“The Development of a Hybrid Manufacturing System Combining Multi-Material 3D-Printing and Silicone Casting, to Create Soft Robotic Parts.”

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COLOPHON

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Figure 1: Octobot, design by Harvard

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1.0 EXECUTIVE SUMMARY

Introduction

This master thesis discusses the development of a hybrid manufacturing system that combines multi-material 3D-printing with silicone casting. The parties involved in this project were soft robotics research group at the University of Technology Delft and Ultimaker. Ultimaker served an advisory role and helped in providing the needed hardware. The starting point of this project was the lack of good production facilities for developing soft robotic parts. During an explorative study of the current production methods arose the value of a hybrid manufacturing system. By combining the material properties of hand casting with the automated process of Fused Deposition Modelling a better manufacturing system could be proposed.

Analysis Phase

During the analysis phase, the research had been divided into three main topics. Soft robotics, multi-materials, and 3D-printing. Each chapter was aimed at finding specific answers that would aid in the development of the concepts.

Soft Robotics

In the soft robotics chapter, a new overview has been created. This overview can be used as building blocks for creating soft robotic parts. Soft robots can prove to be a game changer in a lot of fields due to the resemblance of the natural movement and feel of real humans. The fact that systems can integrated sensor and actuators in a whole allows it to be cheap in production, lightweight and adaptive to its surroundings. This makes it a good solution for Human Robot Interactions (HRI), Medical applications, Telecommunication and autonomous exploration.

The downside of the integrated parts is that it is hard to predict the exact movements. To do so experimental validation is an important prediction tool.

Due to the nature of the hybrid manufacturing set-up, this scope of this project has been narrowed down to pneumatic soft actuators.

Mult-materials

In order to understand how the blending of different materials could lead to new product designs. Research has been conducted in regards to product behavior. The use the new set-up provides new possibilities. Composites can be created as a result of the combination of the two production processes. For the development of these composites, it should be taken into account that the bonding between silicones is limited and only Fiber-reinforced and Structurally reinforced composites might prove to be a useful application. The embedding of big particles in silicones doesn't result in a good bond.

During the different tests conducted there was found that it is possible to print on both liquid as well as solid silicone. For solid silicones, the printed parts lay loose on top of the silicon, while the printed parts on the liquid silicone lay slightly embedded in the silicone but they will come loose as a result of minor loads.

3D-printing

For the implementation of the hybrid manufacturing system, several changes had to be made. In order to operate all cores alongside the silicone nozzle. The nozzle had to be moved out side of the printhead. The placement required adjustments to the building volume of the printer. In addition, the slicer needed to be adjusted in order to slice three materials and keep the offset in mind.

For the implementation of the Flex3Drive, a redesign has been proposed. During the usage of the system, it seized to function due to the slack within the part. This has been improved in a redesign but hasn't been tested yet. It hasn't been tested as a solution was provided by Ultimaker in the form of a part replacement that reduced the amount of slack.

Concept Phase

During the concept phase, the possibilities of the printer have been combined with the functions of the pneumatic actuators. As a result, multiple idea clusters have been developed: Special Molds, Visual Indicators, Sleeves, Stringing, Embedded Mechanisms, Composites, Auxetics Conductive Wiring, Valves, Connections, and Complex Cavities. To determine what areas would be further

investigated over the course of this project two selection methods have been used. The C-Box method has been used to determine the which areas would be feasible and novel. The Weighted Criteria method has been used to determine the added value of the areas for the development of soft robotic parts. There has been chosen to further develop the following search areas: Composites, Complex Cavities, and Hard Inserts.

Composites
During the further development of the composites, two tests have been conducted. These tests have been conducted to determine the effects of PLA and TPU fibers on the silicone. The first test conducted was a Tensile Stress test. The second test was a flexural test. The results have been combined to enable designers to pick the materials with the desired properties.

Complex Cavities
The usage of PVA as a support material provides a lot of form freedom. It should be noted that this freedom is still limited to the extent of the solubility of the support material. To find this limit a dissolve test was conducted. The results showed that it is only a matter of time before the support material will be dissolved. In order to improve the rate at which this happens, the following guidelines have been set. The cavities should be hollow so water can fill the support material in one go. The cavities shouldn't contain fillets as this would lead to the use of extra support material in the corners. When the product is placed in a moving water bath the speed is also increased.

Hard inserts
In order to create a more durable connection point research has been conducted to determine the bonding between the insert and silicone. The result of the test was that it was hard to predict the binding upon forehand. To improve the bonding the contact area of the insert and silicone needs to be increased. In addition, the deformation of the silicone under loads needs to minimalized to reduce the effects of the Poisson's ratio.
The proposed concepts and guidelines have been brought together to display their strengths in a demonstrator. The field that would benefit the most from the concepts was Prosthetics and Orthoses. Therefore there has been chosen to develop a pneumatic bending actuator.

Detailing Phase
The pneumatic bending actuator consists out of a complex cavity. A hard insert at the front to make room for a connector and fibers at the top and bottom layers of the actuator. At the top PLA fibers in the longitudinal direction have been used. to limit the bending strain.At the bottom, PLA crosslinked fibers have been used to limit both the bending as well as the tensile stress strain.
The production of the demonstrator didn't go as smoothly as expected. The biggest issues that have been encountered were: The PVA not sticking on the silicone, limited control over the amount of extruded material, and low-quality molds. To overcome the first issue a primer was used. Increasing the priming and retraction partly solved the limited control issues.
For the demonstrator, the PVA cavities have been optimized over the course of the project. In addition, multiple suggestions have been done for the connector.

Evaluation & Discussion
The MultiCast shows great promise for the production of soft robotic parts. In its current state, the set-up is not yet reliable. In the future, several improvements need to be implemented to make it a reliable system. The extrusion of flexible filament should be supported. The nozzle attachment needs to be replaced by a more durable system. There needs to be more control over the output volume. A solution needs to be found for the continuation of the print after casting silicone as the current solution decreases the silicone-silicone bonding. Other issues that are less demanding but still should be looked into are the volume capacity of the system, the housing of the Ulticast, the usable surface area on the print bed, and expanding the printing capabilities even further.
The demonstrator shows behavioral changes as a result of the embedded fibers. The issues with the PVA not fully dissolving have not been fully solved yet. The amount of force required to insert the connector in the actuator is too high. The usage of a Bayonet lock combined with a rubber seal is advised.
All over this project should be considered the first stepping stone in the development of the MultiCast set-up. A lot of research has been conducted and several issues have been addressed but there is still room for improvements. Also, more clusters could be researched in future projects.

2.0 INTRODUCTION

The field of robotics has grown over the course of 50 years and today robotic technologies are very reliable and widely applied. Almost all of the theories and techniques of robotics are based upon the fundamental assumption and conventional definition of robots being a kinematic chain of rigid links (Cianchetti, 2014). However, advancements in soft and smart materials, compliant mechanisms, and non-linear modeling allow for the development of a new type of robot: soft robots. Soft robotics have bodies made of soft and/or extensible materials that can deform and emulate biological systems resulting in systems that have a relatively large number of degrees of freedom (Rus, 2015).

Although the use of soft robotic parts has been around for a while, the development of dedicated soft robots is a recent development. It is driven by many application requirements in the fields of biomedical, service, rescue robots and haptic-feedback products. The reason that soft robotics look promising as a solution is due to the expectation that they interact more easily and effective with real-world environments (Mazzolai, 2012).

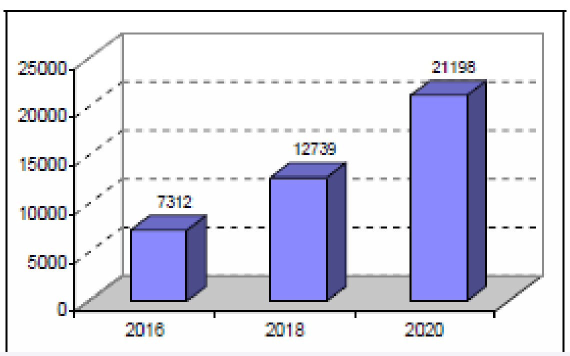


Figure 1: Market value of 3D printing, Wholers 2015

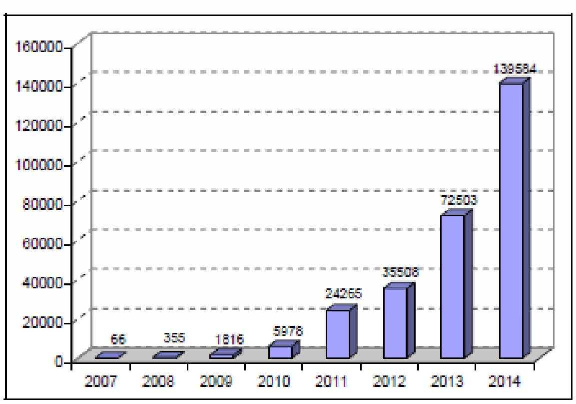


Figure 2: Sales of desktop printers, Wholers 2015

One of the technologies widely applied to create soft robotic parts is 3D-printing, also known as additive manufacturing (AM), gained a lot of momentum over the last years. Although the technology dates back to the 1980's the technology only recently gained momentum. The market of 3D-printing has shown a Continuous Average Growth (CAGR) from 2012-2014 of 33.8%. With this CAGR it is expected that the market value of 3D-printing will reach 21.198 Billion in 2020, see figure 1. The growth is even bigger for desktop 3D-Printers. The sales of desktop 3D-printers have almost doubled to a market value of $4.103 Billion in 2014, see figure 2. Although this is a big increase it is expected that the market is a long way from maturing and has reached only 1-8% of its market potential (Wholers, 2015). The biggest applications for 3D-printing are: functional parts, fit and assembly parts, visual aids, patterns for casting and prototype tooling. See figure 3. What can be noted here is that 3D-printing is often used as a prototyping tool. Of course, this was also the starting point of this technology and over the years this application has proven itself to be useful. As a result, this application has reached the plateau of productivity as shown in Gartner's Hype cycle for 3D-printing (Gartner, 2015).

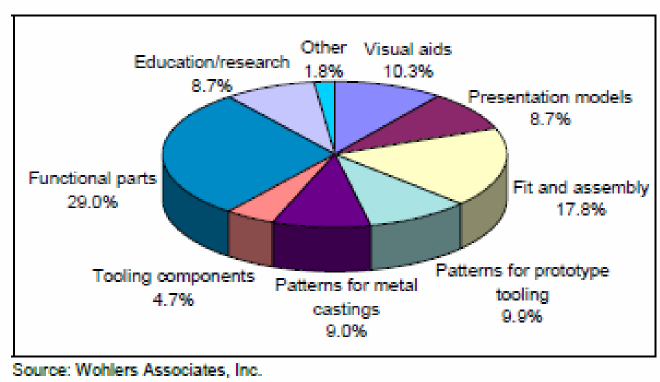
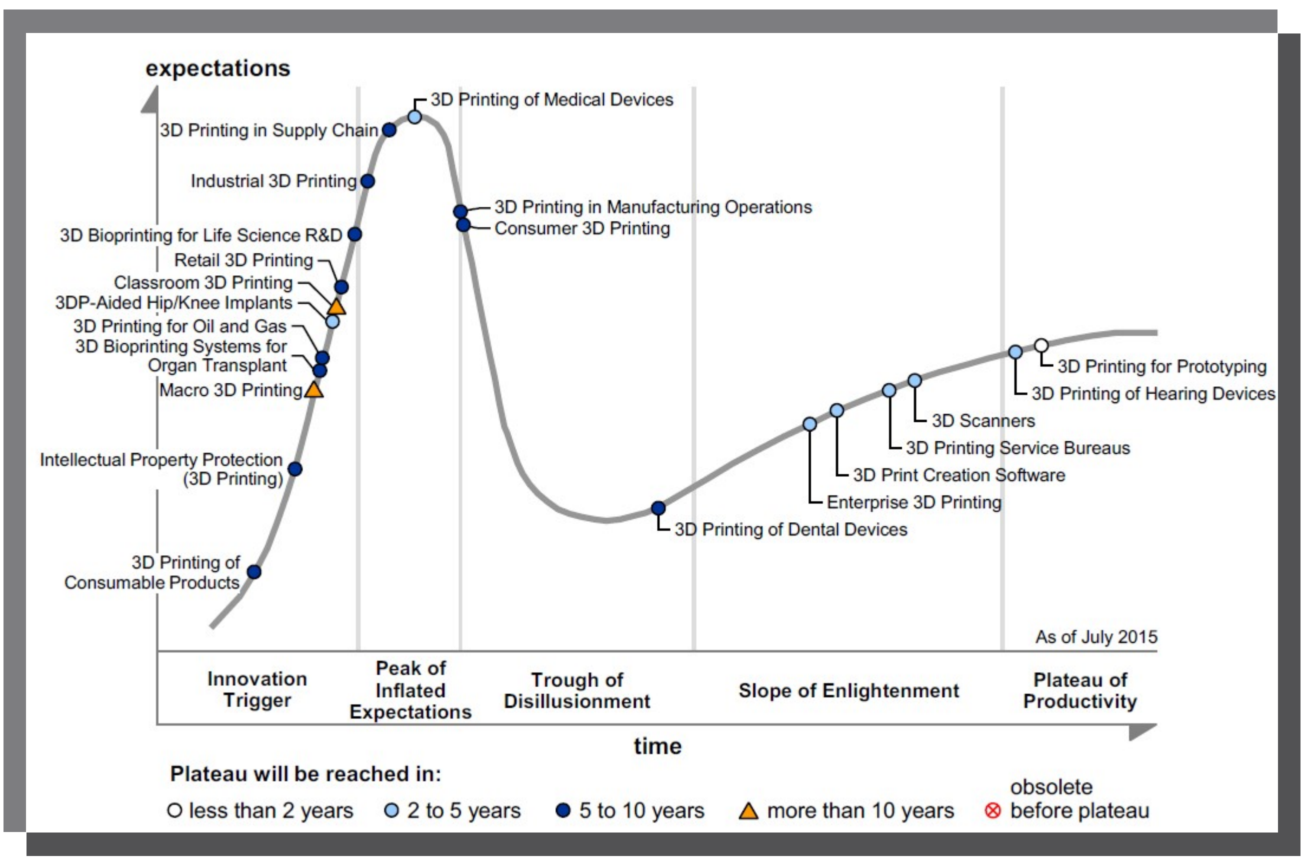


Figure 3: 3D-printin applications, Wholers 2015

The most commonly used 3D-printing technology for prototyping is Fused Deposition Modeling (FDM). A downside of this technology is the production of parts with a high density. To speed up the production process, parts are not fully filled but contain a certain pattern with cavities to accommodate a certain filling percentage. A part that contains only 20% infill would take exponentially less time to produce than a part with 100% infill. To overcome this issue a hybrid manufacturing system was proposed. The system was called a hybrid manufacturing system as it combined the benefits of 3D-printing with those of polyurethane casting. The system solved the low production speeds by combining two component resins to fill the prints (Rossing, 2016). The recent development of this set-up raised the question what the possible applications could be of using such a technology in the creation of soft robotic prototypes.

The aim of this graduation project was the development of a hybrid manufacturing set-up that combined the benefits of multi-material 3D-printing with silicone casting in order to create soft robotic parts. The biggest difference with the set-up created by Lars Rossing during his graduation is the multi-material aspect. This multi-material aspect means that the set-up functions with two separated fully functional nozzles. These different extrusion nozzles allow for the creation of hybrid materials, as well as solvable silicone molds in one print. While developing the new set-up, the added value of such a set-up has been explored. All the new possibilities this set-up provides and the issues that had to be overcome during the production process have been mapped.

This thesis has been divided into three main parts. Firstly the research part in which all the necessary technologies and theories are elaborated on creating insight in the problems, and providing answers to relevant questions. The second phase named the concept phase, focuses on the possibilities that the new manufacturing set-up provides combining it with the previous knowledge gained to generate relevant applications for the new manufacturing set-up. The last part named the detailing phase, provides insight in the development of the demonstrator created for this graduation project.



2.1 STARTING POINT

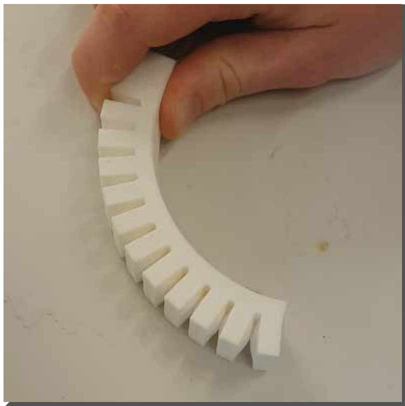
The production capabilities for creating long lasting soft robotic parts in terms of form freedom, production time and material usage is limited. Currently the most common production methods used are 3D-printing and hand casting which both have their downsides.

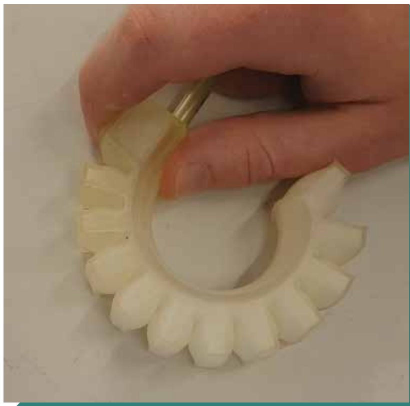
To get a clear overview of the benefits and limitations of the different production methods a hands-on exploration study was conducted. It focused on the creation of a soft robotic bending actuator (finger) with the help of material jetting, FDM and hand casting methods. The SLS and SLA production methods weren't compared as the production facilities at the faculty of Industrial Design engineering weren't available at the time of testing.

Casting by hand works well but it is time consuming and limited in the possible geometries for the resulting parts. For example, thin walled products can't be created by hand because no extra pressure is put upon the cast pushing the liquid silicone in small cavities.

Three different traditional 3D-printing technologies are commonly used to manufacture soft robotic parts. The usage of these three methods often results in parts with inferior material behavior. The flex materials created by means of Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) are often too rigid for the desired applications. The production by means of a Material Jetting with a Polyjet results in products with a limited durability.

To make a fair comparison between the production methods a standard type robotic part has been created. It is based upon the design of soft robotic toolkit website (Polygerinos, 2013) and the work of a mechatronics study group at the University of Technology in Delft. The parts only gained minor adjustments in order to be able to produce the parts with the given methods. After the production the robotic parts were tested on flexibility and durability of the used materials.





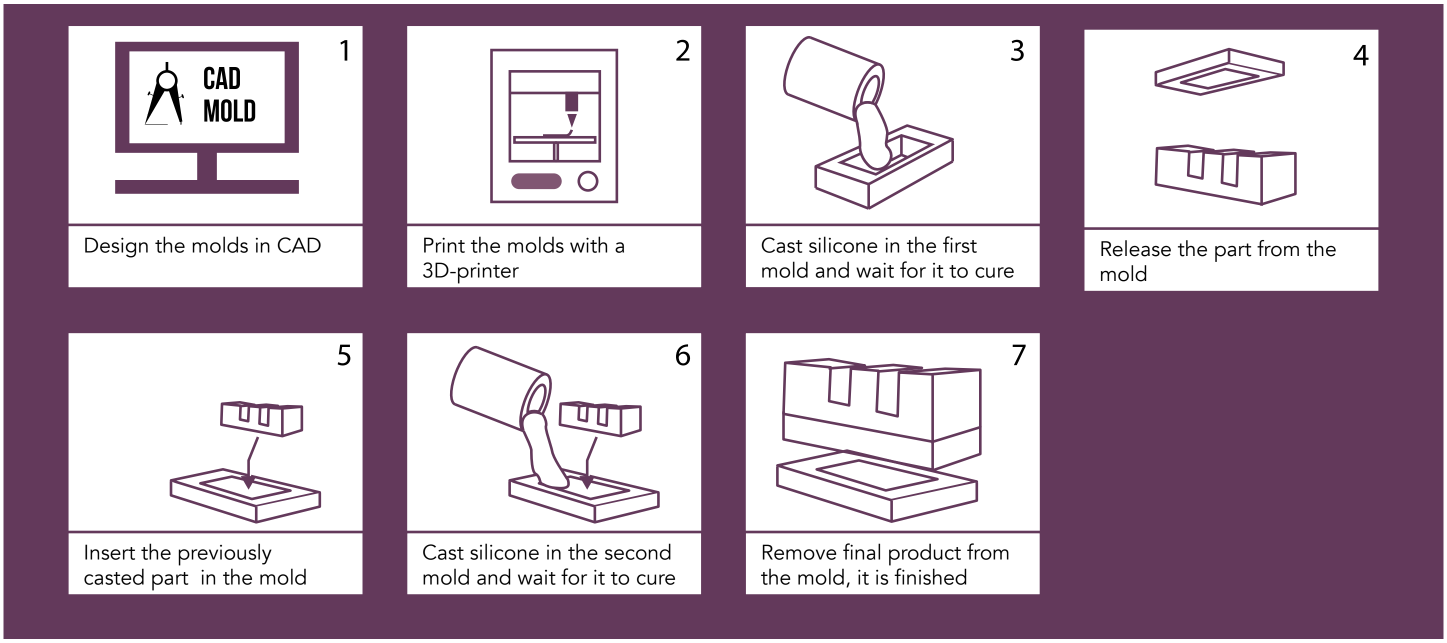


Figure 4: The production process of a pneumatic actuator via silicone hand casting

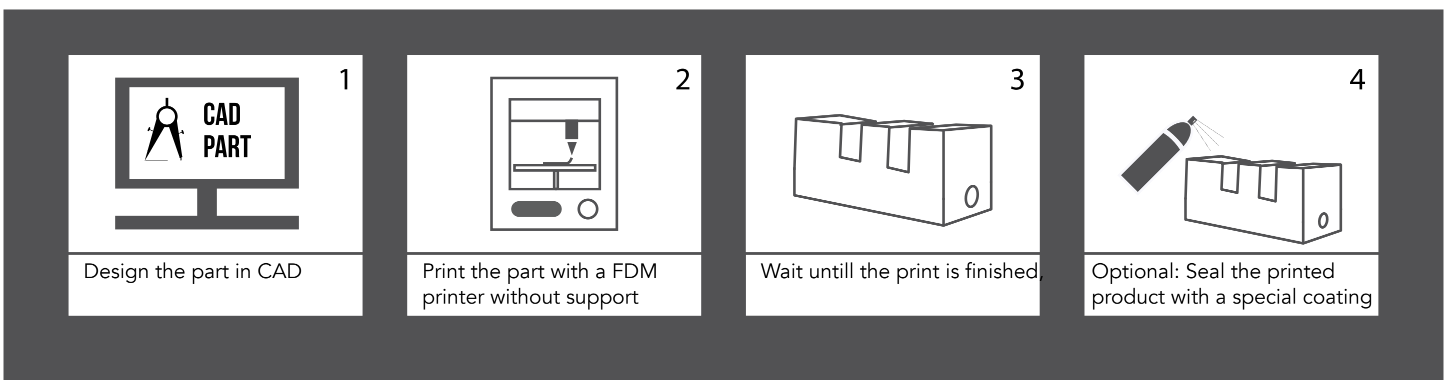


Figure 5: The production process of a pneumatic actuator via FDM.

