version is mainly printed with black & dark grey material. The final data about this gripper can be seen in table 8. The technical drawings of each of the self-designed pieces can be found in the appendices.

TABLE 8. Comparison data between old and new gripper

| | **New gripper** | **Old gripper** |
|---|---|---|
| Total weight: | 4 $kg$ | 8 $kg$ |
| Total height: | 433,56 $mm$ | 310,80 $mm$ |
| Maximum width: | 262 $mm$ | 177 $mm$ |
| Maximum depth: | 85 $mm$ | 150 $mm$ |

Thanks to the AM technology and the parts that are mainly made from plastic this gripper weighs 50% less than the older version.

## 6.2 Safety calculations

### 6.2.1 Strength calculations

<u>Piston rod</u>

*Safety against buckling of the piston rod*

First it needs to be identified what kind of buckling case could occur. The cylinder in this system is mounted on top and has free movement on the bottom so case 1 (see appendix 2) of Euler's buckling cases occurs in this scenario. This means that the buckling length for the calculations needs to be doubled. The next step is to identify if an elastic (Euler) or inelastic buckling occurs. For this the slenderness parameter is needed.

(Wittel et al. 1963, 280)

$$\lambda = \frac{L_{cr}}{i} \qquad \text{( 1 ) Slenderness parameter}$$

- $L_{cr}$ (according to Euler buckling cases, appendix 2) = 2 $\times l$ = 2 $\times$ 181,41 $mm$ = **362,82 $mm$**

(Wittel et al. 1963, 280)

$$i = \frac{d_3}{4} \qquad \text{( 2 ) Radius of gyration}$$

- $d_3$ = diameter of piston rod = 12 $mm$

$$i = \frac{12\,mm}{4} = \boldsymbol{3\,mm}$$

$$\lambda = \frac{362{,}82\,mm}{3\,mm} = \boldsymbol{120{,}94}$$

To identify an elastic or inelastic buckling a comparison to the limiting slenderness is needed.

(Wittel et al. 1963, 280)

| | |
|---|---|
| $\lambda_0 = \pi \times \sqrt{\frac{E}{0{,}8 \times R_{p0{,}2}}}$ | ( 3 ) Limiting slenderness parameter |

- E = Elastic modulus of steel = 210.000 $\frac{N}{mm^2}$
- $R_{p0,2}$ = Yield strength for S235 Steel = 235 $\frac{N}{mm^2}$

$$\lambda_0 = \pi \times \sqrt{\frac{210.000\,\frac{N}{mm^2}}{0{,}8 \times 235\,\frac{N}{mm^2}}} = \boldsymbol{105}$$

$\lambda \geq \lambda_0$ The slenderness is higher or equal to the limiting slenderness so the case of an elastic buckling according to Euler is occuring. Now the buckling stress can be identified.

(Wittel et al. 1963, 280)

| | |
|---|---|
| $\sigma_K = \frac{E \times \pi^2}{\lambda^2}$ | ( 4 ) Buckling stress according to Euler |

$$\sigma_K = \frac{210.000\,\frac{N}{mm^2} \times \pi^2}{120{,}94^2} = \boldsymbol{141{,}70\,\frac{N}{mm^2}}$$

To prove safety for buckling $S$ needs to be $\geq S_{erf} = 3 \ldots 6$

$$S = \frac{\sigma_K}{\sigma_{vorh}} \geq S_{erf} = 3 \ldots 6$$

(Wittel et al. 1963, 279)

$$\sigma_{vorh} = \sigma_d = \frac{F}{A_3}$$ ( 5 ) Occurring stress

- $A_3 = cross - sectional\ area\ of\ piston\ rod = \pi \times r^2 = \pi \times 6\ mm^2 = 113{,}10\ mm^2$
- $F = Force\ occuring\ at\ piston\ rod = 483\ N$

$$\sigma_d = \frac{483\ N}{113{,}1\ mm^2} = \mathbf{4{,}27\ \frac{N}{mm^2}}$$

$$S = \frac{141{,}7\ \frac{N}{mm^2}}{4{,}27\ \frac{N}{mm^2}} = \mathbf{33{,}18} \geq \boldsymbol{S_{erf}}$$

<u>Shaft</u>

*Prove for bending stress of the 8 mm shaft*

(Wittel et al. 1963, 45)

$$\sigma_b = \frac{M_b}{W_b}$$ ( 6 ) Bending stress

- $M_b$ =1539,56 $Nmm$ (see appendix 4)

(Wittel et al. 1963, 132)

$$W_b = \frac{\pi}{32} \times d^3$$ ( 7 ) Resisting torque

- $d$ = 8 $mm$

$$W_b = \frac{\pi}{32} \times 8mm^3 = \mathbf{50{,}27\ mm^3}$$

$$\sigma_b = \frac{1539{,}56\ Nmm}{50{,}27\ mm^3} = \mathbf{30{,}62\ \frac{N}{mm^2}}$$

$\sigma_{b\ zul}$ = 83,33 $\frac{N}{mm^2}$ (see appendix 4)

To prove the shaft for bending $\sigma_b$ needs to be $\leq \sigma_{b\ zul}$

$$\boldsymbol{\sigma_b = 30{,}62\,\frac{N}{mm^2} \leq \sigma_{b\ zul} = 83{,}33\,\frac{N}{mm^2}}$$

A prove for bending stress of the 10 $mm$ shaft is not needed at this point because it is stronger than the 8 $mm$ one.

*Deflection of the 10 mm shaft*

(Wittel et al. 1963, TB-135)

| | |
|---|---|
| $f_m = \dfrac{F \times l^3}{48 \times E \times I}$ | ( 8 ) Deflection |

- $F$ = 483 $N$
- $l$ = distance between two closest bearings = 21 $mm$
- $E$ = Elastic modulus of X5CrNi18-10 ≈ 200.000 $\frac{N}{mm^2}$

(Wittel et al. 1963, TB-132)

| | |
|---|---|
| $I = \dfrac{\pi \times d^4}{64}$ | ( 9 ) Second moment of inertia |

$$I = \frac{\pi \times 10\ mm^4}{64} = \boldsymbol{490{,}87\ mm^4}$$

$$f_m = \frac{483\ N \times 21\ mm^3}{48 \times 200.000\ N/mm^2 \times 490{,}87\ mm^4} = \boldsymbol{9{,}49 \times 10^{-4}\ mm}$$

(Wittel et al. 1963, TB-132)

| | |
|---|---|
| $f_{zul} = \dfrac{l}{3000}$ | ( 10 ) Allowed deflection |

$$f_{zul} = \frac{21\ mm}{3000} = \boldsymbol{7 \times 10^{-3}\ mm}$$

In order to prove against deflection $f_m$ needs to be $\leq f_{zul}$

$$\boldsymbol{f_m = 9{,}49 \times 10^{-4}\ mm \leq f_{zul} = 7 \times 10^{-3}\ mm}$$

<u>Ball bearings</u>

*Strength of the ball bearings*

(Wittel et al. 1963, 533)

$$C_{min} = P\sqrt[p]{\frac{60 \times n \times L_{10h}}{10^6}}$$ ( 11 ) Minimum dynamic load rating

- P = dynamic bearing force = $A_v$ = $B_v$ $= C_v$ $= D_v$ = 120,75 $N$ = 0,12 $kN$
- p = service life exponent (ball bearing) = 3
- n = rotations = $1\frac{1}{min}$
- $L_{10h}$= expected service life = Nr.7 from TB 14-7 (appendix 2) = 14.000 h…32.000 h -> chosen: 14.000 h

$$C_{min} = 0{,}12\ kN\sqrt[3]{\frac{60 \times 1 \times 14.000}{10^6}} = \mathbf{0,11\ kN}$$

The chosen dynamic load rating of the 8 $mm$ ball bearing is **1,3** $\boldsymbol{kN} \geq \mathbf{0,11\ kN}$ . A calculation for the 10 $mm$ bearing is not needed at this point because it is stronger than the 8 $mm$ one.

<u>Circlips</u>

*Safety of the circlips*

A safety calculation is not required as the axial forces are $F_a$ = 0 as shown in figure 25. Carrying capacities of the circlips can be seen in table 9-7 in the appendix 2.

### 6.2.2 Finite element method

The most critical parts of the self-designed pieces are analysed with the finite elements method. This is done with the help of the software Ansys. The parts that are being examined with a static structural analysis are the connection pieces that connect the cylinder with the fingers and the most upper frame that connects the gripper with the flange. These two objects are being analysed about the equivalent Von Mises stress. This method shows that when the maximum value of Von Mises stress interacting on the object is higher than the strength of the material that it is made of it will break (Learning Engineering 2011).

Both objects are made of PLA plastic and their yield strength is 45 $N/mm^2$. The results of these calculations are used to reconsider the structure or even think about another material if the calculations should not be satisfying.

*Analyses of the connection piece*

To identify the force that penetrates the four connection pieces between the cylinder mounting and the fingers, the cos-function is applied to the statics of figure 24. This way the force for the hypotenuse can be calculated and thus the penetrating force of the connection piece identified. The force is divided by the amount of connection pieces because it splits up and penetrates them all equal at the same time.

$$Fx = \frac{Q_{op}}{\cos(\beta_o)\times 4} = \frac{483\ N}{\cos(63{,}3°)\times 4} = \frac{483\ N}{0{,}45\ \times 4}$$

$\boldsymbol{Fx}$ **= 268,74** $\boldsymbol{N}$

This force occurring from the top is being intercepted by the two ball bearings in the holes which are marked as compression supports in this calculation.

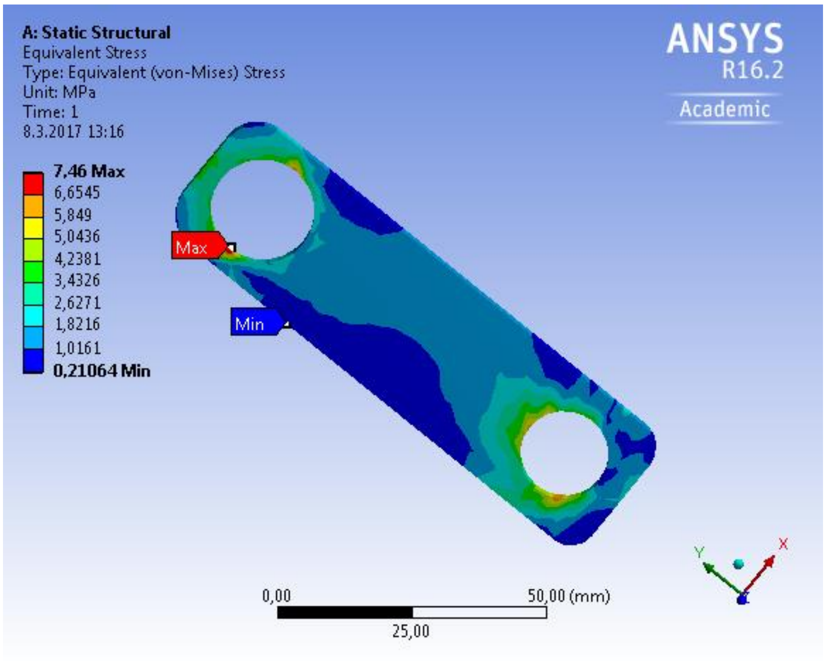



FIGURE 20. FEM Analyses of the connection piece

The highest occurring force in this piece is as shown in figure 20 is ~8 $N/mm^2$.

$$FOS = \frac{F_{allowed}}{F_{occuring}} = \frac{45\ N/mm^2}{8\ N/mm^2} = 5$$

The factor of safety for this piece is 5 and thus it is safe to use because it is $\geq 1$. A safety factor with 1 or lower would mean that the piece gets damaged according to von Mises.

*Analyses of the top frame*

The top frame has four holes on top for the screws that connect it to the flange. These holes are marked as fixed bearings. The frame is penetrated by the weight-force of the whole gripper without the flange $F_B = 36{,}3\ N$ .

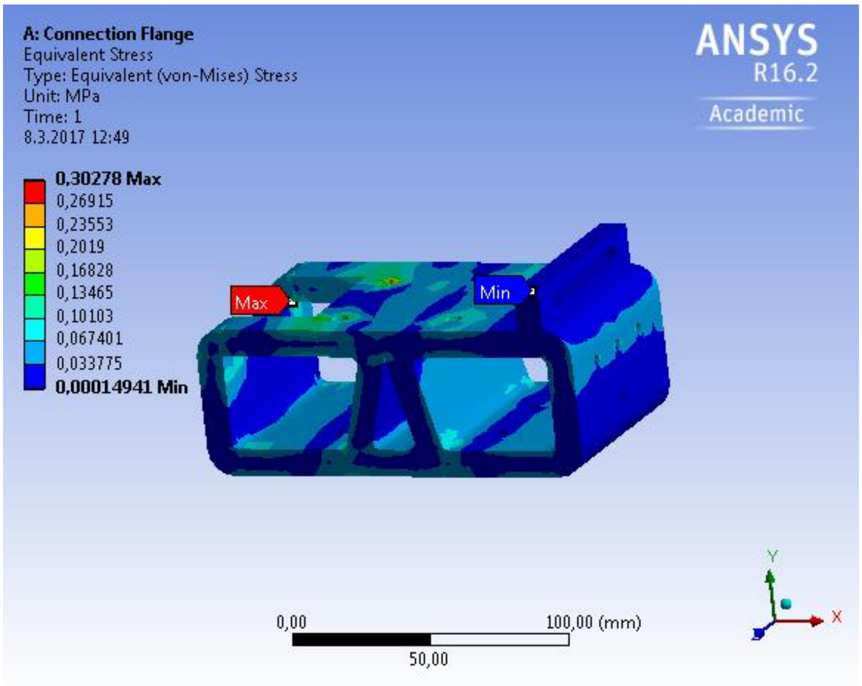



FIGURE 21. FEM Analyses of the top frame

$$FOS = \frac{F_{allowed}}{F_{occuring}} = \frac{45\ N/mm^2}{0{,}3\ N/mm^2} = 150$$

The maximum stress for this piece is 0,3 $N/mm^2$ and thus the factor of safety is 150. The result shows that the frame is overdesigned.