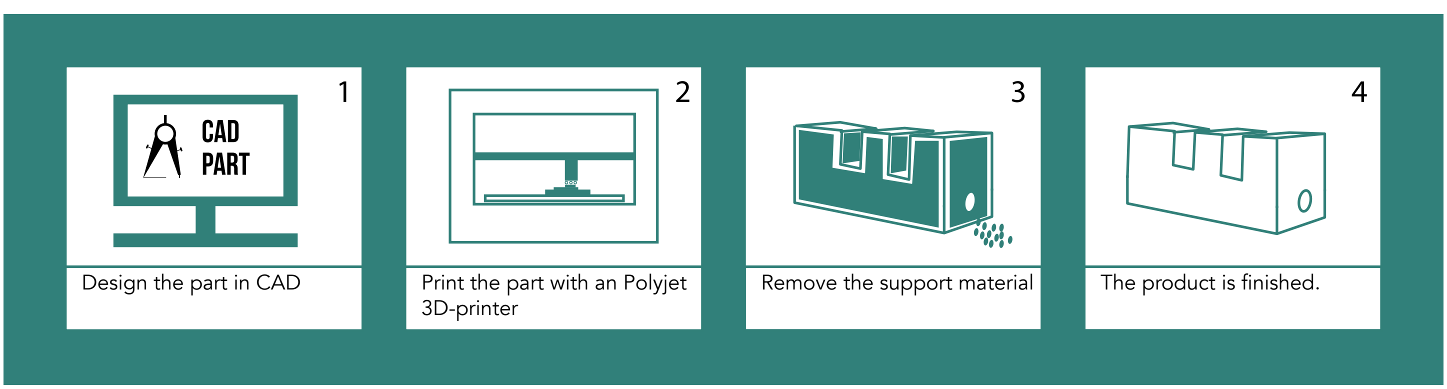


Figure 6: The production process of a pneumatic actuator via material jetting

Silicone Casting

For casting the finger in silicone there where three mold parts designed in SolidWorks. The robotic finger couldn't be casted in one go due to the cavities. After designing the parts they were printed with an Ultimaker 2+. After the prints where finished the top part of the finger had been cast first. After the cast was cured it was removed from the mold. The next step was casting the bottom layer of the finger, which was topped off by the solid top part of the finger. Finally, the finger was removed from the second mold and the edges where trimmed off. A brief overview of the production process can be seen in figure 4.

When tested the Silicone finger showed a quick response to a pressure of 0.1 Bar, displaying it's potential to easily deform under low pressures. Additionally the shape fully returned to its original position after removing the pressure. In the graph there can be seen that for high-pressures the displacement decreases. This is a result of small ruptures in the seams of the hand casted part.

FDM 3D-printing (Ninjaflex)

The design of the finger only needed a minor adjustment in SolidWorks. The hole for the valve has been removed in order to prevent stringing of the material, and allow the print to flow continuously. After designing the finger in SolidWorks it was printed with a Ultimaker 2+ with a Flex3Drive. After printing the print wasn't treated with a spray or anything to seal it. The final design of the finger used for all production methods has an increased wall thickness in order for the print to automatically close with the help of bridging the materials.

During the tests, Ninjaflex proved to be the stiffest material. Only at high pressures, it showed some deformation. The final curvature of the finger was at 2 bar still three times higher than that of Silicone or Agilus.

Material Jetting with a Polyjet (Agilus)

The finger design for the Polyjet had the most adjustments since the product was filled with support material that required removal. In order to remove this material, a stick with a flush channel was printed within the finger. After the stick was removed the support material could be scraped out. The cavities of the chambers were removed with the help of a flow created through the finger with a water jet. After the removal of the support materials, the part was ready for usage. The full production process is shown in image figure 6.

Agilus proved to be the most flexible material during testing with the biggest actuation range at low pressures. This, came with a downside. When the pressure was removed, the finger wouldn't return to its original state. Additionally, the part was also quite sensitive to ruptures as a result of the insertion and removal of the tube that created the pressure.

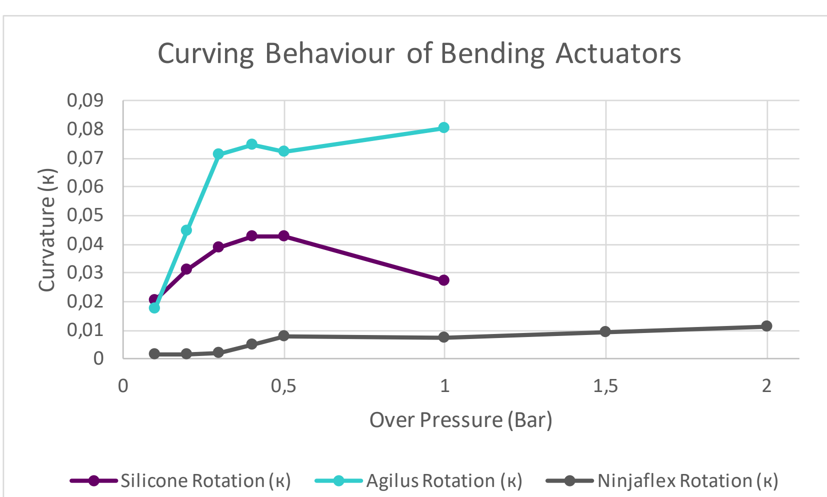


Figure 7: Grapgh of the curving behaviour of the different type of bending actuators

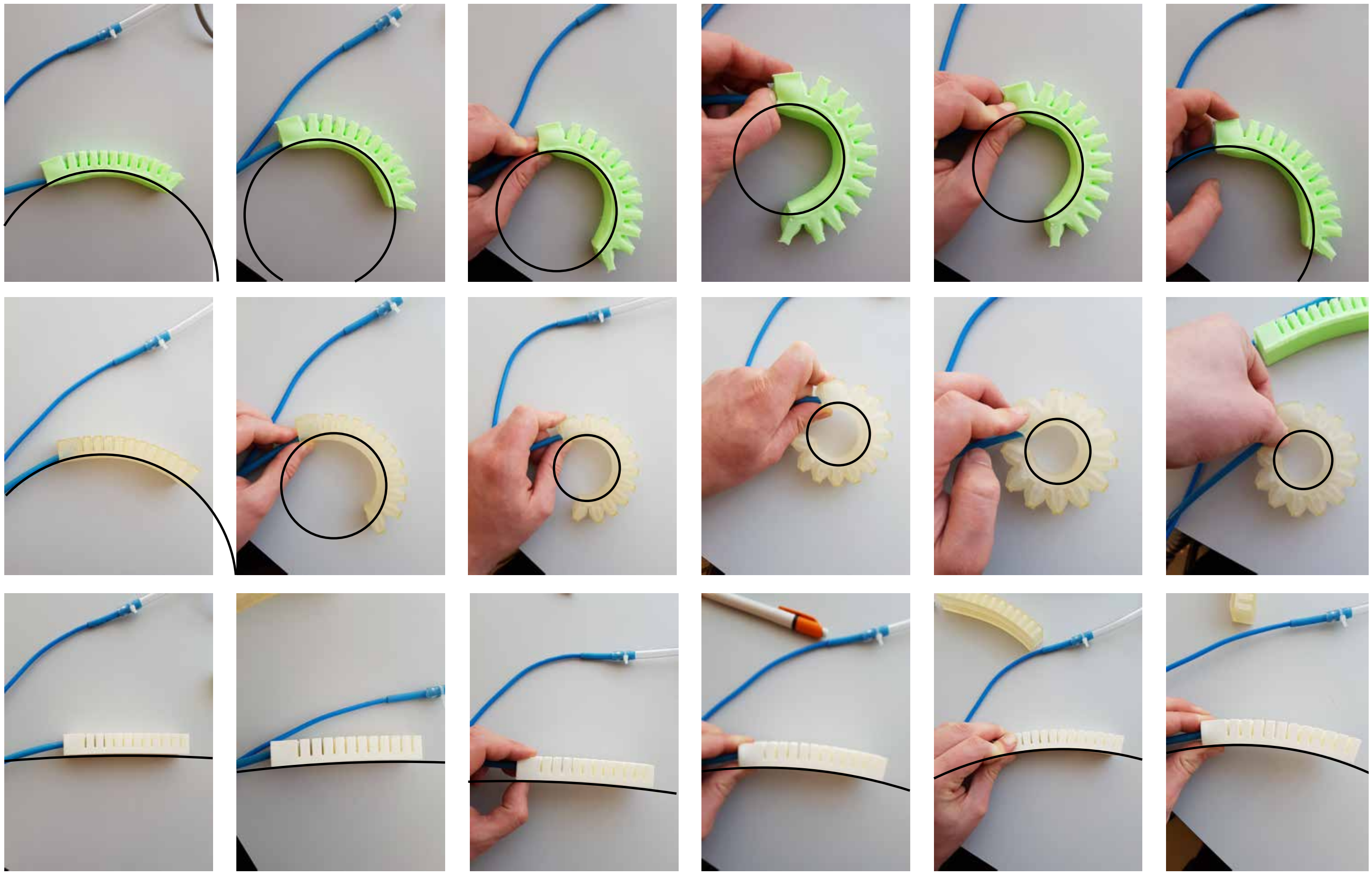


Figure 8: Analysis of the curvature for all the bending actuators.

Criteria	Hand Cast (Silicone)	FDM (Ninjaflex)	Material Jetting (Agilus)
Production Speed	- -	++	+
Production Intensity	- -	++	-
Design Freedom	+	- -	+
Material Durability	+	++	- -
Material Flexibility	++	-	+
Production Cost	+	++	-

Figure 9: Table displaying the advantages and disadvantages of the production methods.

Evaluation

All the previous findings had been gathered and summarized into one overview see figure 9. The criteria used for this overview have been based upon selection criteria that are often used for making a choice of the prefered production method: the price, labor intensity, design freedom and the quality fo the produced parts. The last aspect has been split into two aspects that are important for a pneumatic actuator. Often is the batchsize also taken into consideration, but since the purpose of this set-up is prototyping it isn't relevant. The time required to produce the parts is relevant.

The overview shows that the biggest flaws of the FDM production method are the Design Freedom and the Material Flexibility. Due to the fact, that the wires need to bridge the Design Freedom is limited. In addition, the most flexible material (Ninjaflex Shore 85A) is still quite rigid compared to the other materials used (Silicone and Agilus Shore 30A). FDM performs on the other hand well on the production aspects, as it contains little production steps and treatment after production. Also as a direct result of the relatively rigid material, it is also more durable.

Material Jetting shows to be the worst production method. This is a result of the all over average performance with an added downside in every step. The production, for example, is compared to hand casting low, although removing the support material still requires quite some effort. The biggest upside of support material is that it allows for a great Design Freedom. However, this is limited to the fact that it should still be possible to remove the support material. The biggest downside of this material is its durability. In a short amount of time, it displayed the first signs of wear.

Hand Casting of silicones is the most favorable in terms of material properties. Due to its flexibility and resistance to wear. Although it should be noted that the rupture of the parts in the parting line is a weak spot. The biggest downside of using hand casting is the fact that it is labor intensive. As a result of this, the production speed and cost of parts are also higher.

Conclusion

So in conclusion: there is currently no ideal production process for soft robotic parts. The starting point of this graduation project is to develop a manufacturing system that addresses this issue. The hypothesis is that by combining the advantages of FDM printing with the material and design advantages of hand casting a better functioning manufacturing set-up can be achieved. To do so, a hybrid manufacturing system has been developed that combines multi material 3D-printing with silicone casting. This design is based on a design created by Lars Rossing from Ultimaker.

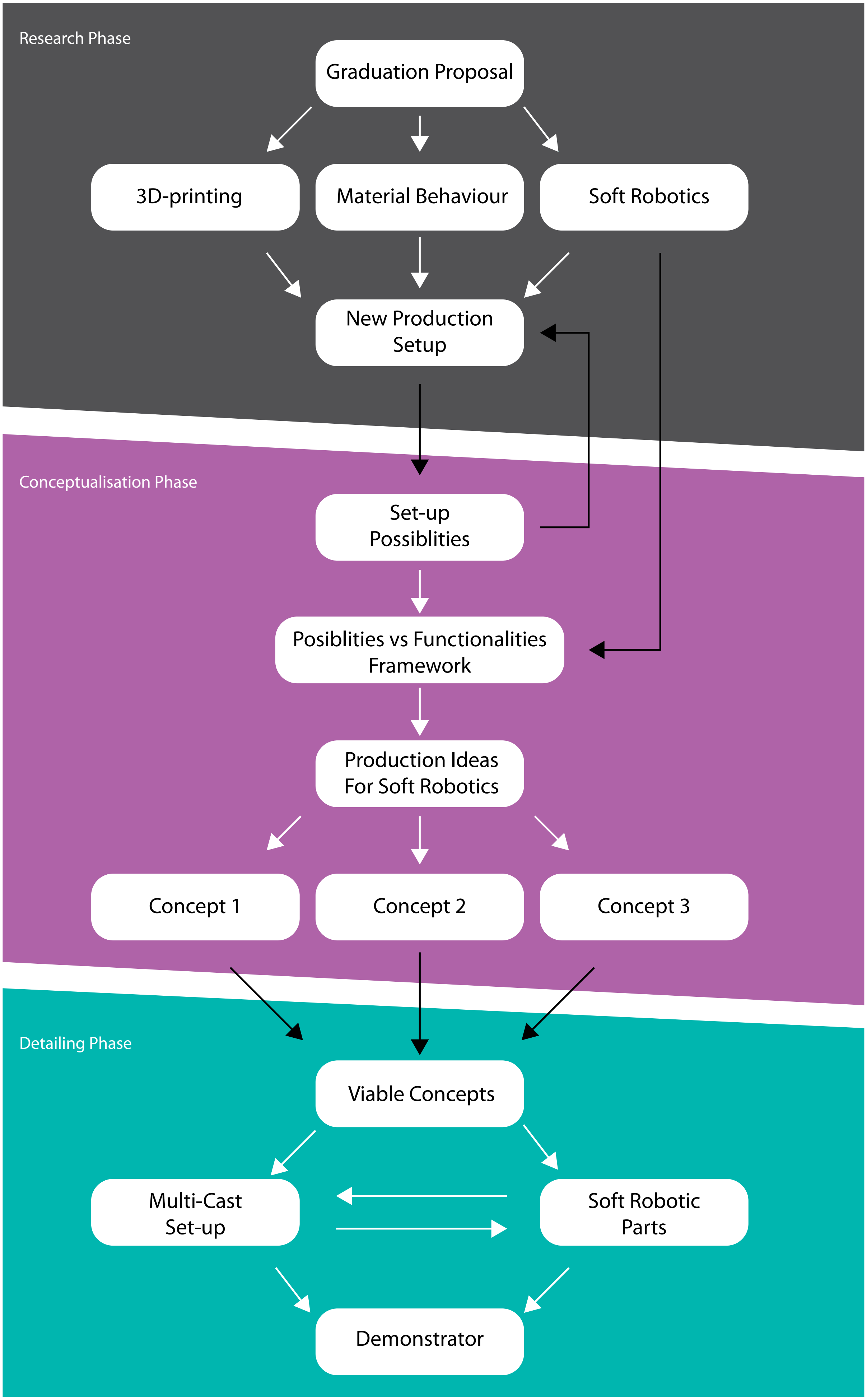


Figure 10: The design process

2.2 RESEARCH APPROACH

This thesis provides an overview of the theory behind the development of the manufacturing process as well as practical insights during the development process. In addition, background information has been provided that is useful for understanding the MultiCast as a whole and why it has been created. Besides the creation of the manufacturing system on its own, this thesis also provides knowledge and practical insights of the production capabilities of this new set-up. An schematic overview of the research approach is shown in image 10.

The research phase was conducted in three fold where the main pillars of the research where 3D-printing and the starting set-up, the usage of different materials (together), their behavior and the topic of soft robotics.
As a result from these first research steps, the first rough concept of a hybrid printer has been developed. This output was then used as an input for the development of the demonstrator and a more refined concept printer.

During the concept phase, a small association process between opportunities of the new manufacturing set-up and the functions from the function-analysis of the soft robotic components was created. As in essence is suggested by Wim Poelman (Poelman, 2005). The method is limited to using the objective functions of the soft robotics analysis.

From these combinations, different search areas were derived. These search areas were then further explored and evaluated in order to define three concepts that have been further investigated.These concepts have been merged for the development of the demonstrator.

Since both the production capabilities and the manufacturing set-up directly affected each other, there has been chosen to work with a Design Inclusive Research method. This method makes use of two design cycles where the first cycles output delivers the input for the second cycle. See image 11 (Horvath, 2013). The first design cycle focuses mainly on the development of the manufacturing set-up. This started with the research on the topics of soft robotics, materials and the currently available systems. This cycle was ended in the research phase with the final set-up used for this project as the abstract prototype. The possibilities formed the starting point of the second design cycle. Eventually leading up to the concepts, and the alterations made to the set-up to make the creation of these concepts possible. The final prototype has been validated and recommendations haven been written.

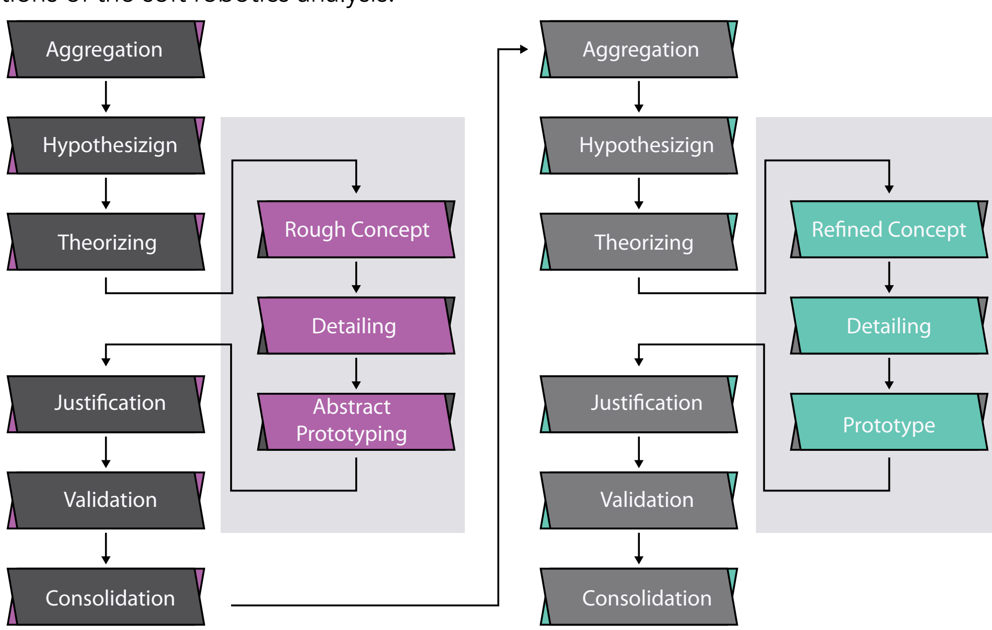


Figure 11: Overview of the Design Inclusive Research Method by Horvath 2013

3.1 SOFT ROBOTICS

3.1.0 INTRODUCTION

The final goal of this graduation project is to develop a 3D-printer that is capable of printing soft robotic parts. But why is it important to develop soft robotics and what is the added value of them?

If we think about robots the first thing that comes to mind is a hard machine, programmed to exercise a certain task, composed of rigid joints and shells. Often these machines are heavy and as rigid in their application as their joints are. Making tasks like moving over rough terrain, and grasping irregular object a difficult task (Martinez, 2017). Soft robotics have the possibility to overcome most of these issues. As they have more degrees of freedom since they are an underdefined system (Rus, 2015; Shepherd, 2012).

But what actually defines a soft robot and when is it classified as a hard robot? The characterizing aspects of a soft robot are displayed in the following overview provided by D. Trivedi et al. in 2008.

Although, one of the aspects that remain true for soft robots compared to their rigid counter parts is that they are composed of combined functions. While for rigid robots there are hard distinctions between each segment, in soft robots these functions can be integrated or combined. Until this date, a lot of information is created on soft robotics. All this information hasn't been gathered in one overview. This part of the research phase is therefore focused on gathering this information and structuring it clearly for future reference. To do so the following research question have been formulated:

- What type of soft robotic actuators would be most suitable for this project?
- Which sensors that are applied in the field of soft robotics could contribute to this project?
- Which types of conenctions could be implemented in this project?
- What power sources are applied in the field of soft robotics and which type would be the most stuiable to use in the final demonstrator?
- What are the up and downsides of the currently used production methods?
- How is the development of soft robotics currently supported?
- In what fields could soft robotics be used?

	Rigid	Discrete hyperredundant	Hard continuum	Soft
Properties				
df	Few	Large	Infinite	Infinite
Actuators	Few, discrete	Many, discrete	Continuous	Continuous
Material strain	None	None	Small	Large
Materials	Metals, plastics	Metals, plastics	Shape memory alloy	Rubber, electroactive polymer
Capabilities				
Accuracy	Very high	High	High	Low
Load capacity	High	Lower	Lower	Lowest
Safety	Dangerous	Dangerous	Dangerous	Safe
Dexterity	Low	High	High	High
Working environment	Structured only	Structured and unstructured	Structured and unstructured	Structured and unstructured
Manipulable objects	Fixed sized	Variable size	Variable size	Variablesize
Conformability to obstacles	None	Good	Fair	Highest
Design				
Controllability	Easy	Medium	Difficult	Difficult
Path planning	Easy	Harder	Difficult	Difficult
Position Sensing	Easy	Harder	Difficult	Difficult
Inspiration	Mammalian limbs	Snakes, fish		Muscular hydrostats

Figure 12: Table with the characterizing aspects of robots byt Trivedi et al. 2008

Figure 13: Pneumatic Bending Actuators by Polygerinos 2013

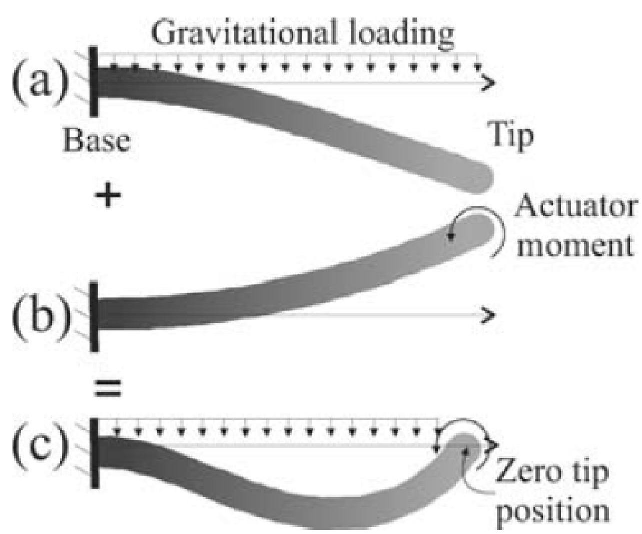


Figure 14: The compensation behaviour of a pneumatic actuator, by Trivedi 2008

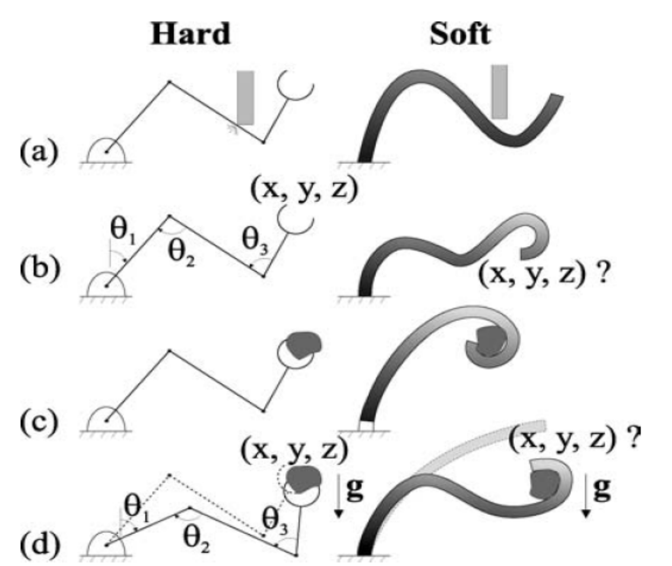


Figure 14: comparisson of body movements of a soft and hard robot, by Trivedi 2008

3.1.1 ACTUATORS

One of the aspects that can be seen in Trivedi's overview of soft robotic characterizations is the fact that actuators are continuous. One of the big differences is that the actuators are integrated within the body. Using the entire body of the robot for their actuation. While hard robots are composed of few locally discrete actuators that perform their actuation. This provides a big advantage when designing a soft robotic component. You can have a lot more form-freedom since you are not restricted by specific actuators. In addition, it enables the soft robotic parts to react to their environment enabling them to grasp various objects.

The downside is that soft robots have issues with sensing and controlling their exact shape. Whereas a classic robot would only be affected by a load on the joints, a soft robot deforms over its entire arm. The embedded sensors and actuators can partly make up for these deformations they cannot fully compensate this effect as is shown in figures 14 and 15 (Trivedi, 2008).

Over the last few years, a lot of progress has been booked in the development of new soft robotic actuators. Ranging from bending actuators up to the more recent torsion actuators. Since there is currently not a big overview of available actuators, sensors, connections, power sources and production types. A new overview has been created to gather these 'building blocks' for future reference. This overview was also created to gather insights of which type of actuators could be implemented within this project.

The overview has been composed of a wide variety of papers describing new advancement in the field of soft robotics. For the actuators the papers gathered where limited to overview papers and pneumatic actuator papers, all other parts come from different overview papers. The sources used are listed below.

(Shepherd, 2012; Mosadegh, Polygerinos, & Keplinger, 2014; Rus & Tolley, 2015; Lynn, Sanan, & Griffith, 2014; Connolly, Polygerinos, & Walsh, 2015; Harvard University and Trinity College Dublin, 2017).

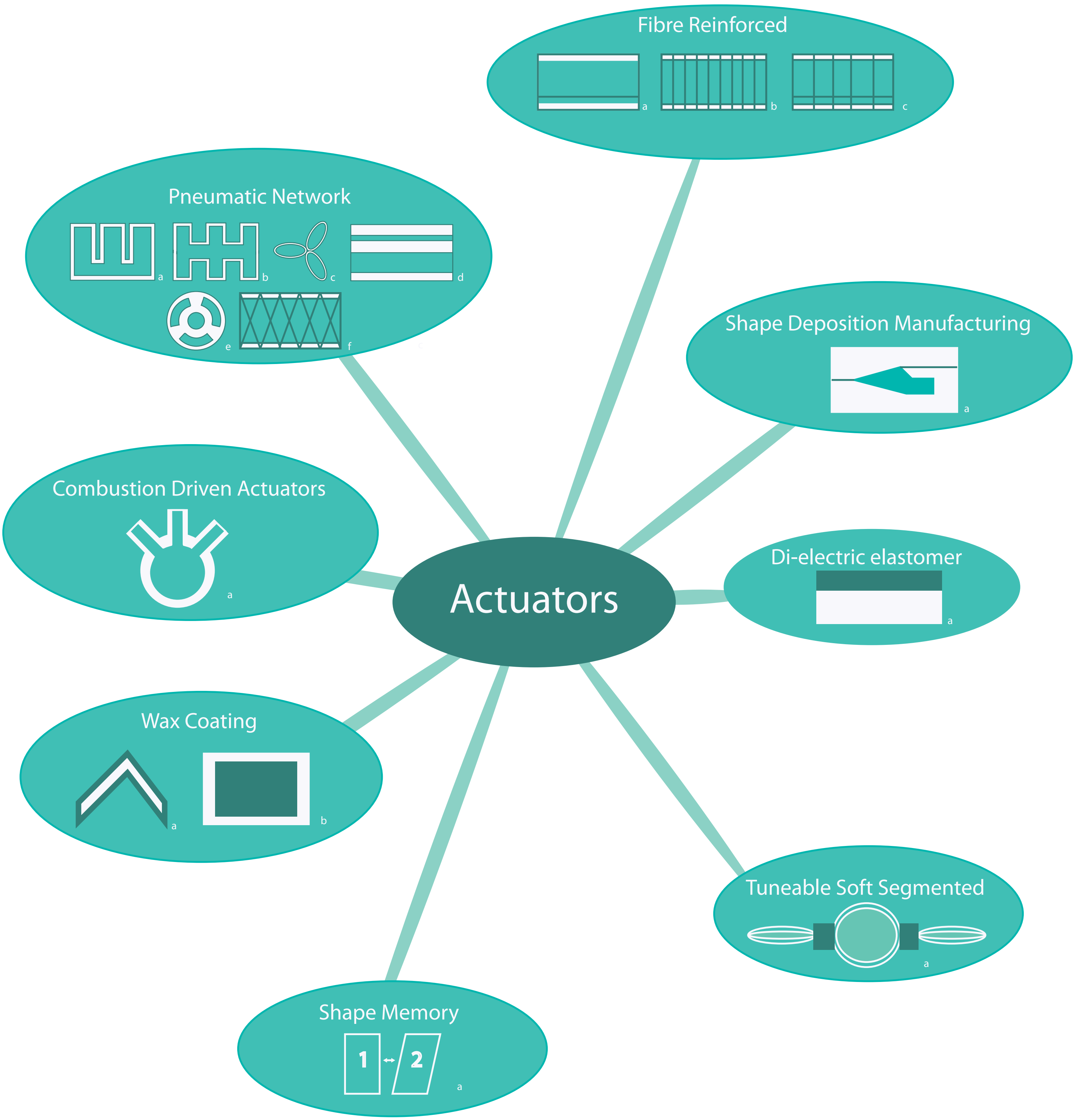


Figure 16: Schematic overview of soft robotic actuators

Pneumatic Network Actuators (PneuNets)

These actuators are controlled by regulating the pressure inside the parts. The parts are all created out of a complex network of chambers defining their mode of actuation. These type of actuators can be combined to create a range of complex motions within one single product. Type a) is a bending actuator that will bend as a result of strain difference within the part. Type b) is also a bending actuator, but the bend is not limited to one axis. The outer chambers can be inflated to create a bending actuation, while the center cavity provides stiffness to the shape when desired. Type c) is a compressing or extending actuator, by putting pressure on the chambers the part wants to elongate. The d) actuator is a torsional actuator. This actuator will twist as a result of increasing or decreasing pressure (Lynn, Sanan, & Griffith, 2014). The e) Type actuator is one composed of two opposite chambers. They behave like muscles, whereas one chamber provides the bending of the actuator while the other chamber can stop the motion halfway by being pressurized. The f) Type actuator is also designed around the principle of a muscle. The air chamber is surrounded by rigid strings which change the way the part inflates. When pressure is applied the actuator contracts but becomes wider, just like a muscle in the human body.

Fiber Reinforced Actuators

These actuators are in essence quite similar to their network counterparts. The type of actuation is defined by the way the fibers are used in the system. Type a) is an example of a bending actuator. If the fiber is pulled it will create a bending actuation of the part. Type b) When the fibers are contracted the material will create an elongated displacement (Rus & Tolley, 2015). Type c) is a combination of the a) and b) types of actuators, all sorts of fiber combinations can be composed in order to create specific actuation is in parts.

Shape deposition manufactured actuators

These soft robotic parts are composed of alternating sequences of rigid and flexible parts. Within the rigid sections, components are embedded like sensors and actuators.

Die-electric elastomer's

These actuators contain an elastomer film that contains an electrode on both sides. When an electric load is applied on this film the part will expand in its planar direction while contracting in its thickness.

Tunable Segmented Soft Actuators

The working principle is not based around complex networks. It is based around the idea of an inflating balloon that initially requires a high pressure for inflation. After the initial peak, the balloon becomes easier to inflate. Up to a certain point when the rubber is stretched so much that it will start to stiffen. By combining balloons with different strain properties elongation can be achieved by opening and closing valves to regulate the pressure (Overvelde, 2015).

Shape memory actuators

These are composed out of alloys or polymers that have been set in a certain shape at a certain temperature or other chemical processes. By heating or for example adding moist the parts start to deform to their secondary configuration. When reversing the steps the part will return to its original configuration in which it was set.

Wax coated actuators

In the systems, the wax is heated to create a predefined movement of the part. The a) type is a structure that is wax coated. When the structure is heated the wax loses its stiffness allowing for the structure to collapse and create the actuation. The b) type has a wax core when heated the wax will expand, causing a type of actuation similar to that of a pneumatic actuator.

Combustion driven actuator

In essence, it works the same like a pneumatic actuator, although the biggest difference is that this part is designed especially for a short impulse. In addition, the part needs two extra channels. One for the sparking of the gas mixture and another one functions as an exhaust.

Conclusion

Due to the nature of the hybrid manufacturing set-up and the materials that will be used, the designs with air chambers such as the Tunable Segmented Soft Actuators, Combustion Driven Actuators and PneuNets seem to be the most viable design options. Since the set-up is capable of producing multiple materials, the principle of the Fiber Reinforce actuators might be a valuable addition as well.

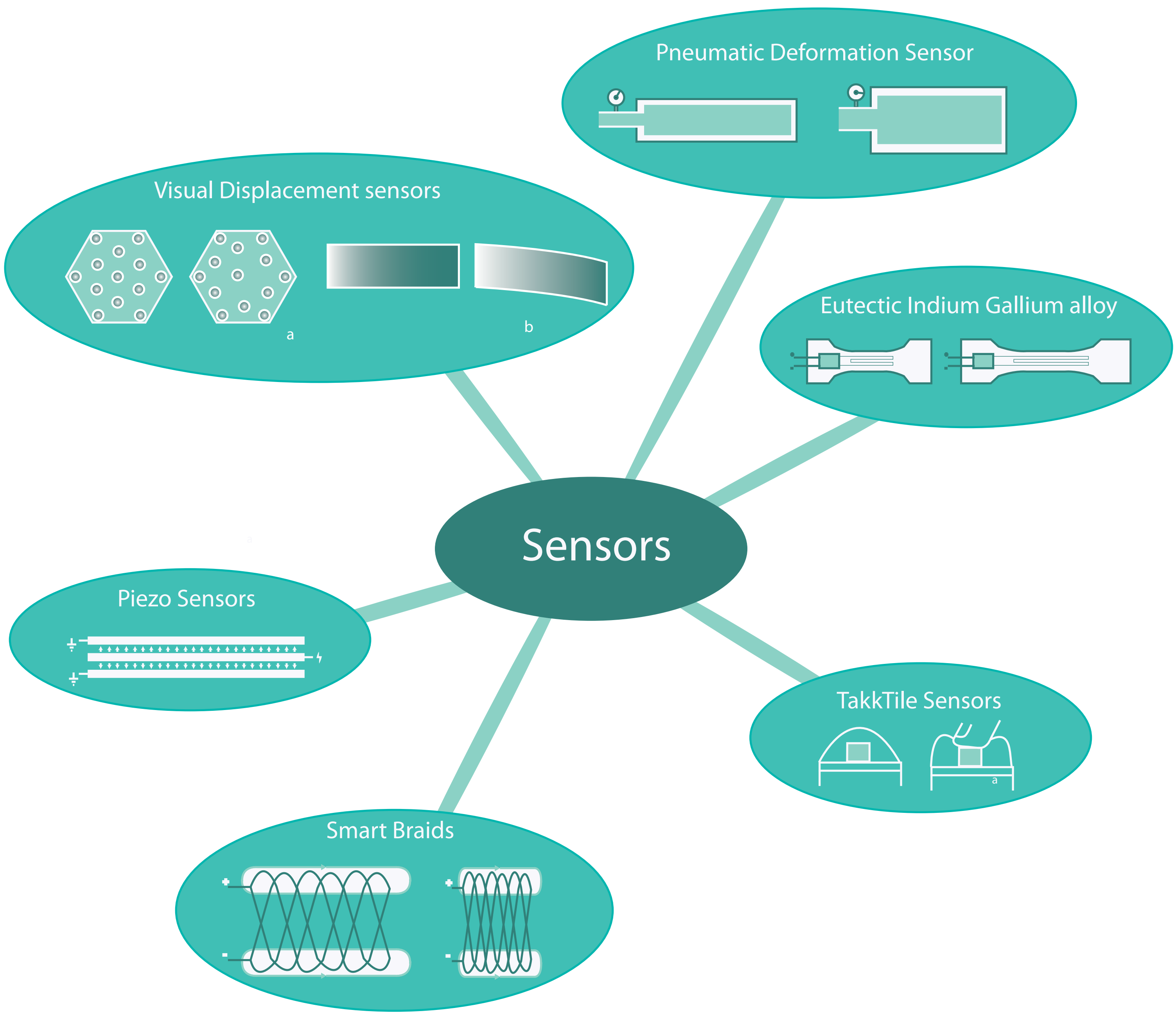


Figure 17: Schematic overview of sensor types used in soft robotics

3.1.2 SENSORS

An essential aspect of monitoring and predicting the behavior of soft robotic parts are the sensors. Although it is hard to extract the exact position of the entire body. A lot of information can be gathered about the parts configuration as a result of specific data profiles. For example, a pressure sensor can sense the pressure in a part which will give specific peaks at certain deformations. With the help of these unique peaks, the rough position of the body can be identified. The goal of this chapter was to find which sensors might prove to be an added value for this project. The generated overview is composed out of commonly used sensors in soft robotics (Harvard University and Trinity College Dublin, 2017). It should be noted that the use of sensors within soft robotics is not limited to only this overview.

Visual Displacement sensors
These are sensors that measure changes in visual appearance. Type a) is a static sensor. By creating a grid of dots on the specific part different conformations can be analyzed. When the grid is distorted the component is in a new conformation. Type b) is based on a gradient transition. By elongation or bending the color disperses differently over the part, creating a unique visual per conformation. Both techniques embed visual markers within the part that can be recorded with a camera.

Pneumatic Deformation sensors
Pneumatic Deformation sensors measure the pressure used in the part. By measuring the pressure the exact position can be determined as described in the previous example.

The Eutectic Indium Gallium Alloy sensor
This is a sensor that consists out of liquid conductive material embedded in elastic material. By measuring the change in resistance of the material, different positions and conformations of the part can be defined. Of course, the usage of conductive material as a sensor is not limited to this example, as long as the used material is flexible enough to maneuver with the soft robotic actuator.

Tactile sensors
These are a type of pressure sensors which are covered with silicone. These sensors are small and therefore can be internally incorporated into the design of the part. These type of sensors are often used in Shape Deposition Manufactured Actuators.

Smart Braids
Smart Braids make use of the electromagnetic fields generated by coils that surround the part. By measuring the change in the magnetic field the behavior of the part can be monitored. Often this is accomplished by making use of flexible conductive fibers embedded in the soft robotic parts. This set-up is ideal for Fiber composed Actuators.

Piezo Sensors
These sensors are based upon the difference in the electric potential between the layers. When one layer changes confirmation as a result of an activated actuator, the correlating potential of that layer changes. This change than can be translated in a certain conformation of the soft robotic part.

Conclusion
The sensory techniques that might benefit this project the most are the Visual displacement sensors and the Pneumatic Deformation sensors. The visual displacement sensors can be easily incorporated within transparent silicone, while the pneumatic deformation sensor suits well with the type of actuation preferred from the previous chapter.

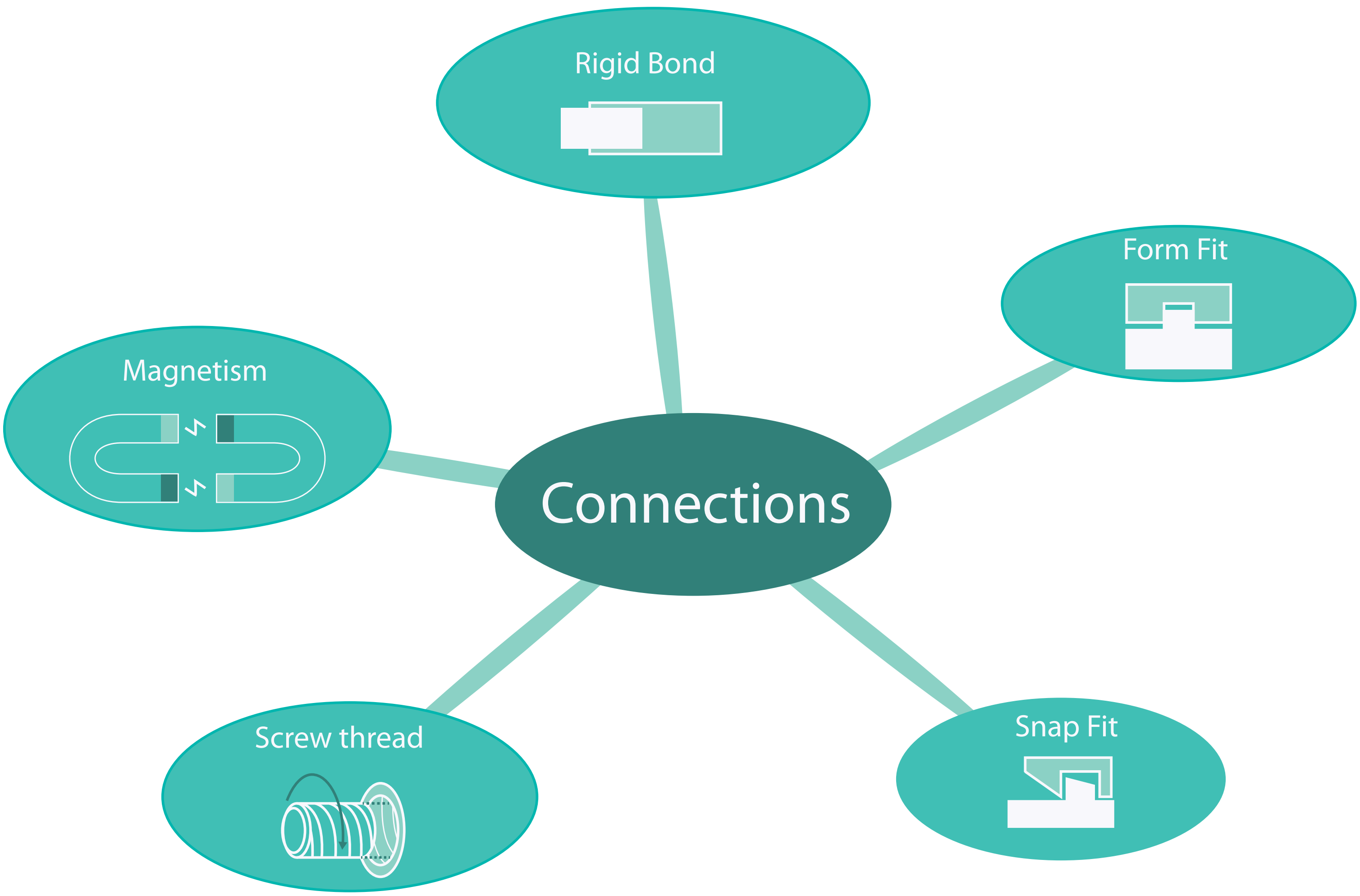


Figure 18: Schematic overview of connection types used in soft robotics

3.1.3 CONNECTIONS

In the actuator section, a few times there is mentioned that specific types of actuation can be combined in order to get fully functional systems. In order to combine these systems, different connection methods can be applied. This section provides an overview of possible connections. It should be noted that all flexible connections are based upon rigid inserts which might compromise the flexibility of all the parts.

Rigid Connection

Is the most basic connection the parts are produced within one whole creating a composite actuator that cannot be altered over time. This is a reliable connection as the part won't fail at where the two functions are merged. A downside is that this system cannot be adjusted for specific needs.

Form-fit

Is a form-fit which limits the degrees of freedom of the part in all directions, accept one. This can be useful if there is a need for a part that is easy to disassemble and doesn't receive a load on one axis.

Snap-fit

A snap-fit is a type of connection which basically does the same as the form-fit. Instead, it can also withstand loads in all directions. It is a lot harder to disassemble since the part needs to be moved beyond its elastic limit in order to get in and out of the shape. This type of connection can be used in airtight systems and provides great flexibility (Lee, 2016).

Screw Thread

The screw thread is also a flexible connection often found in all sorts of applications. This part is a bit harder to assemble than a snap fit. However, it is easier to disassemble. This type of connection can also be used in airtight systems. In the paper of Jun-Young Lee, this was reviewed as the best mechanical connection (Lee, 2016).

Magnetism

A magnetic connection can be achieved by both electromagnetic fields as well as the embedding of magnetic components. The upside of this type of connection is the self-alignment that is possible with these parts and the flexibility it provides in assembly (Sen, Morin, & Mosadegh, 2013).A downside of this connection is that the amount of pressure that can be applied upon the parts is limited to the force the magnetic field can withstand. In addition, the seal is not completely airtight and might cause minor leakage of air.

Conclusion

For the continuation of this project, a multitude of bonds might prove to be useful. The only two bonds that might not be relevant are the screw-thread and magnetism. As the magnetism would require an extra production step to insert the magnets. While fine screw thread is hard to produce with FDM.

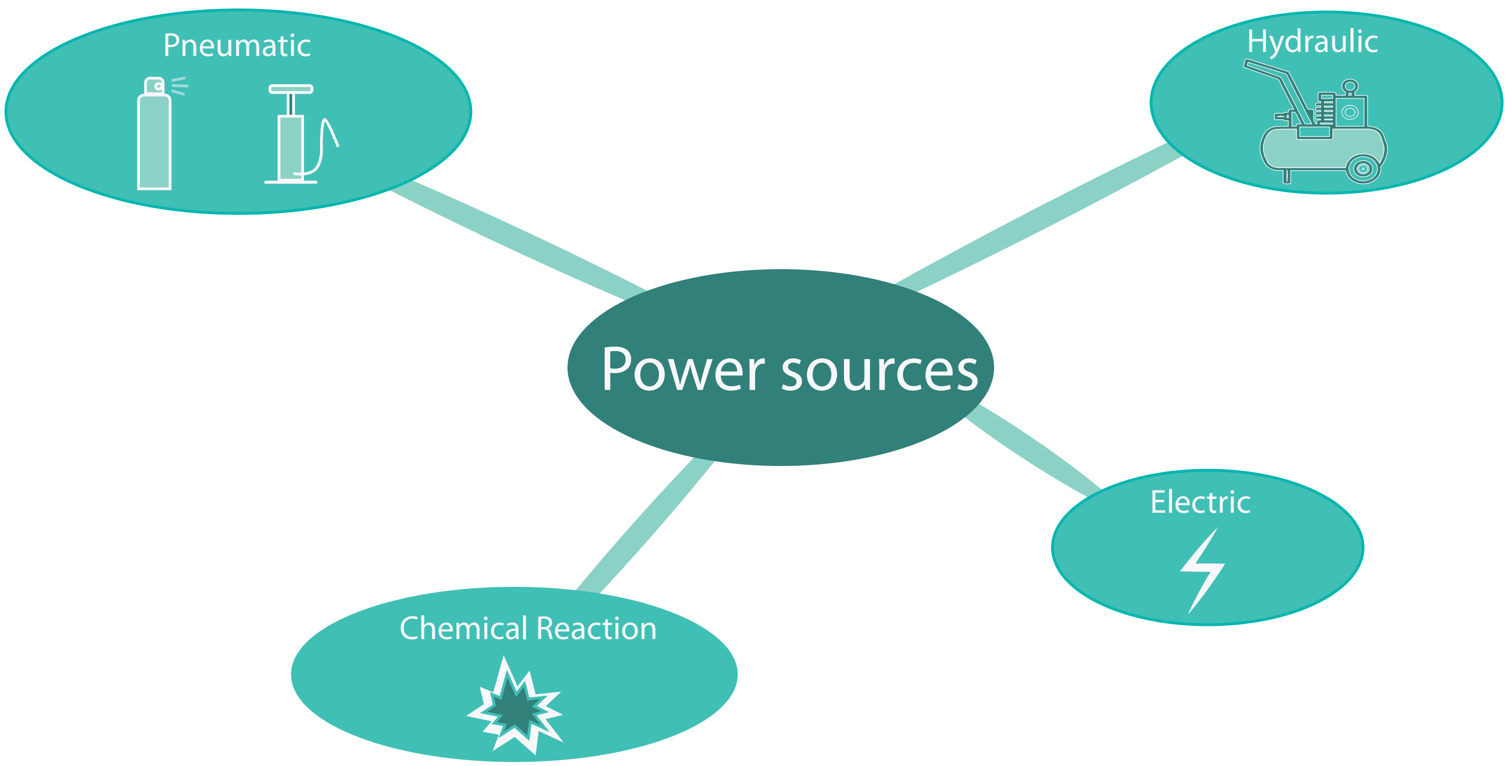


Figure 18: Schematic overview of common power sources for soft robotics

3.1.4 POWER SOURCES

In order for the soft robotics systems to operate some sort of power source needs to be used. This is one of the biggest challenges for soft robotics since it needs to be stretchable and portable. For existing soft robotics solutions, rigid systems are embedded which are often big and bulky limiting the flexibility of the soft robotic systems (Rus & Tolley, 2015). The following overview consists of the most commonly used power sources for soft robotics. All categories are composed out of a container mode and a continuous mode.