## 6.3 Pneumatic control

Figure 22 (Schunk SDV-P 2016, modified) shows the pneumatic structure that this gripper system is powered with. To get the pneumatic operation started, all the user needs to do is press the “open” and “close” buttons on the control panel of the robot. The compressed air is then being transferred and handled by a 5/2 valve which passes the air through the safety valve. From there the air is being transferred to the double-acting cylinder and makes the cylinder move for- and backwards. As mentioned above, the safety valve in this system prevents the air loss in the cylinder in case of a pressure loss and thus the object that is being handled at this moment is not dropped and damaged.

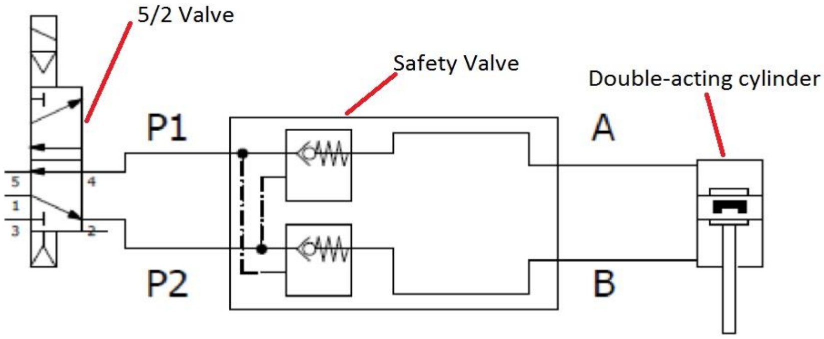



FIGURE 22. Pneumatic plan

## 6.4 Safety engineering

With every new workpiece that is being designed there is always also safety features that need to be fulfilled before the object can be introduced and distributed. Before it is made accessible to the public, all safety regulations need to be installed and ready so that the risk of getting injured is limited to the minimum extent.

Concerning this gripper, the biggest risk is getting hurt by the moving piston of the cylinder. It is because of that reason that cover plates for the frame have been designed. They serve as a blockage between the cylinder and anything else that might encounter it or the inside of the frame.

Another risk that comes with every gripper is getting fingers or other body parts stuck between the gripper jaw. To prevent this from happening two steps need to be followed:

the gripper should never grasp an object directly from the hand, always only from a platform or something similar. Also, one should always use the control panel to open and close the gripper and make sure they have a safe distance to the robot when it is operating.

### 6.5 Documentation of the costs

In the appendices, the detailed listings for the costs of this gripper can be found. The lists were divided into parts that needed to be ordered externally and parts that were possible to 3D-print. Costs for screws, nuts, circlips, shafts, tubes and fittings were left out in this calculation because these are always in stock at TAMK and were not needed to be ordered for this project.

The gripper was printed with PLA plastic. These plastics come rolled up in a spool which are then installed for printing in the 3D-printer. The cost of a PLA spool for the Ultimaker printer with 119 *m* of material is 18,00 € and for the Prenta Duo XL printer with 330 *m* of material is 18,00 €. These figures are converted into the actual used amount of material in the table of the self-designed pieces in the appendices to get the exact price of every piece.

Total costs for external ordered units: 721,52 €
Total costs for additively manufactured units: 47,62 €
**Total cost for gripper: 769,14 €**

The price of the old gripper was approximately 2000 € which means that this version is 1230,86 € cheaper. Due to the help of the AM method it was possible to make this gripper 61% cheaper than the older one.

# 7 MANUFACTURING AND ASSEMBLING

This chapter documents the manufacturing process of the self-designed pieces, followed by a look into the assembling of the parts with the external ordered ones. The explanation of the manufacturing is based on figure 3 which states the steps of the 3D-printing process.

The manufacturing process is demonstrated by one of the gripper fingers. After the design was created with the CAD-software SolidWorks, it needed to be converted to a STL-Format. As a repair software Cura was used in this case because it is very suitable with the Ultimaker printers, which this piece is going to be printed on.

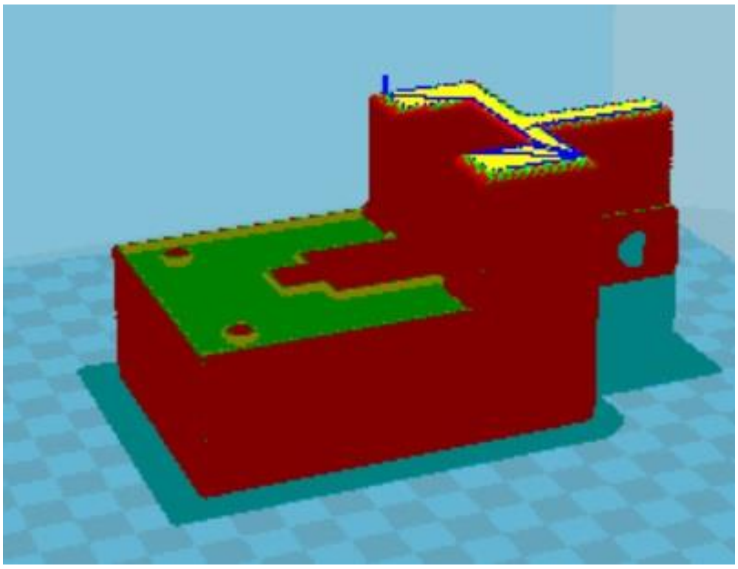
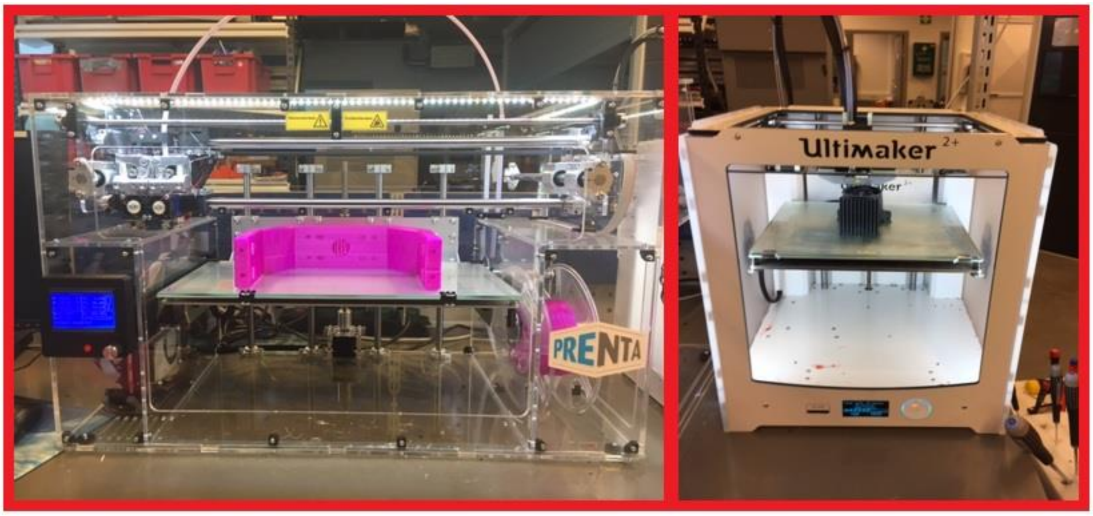


FIGURE 23. Workpiece in Cura software

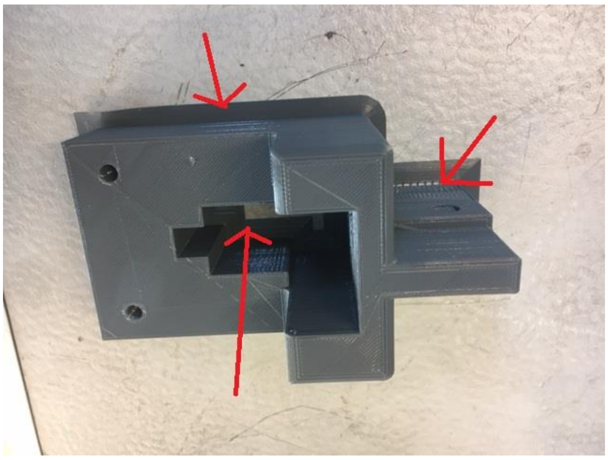
In the figure above the workpiece is shown in the Cura environment. In this software, the piece can be rotated, scaled up or down and duplicated. Also, all information concerning the print can be entered in this program, for instance layer thickness, print speed and fill density. The red and green surfaces in the figure above are the actual material that the gripper finger is made of. The yellow colour visualizes the last layer on top of the piece and the turquoise colour on the edges and the bottom are the support material that is needed for this print to be stable. Once all the information is put into the system, the file needs to be saved on a SD-card and be sent to the printer. Since all the printing information was already put into the software file, no further adjustments need to be done at the printer.

The next step is the actual print which is done completely automatic by the machine itself. The components for this gripper are manufactured with the Ultimaker 2+ and Prenta Duo XL (picture 5) printer in the open lab. These 3D-printers use the FDM technology, meaning that the plastic material gets heated and placed on the platform layer by layer through the nozzle. Both printers work with a 0,4 *mm* nozzle. The FDM technology has a general tolerance of about $\pm 0{,}5$ *mm* or twice the amount of the chosen layer thickness. The support material that might be needed during the printing process is printed through the same nozzle in these printers. Several different plastics can be used for this process but the parts for this project were manufactured with PLA.



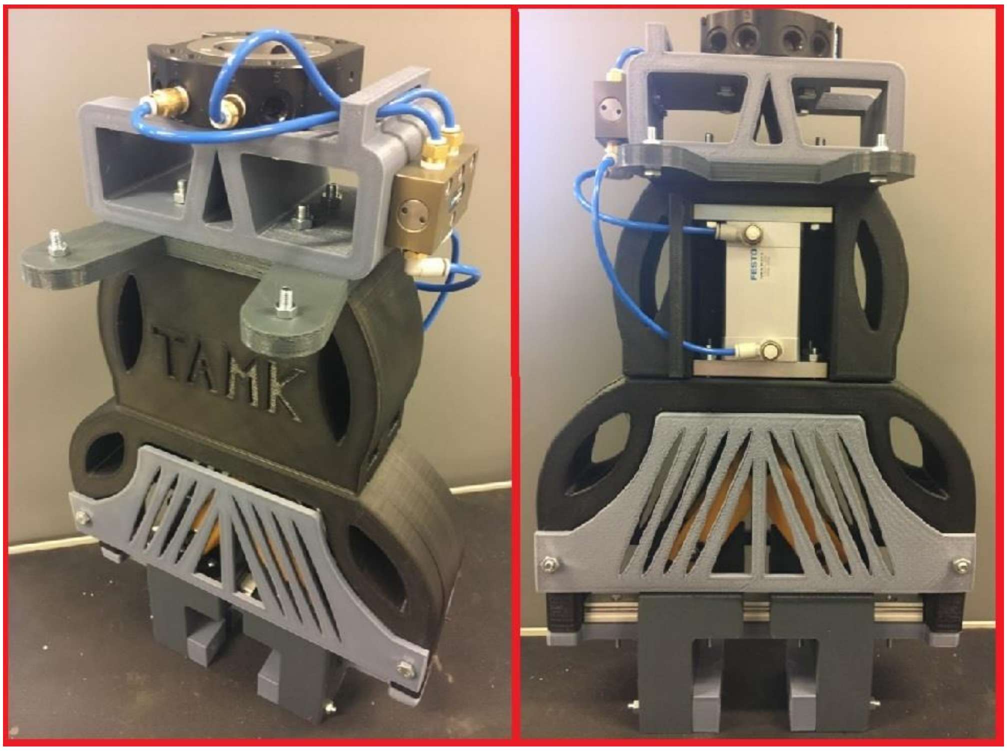

PICTURE 5. Prenta Duo XL (left) and Ultimaker 2+ printer (right)

When the print is done, the piece needs to be taken of carefully from the building platform. Tools like tweezers or similar thin and sharp objects might help if the piece is stuck to the platform. The most difficult and last step before the piece can be taken into usage is the post-preparation of it. The support material that needed to be applied to the structure needs to be removed. This is not that easy because in some cases it is strongly attached to the workpiece. Tools might be required to remove it but it should always be done with much carefulness to not damage the actual piece. As mentioned in the DFAM chapter, it is very important to think of the removal of the support material when designing the object. There is always the need of an opening or a hole to reach and dispense the support structure. Picture 6 shows the support material, marked with red arrows that is stuck to the work piece after the print.



PICTURE 6. Post-processing of workpiece. Removal of the support material

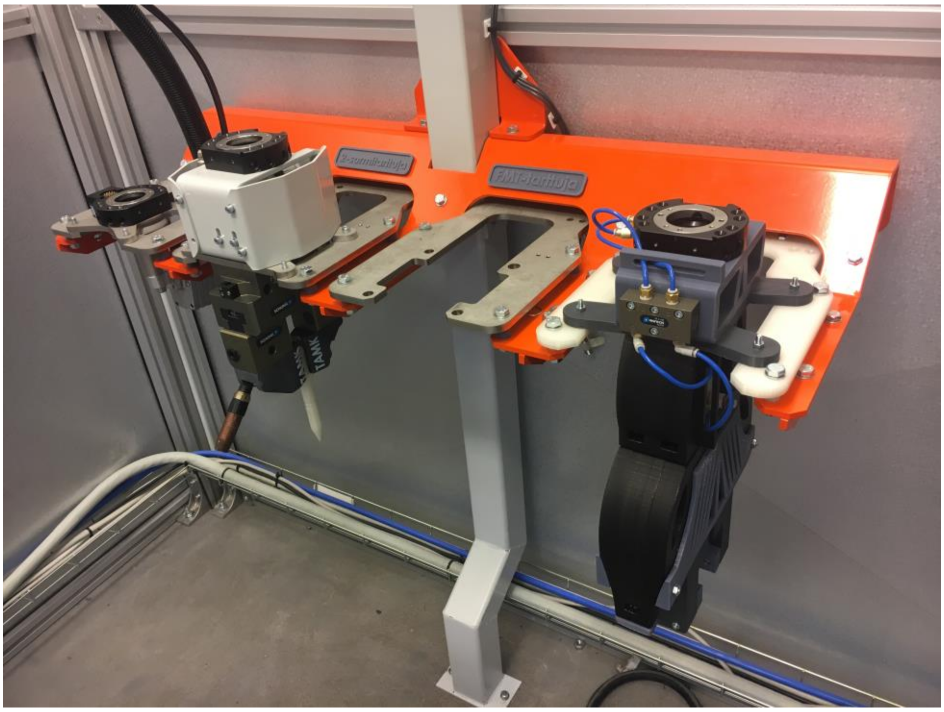
The removal might have left some remains of the material on the object which now needs to be removed to ensure a smooth surface to work with. This can be done with sandpaper or a rasper. When the surface is smooth and free from the support material the workpiece is ready to be used. Now that all the self-designed parts are printed they can be assembled with the external ordered ones. Besides the connection of the shafts, which are being fixed by circlips, all the other parts are being held together by screws and nuts which results in an easy assembly.




PICTURE 7. Complete gripper design. Front view (left) and back view (right)

After all the screws and the circlips have been fixed, the gripper is now ready to be installed to the robot.  Picture 7 shows the assembled gripper with all its manufactured and ordered parts.

The next step is to do the same procedure for the rack in the shelf. The only exception is, that for this object no external parts are needed, except for the screws and nuts. After all the three parts for the rack have been printed, they are assembled together and fixed to the shelf with four screws. Picture 8 shows the rack holding the gripper in the shelf. The robot can now be programmed in such way, that it will always drop the gripper only in this rack when it is not needed.



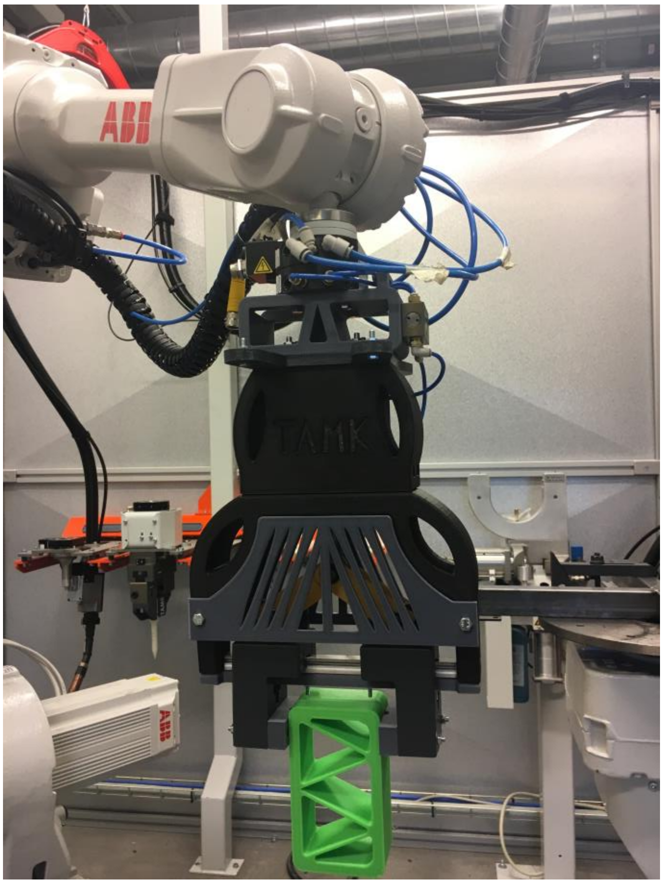

PICTURE 8. Gripper positioned in rack for the shelf

Since also the tubes and fittings for the pneumatic air connections have already been installed, the robot gripper is now ready to be tested to prove its functionality.

# 8 APPLICATION TESTING AND RESULTS

To test the final functionality of the gripper and thus prove that all the requirements from the agreed requirements list are fulfilled, a prehension with an 80 $mm$ wide and ~1 $kg$ heavy object is demonstrated. Only if the gripper succeeds in doing a full prehension process without either dropping the object nor damaging it, the functionality of this gripper is proven and the goal of this thesis reached.

As mentioned, this gripper does not only have a demonstration purpose to show how far the AM technology can be taken into consideration when it comes to grippers, but it is also used in the TAMK laboratory in class for students to learn the basics of the robot. Once they got to know the robot, the gripper and the control panel, it is their task to move an object from one place to another – a Pick-and-Place task. To make sure that the gripper can do so, this is going to be the final test of the gripper. After the self-designed gripper is installed to the robot and the pneumatics, the open and close functions were tested with the control panel. Since no problems were detected during this phase, everything was set for the final test. Picture 9 shows the testing phase and how the object is being handled.




PICTURE 9. Testing-phase of the gripper. Doing a prehension with test object

As seen in the picture the gripper can do a safe prehension process and thus the aim of this thesis is completed. With the different kind of gripper attachments that are easy to install the gripper is now able to grasp objects of many different sizes and shapes. As calculated in the beginning, the theoretical maximum weight of an object it can handle is 1,62 $kg$.

## 8.1 Comparison of early determined requirements

Table 9 shows the comparison of the early determined requirements which were defined together with the customer in chapter 3.2. The desires that were determined at the same time are not part of this comparison because they were not mandatory for this project and thus they are not part of the measure that show the progress of the customer's expectations.

TABLE 9. Comparison of early determined requirements

| Requirement | Fulfilled | Not fulfilled |
|---|---|---|
| Pick up an 80 $mm$ wide, 1 $kg$ heavy object | ☑ | |
| Fit the attachments of the ABB IRB 2600 | ☑ | |
| Lighter than the current gripper | ☑ | |
| Neither object nor gripper get damaged during prehension | ☑ | |
| Power from pneumatic drive | ☑ | |
| Impactive two finger jaw | ☑ | |
| Open and close function | ☑ | |
| Safe handling of the gripper | ☑ | |
| Cheaper than the current gripper | ☑ | |
| Product ready by 31$^{st}$ of March 2017 | ☑ | |
| Build rack different from current ones that holds gripper | ☑ | |

# 9 CONCLUSION AND DISCUSSION

Chapter 8 of this thesis proves, that the main goals of this thesis were fulfilled. The goal was to design, manufacture and implement a new gripper for the open lab that would demonstrate how far the AM technology can be taken into consideration when it comes to the production of a new product like this one. All the parts that could be 3D-printed and fitted the DFAM rules were additively manufactured. The design process was based on the German VDI 2221 rules. To test the functionality of the design, a prototype was produced first. The prototype was functioning and thus began the design of the final product. Various calculations proved the stability of the gripper and after assembling the manufactured pieces with the external ordered ones the gripper was tested for its purpose.

The advantages of this new gripper are now used in the laboratory to teach students the basics of the robotics when they do Pick-and-Place tasks with the new designed gripper. This product is not only cheaper and lighter thanks to the AM method but also more flexible because it can pick up variable objects sizes and shapes.

This gripper does not demonstrate the state of the art though. Companies having much more resources and possibilities can make the gripper an even better fit for the situation. There is still much room for more improvements. For example, sensor technology could be built into the system to make the gripper smarter and able to communicate with the robot and the user. Also with the help of the Finite Element method every single part could be tested for surface and volume optimization. Both steps have not taken place in this work because it would extend the complexity of this work by far.

In conclusion, AM opens a whole new feature for companies considering the manufacturing process. Shapes can now be designed that have yet not been able to be manufactured. Also, the production cycle is now much shorter than originally since the pieces can just be printed directly from the CAD model without having to rely on any suppliers first. A 3D-printer is mobile and can be placed anywhere so production can be moved to the companies' country of origin again and does not have to be outsourced anymore.

But it does not only have its positive sides. It also needs to be taken into consideration that mass production is not yet possible with 3D-printing. The process just takes too long as if it would be possible to do so. This problem costs the company not only time but also a lot of money. However, mass production might not be the main purpose of SD printing, it more likely impresses with its flexibility.

Another problem right now is the tolerance of the printers which are not suitable for some industries yet. The tolerances need to become much lower to manufacture pieces for machines for example. Until these improvements have not been achieved 3D-printing is not yet suitable for some industries. When it comes to the tolerances of the workpieces for this thesis though one needs to consider that no industrial printers were used for the prints. The Ultimaker 2+ and the Prenta Duo XL are both 3D-printers which are not meant for industrial purposes. They can be considered as printers for private uses only. Industrial printers, which are mostly bigger and much more expensive, show much better tolerances and accuracy in its prints.

Another factor that needs to be taken into consideration is the material. It has its advantages, for instance that it is now possible to implement different materials in one single object to fit the different forces in every location of the workpiece. But there is a possibility that the materials that can be used for 3D-printing are not strong enough and thus this technology cannot even be taken into consideration in the first place.

All things considered, it is safe to say that AM is going to shape the future of a lot of business fields when it comes to the manufacturing process. The flexibility of this technique has already influenced the technology in the fields of the medical sector for example. Many prostheses are nowadays produced by AM to exactly fit the needs of the customer. With all these advantages from this technology it is only a matter of time until 3D-printing is going to be found in many other business fields.

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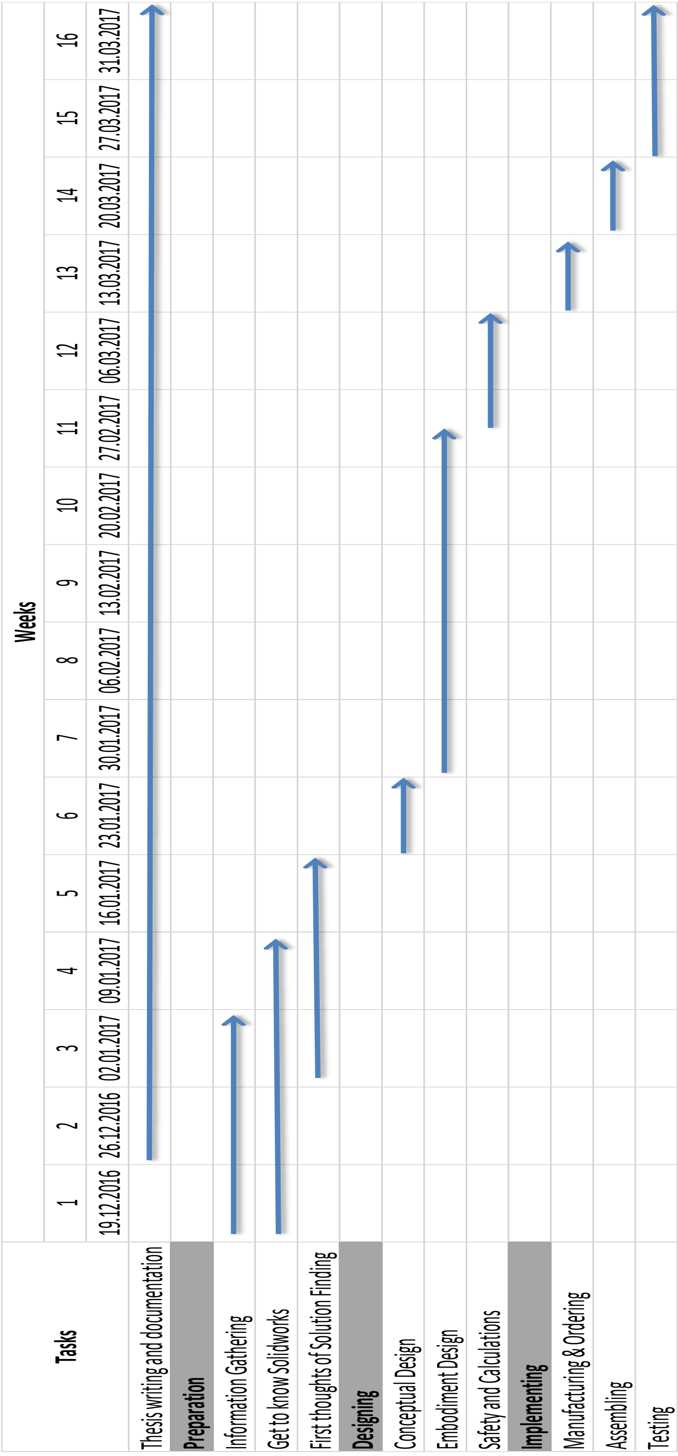
# APPENDICES

## Appendix 1. Project plan



# Appendix 2. Tables used for calculations



## Approximate values for pre-selection of screws

**TB 8-13** Richtwerte zur Vorwahl der Schrauben

| Festig-keits-klasse | Nenndurchmesser in mm für Schaftschrauben bei Kraft je Schraube[1) ] $F_B$ bzw. $F_Q$ in kN bis | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | stat. axial<br>dyn. axial<br>quer | 1,6<br>1<br>0,32 | 2,5<br>1,6<br>0,5 | 4<br>2,5<br>0,8 | 6,3<br>4,0<br>1,25 | 10<br>6,3<br>2 | 16<br>10<br>3,15 | 25<br>16<br>5 | 40<br>25<br>8 | 63<br>40<br>12,5 | 100<br>63<br>20 | 160<br>100<br>31,5 | 250<br>160<br>50 |
| 4.6 | | 6 | 8 | 10 | 12 | 16 | 20 | 24 | 27 | 33 | – | – | – |
| 4.8, 5.6 | | 5 | 6 | 8 | 10 | 12 | 16 | 20 | 24 | 30 | – | – | – |
| 5.8, 6.8 | | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 18 | 22 | 27 | – | – |
| 8.8 | | 4 | 5 | 6 | 8 | 8 | 10 | 14 | 16 | 20 | 24 | 30 | – |
| 10.9 | | – | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 27 | 30 |
| 12.9 | | – | 4 | 5 | 5 | 8 | 8 | 10 | 12 | 16 | 20 | 24 | 30 |