Pneumatic power sources
These are used for the most commonly used activations methods of Pneumatic Network Actuators. By increasing the pressure in the parts an actuation is provided. The container allows for power for a limited amount of time. The advantage is that this allows the soft robot to function fully autonomous. The pump allows for an infinite amount of power, the downside of this system is that the maneuverability of the soft robot will be limited.

Hydraulic systems
These also can come in the form of containers and pumps. The advantage of the hydraulic systems is that they can take heavier loads. A downside is the fluid systems are often more bulky and heavier.

Electrically powered systems
These systems can be used to power specific actuators like hydraulic pumps and compressors, but they can also provide actuation on their own due to electromagnetic fields. In addition, they can also heat parts to deform. Besides the actuation, these systems often are also needed to power the sensors. The static solution is electricity from the net with an adapter while the autonomous solution can be found in a battery.

Chemical reactions
The most commonly known chemical reaction used for propulsion is combustion. This chemical reaction causes a quick expansion of gases, ideal for the creation of impulse motions like jumping. Another example of chemical reactions is shown in the newly Octobot which makes use of hydrogen-peroxide which decomposes when being brought into contact with platinum releasing water(L/G) and oxygen(G). It can also create pneumatic actuation (Wehner, Truby, & Fitzgerald, An integrated design and fabrication strategy for entirely soft, autonomous robots, 2016). Other possibilities, although not mentioned in the found papers, are phase changes, where materials can temporarily change from state or volume changes where materials have the ability absorb for example water which can, later on, be released to return to the original state.
Also, it is possible to make use of hybrid systems. An example of this could be the use of a micro compressor powered by a battery. In the paper of Wehner, Tolley and Mengüc this was described as the most efficient method to power PneuNets (Wehner, Tolley, & Mengüc, 2014).

Conclusion
Although power sources are not fully within the scope of this project. It should be noted that both hydraulic and pneumatic systems would work with the pneumatic actuators. Chemical reaction actuators also might prove to be a useful outcome in specific applications.

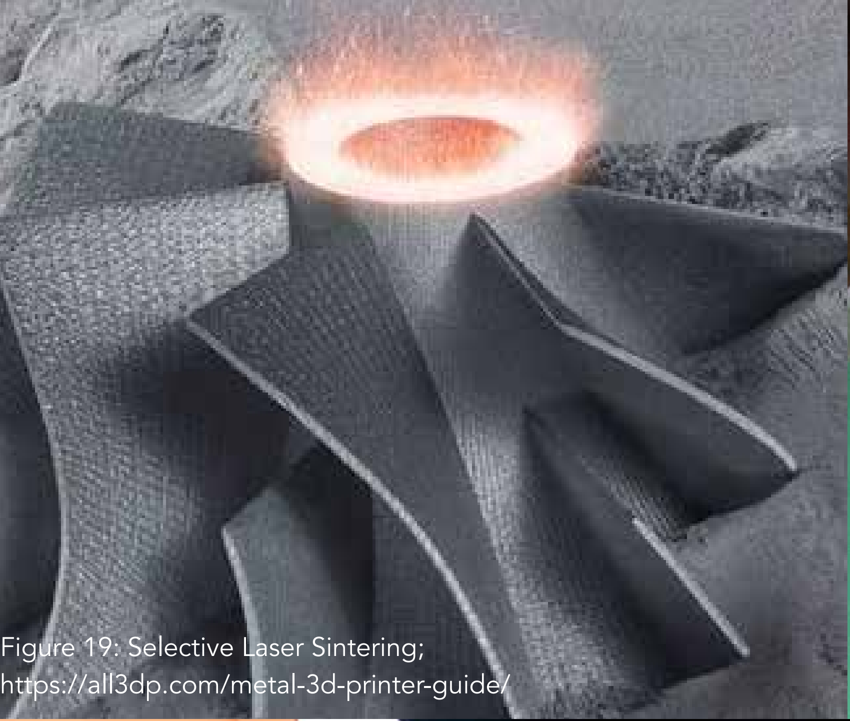


Figure 19: Selective Laser Sintering;
https://all3dp.com/metal-3d-printer-guide/

Figure 20: Hand castes Silicone;
https://lassospb.ru/articles/149207

Figure 21: Material Jetting
Screenshot from: 3D Printing - Polyjet - Additive Technologies

Figure 22: Rotation molding;
https://www.rotationalmoulding.com/rotomoulding/machinery/

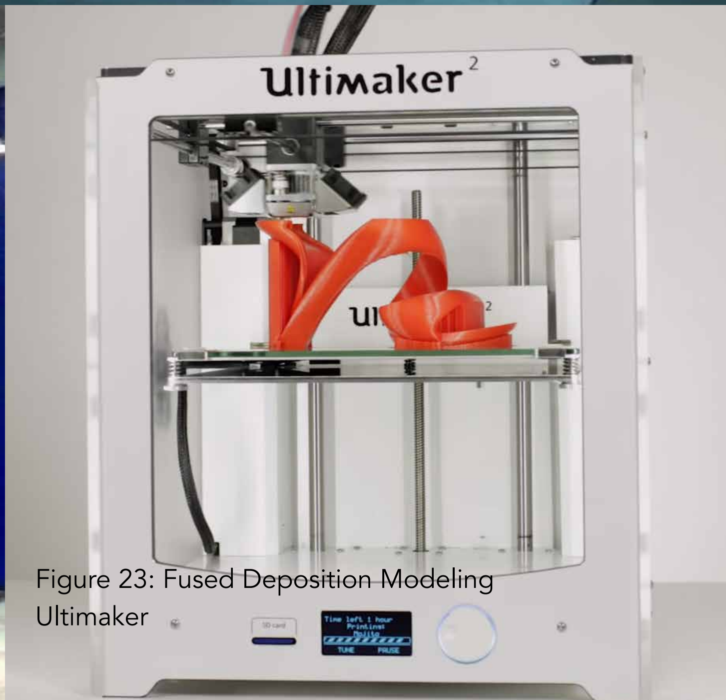


Figure 23: Fused Deposition Modeling
Ultimaker

3.1.5 PRODUCTION

The production of soft robotic parts has a lot of advantages over the production process of classic robots. The amount of components required is limited since sensors and actuators are integrated within the body. This reduces the production cost. A downside is that the parts that need to be created are more complex. Another downside of this aspect is that if the parts fail, the whole soft robotic part needs to be replaced instead of only a sensor or actuator (Scharff, 2015). Another big difference is the type of materials classic robots are composed of. They are created with metals and hard plastics which have moduli in the order of 109 – 1012 pascal. Soft robots are composed of more skin like materials like silicone which have moduli in the order of 104 – 109 pascals (Rus & Tolley, 2015).

The most commonly used production method for soft robotics is 3D-printing, also named additive manufacturing. The most commonly used 3D-printing methods used are the following:

Selective Laser Sintering (SLS):
This method melts layers of a polymer powder into solid parts in order to create complex parts.

Fused Deposition Modeling (FDM):
Makes use of strings of plastic which are melted by a nozzle to create thin layers of plastic in the desired position. By stacking these thin layers solid parts are created.

Material Jetting:
Material Jetting works with small droplets of UV curable resin which is printed on the bed. After the layer is deposited the droplets are hardened and melted together with UV-light.

Although these techniques provide a lot of flexibility in the production process it also has its limitations. One of the biggest limitations is the lack of usable materials and material combinations. In addition, the prints need to be supported by a structure which reduces the quality and finally, it takes a long time for the prints to finish (Trimmer, 2015).

A more primitive production method used is silicone casting by hand. The material properties of silicones are ideal for soft robotics as these are skin friendly, can be food safe and mimics the properties of the human skin quite well. With the help of molds, complex parts can be created however this is time-consuming and gets really expensive in mass production.

A solution to the previously mentioned option might be Rotation Molding proposed by Huichan Zhao. The advantages of such a system are that it is capable of producing silicone parts in a simple way. In addition, it allows the production process to be automated and creation can be done in parallel. Another big advantage of this production method is that parts don't contain a seam where the two parts of hand cast parts join together. A notable downside of this production process is it's not as flexible as the other production methods for adjustments.

Conclusion

All of these production methods have proven to be a valuable asset in creating soft robotic parts. The new manufacturing set-up should be able to compete with these methods for the developement of prototypes. As the focus of this set-up is to create prototypes al most everytime a new design will be produced therefore making upscaling the process obsolete.

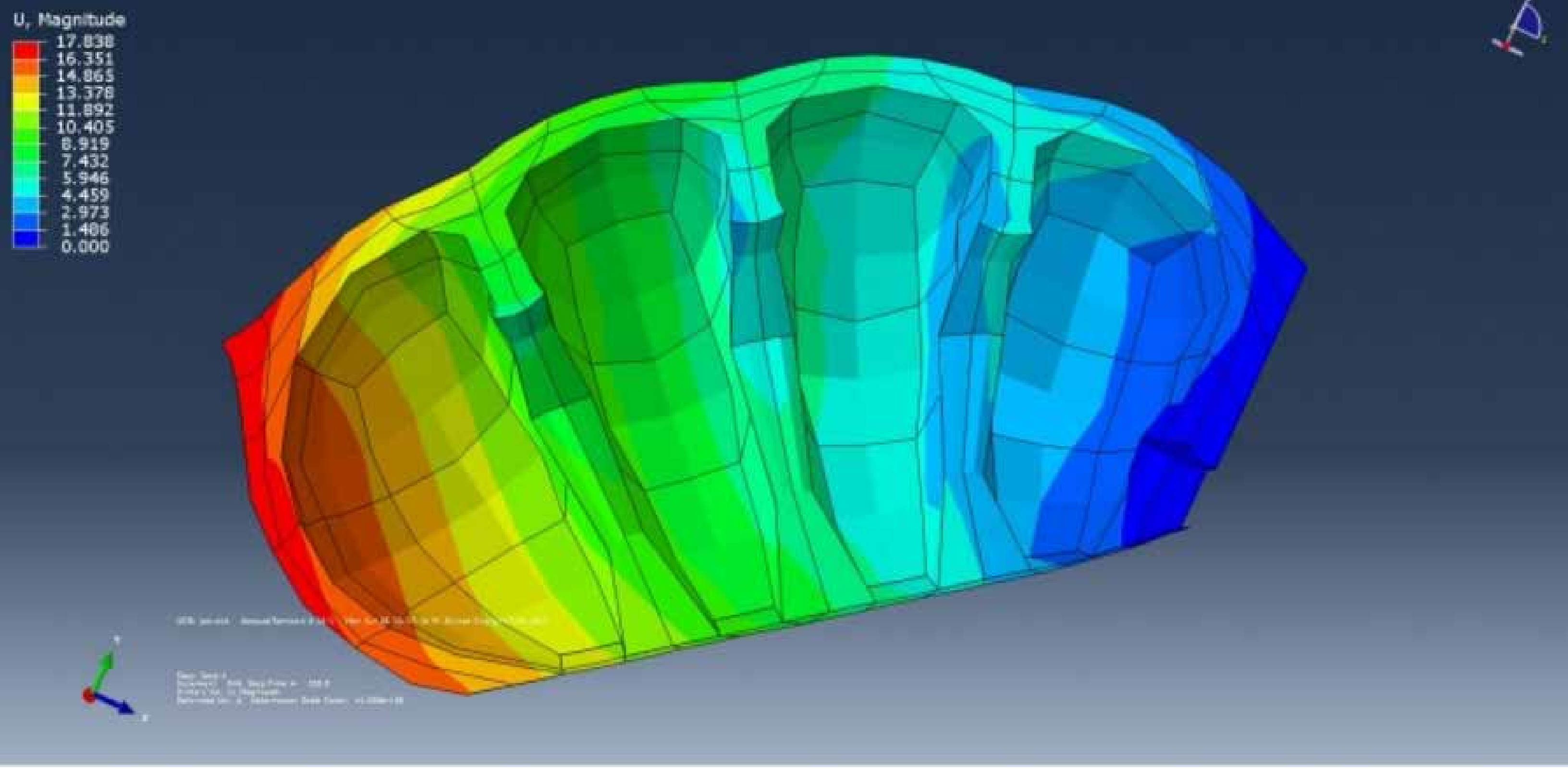


Figure 24: Simulation of a pneumatic bending actuator in Abaqus;
Softrobotic Toolkit

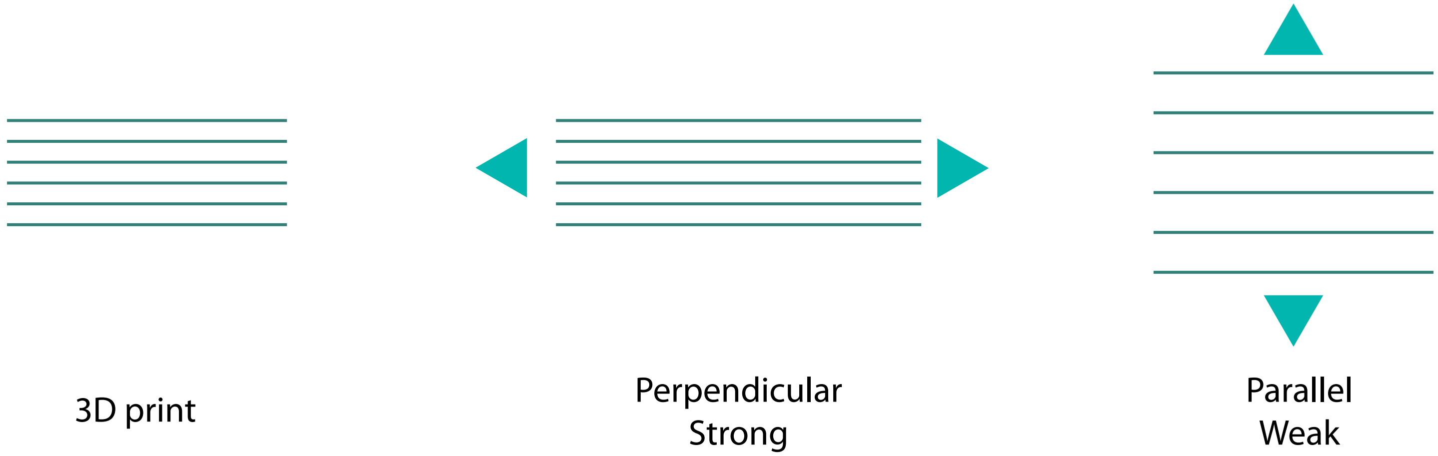


Figure 25: Directional strength of 3D printed parts.

3.1.6 DEVELOPMENT SUPPORT

During the development of soft robotics there are many uncertainties. Due to their under actuated nature as well as the large deformations that the parts experience. This chapter tries to provide an overview of the used methods to predict the exact behaviour of the soft robots. In addition, the effects of the production method on the behaviour is researched to answer the following question: How can the impact of the production method upon the functioning of the soft robotic actuator being minimalized?

For rigid body robots, there are a lot of well-defined methods to model the behavior of parts by forehand. This is not the case for soft robotics. Due to the huge deformations, caused by the nonlinear anisotropic soft materials used, and the high-pressures. The Finite Element analysis is not a suitable simulation method. (Trimmer, A Journal of Soft Robotics: Why now?, 2014). The Finite Element Method is based on the base principle that only small deformations occur which is not the case for soft robotics.

There are other ways to predict the movement of soft robotics besides the Finite Element Method. In theory, the final shape of a complete soft robot can be described by a continuous function. Modeling this behavior also requires continuous mathematics. Researchers have developed new static, dynamic and kinematic models to predict and capture their flexing and bending (Rus & Tolley, 2015). Additionally, the piecewise constant curvature (PCC) model is used to predict the behaviour of the soft robots.

In terms of software, Abaqus is used since it is more capable of dealing with nonlinear material behavior. In addition, it can take into account big deformations and calculate force transmissions between self-intersecting parts. One essential condition is that all the materials characteristics are well known.

The last aspect is one of the biggest issues. Soft robotic actuators are often prototyped by means of 3D-printing. One of the known characteristics of 3D-printed materials is that the material doesn't display isotropic behaviour. This is the result of the way shapes are created. The material is extruded in a certain shape and directions. This direction already determines in which direction the biggest loads can be handled. The weakest direction of a print is the Z direction. This is the result of the weaker bonding between the layers that are stacked upon eachother the effect are displayed in figure 25.

Not only the 3D-printing production method suffers from impurities in the material and anistoropic behavior. Also hand casted silicone contains errors. Often there are small air pockets throughout the silicone, resulting in a non-homogeneus actuator.

Experimental verification is always used to verify the results of presicriptive models as the uncertainties of the production methods have to be taken into account. The method can also be used to not only verify movements but also to predict them. This can be applied on a material level, where the material characteristics are determined whilst it is also possible to do the verification on a functional level. By setting a set amount of parameters like below height wall thickness etc. relationships can be observed and used for future reference.

Conclusion

To minimalize the effects of the production method upon the behaviour of the actuator, the produced part should be pressure casted. This way an almost homogeneus actuator can be created. The use of experimental verification is necessary.

Figure 26: Prostetic Hand with silicone fingers;
Silicone-Bio-Hand: Bio-inspired Body Actuated low cost Soft Prosthetic hand

Figure 27: Orthoses to improve the gripping force of a hand;
Design, fabrication and control of soft robots

Figure 28: Singing and talking soft robot;
Professor Sawada future Talking Robot , one step closer to the Robocalypse

3.1.7 APPLICATIONS

In the field of soft robotics, a lot of developments are achieved. However, the actual applications in which it might provide value for the society is often not indicated. This section provides insight in which applications soft robotics can prove to be an added value and why it can be an added value. At the end over every section, the added values are summarized and points of attention formulated. The main application areas are based on the areas defined by Rob Scharff in his thesis.

Prostheses

One of the first aspects that come to mind when talking about soft robotics is the resemblance of the actuators to the behavior of humans. As a result one of the first product solutions that are found for this application is the use of soft robotics for a prosthesis. Besides the natural movement and feel of the actuators, they have the advantage of being underactuated. This allows the actuators to adapt to their surroundings. Other aspects that make it appealing for this application is the efficiency of such an actuators as a result of the little energy required for their actuation and the fact that they are light weight. The durability of both the energy source as a direct result of the efficiency as well as the durability of the used materials. Finally, there is also the relatively cheap production cost of the prosthetics which in turn also allows to customize them to the specific needs of the users. A good example of a prosthetic could be a pneumatic hand.

The biggest challenges for this applications will be in regards of combining the right actuation types of the soft robots to mimic a human movement as close as possible. In addition, the right balance has to be found between the degrees of freedom, and the limitation in movements.

* Human movement and feel * Conformability * Durability * Low Production Cost * Customize	+	* Mimicking human movements * Balancing degrees of freedom and limitations	!

Orthoses

Orthoses are closely related to the prosthesis instead of replacing human parts of the body they help the parts move. Currently, this is also the most developed product solution (Rus, 2015). Again the aspects of having a close resemblance of the behavior of humans is a big benefit, in both movement and feel. In addition, it can make the orthoses feel more like second skin instead of a machine helping the patient. Also, the direct interaction of sensing and actuation can provide valuable feedback to the wearer allowing for a better support during a revalidation process. Examples can be aiding patients that had a stroke with grasping objects or supporting an ankle for patients that suffer from gait abnormalities like drop feet (Majidi, 2013).

In terms of challenges, this application also needs to mimic the human movements as close as possible. In addition to this, it also needs an understandable way of communicating its sensory input into an understandable output for the user, which can be quickly interpreted.

* Interactive * Natural movement and feel * Customize	+	* Mimicking human movements * Human Product Interaction	!

Human Simulation Robots

An additional field of interest is the human-simulating robots. These type of robots need to have a close resemblance to real humans in order to provide a decent simulation. Due to the used materials and the lifelike capabilities, soft robotics have these qualities (Majidi, 2013). In addition, the capacity of soft robots to sense and actuate with the same part allows for quick feedback loops. This feedback can be in the form of haptic simulating a human reflex in proving the training experience of the users. Finally, the ability to quickly alter the production models and print these allows for very specific customized simulation situations. An example of a (semi-) soft robot is the talking and singing robot from Kagawa University. see figure 28 (Nakamura & Sawada, 2006).

The biggest challenge in this field will be to create realistic reactions of that of a human. An example could be a human gag reflex.

* Natural movement and feel * Interactive * Customizability	+	* Mimicking Human Responses	!