(Wittel, Muhs, Jannasch & Voßiek 1963, TB-111)

## Guide values for service life of ball bearings

**TB 14-7** Richtwerte für anzustrebende nominelle Lebensdauerwerte $L_{10h}$ für Wälzlagerungen (nach Schaeffler-AG)

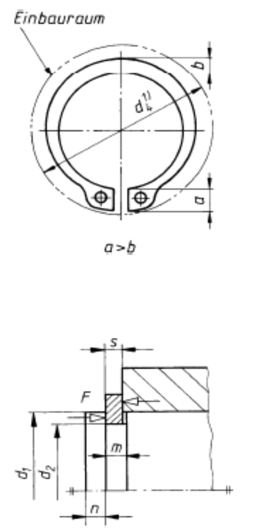
| Nr. | Einsatzgebiet | Anzustrebende Lebensdauer $L_{10h}$ in $h$[1)] Kugellager | Rollenlager |
|---|---|---|---|
| 1 | E-Motoren für Haushaltsgeräte | 1700 ... 4000 | – |
| 2 | Serienelektromotoren | 21000 ... 32000 | 35000 ... 50000 |
| 3 | große Elektromotoren (>100 kW) | 32000 ... 63000 | 50000 ... 110000 |
| 4 | elektrische Fahrmotoren | 14000 ... 21000 | 20000 ... 35000 |
| 5 | Universalgetriebe, Getriebemotoren | 4000 ... 14000 | 5000 ... 20000 |
| 6 | Großgetriebe, stationär | 14000 ... 46000 | 20000 ... 75000 |
| 7 | Werkzeugmaschinengetriebe | 14000 ... 32000 | 20000 ... 50000 |
| 8 | Motorräder | 400 ... 2000 | 400 ... 2400 |
| 9 | PKW-Radlager | 1400 ... 5300 | 1500 ... 7000 |
| 10 | mittlere Lastkraftwagen | 2900 ... 5300 | 3600 ... 7000 |
| 11 | schwere Lastkraftwagen | 4000 ... 8800 | 5000 ... 12000 |
| 12 | Straßenbahnwagen, Triebwagen, Außenlager v. Lokomotiven | – | 35000 ... 50000 |
| 13 | Reise- und Güterzugwagen, Abraumwagen | – | 20000 ... 35000 |
| 14 | Landmaschinen (selbstfahr. Arbeitsmaschinen, Ackerschlepper) | 1700 ... 4000 | 2000 ... 5000 |
| 15 | Schiffsdrucklager | – | 20000 ... 50000 |
| 16 | Förderbandrollen/allgemein, Seilrollen | 7800 ... 21000 | 10000 ... 35000 |
| 17 | Förderbandrollen/Tagebau | 46000 ... 63000 | 75000 ... 110000 |
| 18 | Förderseilscheiben | 32000 ... 46000 | 50000 ... 75000 |
| 19 | Sägegatter/Pleuellager | – | 10000 ... 20000 |
| 20 | Ventilatoren, Gebläse | 21000 ... 46000 | 35000 ... 75000 |
| 21 | Kreiselpumpen | 14000 ... 46000 | 20000 ... 75000 |
| 22 | Zentrifugen | 7800 ... 14000 | 10000 ... 20000 |
| 23 | Spinnmaschinen, Spinnspindeln | 21000 ... 46000 | 35000 ... 75000 |
| 24 | Papiermaschinen | – | 75000 ... 250000 |
| 25 | Druckmaschinen | 32000 ... 46000 | 50000 ... 75000 |

(Wittel, Muhs, Jannasch & Voßiek 1963, TB-157)

## Circlips for shafts

**TB 9-7** Sicherungsringe und -scheiben für Wellen und Bohrungen (Auswahl); Abmessungen in mm

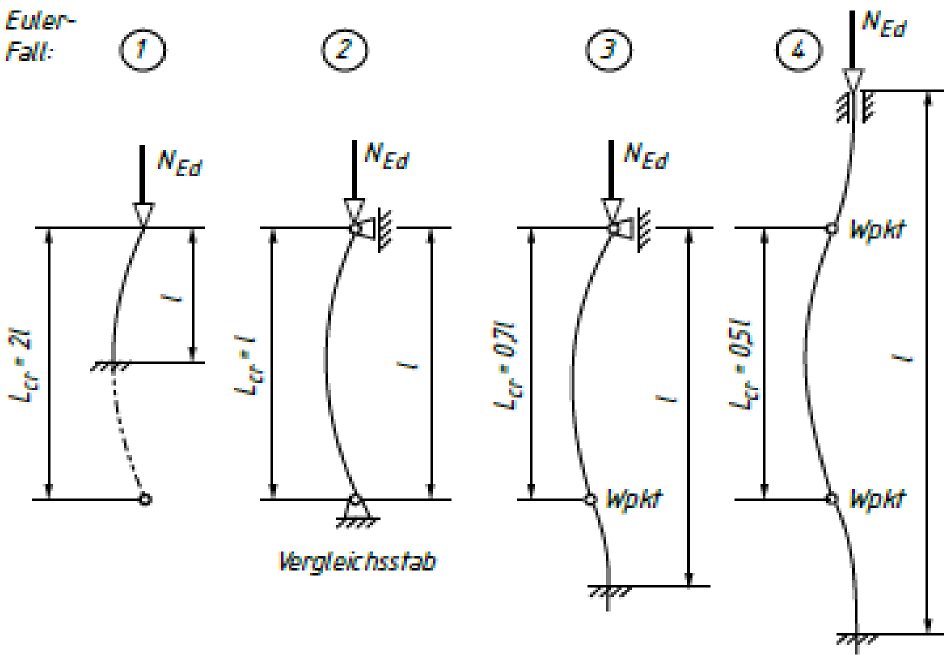
Sicherungsringe für Wellen (Regelausführung) DIN 471




| Wellendurchmesser $d_1$ | Ring $s$[3] | Ring $a$ max | Nut[8] $d_2$[4] | Nut[8] $m$ H13 | Nut[8] $n$ min | Tragfähigkeit Nut $F_N$[6] kN | Tragfähigkeit Ring $F_R$[7] kN |
|---|---|---|---|---|---|---|---|
| 6 | 0,7 | 2,7 | 5,7 | 0,8 | 0,5 | 0,46 | 1,45 |
| 8 | 0,8 | 3,2 | 7,6 | 0,9 | 0,6 | 0,81 | 3,0 |
| 10 | 1 | 3,3 | 9,6 | 1,1 | 0,6 | 1,01 | 4,0 |
| 12 | 1 | 3,3 | 11,5 | 1,1 | 0,8 | 1,53 | 5,0 |
| 15 | 1 | 3,6 | 14,3 | 1,1 | 1,1 | 2,66 | 6,9 |
| 17 | 1 | 3,8 | 16,2 | 1,1 | 1,2 | 3,46 | 8 |
| 20 | 1,2 | 4 | 19 | 1,3 | 1,5 | 5,06 | 17,1 |
| 25 | 1,2 | 4,4 | 23,9 | 1,3 | 1,7 | 7,05 | 16,2 |
| 30 | 1,5 | 5 | 28,6 | 1,6 | 2,1 | 10,73 | 32,1 |
| 35 | 1,5 | 5,6 | 33 | 1,6 | 3 | 17,8 | 30,8 |
| 40 | 1,75 | 6 | 37,5 | 1,85 | 3,8 | 25,3 | 51,0 |
| 45 | 1,75 | 6,7 | 42,5 | 1,85 | 3,8 | 28,6 | 49,0 |
| 50 | 2 | 6,9 | 47 | 2,15 | 4,5 | 38,0 | 73,3 |
| 55 | 2 | 7,2 | 52 | 2,15 | 4,5 | 42,0 | 71,4 |
| 60 | 2 | 7,4 | 57 | 2,15 | 4,5 | 46,0 | 69,2 |
| 65 | 2,5 | 7,8 | 62 | 2,65 | 4,5 | 49,8 | 135,6 |
| 70 | 2,5 | 8,1 | 67 | 2,65 | 4,5 | 53,8 | 134,2 |
| 75 | 2,5 | 8,4 | 72 | 2,65 | 4,5 | 57,6 | 130,0 |
| 80 | 2,5 | 8,6 | 76,5 | 2,65 | 5,3 | 71,6 | 128,4 |
| 85 | 3 | 8,7 | 81,5 | 3,15 | 5,3 | 76,2 | 215,4 |
| 90 | 3 | 8,8 | 86,5 | 3,15 | 5,3 | 80,8 | 217,2 |
| 95 | 3 | 9,4 | 91,5 | 3,15 | 5,3 | 85,5 | 212,2 |
| 100 | 3 | 9,6 | 96,5 | 3,15 | 5,3 | 90,0 | 206,4 |
| 105 | 4 | 9,9 | 101 | 4,15 | 6 | 107,6 | 471,8 |
| 110 | 4 | 10,1 | 106 | 4,15 | 6 | 113,0 | 457,0 |
| 120 | 4 | 11 | 116 | 4,15 | 6 | 123,5 | 424,6 |
| 130 | 4 | 11,6 | 126 | 4,15 | 6 | 134,0 | 395,5 |
| 140 | 4 | 12 | 136 | 4,15 | 6 | 144,5 | 376,5 |
| 150 | 4 | 13 | 145 | 4,15 | 7,5 | 193,0 | 357,5 |

(Wittel, Muhs, Jannasch & Voßiek 1963, TB-119)

## Euler buckling cases




(Wittel et al. 1963, 163)

Appendix 3. Defining the size of the pneumatic cylinder



(Monkman et al. 2007, 88)

$$F_{Gct} = \frac{m \times (g_a + a) \times S}{\mu \times n}$$ ( 12 ) Theoretical closing gripping force

- m = workpiece mass = 1 $kg$
- $g_a$ = acceleration due to gravity = 9,81 $\frac{m}{s^2}$
- a = acceleration in the z-axis = 6 $\frac{m}{s^2}$
- S = safety factor = 3 (Monkman et al. 2007, 52)
- μ = friction coefficient = 0,3 (Monkman et al. 2007, 88)
- n = number of Fingers = 2

$$F_{Gct} = \frac{1\ kg \times \left(9{,}81\ \frac{m}{s^2} + 6\ \frac{m}{s^2}\right) \times 3}{0{,}3 \times 2} = \mathbf{79{,}05\ N}$$

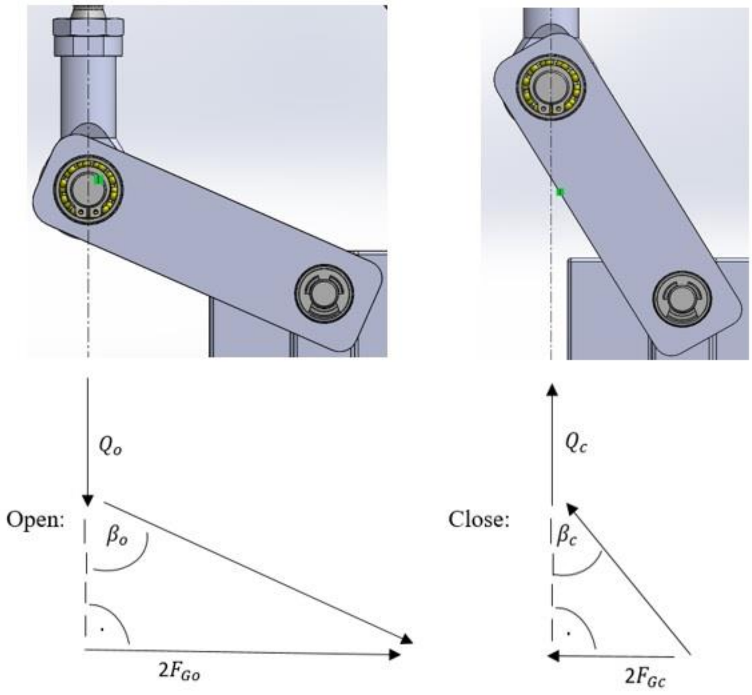



FIGURE 24. Conversion from piston to gripping force during opening and closing

(Monkman et al. 2007, 105)

$$Q_{ct} = \frac{2 \times F_{Gct}}{\tan(\beta_c)}$$ ( 13 ) Theoretical piston closing driving force

- $\beta_c$ = lever angle when gripper closed = 31,7°

$$Q_{ct} = \frac{2 \times 79{,}05\ N}{\tan(31{,}7)} = \frac{2 \times 79{,}05\ N}{0{,}62} = \mathbf{255{,}99\ N}$$

(AHP Merkle 2017)

$$D = \sqrt{\frac{4 \times Q_{ct}}{p_e \times \pi \times \eta}}$$ ( 14 ) Cylinder diameter

- $p_e$ = pneumatic pressure = 6 $bar$ = 6 $\times 10^5$ $Pa$
- η = piston efficiency = 0,7 (Monkman et al. 2007, 84)

$$D = \sqrt{\frac{4 \times 255{,}99\ N}{6 \times 10^5\ Pa \times \pi \times 0{,}7}} = \mathbf{0{,}028\ m} = \mathbf{28\ mm}$$

$Q_{cp}$ = practical closing driving force from chosen Festo cylinder = 415 N

$F_{Gcp}$ = Practical closing Gripping force =

$$\frac{\tan(\beta_c) \times Q_{cp}}{2} = \frac{0{,}62 \times 415\ N}{2} = \mathbf{128{,}65\ N}$$

Maximum mass of the item to be handled =

$$m = \frac{F_{Gct} \times \mu \times n}{(g_a + a) \times S} = \frac{128{,}65\ N \times 0{,}3 \times 2}{\left(9{,}81\ \frac{m}{s^2} + 6\ \frac{m}{s^2}\right) \times 3} = \mathbf{1{,}62\ kg}$$

# Appendix 4. Defining the size of the shafts



*Defining the size of the 10 mm shaft*

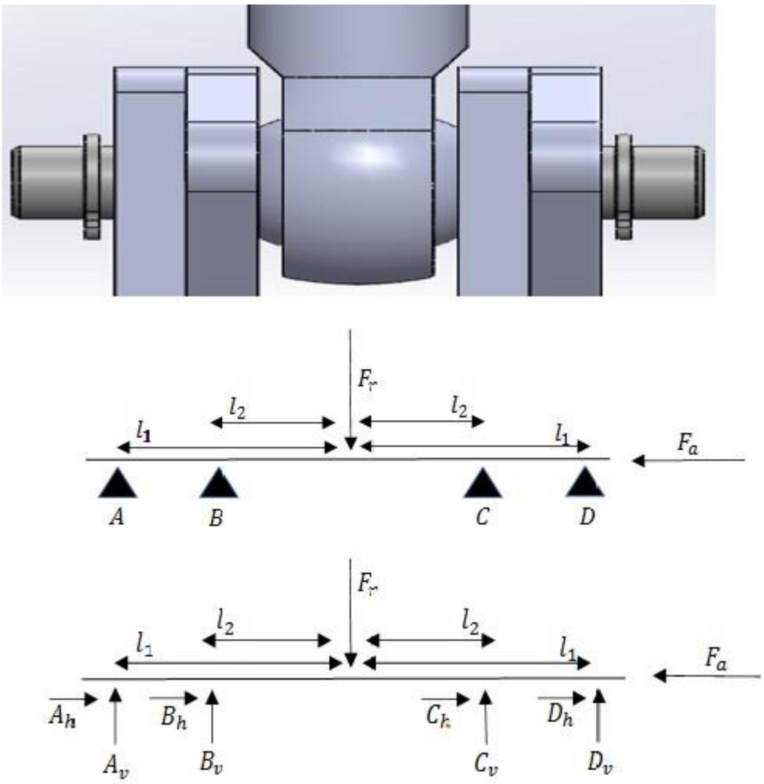



FIGURE 25. Forces occurring at the shaft

- $F_r = Q_{op} = 483\ N = A_v + B_v + C_v + D_v$
- $A_v = B_v = C_v = D_v = 120{,}75\ N$
- $F_a = A_h = B_h = C_h = D_h = 0\ N$
- $l_1 = 12{,}75\ mm$
- $l_2 = 7{,}75\ mm$

(Wittel et al. 1963, 371)

$$d \geq \sqrt[3]{\frac{32 \times M_{b\,max}}{\pi \times \sigma_{b\,zul}}}$$

( 15 ) Shaft diameter according to bending moment

(Wittel et al. 1963, 371)

| | |
|---|---|
| $M_{b\ max} = A_v \times l_1$ | ( 16 ) Maximum bending moment |

$M_{b\ max} = 120{,}75\ N \times 12{,}75 mm\ =\ \mathbf{1539{,}56\ Nmm\ =\ 1{,}54\ Nm}$

(Wittel et al. 1963, 371)

| | |
|---|---|
| $\sigma_{b\ zul} = \frac{\sigma_{bD}}{S_{D\ min}}$ | ( 17 ) Allowed bending stress |

- $S_{D\ min}$ = 3…4 = chosen -> 3
- $\sigma_{bD}$ = fatigue strength for X5CrNi18-10 = 250 $\frac{N}{mm^2}$

$$\sigma_{b\ zul} = \frac{250\ \frac{N}{mm^2}}{3} = \mathbf{83{,}33\ \frac{N}{mm^2}}$$

$$d \geq \sqrt[3]{\frac{32 \times 1539{,}56\ Nmm}{\pi \times 83{,}33\ \frac{N}{mm^2}}} = \mathbf{5{,}73\ mm}$$

Chosen shaft diameter: **10** $\mathbf{mm \geq}$ **5,73** $\mathbf{mm}$

*Defining the size of the 8 mm shaft*

A calculation is not needed at this point since the minimum diameter was calculated as 5,73 $mm$. **8** $\mathbf{mm \geq}$ **5,73** $\mathbf{mm}$

Appendix 5. Comparison of ABS and PLA as building material

| **Material** | **ABS Acrylonitrile butadiene styrene** | **PLA Polylactide** |
|---|---|---|
| Density | 1,04 $g/cm^3$ | 1,24 $g/cm^3$ |
| Tensile strength $[N/mm^2]$ | ~35 | ~45 |
| Flexural strength $[N/mm^2]$ | ~36 | ~55 |
| E-Modulus $[N/mm^2]$ | ~2300 | ~3500 |
| Shrinkage | ~8 % | ~2 % |
| Pros | -can undergo more heat, temperature and stress<br>-better for wear and tear<br>-better properties for post processing (e.g. drilling) | -Not temperature sensitive during printing process<br>-great surface quality<br>-decent strength<br>-can handle more weight before breaking<br>-more complex design features |
| Cons | -temperature sensitive during printing process<br>-susceptible to curling and warping during print<br>- will bend under stress | -not made for a lot of wear and tear<br>- will break under stress<br>-lower melting point |

(Gartner 2014)

Appendix 6. Complete part list

1(3)

| **Part-Nr.** | **Item** | **Quan-tity** | **Unit** | **Additively Manufac-tured** | **Exter-nal Order** |
|---|---|---|---|---|---|
| **1.** | **Basic Unit** | | | | |
| 1.1 | Flange Unit SWA-021-000-000 | 1 | pc. | | X |
| 1.2 | Frame | 1 | pc. | X | |
| 1.3 | Robot rack-attachment | 1 | pc. | X | |
| 1.4.1 | Rack for shelf – left side | 1 | pc. | X | |
| 1.4.2 | Rack for shelf – right side | 1 | pc. | X | |
| 1.4.3 | Rack for shelf – connection piece | 1 | pc. | X | |
| 1.5 | Connection piece for Rack | 1 | pc. | X | |
| 1.6 *(1)* | M6 x 20 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 1.7 *(4)* | M5 x 20 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 1.8 | M5 – 8 – ISO 4032 | 4 | pc. | | X |
| 1.9 *(13)* | M6 x 30 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 1.10 | M6 – 8 – ISO 4032 | 4 | pc. | | X |
| 1.11 *(14)* | M8 x 40 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 1.12 | M8 – 8 – ISO 4032 | 4 | pc. | | X |
| **2.** | **Drive System** | | | | |
| 2.1 | Pneumatic Drive ADN-32-40-A-P-A. ISO 21287 | 1 | pc. | | X |
| 2.2 | FNC-32. ISO 15552 | 2 | pc. | | X |
| 2.3 | Schunk Safety Valve SDV-P 04 | 1 | pc. | | X |
| 2.4 | Fitting | 8 | pc. | | X |
| 2.5 | Tube | 4 | pc. | | X |
| 2.6 | Frame | 1 | pc. | X | |
| 2.7 *(2)* | M4 x 30 – 8.8 – ISO 4762 | 4 | pc. | | X |
| 2.8 | M4 – 8 – ISO 4032 | 4 | pc. | | X |

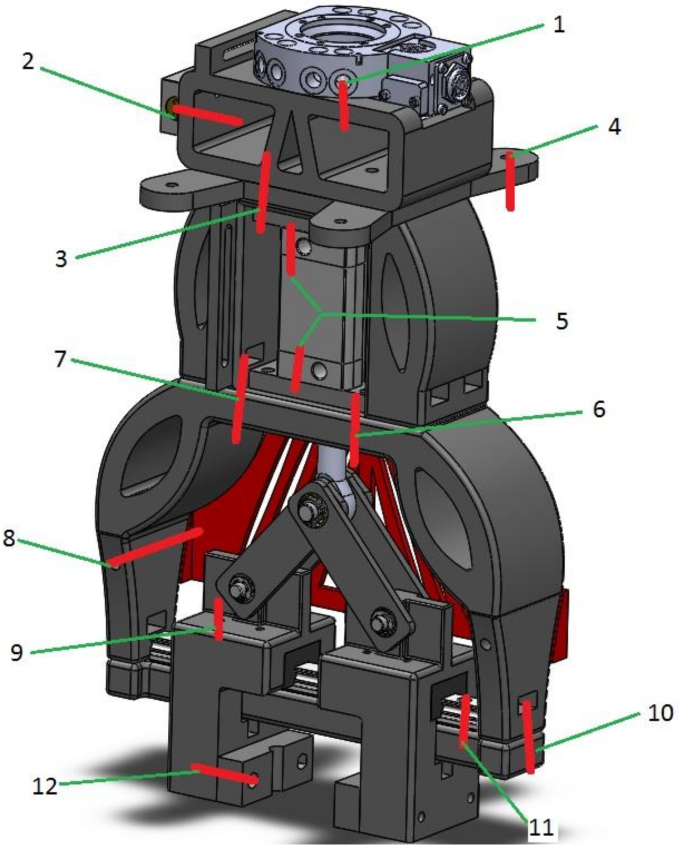
2 (3)

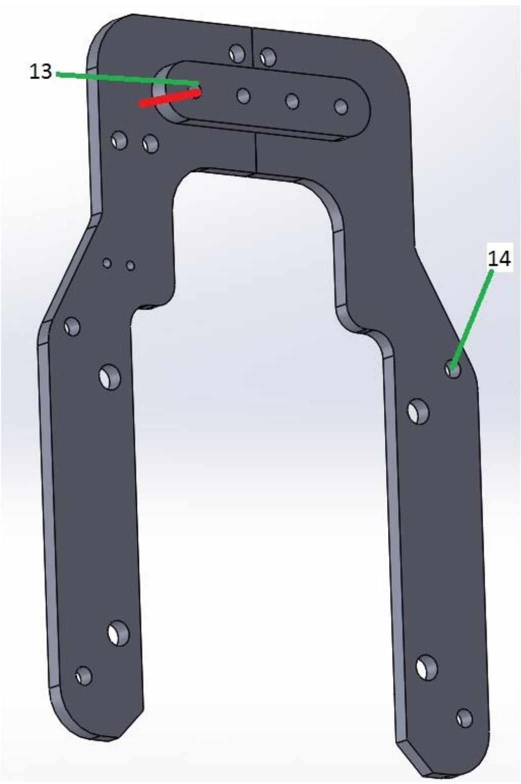
| | | | | | |
|---|---|---|---|---|---|
| 2.9 *(3)* | M6 x 50 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 2.10 | M6 – 8 – ISO 4032 | 4 | pc. | | X |
| 2.11 *(6)* | M6 x 40 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 2.12 | M6 – 8 – ISO 4032 | 4 | pc. | | X |
| 2.13 *(5)* | M6 x 20 – 8.8 – ISO 4762 | 8 | pc. | | X |
| **3.** | **Kinematic System** | | | | |
| 3.1 | Rod eye SGS-M10x1,25 DIN ISO 8139 | 1 | pc. | | X |
| 3.2 | Piston/Finger-connection | 4 | pc. | X | |
| 3.3 | Linear Rail A15-220 | 1 | pc. | | X |
| 3.4 | Linear Sliders GNS15 | 2 | pc. | | X |
| 3.5 | Frame | 1 | pc. | X | |
| 3.6 | Frame cover | 2 | pc. | X | |
| 3.7 | Frame-base | 1 | pc. | X | |
| 3.8 | Ball Bearing D: 8 *mm* | 4 | pc. | | X |
| 3.9 | Ball Bearing D: 10 *mm* | 4 | pc. | | X |
| 3.10 | Shaft D: 8 *mm* | 2 | pc. | | X |
| 3.11 | Shaft D: 10 *mm* | 1 | pc. | | X |
| 3.12 | Circlip D: 8 *mm* | 4 | pc. | | X |
| 3.13 | Circlip D: 10 *mm* | 2 | pc. | | X |
| 3.14 *(7)* | M5 x 40 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 3.15 | M5 – 8 – ISO 4032 | 4 | pc. | | X |
| 3.16 *(8)* | M6 x 80 – 8.8 – ISO 4017 | 2 | pc. | | X |
| 3.17 | M6 – 8 – ISO 4032 | 2 | pc. | | X |
| 3.18 *(11)* | M4 x 30 – 8.8 – ISO 4762 | 4 | pc. | | X |
| 3.19 | M4 – 8 – ISO 4032 | 4 | pc. | | X |
| 3.20 *(10)* | M5 x 40 – 8.8 – ISO 4017 | 2 | pc. | | X |

| | | | | | |
|---|---|---|---|---|---|
| 3.21 | M5 – 8 – ISO 4032 | 2 | pc. | | X |
| **4.** | **Gripping Area** | | | | |
| 4.1 | Finger | 2 | pc. | X | |
| 4.2 | Finger attachment 1 | 2 | pc. | X | |
| 4.3 | Finger attachment 2 | 2 | pc. | X | |
| 4.4 *(12)* | M5 x 50 – 8.8 – ISO 4017 | 4 | pc. | | X |
| 4.5 | M5 – 8 – ISO 4032 | 4 | pc. | | X |
| 4.6 *(9)* | M4 x 16 – 8.8 – ISO 7045 | 8 | pc. | | X |

The cursive numbers in apprentices indicate the screw connection (see appendix 7).

Appendix 7. Visualization of the Screw-connections




The red lines indicate the parts that the screw connections hold together.