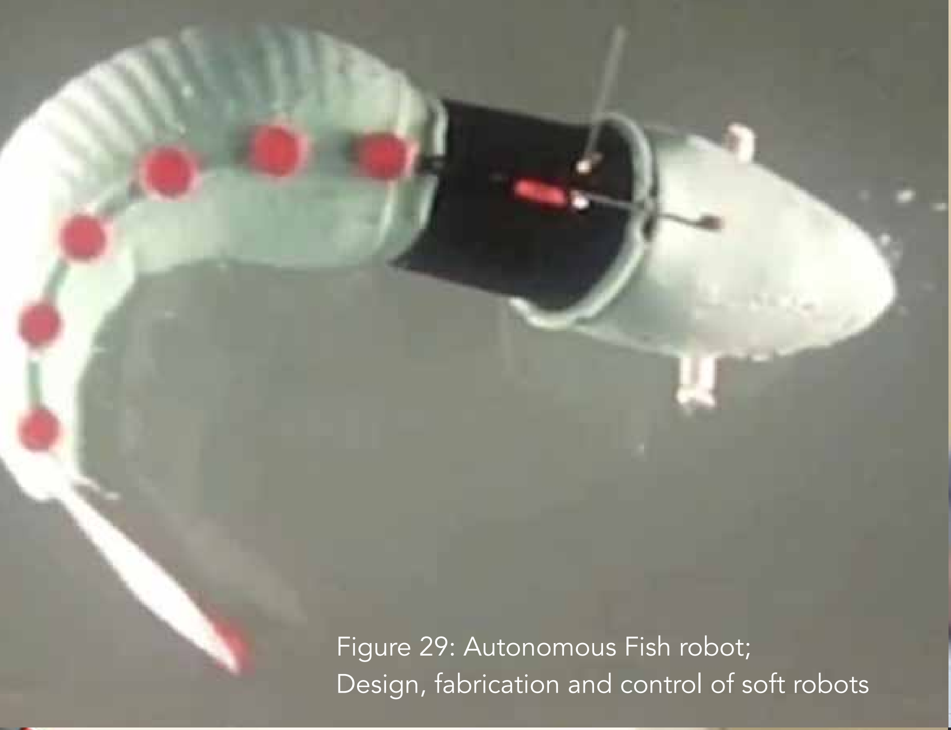


Figure 29: Autonomous Fish robot;
Design, fabrication and control of soft robots

Figure 32: The frebble a telecommunication device the functions via hapticfeedback;
http://myfrebble.com/

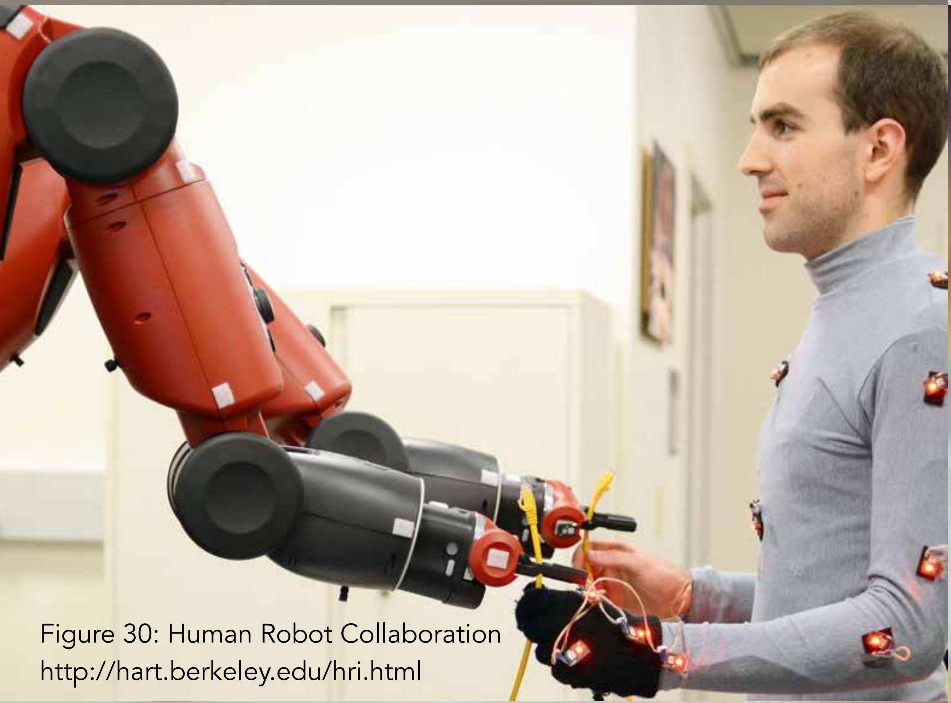


Figure 30: Human Robot Collaboration
http://hart.berkeley.edu/hri.html

Figure 31: Surface with a hapitic feedback to the user
http://fullinsight.com/blog/2013/10/surface-matters

Figure 33: Soft Robotic Gripper an example of an industrial mechnism.
Soft Robotics Inc. - Bakery Automation with a Soft Touch

Exploration Robots

Besides the close resemblance to the way, humans behave soft robots have also other main advantages. One of these advantages is due to the soft bodies and the pulsated mode of actuation the robots can lend themselves for locomotion allowing them to explore its surroundings (Rus, 2015). This combined with their conformability to their surroundings as a result of their under-actuation and the possibility to operate them fully autonomous, allows soft robots to explore areas where no human could reach. A good example of an Explorative robot is the robot fish of figure 29 (D, Onal, & Rus, 2014)

The biggest challenge for explorative robots is their power source. It needs to be integrated into a soft robot. Currently, they are still heavy and bulky (Rus, 2015). In addition, the compliance matching is a crucial aspect for this kind of robots, which means that the forces on the robot and traveling surfaces should be equal to prevent damage.

* Autonomous * Conformability * Locomotion +	* Lasting Power sources * Compliance Matching !

Industrial Mechanisms

The industrial field already makes widespread use of robotic systems for simple pick and placement tasks. Soft robots can also be an added value in this field. Due to their conformability grippers are capable of grasping irregular objects that else would be hard to grasp. In addition, soft robots are capable of quick actuation as a result of their lightweight nature and their ability to conform to their surroundings. In addition, the costs of using such a system should be relatively low. The production costs of pneumatic grippers are relatively low. This is not only as a result of the production process. Also due to the fact that the amount of components needed, to create such a gripper, are less than that of conventional robots. This also has benefits in regards to durability, as it is less likely that parts will break down. It should be noted that when an actuator breaks down the entire part should be replaced.

The control of the degrees of freedom is also for this application valuable, as you don't want the robots to create unintended movements. Additionally, the usage of materials should also be considered depending on the operating context. In some environments food, safe grippers can be an added value.

* Conformability * Actuation Speed * Durability * Low production Cost +	* Balancing degrees of freedom and limitations * Material usage !

Cooperative Robots

One step further than only grippers would be implementing entire soft robots in an industrial environment. The main advantage of doing so is that the gap between user and machine becomes smaller. The robot has similar qualities a human and in addition, it is capable to provide a more natural way of feedback due to mimicking human interactions. As this robot will be in close contact with humans, it is important that it is capable of mimicking human movements but also to communicate with humans in a relatable manner.

*Natural movement and Feel +	*Mimicking Human Movements *Mimicking Human Responses !

Telecommunication

The last mentioned aspect is the main driver for this possible application. The ability to mimic human interactions can truly be an added value for long distance communications. This benefit can be enhanced by the fact that a soft actuator is capable of sensing and actuating at the same time. By sensing this data a direct output could also be created on the receiving side. The biggest challenge here is to convert a human input to a realistic output on the receiving side.

* Interactive * Low Production Cost +	* Human Product Interaction !

Haptic Feedback

The most trimmed down version of a soft robotic application is that of using it solely for the purpose of haptic feedback. The usage of soft robots for haptic feedback allows for a whole new world of interactions a user can have with a product. Additionally, the relatively cheap production prices of soft robotic parts make this also an interesting option to integrate into existing product solutions.

* Natural movement and Feel * Interactive +	*Mimicking Human Movements *Mimicking Human Responses !

Conclusion

Looking at all the possible applications there are some factors that return more often than others. These aspects should be taken into account as a starting point for improving the development of soft robotics. The aspects are Likeliness to humans, Customizability of the parts, Conformability to its environment and Interaction with the surroundings.

3.1.8 CONCLUSIONS

Soft robots can prove to be a game changer in a lot of fields due to the resemblance of the natural movement and feel of real humans. Also, the fact that systems can integrated sensor and actuators in a whole allows it to be cheap in production, lightweight and adaptive to its surroundings. This makes it a good solution for Human Robot Interactions (HRI), Medical applications, Telecommunication and autonomous exploration.

This technology doesn't come without its own downsides. Due to the nature of soft robotics, the bodies of soft robots are hard to fully control. The final modes can be discovered and corrected but this doesn't compensate for the entire body. In addition, the behavior of a specific part is hard to predict due to the nonlinear material behavior combined with the large deformations of the parts. Therefore, new simulation methods need to be developed and improved. In the meanwhile, the experimental validation method is an important prediction tool.

To speed up the process of the experimental validation method a new production method is desired. The production methods currently used are limited in the applicable materials and flexibility in the production process. The development of a hybrid manufacturing system can provide an outcome.

The focus of the soft robotic parts ,that will be produced with the set-up, is upon pneumatic actuators. Sensors that could be implemented are visual displacement sensors. Connenctions that aren't suitable to use are screwthread and magnetism. In order to power the actuator air pressure, hydraulics and chemical reactions could be used. In order to let the system print pneumatic actuators the set-up should fulfill the following functions:

- The system should be capable of casting silicone
- The system should be able to print solvable molds

The complete overview of the final list of requirements can be found in appendix 8.1.

Finally, for the composition of a fully autonomous soft robot, there are two essential parts limiting the flexibility of the system. Firstly the connectors, these are often rigid since the connections have to be air tight. Secondly the power sources, which are often big and bulky. In order for the soft robots to become more autonomous, these issues should be addressed.

3.2.0 INTRODUCTION

In the conclusion of the soft robotics chapter, one of the issues that needs to be addressed is the lack of different materials that can be used in the production process of creating soft robotics. In order to gain insight into what is possible in regards to material use, different possibilities have been researched.

- What kind of materials are currently available for 3D-printing?
- What kind of materials are still under development and which types can be interseting for this project?

In additon research has been conducted on the mesolevel of the materials. The mesostructure is easy to control in the desired production process of 3D-printing. The investigated aspects are the behavior of metamaterials, auxetics in particular. The main question was:

- How can auxetics have a valuable contribution to the production of soft robotic parts.?

Another aspect that has been investigated is the creation of composite materials. The set-up is capable of blending two materials together, so the following research questions haven been formulated.

- What kind of composites are there and how can they be used during this project?
- How can the bonding between fibre and matrix be improved?

Finally some first tests have been conducted. These tests have been conducted to gather preliminary findings as well as testing theories.

All the gathered answers and insights allowed for the formulation of some more design criteria for the hybrid manufacturing set-up. In addition, the research inspired the development of some of the idea clusters.

	ABS	PP	HIPS	PC	PA	PET	PLA	TPU	PVA	CPE	(S)PLA
Fast							●				●
Corrosion Resistant					●						
Reliable							●				
Durable					●						
Strong				●				●		●	
Heat-Resistant				●						●	
Stable	●		●							●	
Though	●		●							●	
Impact-Resistant	●		●								
Flexible					●			●			●
Chemical-Resistant		●				●				●	
Soluble			●						●		

Figure 34: Table of 3D-printing materials and their main purposes

Silicone Type	Color	Viscosity	Pot Life	Cure Time	Hardness	Tensile Strength
DragonSkin Addition	Translucent	1800 cSt	12 min	40 min	2A	2 N/mm2
Green Addition	Green	6000 cSt	60 min	6 hours	30A	5 N/mm2
Tranlucent Addition	Translucent	4000 cSt	130 min	20 hours	24-27A	2 N/mm2

Figure 35: Table of different types of silicones used during this project and their material properties

3.2.1 BASE MATERIALS

For this project, two different production-types have been combined silicone casting and 3D-printing. This chapter aims to find materials that are relevant to this project and to determine how they can be applied in the production set-up.

Current Printing Materials

With the rise of FDM printing, a broader range of supported materials is being used to create unique parts. The most commonly used materials up to date are (Wholers, 2014);

ABS - acrylonitrile butadiene styrene
HIPS - High Impact Polystyrene
PC - Polycarbonate
PET - Polyethylene terephthalate
PVA - Polyvinyl alcohol
PA - Polyamide
PLA - Polylactic acid
TPU - Thermoplastic Polyurethane Shore 95A
(S)PLA - Soft Polylactic acid
Ninjaflex - Thermoplastic Polyurethane Shore 85A

The main focus around these materials is their moldability. During the development of FDM-printers reliable filament had to be developed for consistent prints. Over the last couple of years, this standard set of filaments has been expanded with a new special filaments. These are mostly flexible filaments or filaments that are a bit more durable than the most commonly used filament PLA. Within this list, only PVA is not intended to create full parts with. It is designed as a soluble support material, to help in the production of other parts. All the main purposes of the materials are shown in the overview in figure 34.

New Printing Materials

Currently, new filaments are still under development. These developments are based upon creating even tougher filaments than those that already exist. Like carbon fiber infused or filled fillaments. Parts with graphite particles in them. Or just more types of flexible filaments like flexible PA.

Besides the research in the tougher aspects, some of the previously mentioned filaments also have another potential. Namely, conductive properties. The new generation of filaments that is bein experimented and designed with is conductive filaments. Examples of these types of filament are; Black magic 3d, Proto Pasta and Copper and Brons infused filaments.

Silicones

For the creation of silicone parts a wide variety of silicones are available. These types can be split into two main groups. The additive silicones and the condensation silicones. The names refer to how the chemical reactions of the two components create the final compound.

During this project there has only been worked with additive silicones. The first type of silicone used is DragonSkin this silicone has a low hardness and a low viscosity. The second type is green addition silicone from silicones and more. This compound has a higher hardness and viscosity. Finally there is the transparant addition silicone which fall in terms of mechenical properties in between both previously mentioned materials. All of this is combined in a simple overview see figure 35.

Conclusion

There is a lot of research still being conducted in the development of new filaments. For this project, special interest will go to the flexible filaments, for the soft robotics application. Additionally, the newly developed conductive filaments might prove to be of value for this application as well. In terms of asthetics the transparant compounds could be an interseting option, while on the functional aspects the green silicone seems more appealing.

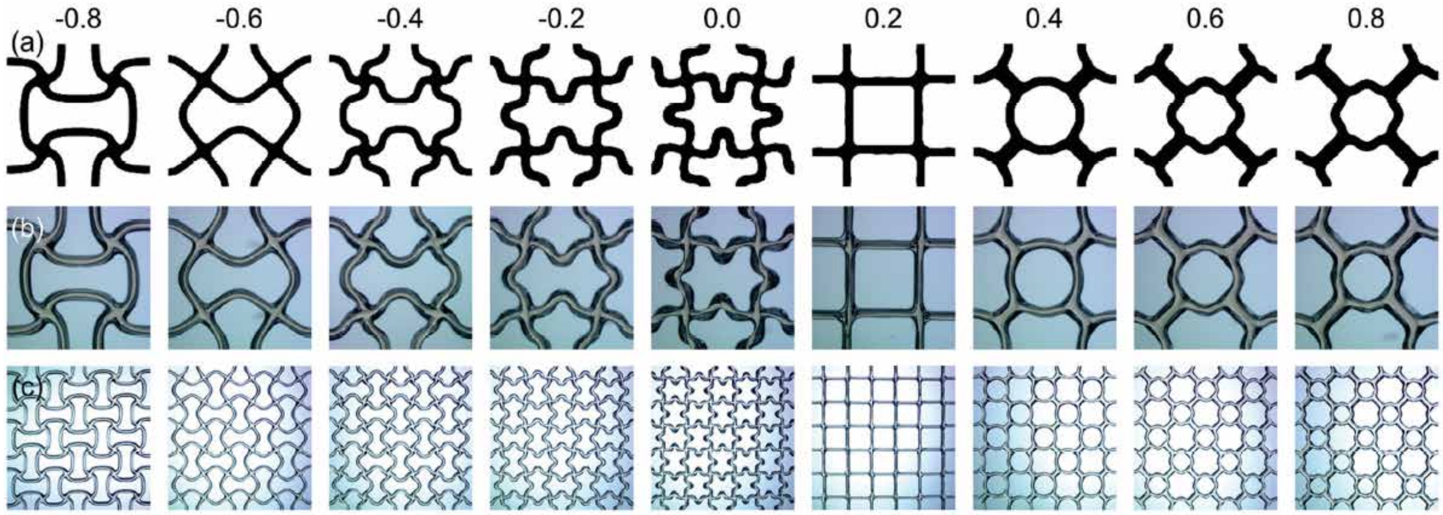


Figure 36: Topologies that result in different Poisson' s ratios; Greaves, Greer & lakers 2011

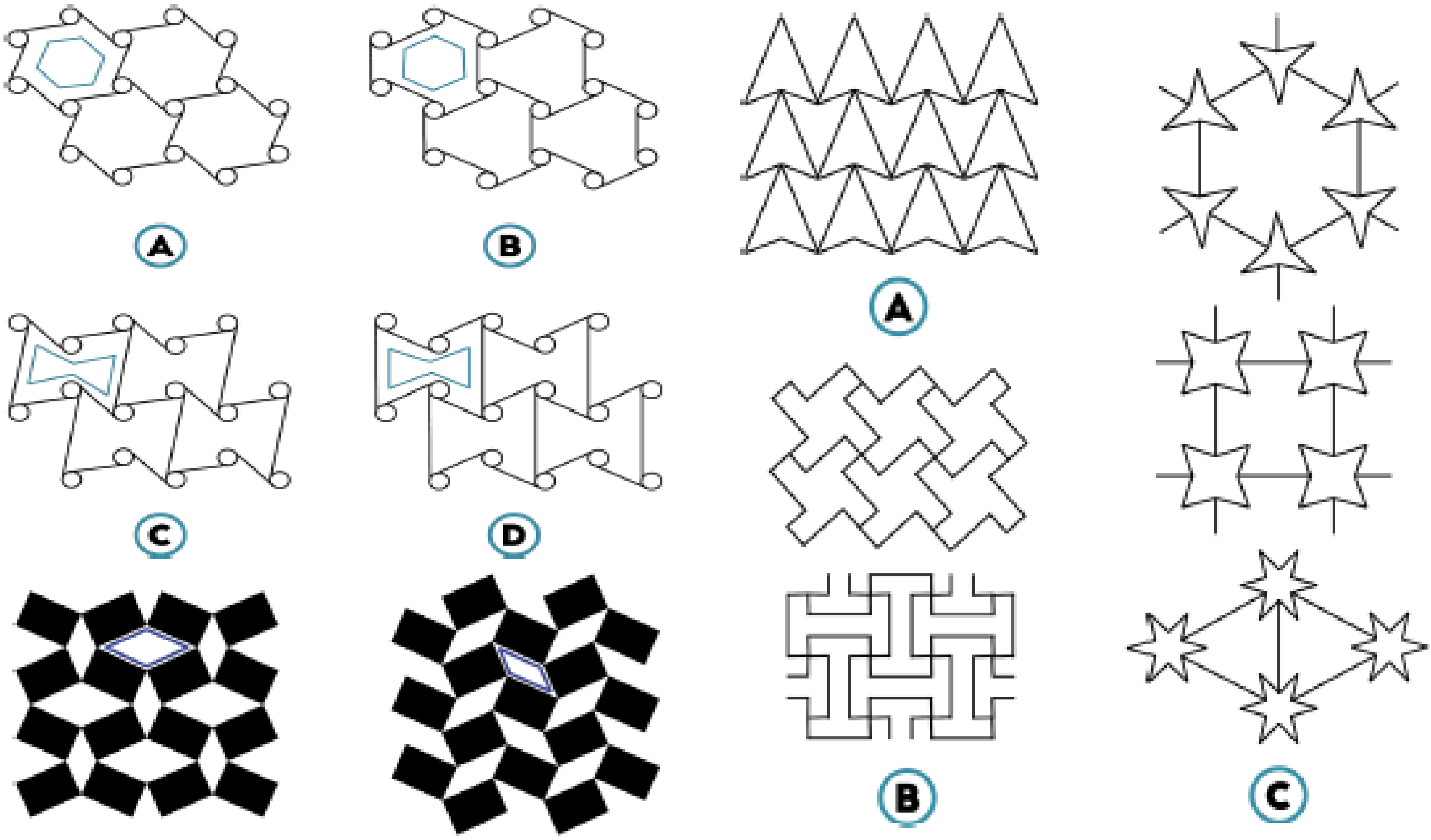


Figure 37: Examples of Re-entrant structures A-D, Chiral structures A-C, and Rotating rigid structures; Kolken & Zadpoor 2017

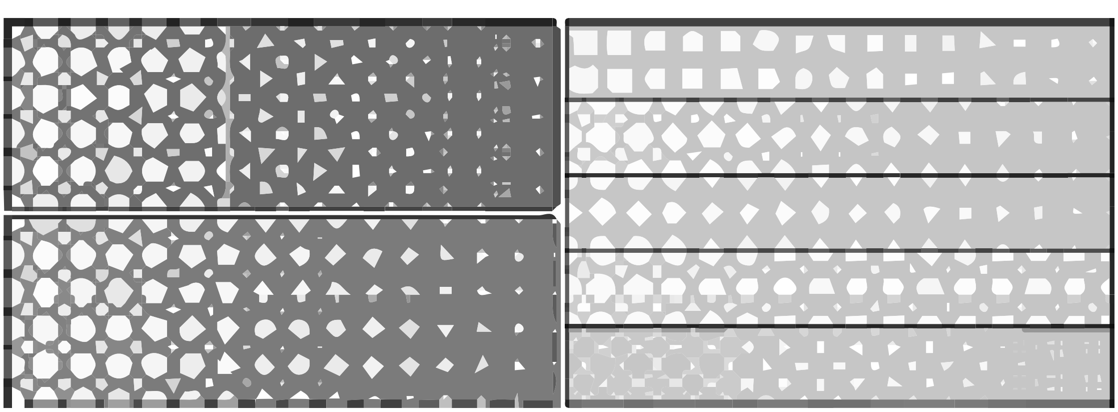


Figure 38: Gradient Transition from different Poisson's ratios. Schumacher, Bickel & Rys 2015

3.2.2 META-MATERIALS

Meta-materials is the term for artificial materials that are engineered to provide properties which may not be available in nature. Such as negative refraction indexes, negative Poisson ratios and other unique mechanical, electromagnetic, photonic and acoustic properties (Kolken & Zadpoor, 2017). This section is focused upon the mechanical meta-materials and how they might be an added value for the development of soft robotic parts with this new set-up.

Examples of mechanical meta-materials are auxetics, materials with a vanishing shear modulus, materials with negative compressibility, singularly nonlinear materials and topological meta-materials (Florijn, Coulais, & Hecke, 2014). Digital fabrication has been an important factor in the development of these meta-materials as it allows the fabrication of 3D geometries made out of a wide range of materials. The use of these designed materials is central in many branches of engineering including soft robotics (Reis, Haeger, & Hecke, 2015). Therefore it enjoys a lot of research and development, one of the best-described meta-materials are auxetics.

Poisson's Ratio

In order to understand how an auxetic material behaves, there first needs to be a bit of understanding of the Poisson ratio. The Poisson-ratio is a numerical expression of the ratio of lateral contraction to that of the axial stretch. See Figure 36. For isotropic materials, this means that a value between -0.1 up to +0.5 can be found. Greaves et al. describe the Poisson-ratio as the resistance of a material to distort under mechanical load instead of altering in volume (Greaves, Greer, & lakes, 2011).

This distortion in the material is a result of the reconfiguration of the mesostructure of the material. There are three main groups of mesostructures that can display negative Poisson ratios (NPR's) namely: re-entrant structures, chiral structures and rotating rigid structures (Kolken & Zadpoor, 2017). The structures work on any level since the Poisson ratio is scale independent. Examples of each type of structure can be seen in figure 37.

Structures

Within the field of auxetics there are many different sort of structures. Re-entrant structures are structures that have internal negative angles under stress the negative angles start to hinge and re-align, making up for the required deformation. Chiral structures will rotate under mechanical loading, causing the ligaments to flex resulting in a folding or unfolding behavior of the ligaments. This folding mechanism makes up for the required deformation. Rotating rigid structures contains rigid squares that are connected by simple hinges. When mechanical loading is applied the squares will rotate, expanding or contracting depending on the type of load. This expansion or contraction also make up for the required deformation of the material (Kolken & Zadpoor, 2017).

Controlling the Poisson's Ratio

With the help of 3D-printing and computer simulations, special auxetics have been designed with specified Poisson ratios ranging from -0.8 up to +0.8. See Figure 38. The design process was based on linear models for the +0.8 and nonlinear models for the -0.8. By interpolating the shapes , configurations could be derived for each specific Poisson ratio (Wang & Jensen, 2015). Allowing the creation of metamaterials with preprogrammed behavior.

Even more elaborate ways of implementing auxetics have been achieved by means of voxel 3D-printing (voxels are the pixels of a printer, the smallest cube the printer can produce). By making use of programmed voxels, smooth gradients can be created between Poisson ratios allowing for a smooth transition from mechanical properties. See figure 38 (Schumacher, Bickel, & Rys, 2015). However, this might pose a problem for FDM printing since the voxels are quite large to work with and the FDM process is intended as a continuous extrusion process, instead of depositing small droplets.