Appendix 8. Documentation of the costs

Detailed costs of the external ordered units 1 (2)

| Part-Nr. | Item | Quantity | Unit | Cost per unit | Total cost |
|---|---|---|---|---|---|
| 1.1 | SCHUNK Flange Unit SWA-021-000-000 | 1 | pc. | 281,24 € | 281,24 € |
| 2.1 | Festo Pneumatic Drive ADN-32-40-A-P-A | 1 | pc. | 66,60 € | 66,60 € |
| 2.2 | Festo FNC-32 attachment | 2 | pc. | 18,68 € | 37,36 € |
| 2.3 | SCHUNK Safety Valve SDV-P 04 | 1 | pc. | 172,46 € | 172, 46 € |
| 3.1 | Festo Piston rod attachment SGS-M10x1,25 | 1 | pc. | 24,86 € | 24,86 € |
| 3.3 | Linear Rail A15-220 | 1 | pc. | 80,60 € | 80,60 € |
| 3.4 | Linear Sliders GNS15 | 2 | pc. | | |
| 3.8 | Ball Bearing D: 8 $mm$ | 4 | pc. | 4,80 € | 19,20 € |
| 3.9 | Ball Bearing D: 10 $mm$ | 4 | pc. | 9,80 € | 39,20 € |
| | | | | | **∑ 721,52 €** |

PLA spool for the Ultimkaker 2+ with 119 *m* of material: 18,00 €

PLA spool for the Prenta Duo XL with 330 *m* of material: 18,00 €

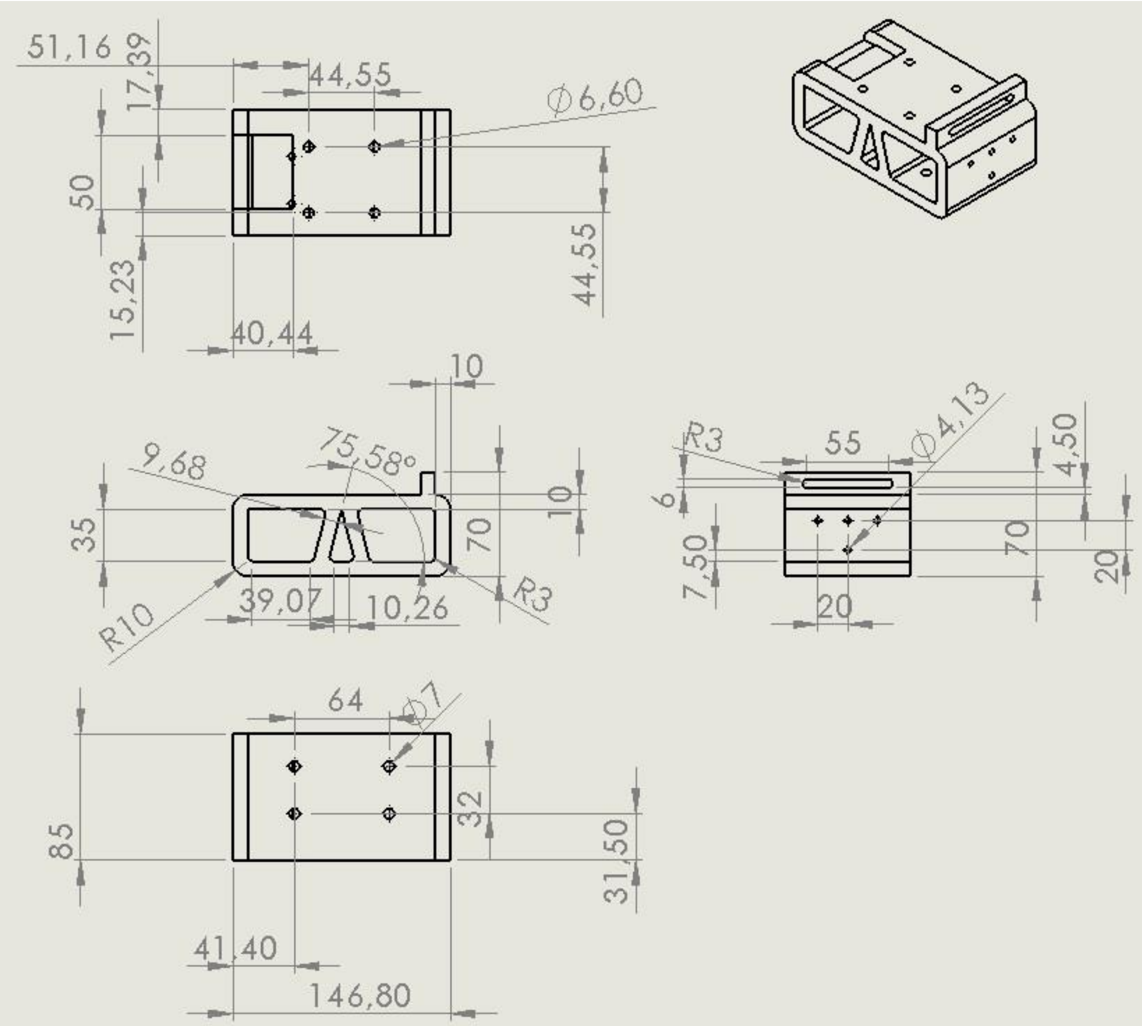
| Part-Nr. | Item | Printer | Used amount of PLA | Cost |
|---|---|---|---|---|
| 1.2 | Frame | Prenta Duo XL | 122,34 m | 6,66 € |
| 1.3 | Robot rack-attachment | Ultimaker | 23,51 m | 3,55 € |
| 1.4.1 | Rack for shelf – left side | Prenta Duo XL | 35,00 m | 1,90 € |
| 1.4.2 | Rack for shelf – right side | Prenta Duo XL | 35,00 m | 1,90 € |
| 1.4.3 | Rack for shelf – connection piece | Prenta Duo XL | 5,27 m | 0,29 € |
| 2.6 | Frame | Prenta Duo XL | 139,6 m | 7,61 € |
| 3.2 | Piston/Finger – connection | Ultimaker | 7,09 m | 1,07 € |
| 3.5 | Frame | Prenta Duo XL | 178,35 m | 9,73 € |
| 3.6 | Frame cover | Prenta Duo XL | 38,72 m | 2,11 € |
| 3.7 | Frame-base | Prenta Duo XL | 19,47 m | 1,06 € |
| 4.1 | Finger | Ultimaker | 63,44 m | 9,60 € |
| 4.2 | Finger attachment 1 | Prenta Duo XL | 13,59 m | 0,74 € |
| 4.3 | Finger attachment 2 | Ultimaker | 9,27 m | 1,40 € |
| | | | | ∑ **47,62 €** |

Appendix 9. Technical drawings of self-designed pieces



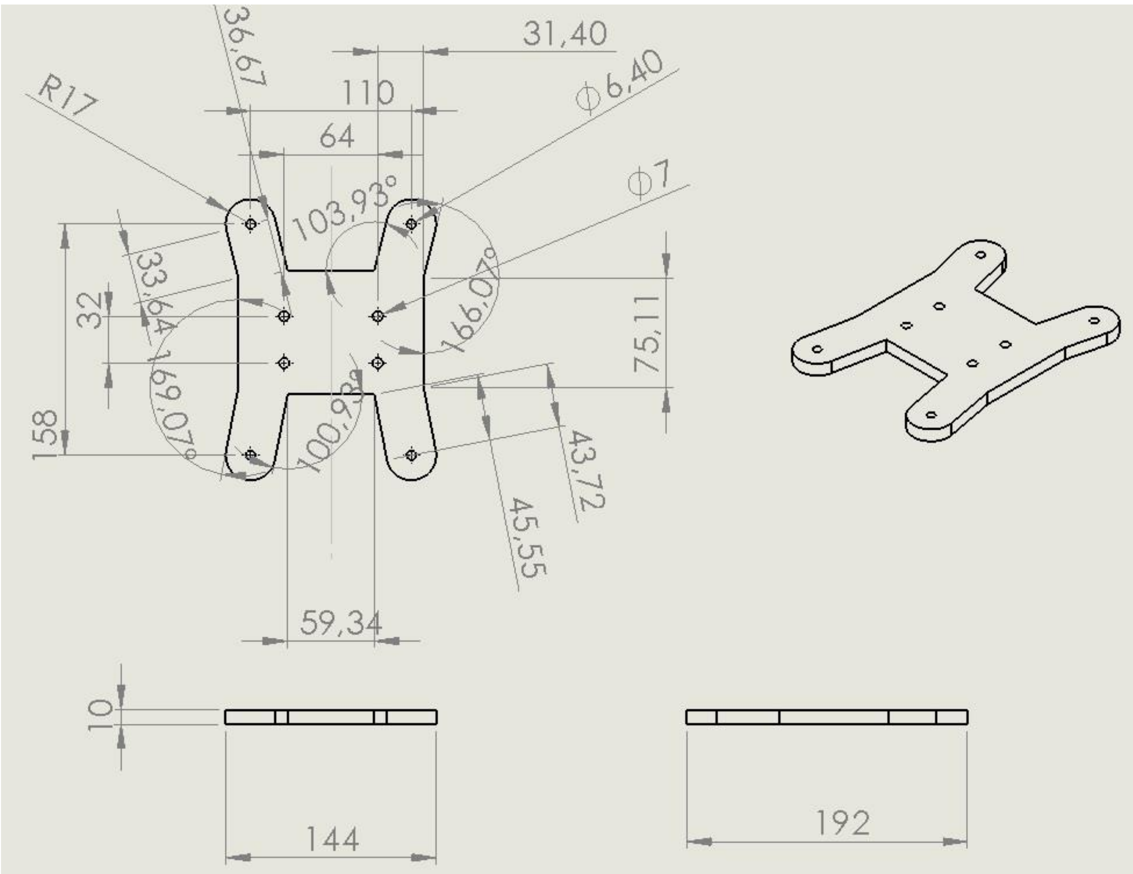
Part 1.2: Frame

Weight: 0,347 kg

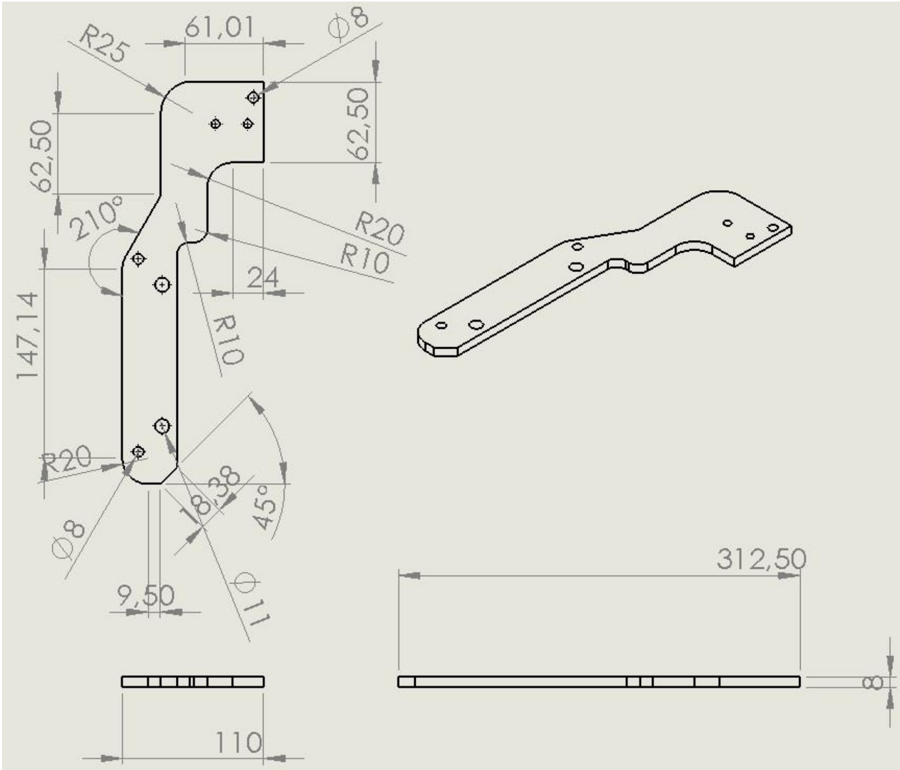


Part 1.3: Robot rack-attachment

Weight: 0,121 kg

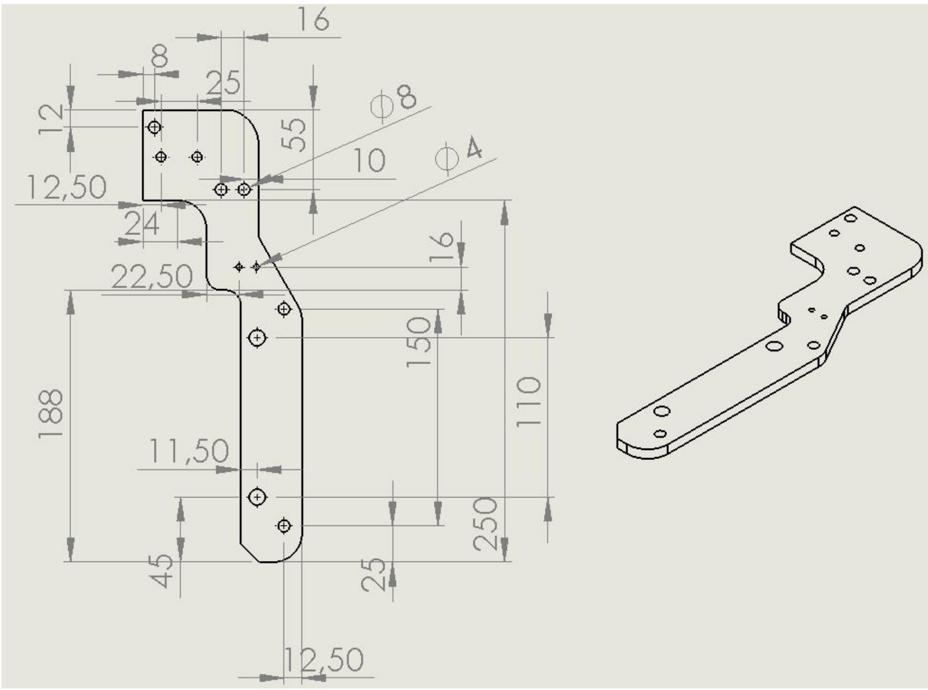


Part 1.4.1: Rack for shelf – left side

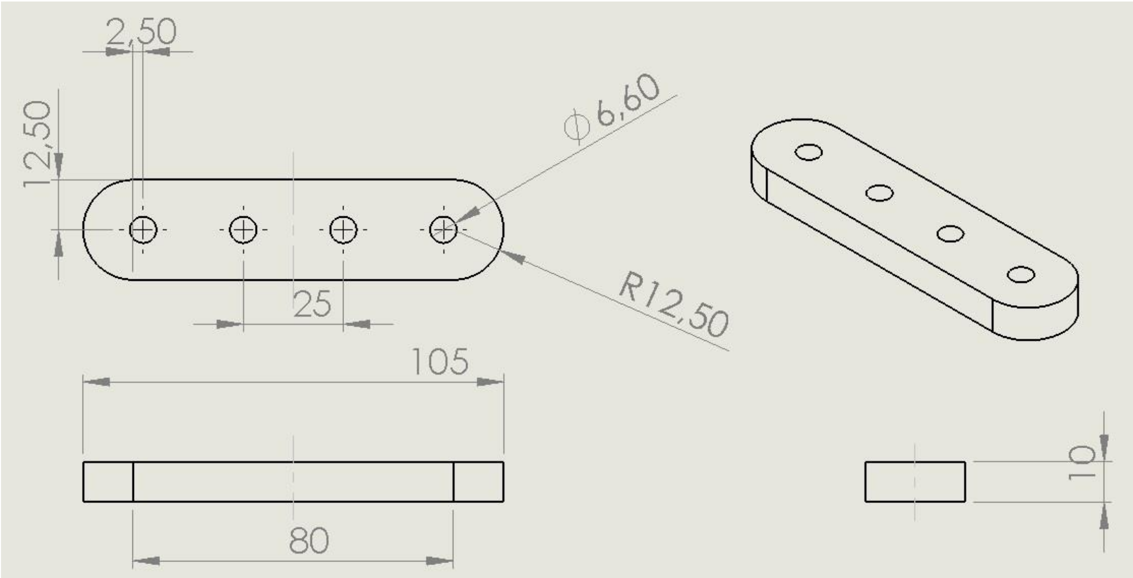



The left and the right side of this workpiece are identical except for the four additional holes that are added to the right part. The drawing below only shows measures that were not shown in the above drawing and vice versa.