Conclusion

All over, the programmability of the Poisson ratio of materials as a result of certain geometries might prove to be a valuable asset. By implementing this, specific deformations in the soft robotic parts might be achieved by pressurizing certain types of chambers or walls. By doing so, unique behavior and actuation possibilities can be created.

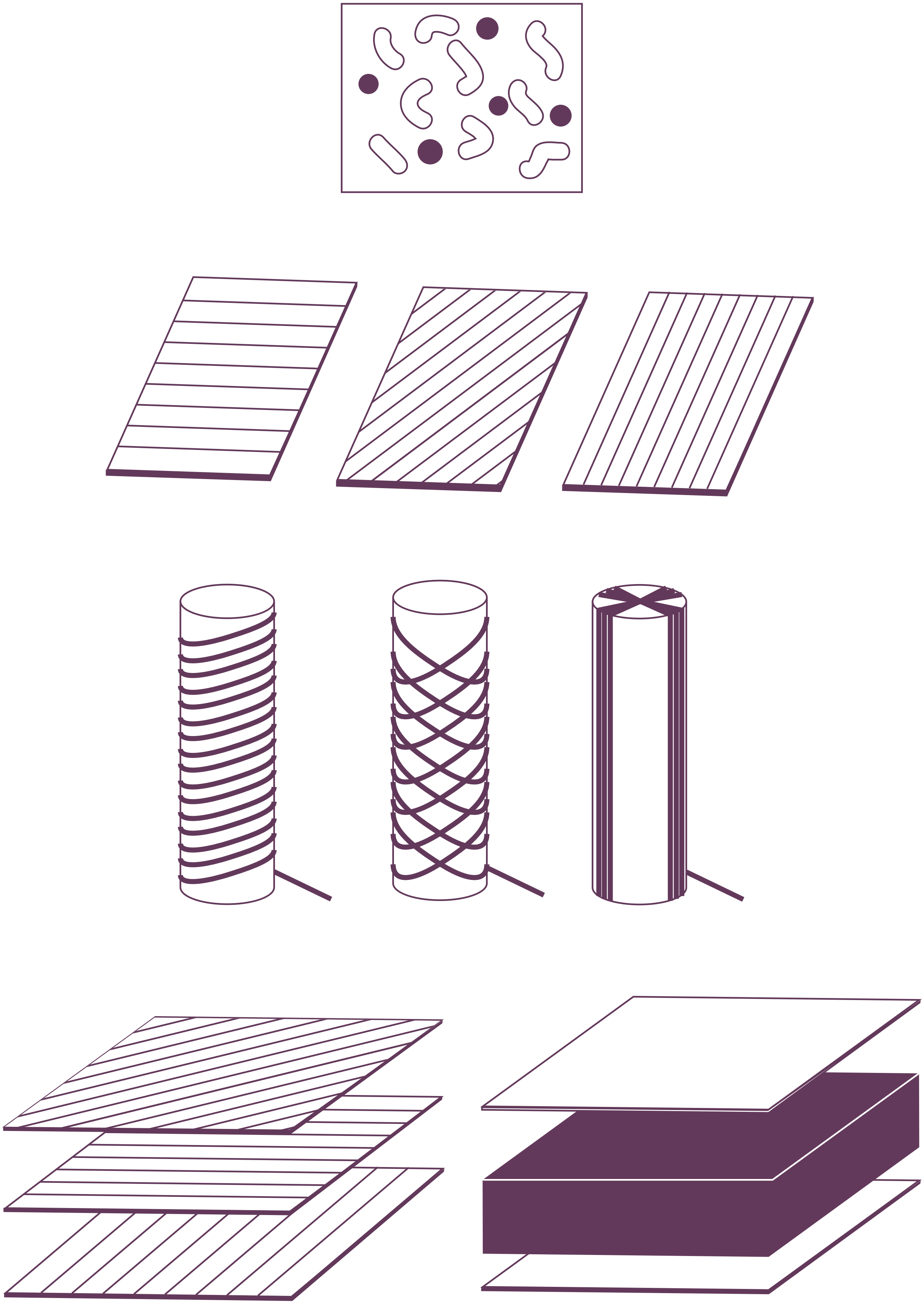


Figure 39: Overview of the types of composites disucssed in Callister & Rethwish

3.2.3 COMPOSITES

Since the new printing set-up allows for the creation of multi-materials, insights are required on how different materials interact with one and another. This chapter provides insight into the behavior of these composites. In Material Science and Engineering different types of composite materials are derived in three main categories. Particle-reinforced, Fiber-reinforced, and structural composites.

Particle-reinforced

For the application of particle-reinforced composites neither dispersion-strengthened as large-particle-reinforced composites are suited. The first method requires altering of the material on the atomic or molecular level. The second method uses larger particles ranging from 100μm up to 100nm. (Callister & Rethwisch, 2011) The Ultimaker might be able to reach 100μm in ideal circumstances due to the continuous printing behavior of the printer, this is not redeemed as ideal.

Fiber-reinforced

Fiber-Reinforce Composites, on the other hand, can prove to be a useful application. The minimum fiber thickness that can be created by an Ultimaker is theoretically the same diameter of the nozzle. The smallest nozzle size is 0.25mm allowing for the creation of 0.25mm thick fibers. The critical fiber length is determined by the tensile strength of the fiber, the diameter and the bonding between the fiber and matrix. This according to the following equation:

$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

The problem that arises with this relation, is that there is little known about the composites that use silicone as a matrix and a tougher material as the fiber. Therefore it is hard to determine the critical fiber length. To address this issue, a consultation was done with Kaspar Jansen, his advice was to create as much contact surface area between fiber and matrix as possible to increase the shear stress of the material. Another issue that was addressed during this consult was unlikeliness of the bonding between fiber and silicone since silicones are known not to stick well to other materials. This making it impossible to predict the elastic behavior since this often requires isostrain and isostress situations, which can only be assumed with very good inter facial bonds. (Callister & Rethwisch, 2011)

Structural composites

The last type of composite, namely the structural composites, knows two sorts: laminar composites, and sandwich panels. The use of laminar composites should be a viable option, as it makes use of stacking fiber-reinforced layers for a laminar composite. The usage of sandwich panels might provide a limited solution, as this might only work with the silicone as the encapsulated component or in cases where the load is transverse to the layer stacking. This is due to the weak bonding behavior of silicone with materials.

Conclusion

The usage of particle-reinforced composites doesn't seem a very good application with the new set-up, as it really pushes the machines basic principles. Fiber-reinforce composites seem suitable, since this is a continuous deposition process. If continuing with this type of composites one of the main points that need to be addressed first is the bonding between matrix and fiber. Finally, stacked fiber slabs might prove to be useful for soft robotics contrary to the sandwich panels.


Figure 40: TPU printed on top of hardened silicone

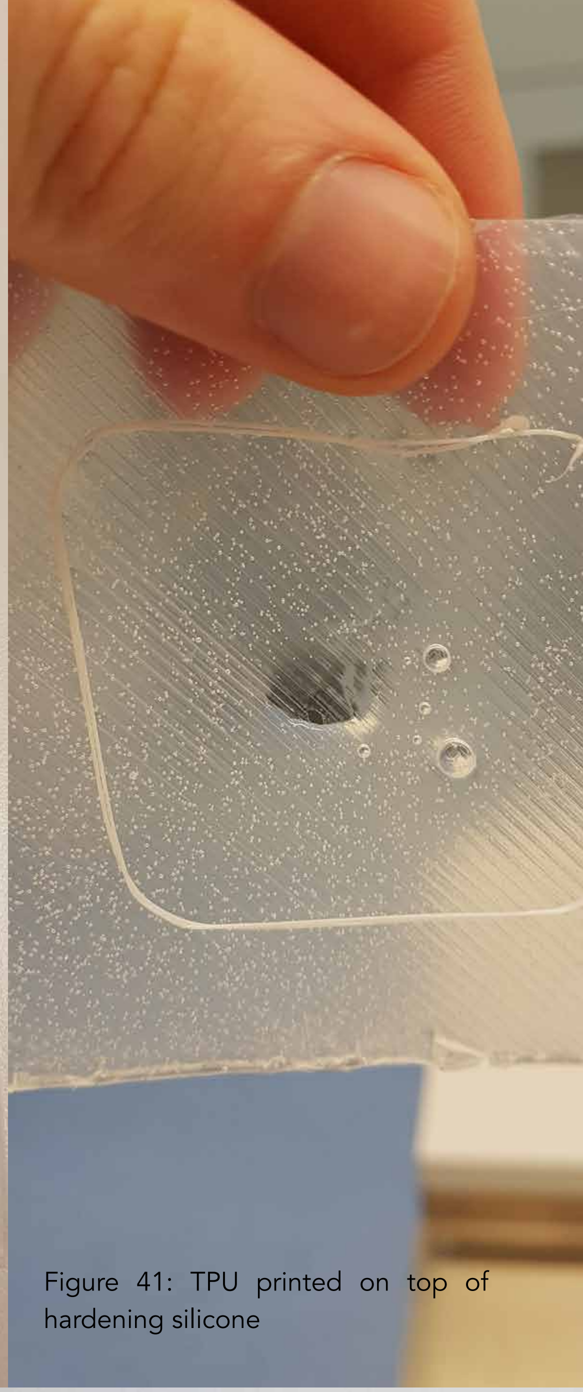


Figure 41: TPU printed on top of hardening silicone


Figure 42: TPU shape printed in liquid Silicone


Figure 43: Dissolving test of PVA

3.2.4 FIRST PRINTING TESTS

To gather insight in the behavior of silicones in combination with different materials several tests were conducted. The following section contains an overview of the conducted tests, their goals and the findings gathered from these tests.

Printing on top of Silicone

This test was conducted in order to find out whether it was possible to print materials on top of a cured slab of silicone. This aspect was interesting, as it would allow the usage of silicone as support material. Making it possible to make complex shapes and allowing the materials to blend. The test was conducted with a sample of Dragonskin Silicone (Shore 2A) created from a 50:50 mixture and cured over 30min. The slab was 2mm thick and 80x80mm. This slab was placed on the print-bed which was heated to 70°C. The filament used for the print was Ultimaker TPU Shore 95A. The result was a print that started of stringy but allowed for the printing on top of the silicone over time. See Figure 40.

Printing on liquid Silicone

This test was conducted, to see if the adhesion of the Ultimaker TPU would be better if it was printed on the silicone while it was still liquid. The test was conducted with a sample of Dragonskin Silicone (Shore 2A) created from a 50:50 mixture uncured placed on the printer after 4min. The liquid slab was also 2mm thick and 80x80mm. The print-bed temperature was 32°C. During the printing process if the nozzle hit the silicone, it would instantly cure resulting in a spaghetti mixture. The second attempt with the same parameters resulted in a print where the first layer would sink into the silicone and shows a decent adhesion, rest of the print didn't stick since the silicone had cured. The print showed promising results for printing materials in and on top of silicone while not being fully cured.

Printing in liquid Silicone

After the results with print on liquid silicone, a follow-up was done to see if it was possible to print while it was still completely fluid and if it would benefit the adhesion. This time the print-bed temperature was 23°C and the slap was placed 1min after mixing the two components. This resulted in a print that would stick fully to the silicone and allowed for a good foundation to further print on. However, the adhesion was not good enough to put a load on. If a load is put on the sample, both components tear off each other.

Dissolve diameter PVA and Silicone PVA interaction

The minimum diameter for removing support material from a Material Jetted print is known to be 8mm (Slyper & Hodgins, 2012). This test was conducted to find out what the minimum diameter was for FDM with the use of PVA support material. During the test, a few things didn't go as planned. First off, the 1 and 2mm diameters didn't print support at all. Apparently, it was not necessary for these diameters as the FDM printer could bridge these distances. Secondly, the printer stopped midway with printing PLA. To still be able to conduct this test Silicone was cast in the PVA shells. As a result combined parts were created with PLA and Silicone. The PLA remained good in place since it was partially encapsulated by the silicone. The second finding was that there were only issues for the removal of the PVA for holes with the diameter of 3mm. Of course, it is up for debate, if big hollow cavities would display the same result as these singular rods.

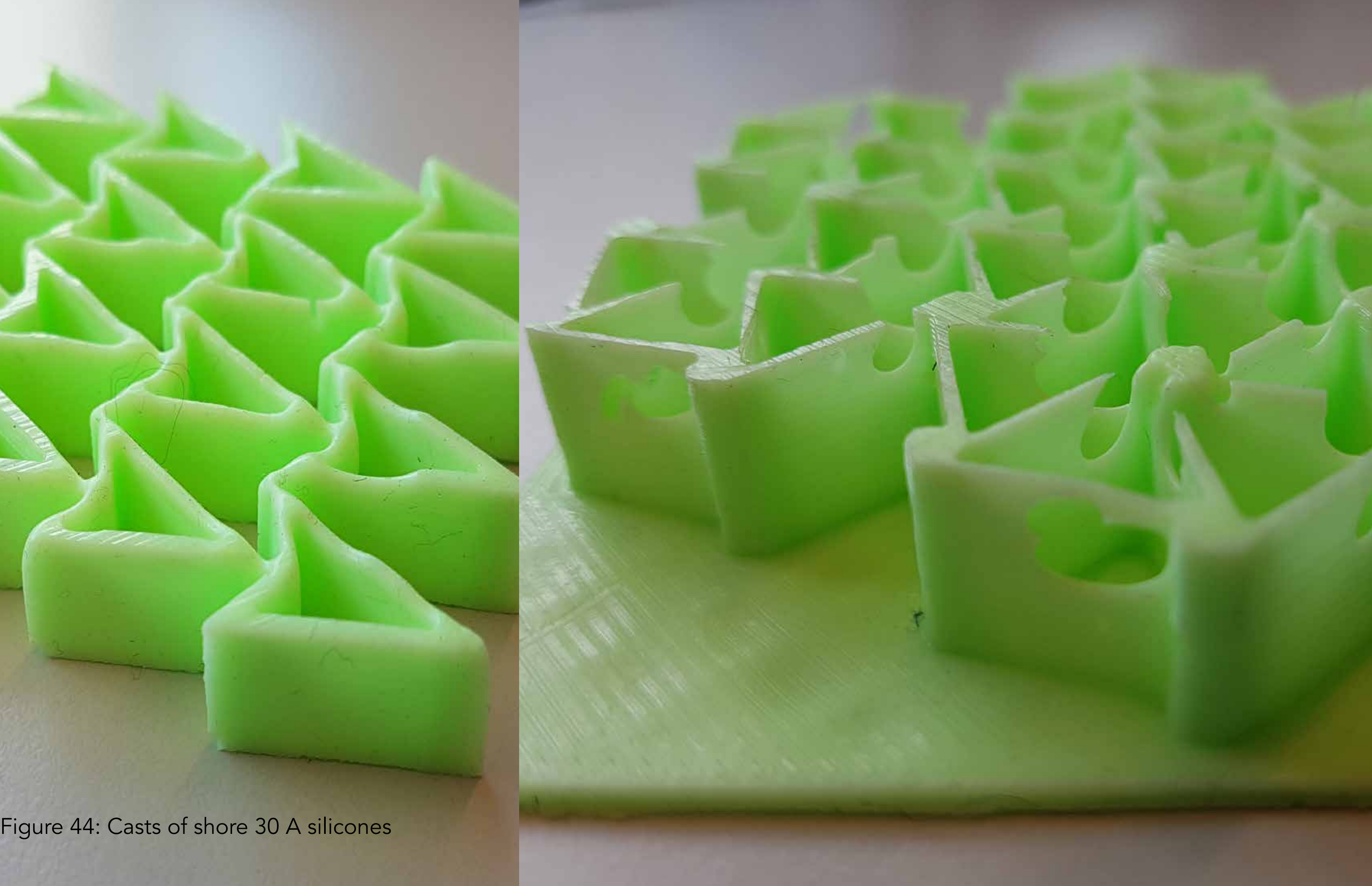


Figure 44: Casts of shore 30 A silicones

Figure 45: Adhesion tests of Ninjaflex parts in silicone

Casting Silicones Shore 2A and 30A

The goal of this test was to determine the limitations of casting silicones by hand. First of silicone auxetic structures were cast by making use of DragonSkin Silicone Shore 2A with a 50:50 ratio. These casts showed no failures. However, the stiffness of the 2A was too low to provide any structural integrity. In addition, the cast showed small air bubbles. The second cast was done with green poly-addition silicones Shore 30A with a 50:50 ratio. The cast with a wall thickness of 2mm showed little to no air-pockets. The cast with a wall thickness of 1mm showed big gaps in the final product as a result of the high viscosity of the silicone mixture.

Inserting Ninjaflex Parts in Silicone

After the tests with printing in and on the DragonSkin Silicone, the result was that the parts were easy to peel off. In order to find out whether these parts would move with the silicone when surrounded by it, the following test was conducted. There was an extra interest in this test, as its finding would prove the feasability of 3D printed silicone composites. First, a 2mm thick slab of silicone was produced after that a 5mm high Ninjaflex print was pressed into the silicone while it was still hardening. The same was done for the other sample this sample was only 2mm high. After the samples were cured, their behavior was tested. Both parts didn't stretch with the silicone, instead, the Ninjaflex parts would tear loose.

Improving adhesion Ninjaflex in Silicone

After reading the literature of silicones and the consultation with Kaspar Jansen, the goal of this test was to determine whether the bonding between Ninjaflex and Silicone would improve if the contact area would increase. The first test was done by creating bars with the same outer sizes, but branching of the ending. These bars were then placed in Shore 30A Green silicone. The result was a better bonding between the two components with the increase of branches at the end, the parts would still come loose. The Second test was done by means of a fiber-mat created out of Ninjaflex which was embedded in the liquid Green Shore 30A silicone. The result was a composite, that was fully functional and wouldn't separate into two different components.

Conclusion

Although challenging, it is possible to print on liquid silicone it is easier to do so on hardened silicone. To do so knowledge is needed of the amount of silicone deposited in the mold for the layers to bond. Nothing sticks well to silicone, the only promising bonding type is fibers. To increase the bonding between silicone and fibre, it is advised to make use of materials that have an elasticity modulus that is closely matched. Therefore the manufacturing setup should be able to print flexible filaments to accomodate this. The minimum hole size for dissolving PVA seems 4mm. Without pressure, Silicone can be cast without issues up to a wall thickness of 2mm.

3.2.5 CONCLUSIONS

Regarding the use of new materials, the new set-up provides a lot of new possibilities. Composites can be created as a result of the combination of the two production processes. For the development of these composites, it should be taken into account that the bonding between silicones is limited and only Fiber-reinforced and Structurally reinforced composites might prove to be a useful application. To determine the critical fiber length, the bonding between the different materials and silicone should be studied per different material.

The embedding of big particles in silicones doesn't result in a good bond, resulting in parts that don't interact with their matrix. A way of improving the bonding between fibre and matrix is the usage of materials that have moduli that are close to eachother. Although the bad bonding behaviour might look as a downside, it might also provide possibilities for certain applications. For instance, the badly bonding behavior can be exploited to create moving parts through the silicone in a pre-assembled print.

During the different tests conducted there was found that it is possible to print on both liquid as well as solid silicone. For solid silicones, the printed parts lay loose on top of the silicon, while the printed parts on the liquid silicone lay slightly embedded in the silicone but they will come loose as a result of minor loads.

In terms of casting silicone, the high viscosity might prove to be an issue as it seems that parts can't be created with a wall thickness smaller or equal to 1mm. This might be overcome if the system can create pressurized casts.

For the minimum diameter that can be created, it can be stated that the diameter must not be around 3mm. This leaves too little space for the PVA to solute in water, for small rods this doesn't prove to be an issue with a diameter of 4mm and up. Diameters of 2mm and lower don't require any support thus can be created without any support dissolving issues.

The usage of meta-materials might be interesting for this project. It can serve as a new type of actuation by vacuuming or pressuring chambers to increase their volumes. Create the walls with such a structure that it creates predefined deformations.

The criteria that can be formulated as a result from this research area are:

- The set-up should be able to print composite materials.
- The hybrid manufacturing set-up shoud be capable of printing flexible materials.

3.3.0 INTRODUCTION

Besides the soft robotics, the other main theme is the development of the MultiCast which is based upon an Ultimaker 3 combined with their Ulticast. This chapter will provide an overview of the used systems for the final manufacturing set-up. It will as well discuss the possibilities and limitations that the MultiCast set-up provides.

For the Ultimaker 3, the system has been analyzed upon the three main aspects; Software, Firmware and Hardware. The research question for this chapter where:

- What aspects needed to be adjusted?
- Where is room left in the printer for tweaking?

One of the conclusions in the material chapter was the need of the set-up to print flexible filament. Therefore a redesign of the Flex3Drive system needs to be developed. To help speed up the development the following question where addressed:

- How does the current system work?
- What features can be used in the redesign and which aspects need to be adjusted?

Finally the Flex3Drive prototype has been tested and evaluated.

The Ulticast system is the basis for the MultiCast set-up. To implement the system an analysis has been conducted of the working principle of the system. The goal of the analysis was to answer the following question:

- What aspects need to be adjusted in the system?
- How do these changes effect the working principle of the Ulticast and Ultimaker?

Finally, all systems will be combined into the final set-up used for production. All changes will be highlighted and the new possibilities and limitations will be discussed in the according to sections. All these findings will be summarized in the conclusion.

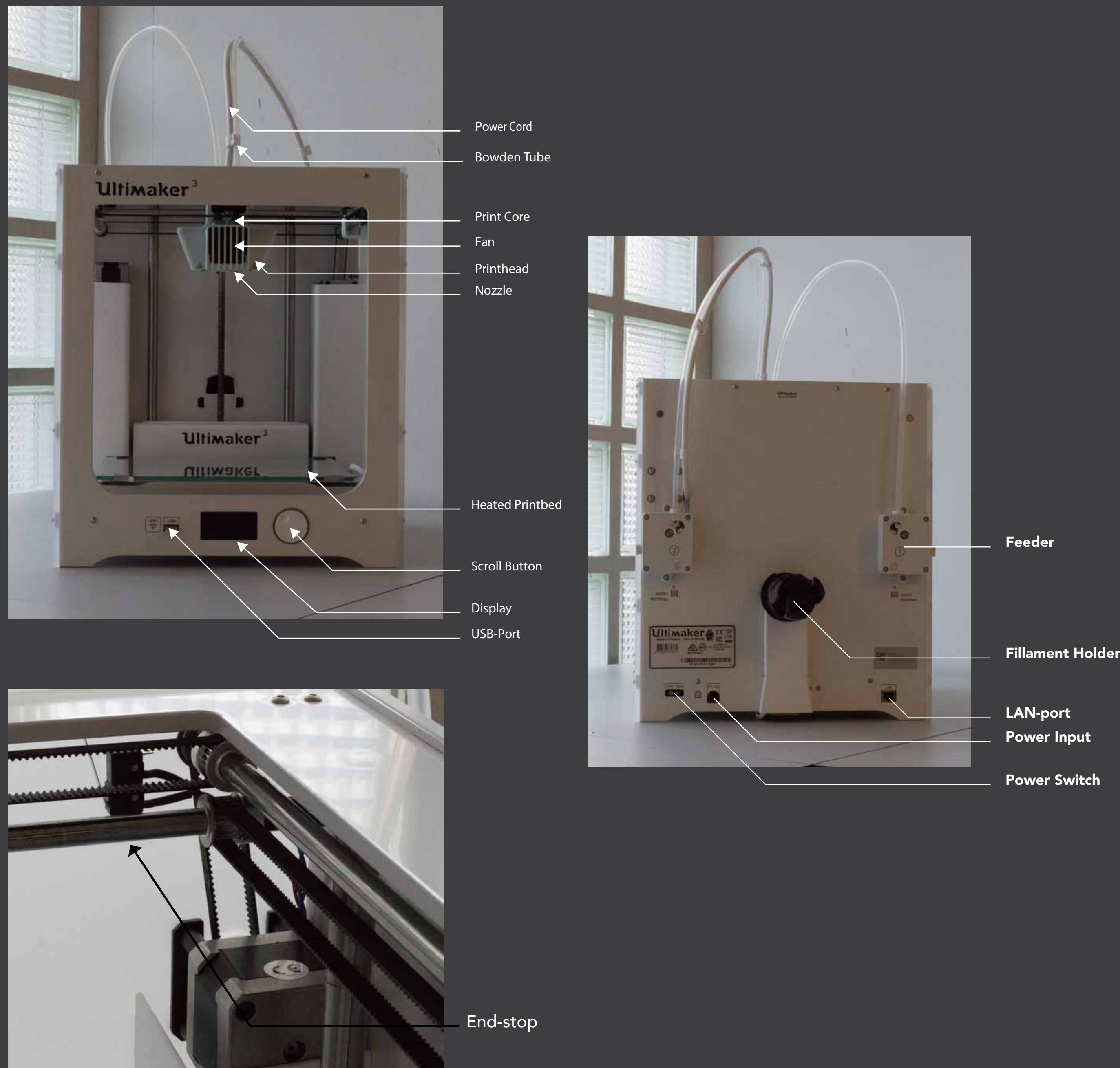


Figure 46: Overview of the Ultimaker 3 and its componets

	Nylon	PVA	PLA	ABS	CPE
Nylon	—	√	—	—	—
PVA		—	√	—	√
PLA			√	—	—
ABS				√	—
CPE					√

Figure 47: Overview of material combinations that deliver good quality prints, accoridng to Ultimaker

3.3.1 ULTIMAKER 3

The Ultimaker 3 is the latest printer created by Ultimaker. This is the first multi-material printer Ultimaker created. The system is based around FDM printing with one print head that contains two nozzles. The first nozzle contains an AA-core which is suitable for printing Nylon, PLA, ABS and CPE. The second nozzle supports an AA-core and a BB-core. The BB-core is suitable for PVA, which is a support material that dissolves in water.