Part 1.4.2: Rack for shelf – right side

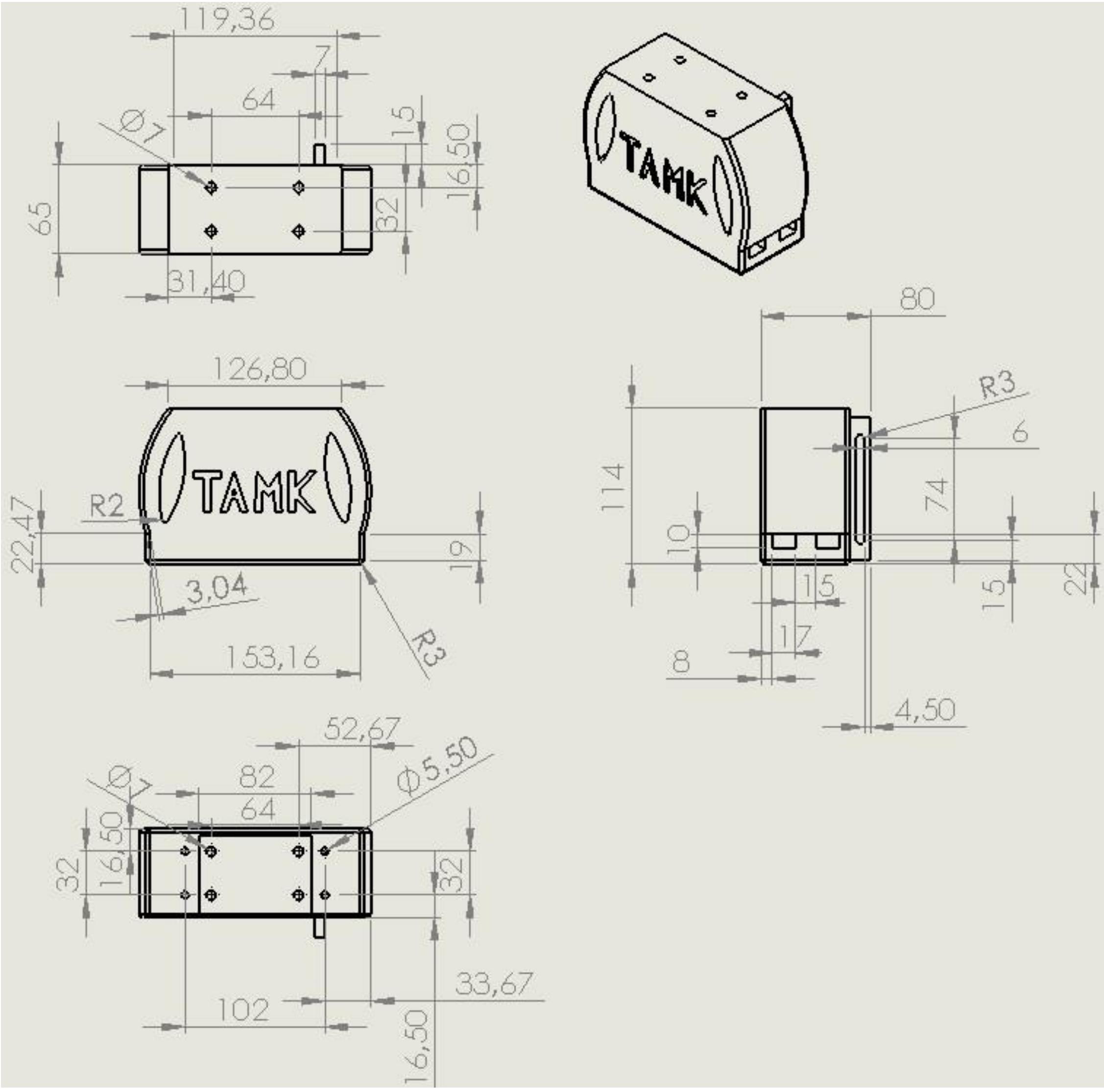


Part 1.4.3: Rack for shelf – connection piece



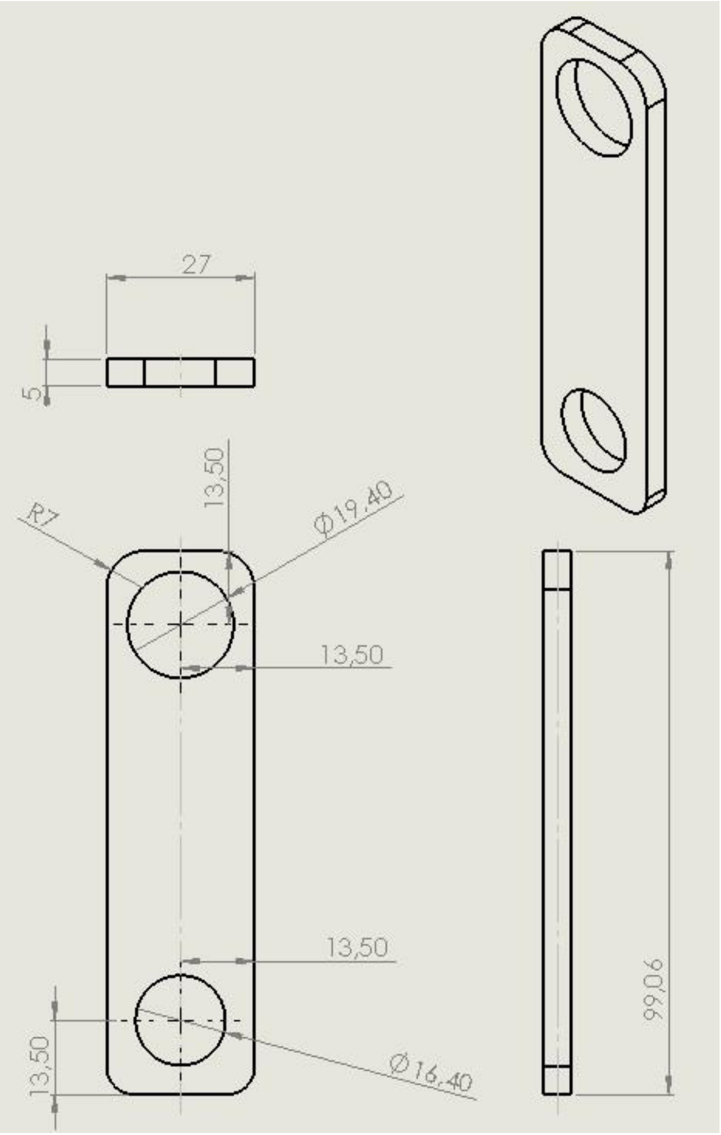
Part 2.6: Frame

Weight: 0,381 kg



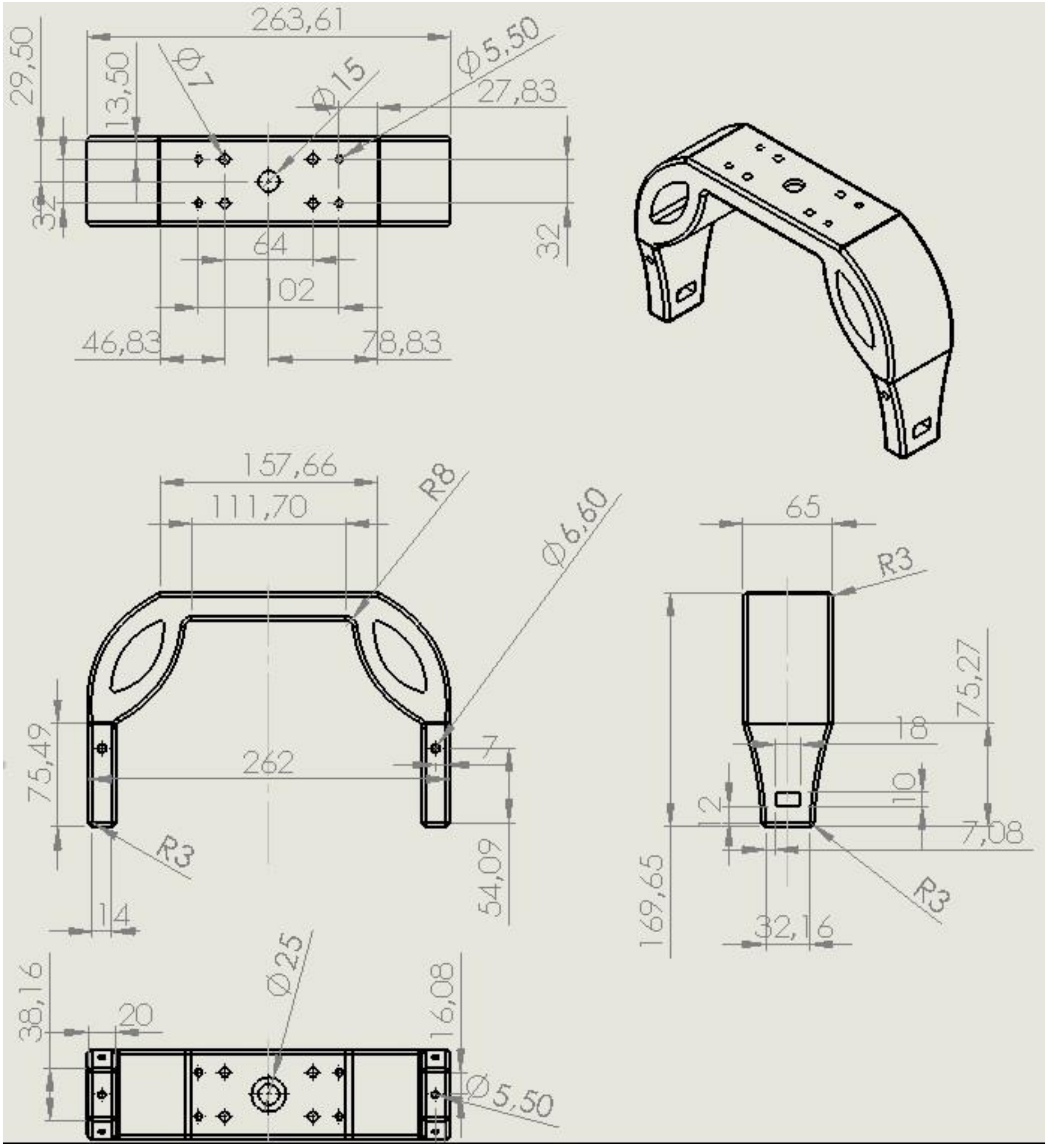
Part 3.2: Piston/Finger-connection

Weight: 0,0118 kg x 4 = 0,0472 kg



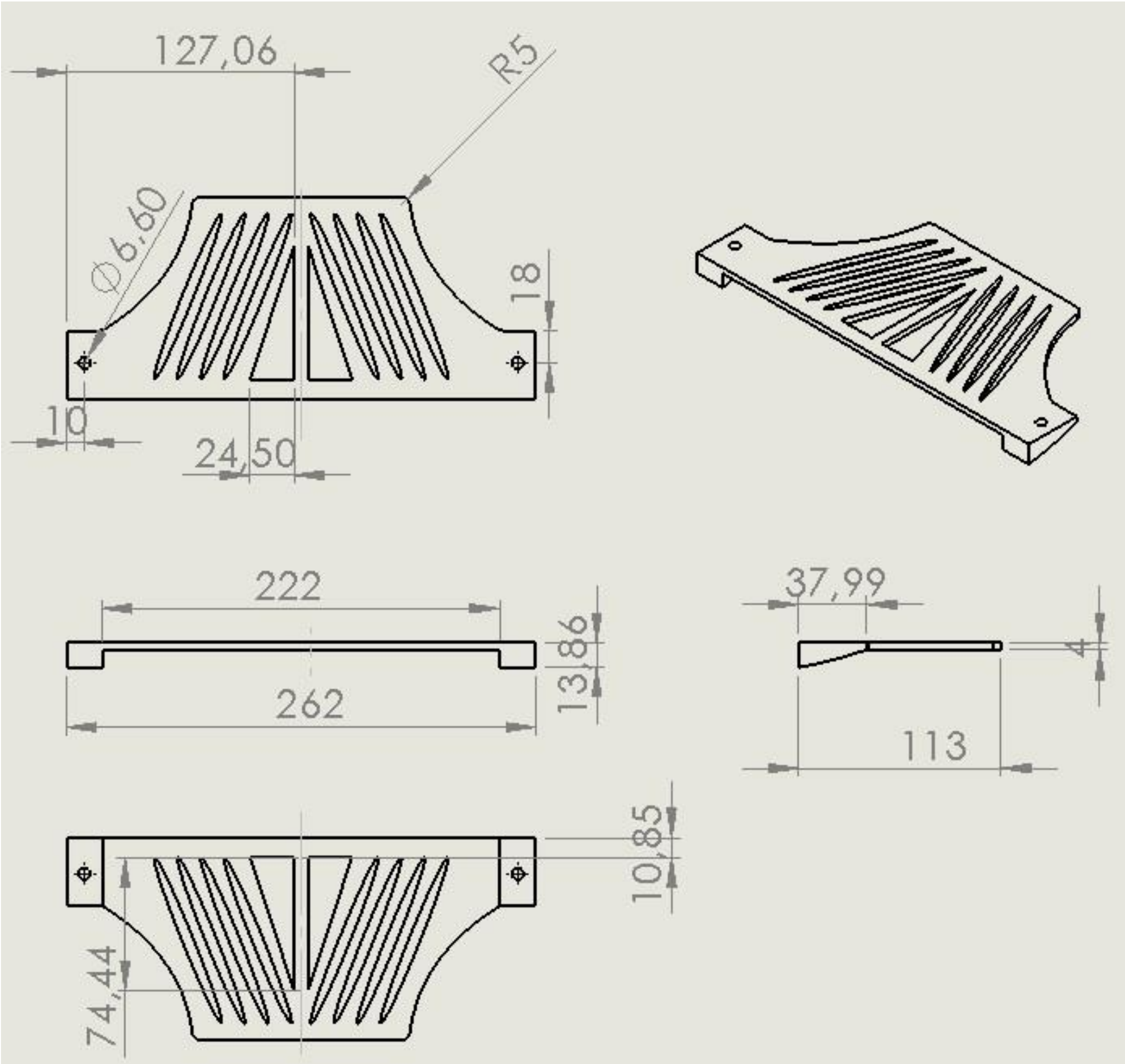
Part 3.5: Frame

Weight: 0,493 kg



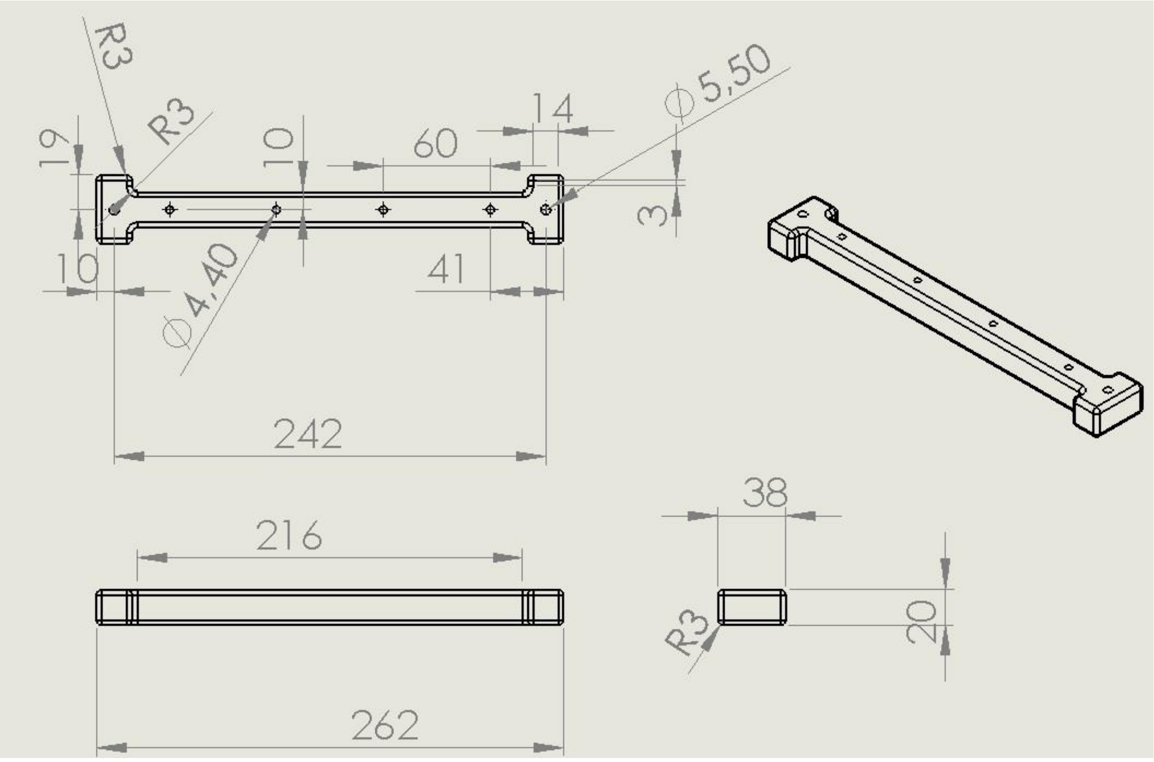
Part 3.6: Frame cover

Weight: 0,0542 kg x 2 = 0,108 kg



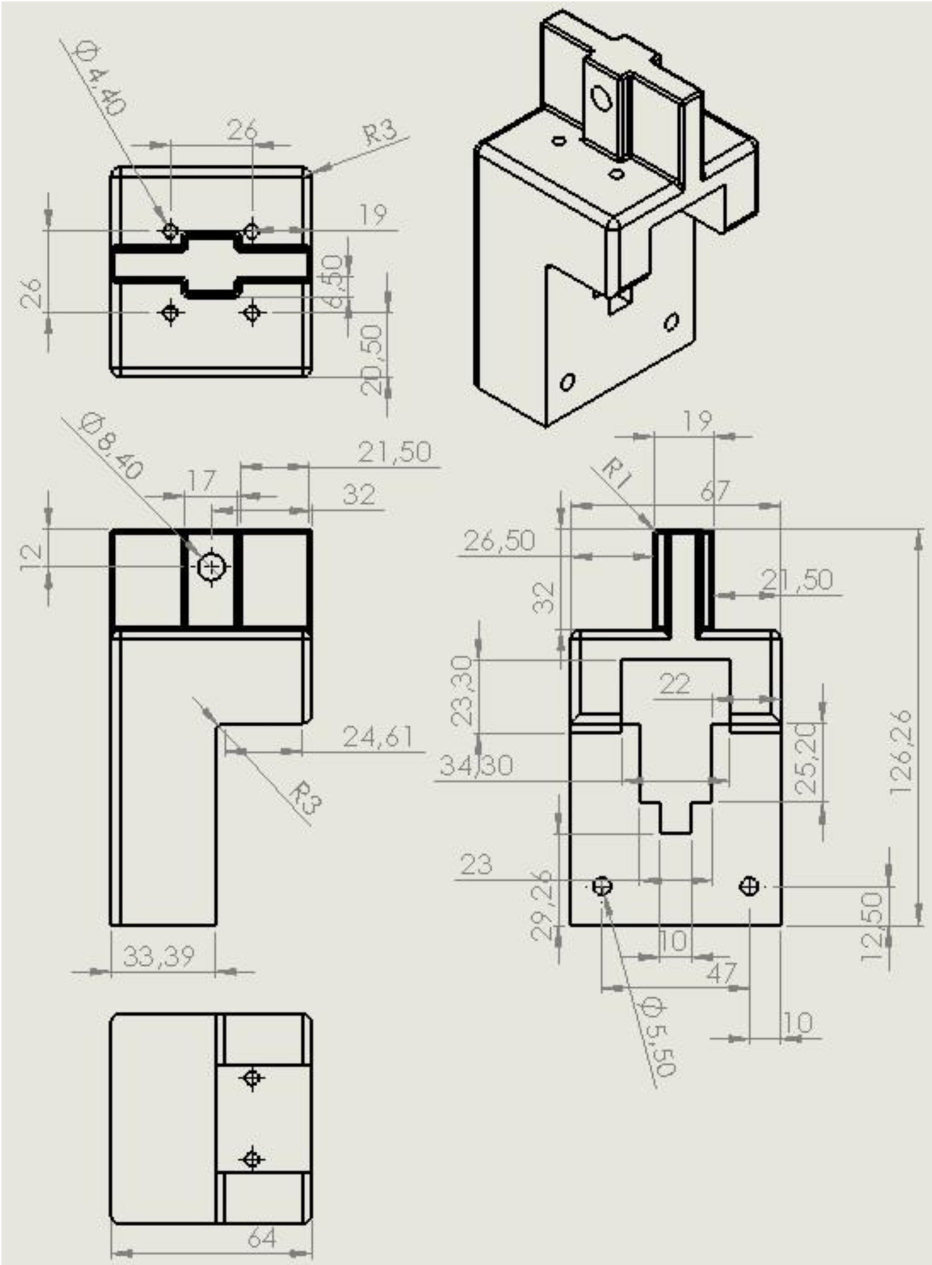
Part 3.7: Frame base

Weight: 0,056 kg



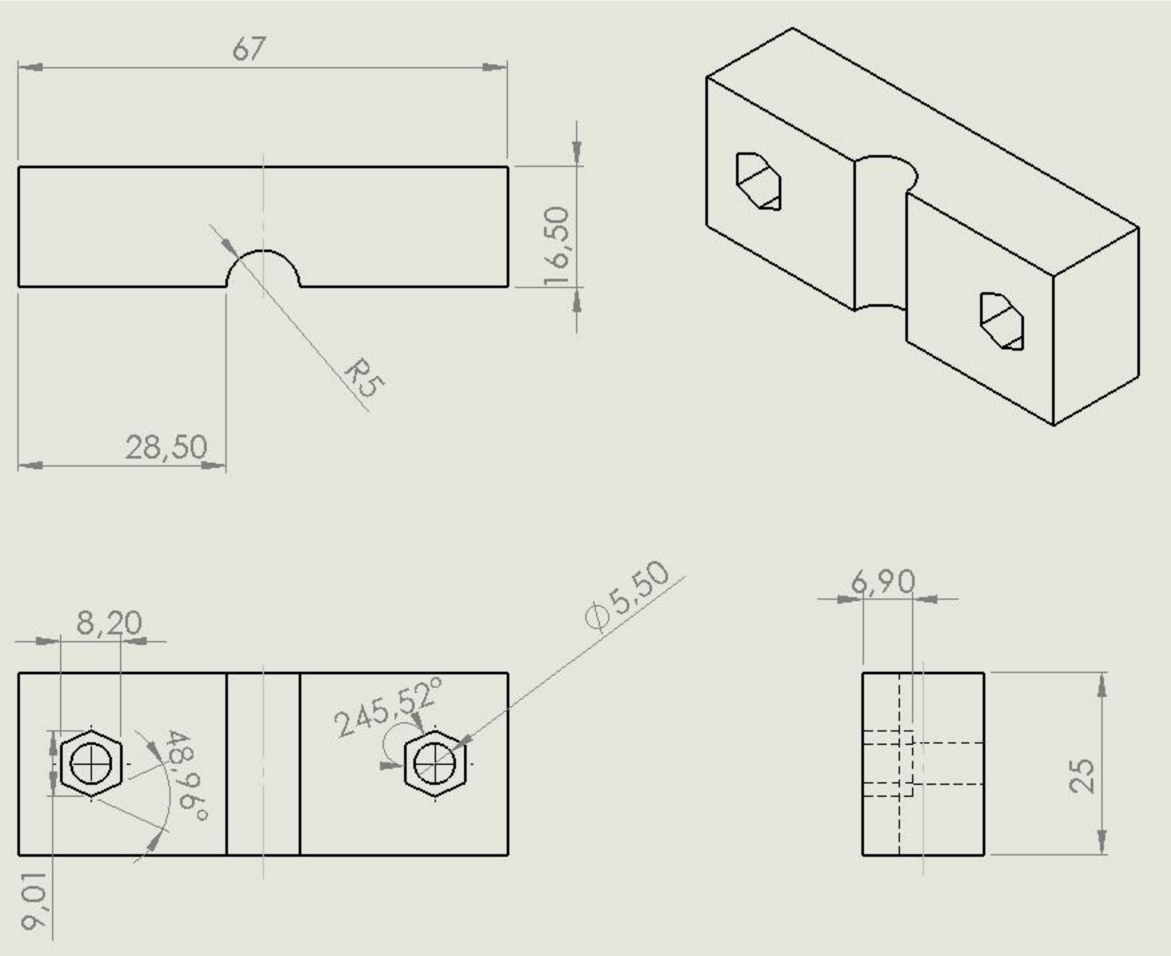
Part 4.1: Finger

Weight: 0,178 kg x 2 = 0,356 kg



Part 4.2: Finger attachment 1

Weight: 0,0188 kg x 2 = 0,0376 kg



Part 4.3: Finger attachment 2

Weight: 0,0221 kg x 2 = 0,0442 kg