The Ultimaker system can be divided into three main branches. The hardware, which is the body of the Ultimaker 3, composed out of the material feeder, print-bed, and extrusion nozzle. The firmware is the software that controls the hardware, by means of the incorporated electronics and processors. The firmware of the Ultimaker 3 is specifically developed for dual extrusion and updated on a regular basis. The software is Ultimaker's own slicer called Cura which is developed in collaboration with the 3D-printing community. This software also updates on a regular basis and is currently in the 2.6 version.

Hardware
The following section will zoom in further on the functioning mechanisms of the hardware, and which sections posed to be of interest in the development of the printer. At figure 46 is a quick overview of all the components and their appropriate names.

The parts that require special attention in this overview is the feeder, print head and the end-stops of the printer. First off, the feeder is a Bowden based design. A Bowden based design has the feeder separated from the hot end which is bridged by a tube in which the filament travels. The advantages of this system over a direct extrusion system are that the there is less weight on top of the print head. This resulting in faster and more accurate prints. The downside of such a system that the filament needs some slack in the tube to travel through. As a result, flexible materials are harder to print as they tend to get stuck as a result of this slack. (Stevenson, 2015) To overcome this issue a special system has been designed called a Flex3Drive. The Flex3Drive chapter will go into detail about the working principle of this system.

The print head of the Ultimaker 3 is currently designed to support the use of dual extrusion. This allows the creation of multi-material parts composed out of many possible combinations. Ultimaker indicated that the materials in figure 47 deliver good results up to their standard. To manage the extrusion rate of both nozzles they both function as two loose feeding systems that end up in the same print head. The feeders are powered by stepper motors that are plugged into the Ultimaker mainboard. The design of the printer didn't leave room for upgrades like the addition of an extra nozzle. In order to add this extra nozzle, the print head needed extra room to accommodate an extra nozzle. In addition, the feeding mechanism needed to be plugged into extra mainboard since there was no more room on the original board.

As a direct result of the nozzle placement, the actual printing area had to be reduced. To implement this the end-stop had to start functioning earlier, as well as a change in the firmware to reduce the usable area of the build plate.

Firmware
The second main branch namely, the firmware, needed several adjustments as well in order to accommodate the new Flex3Drive and the usage of a second Ultimainboard. The changes will be discussed in detail at the Flex3Drive and Ulticast chapters.

Software
The software, which is the third main branch, requires some changes. First off, the printer needs to be able to slice the part with three different material properties as every nozzle can deposit a different material in the design. The current version of Cura only supports extrusion of two materials.

Secondly, the G-code created for the casting nozzle needs to be adjusted in two ways. Firstly, the g-code needs to be recognized by the Linux board too send the code to the Ulticast mainboard. Also the position of the casting nozzle is different than that of the original nozzle. A translation is required for both the X and Y coordinates. Unfortunatly the automization couldn't be achieved during this project so the g-code was written manually.

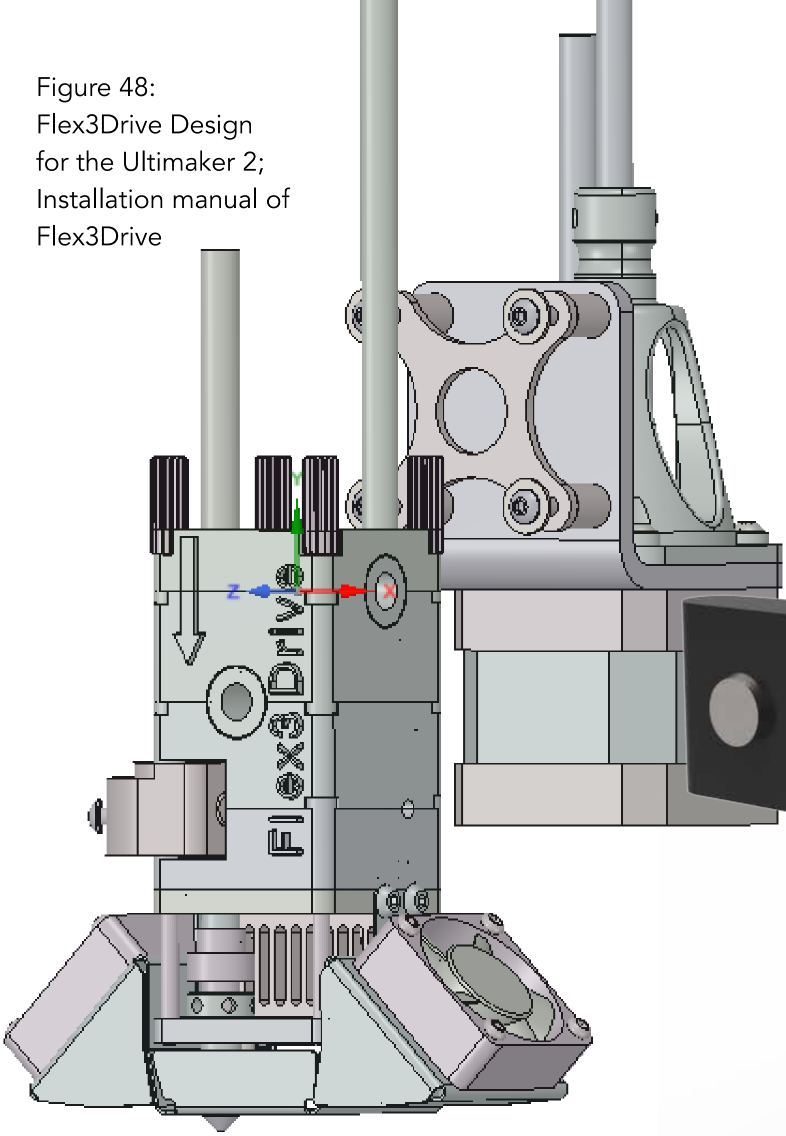


Figure 48: Flex3Drive Design for the Ultimaker 2; Installation manual of Flex3Drive

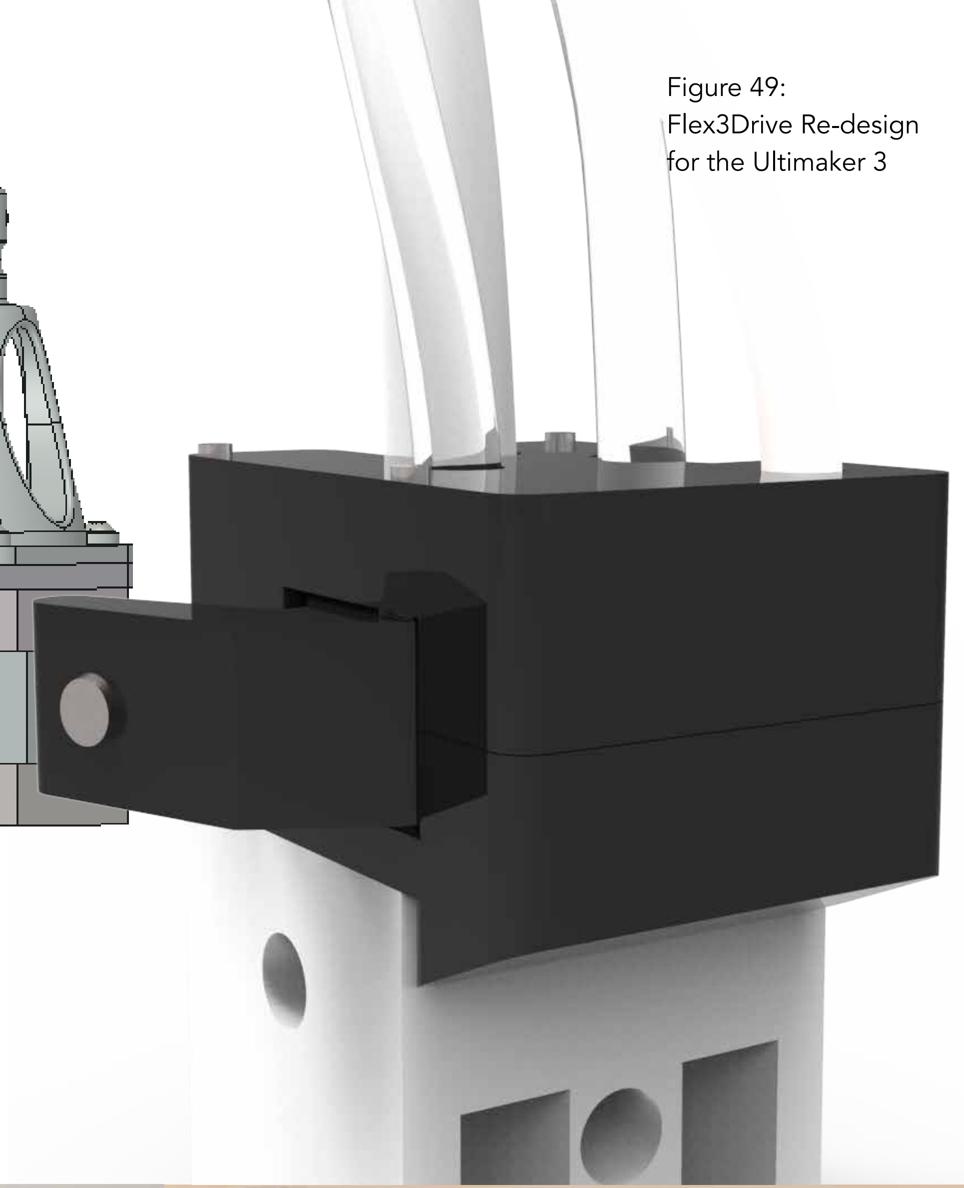


Figure 49: Flex3Drive Re-design for the Ultimaker 3

Figure 50: The housing design of the Flex3Drive for the Ultimaker 2

Figure 51: The housing re-design of the Flex3Drive for the Ultimaker 3

3.3.2 FLEX3DRIVE

As briefly discussed in the Ultimaker 3 section for the extrusion of flexible materials a new feeding mechanism needed to be developed. For the Ultimaker 2, such a system was already available. See figure 48. For the Ultimaker 3 there wasn't such a system. To speed up the development process the system of the Ultimaker 2 was taken as a starting point.

The original Flex3Drive

The Flex3Drive for Ultimaker 2 has been developed by Flex3Drive in collaboration with Ultimaker. The design has been built around a compact 40:1 gear reduction and is driven by a flexible shaft. The flexible drive-shaft enables the stepper motor to be mounted on the back of the Ultimaker printer (Flex3Drive, 2017). This enables the feeder to work as a Bowden system while having the advantages of a direct extrusion system.

The working principle is as follows. The original 0.9 stepper motor is replaced by a 1.8 stepper, this stepper motor is mounted on the back and initiates the rotation of the flexible shaft. This flexible shaft is mounted into a worm that starts the rotation of the worm gear system. The gear is mounted on an axis that rotates the gripping wheel. This gripping wheel grabs the filament and pulls it through the Bowden tube. To keep the right tension on the filament a tension arm incorporated within the design. This tension arm can be adjusted to decrease or increase the tension depending on the loaded filament. Flexible filament requires less tension than stiff filament.

The reason that the stepper motor is replaced is to decrease the number of revolutions the stepper motor has to take to compensate for the different gear ratio. The original Ultimaker gear system uses a ratio of 36:11 while the Flex3Drive has a ratio of 40:1. Still, the number of steps per mm filament needs to be adjusted in the firmware to further compensate for the difference. The steps per mm need to be increased. An approximation of the steps per mm can be calculated with the following formula (Hunter, 2015) :

$$E_{steps/mm} = \frac{(Motor_{steps/rev} * Driver_{microstep}) * (Teeth_{BigGear}/Teeth_{SmallGear})}{D_{hob} * \pi}$$

This formula is an approximation because the formula doesn't take into account what the effects might be of the grip upon the filament. In order to determine the right amount of steps per mm required. Extensive research needs to be conducted taking those aspects into account. However, measuring the real amount of filament moved compared to the expected amount and adjusting accordingly is a quicker and less extensive method.

Redesign

For the redesign of the Flex3Drive, there were the following leading wishes

The U3 Flex3Drive should contain as much of the original parts of the U2 design as possible
The U3 Flex3Drive should reduce the usable print area as little as possible
The U3 Flex3Drive has to be implemented as quickly as possible

Based upon these wishes the following re-design has been created. See figure 49. The design uses the same components as the original U2 design but has a whole new casing and an adjustment in the tension arm.

Tension Arm

The tension arm deliveres tension in the U2 design by pushing the arm off the casing by means of a screw. The redesigned part does exactly the opposite. By adjusting the bolt it will pull the arm more towards the casing. This controls the amount of tension on the filament. To accommodate this a nut with screwthread is embedded in the casing. As a result of this redesign, there was still some slack in the arm, to reduce this slack a spring was added over the bolt to keep tension on the arm.

Casing

The casing knows a lot of adjustments compared to the casing of the U2. The original design was made to replace all plastic parts of the printer head, while the version for the U3 truly functions as an add-on. Therefore, only three out of the five main body parts had to be redesigned namely; casings A, B, and the tension arm.

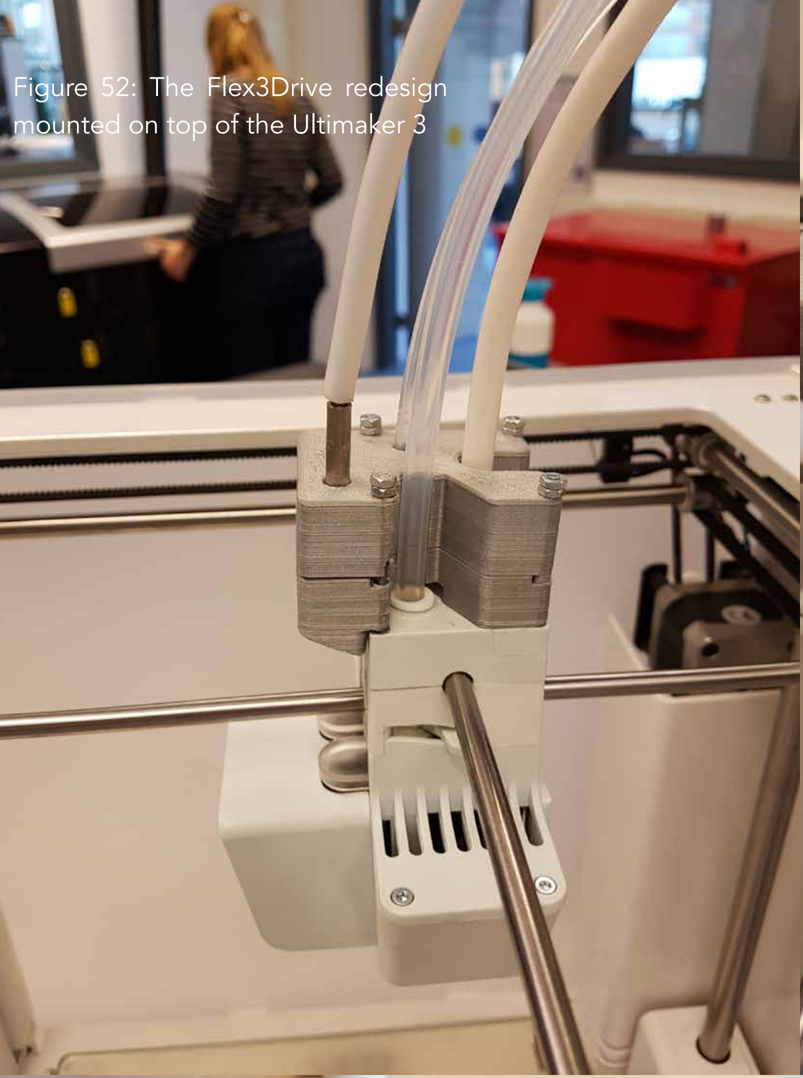
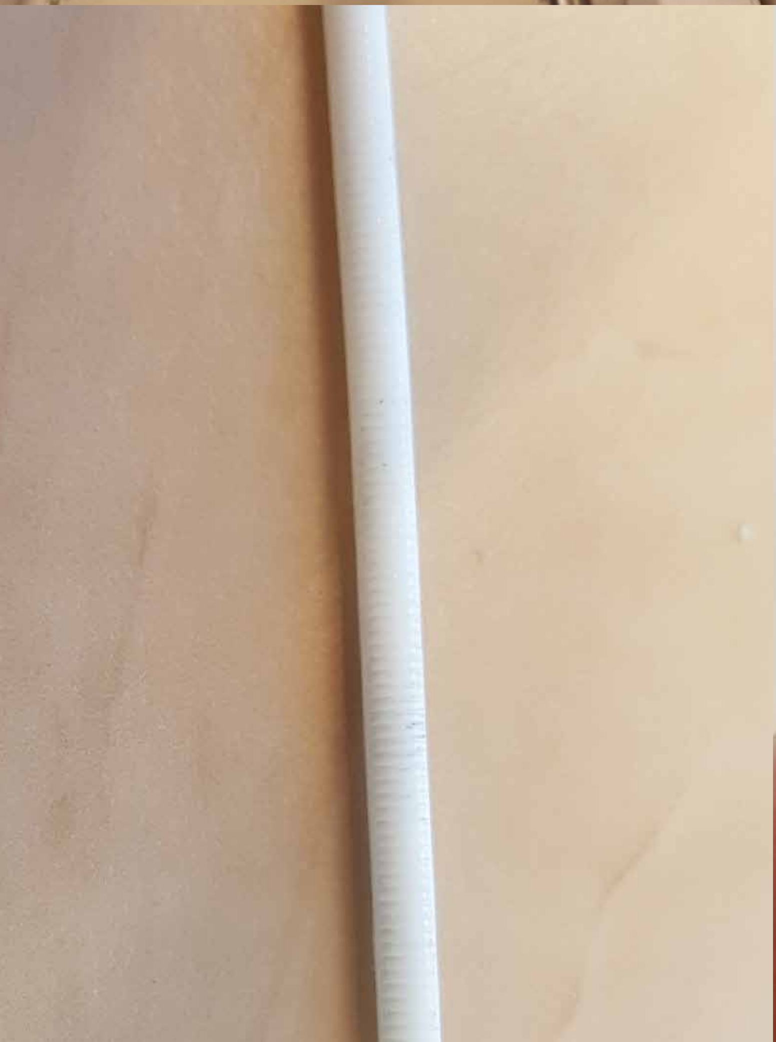


Figure 52: The Flex3Drive redesign mounted on top of the Ultimaker 3

Figure 53: Failure of the flex3Drive redesign



Mounting

The design of the U3 print head leaves little room to play around with in the nozzle. To decrease the amount of surface area placed outside of the current footprint of the print head, the mechanism has been tilted. This led to the design, hanging outside on one side of the print head. To reduce the number of adjustments needed to the firmware of the printer, there has been chosen to place the overhang from 10mm to the front side. To not reduce the printer in its original functions cavities were created to fit the original power cord and the second Bowden tube through the design.

Finally for the mounting the original mounting positions of the print head where used. The entire casing increases the height of the print head by 30mm, thus for the mounting custom screws needed to be made. The entire assembly of the system is for the rest the same as with the previous design. To change the material flow, to match that of the original U3 system, two adjustments can be done.

Corrections

One is to adjust the diameter of the filament to compensate for the decreased flow as a result of the changed drive train. By correcting for the decreased amount of steps and the new gear ratio a correction factor of 6.1 had been determined. This resulted in an ideal filament diameter of 0.47mm instead of the used 2.85. Of course, this is also an approximation not taking external forces on the filament into account.

The second method is by increasing the steps per mm in the .json file of the printer. The .json file is a file that the firmware reads out every time it reboots. To adjust the .json file the printer needs to be accessed via an SSH protocol. For the printer, in this case, the Jedi.json file needed to be adjusted in the /usr/share/griffin/griffin/machines folder. By default the steps per mm was 369, this needed to be adjusted to approximately 4060 steps per mm (based upon a 10mm Dhob). The downside of adjusting the .json file is that this change in steps per mm effects both feeders.

Evaluation

After being a while fully operational, the Flex3drive broke down. The transmission fainted on the required torque. After analysis, there was found that the high torque was required due to slack within the part, as well as the too tight grip of the wheel on the filament. It resulted in jamming of the gears within the housing. For future usage, the amount of freedom of the parts within the housing has been limited. As a result, the required torque should be a lot less, as well as the material flow should be more consistent.

The new design has not been tested since the increase of steps per mm resulted in buggy behavior of the x and y maneuvering and handling of steps. Additionally, in order to use the second extruder, the steps per mm needed to be separated from the usage of the second feeder as they are linked in the firmware. Another option could be redesigning the flex3drive to accommodate the feed of two materials.

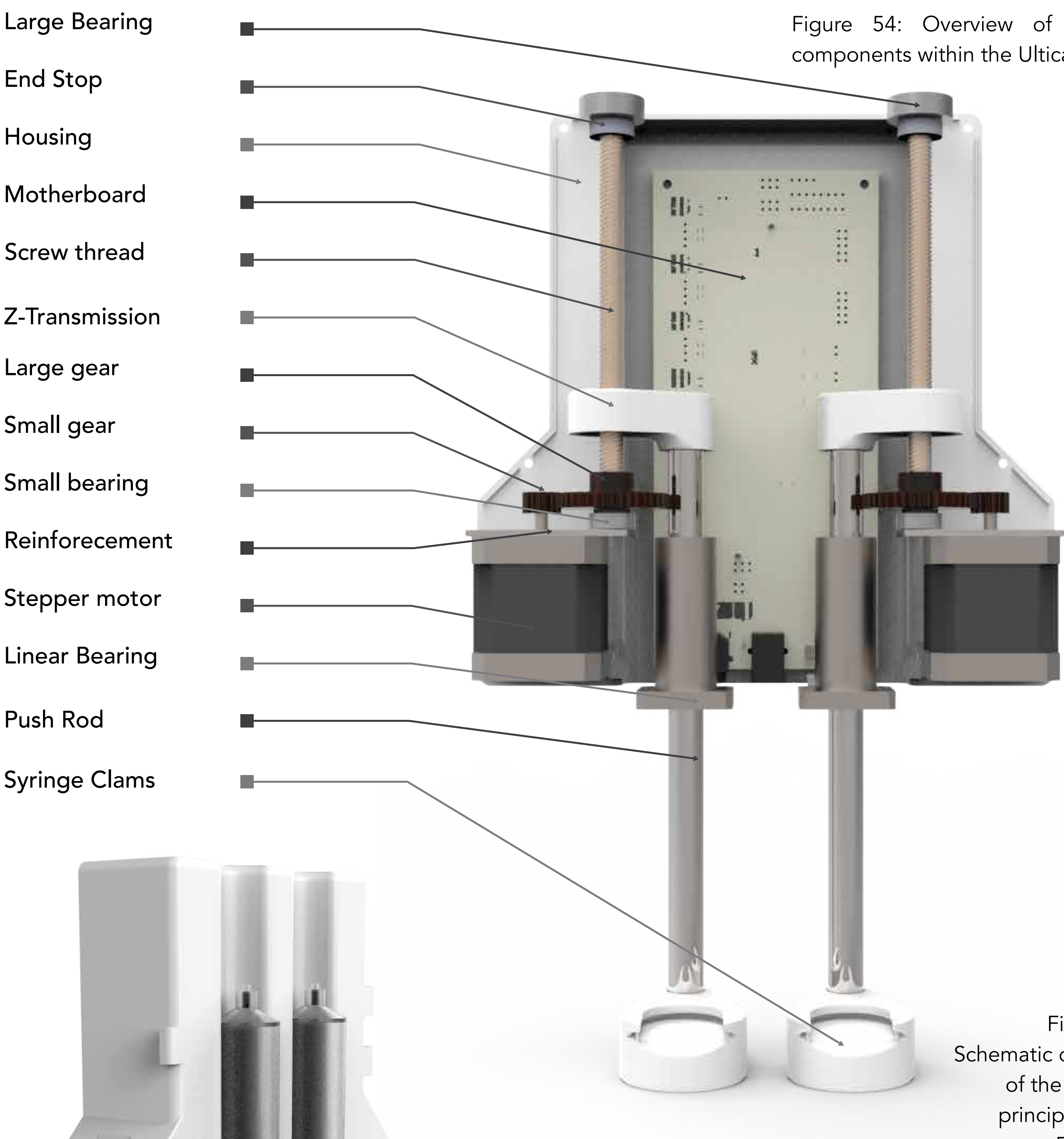


Figure 54: Overview of all the components within the Ulticast

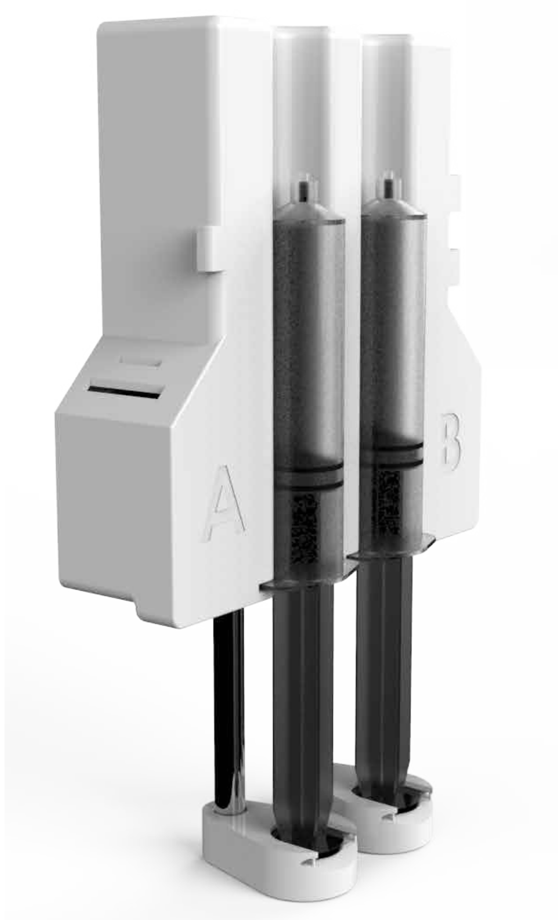
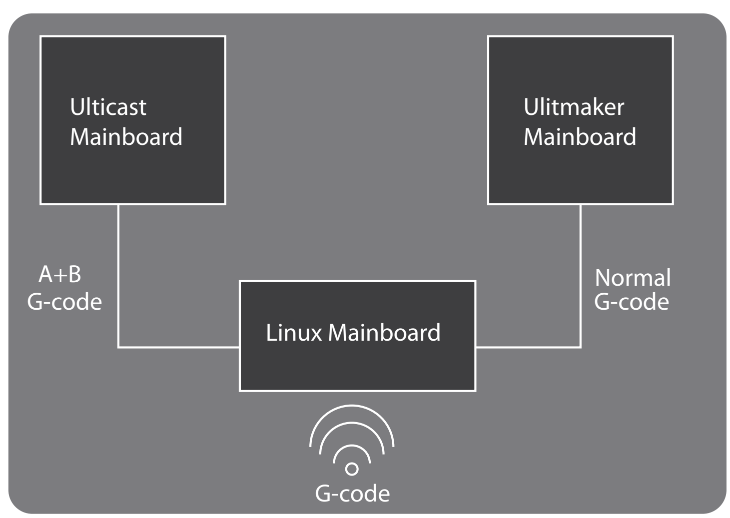


Figure 55: Schematic overview of the working principle of the Firmware



3.3.3 ULTICAST

The Ulticast system is a system designed by Lars Rossing at Ultimaker. In continuation of his graduation project: "Ulticast - The Designing an add-on that creates new material benefits and increases the printing speed for FDM printed parts". At first, the project was aimed at the development of quickly creating solid prints by using two components polyurethane as infill. Due to the market demand, this has shifted to the development of a hybrid manufacturing system that is able to create silicone parts. In order to do so, the set-up uses two components silicone that is joined to gather in a static mixing nozzle.

Just like the Ultimaker, this set-up can be divided into three main domains, hardware, firmware, and software. However, the set-up shares some of these domains with the Ultimaker in order to function. The following sections will elaborate on the working principles of each of these domains.

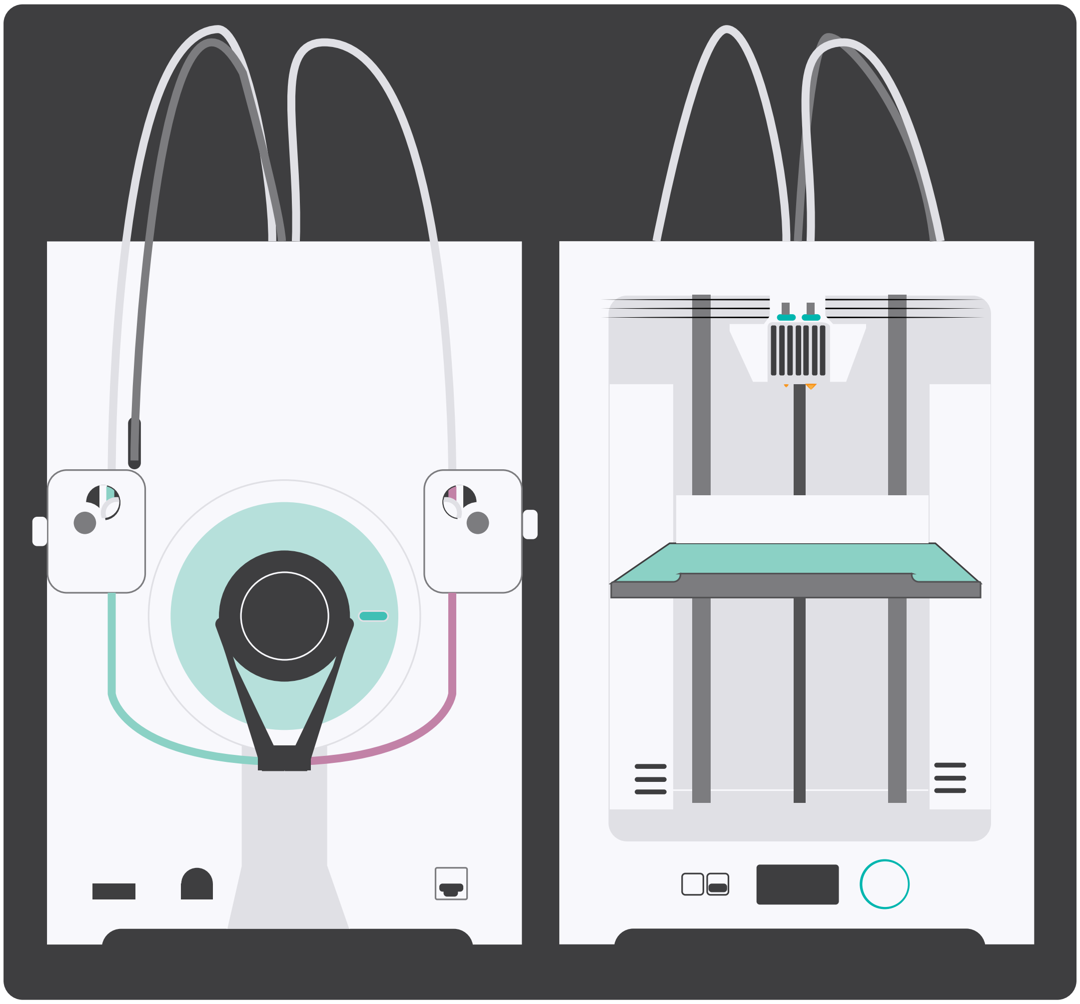
Hardware
The hardware is composed out of the feeding mechanism, see figure 54, a static mixing nozzle, an own main board and a Linux board that is being shared with the Ultimaker. The feeding mechanism is composed out of two stepper motors. They indirectly control the compression of the two syringes loaded with the loose components of silicone. The rotation of the 1.8° stepper motor rotation is translated with an 11:36 gear ratio on trapezoidal screw thread with a pitch of 6 revolutions per 10mm. By rotating the thread, a nut is moved up and down, which is directly linked to the syringes. All of this is controlled by an Ultimaker main board, mounted on the inside.

Firmware
This Ultimaker main board runs firmware specifically designed by Ultimaker for this application. This limits the functions of the board only to control the movement of the stepper motors. The system also shares the firmware with the Ultimaker 3 on which it is mounted. This firmware is for the Linux board. The Linux board divides the g-code over the internal board of the Ultimaker 3 and the external board of the Ulticast. In order to make this possible for the Linux board, the g-code destined for the Ulticast contains A and B drive commands instead of X and Y. The Linux board recognizes these lines of code and then translates them to X and Y commands for the Ulticast mainboard. A working Schematic of this principle is shown in figure 55.

Software
Of course, the alteration of the g-code is done in the software. To create this deviation in g-code a post-processing script has been created in Cura 2.6. This script rewrites all the X and Y coordinates for the Ulticast into A and B. The entire code is then sent to the Ultimaker 3 which can then tell which part of the code is destined for the Ultimaker 3 and which is destined for the Ulticast.

When all the commands have been sent the stepper motors start turning and the material starts extruding from the syringes. In order to deposit the material on the print bed, a static mixing nozzle has been developed that uses a helix spiral to mix the two components together. The mixing nozzle is placed in the slot holder of the second nozzle of the print head allowing for a controlled placement of the liquid silicone.

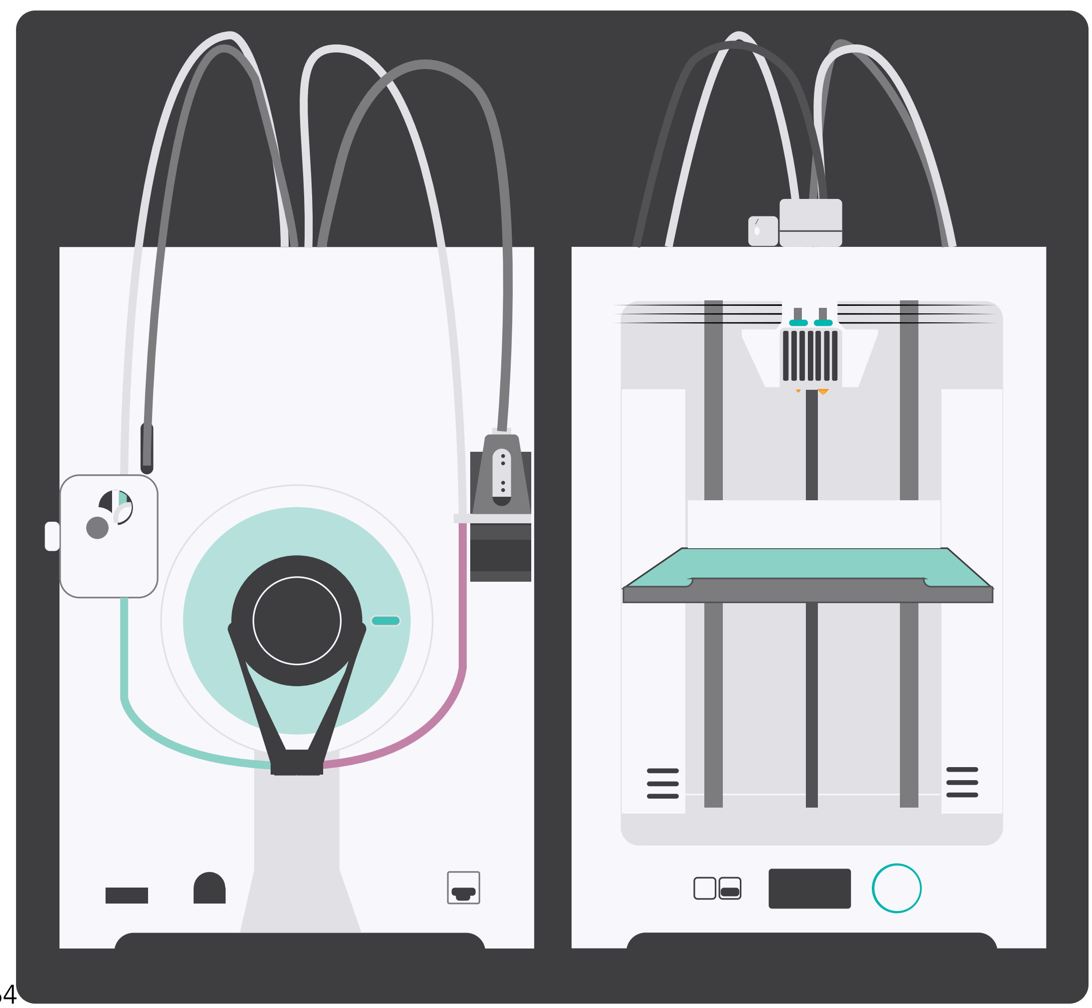
Requirements for this Project
For the development of the hybrid manufacturing system that combines multi-material 3D-printing with silicone casting, the second place holder is needed for printing materials. Therefore the static mixing nozzle should be placed externally. This only has an impact on the printing range and material slicing as discussed in the Ultimaker chapter. The rest of the set-up can be used as presented in this chapter.



Basic Ultimaker 3
Capable of printing two base materials blended through each other. This was the starting point of this project.

Upside: Reliable, and high-quality prints.

Downside: Not capable of printing flexible filaments and doesn't support the creation of silicone parts.



Ultimaker3+ Flex3Drive
Capable of printing normal as well as flexible materials from the AA core.

Upside: The printer can print Flexible Filament

Downside: Not capable of using the BB-core due to the stepper adjustment. Smaller printing range. No silicone casting supported.

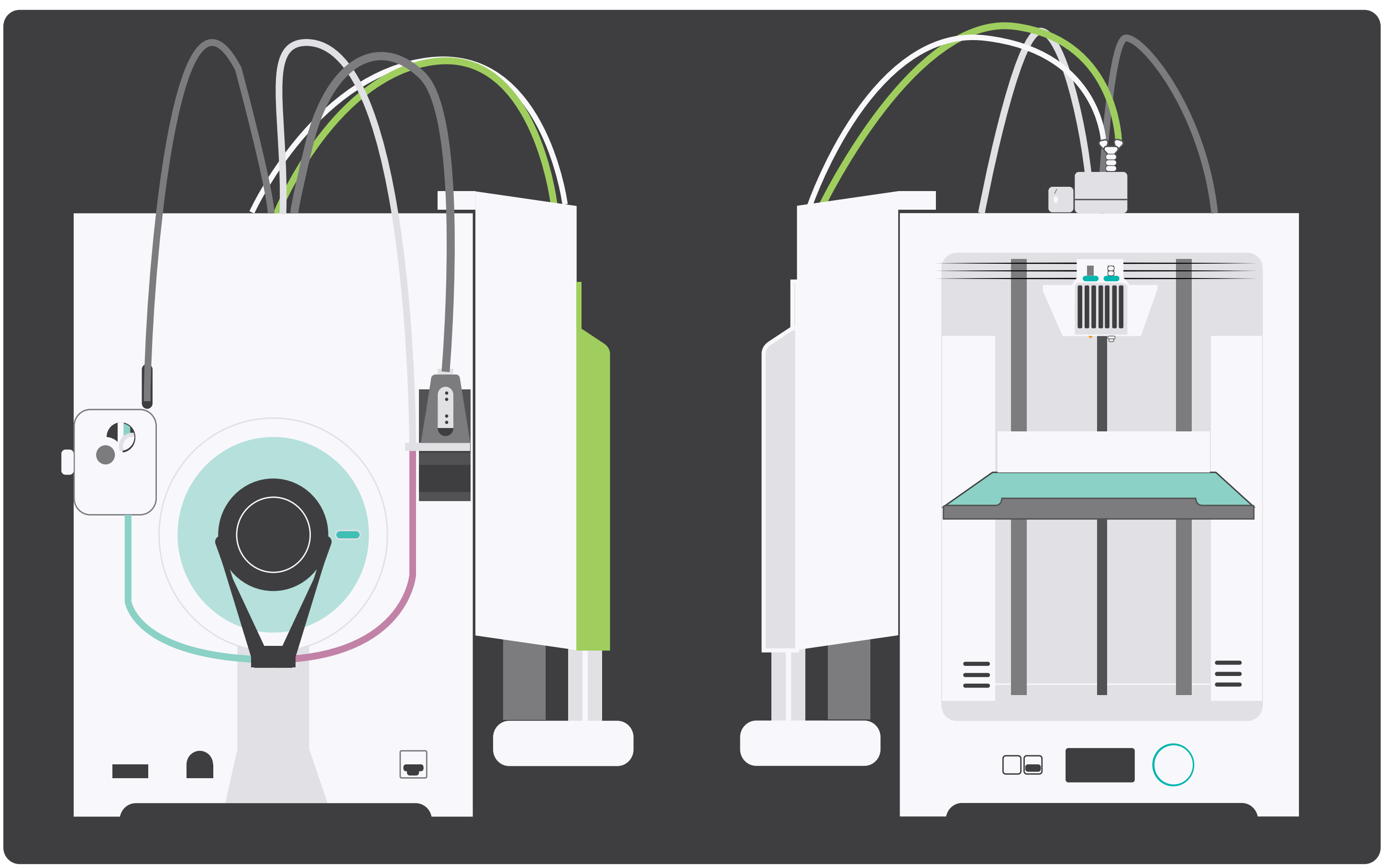
3.3.4 CHANGES IN THE SET-UP

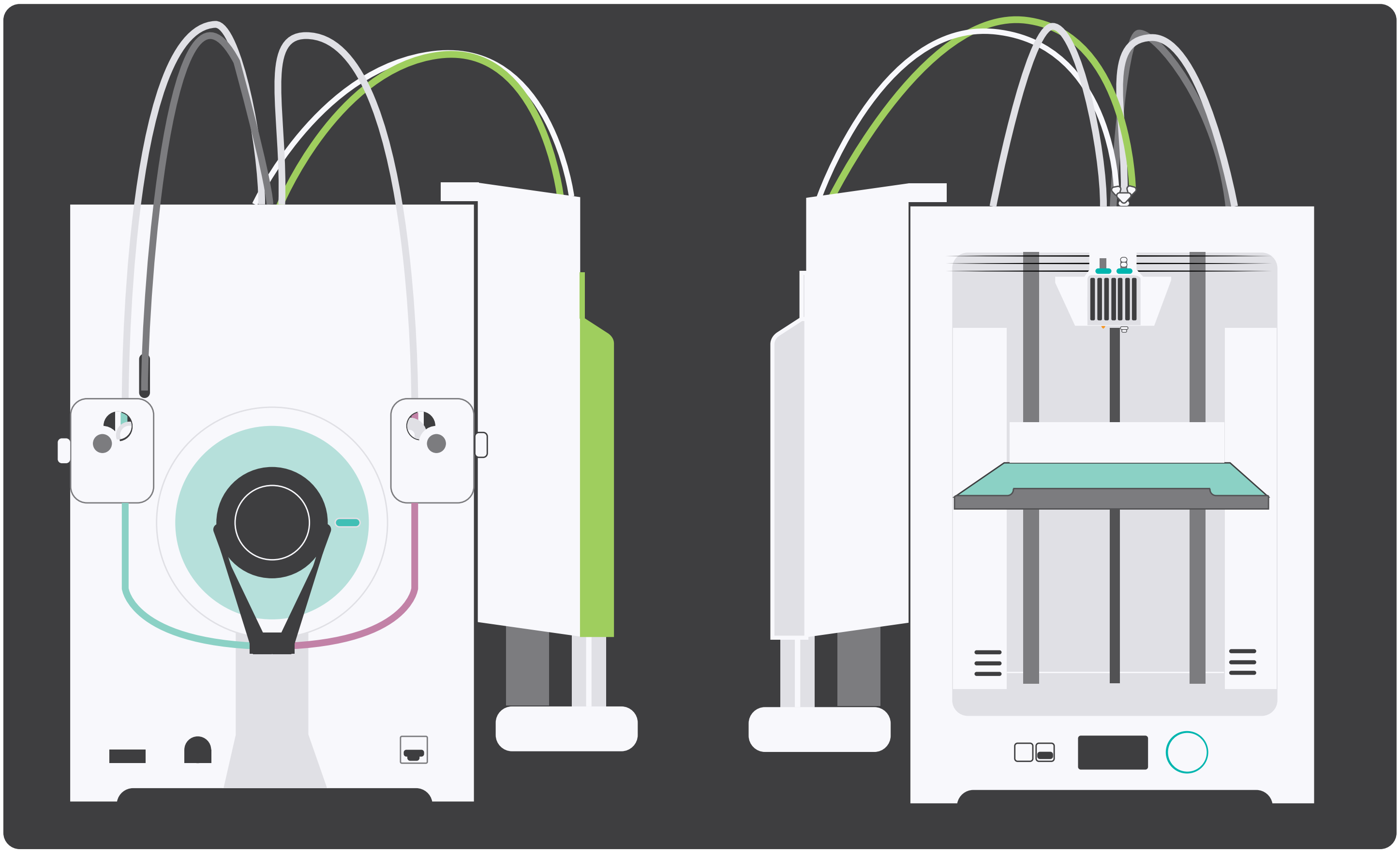
During the project, the set-up has gone over several changes. As a result of increasing its capabilities as well they, forced changes due to fatal errors in previous designs. This section will briefly discuss each change on a step by step basis. Each step will be accompanied with a brief description of the changes made to the design. For every change, the added value has been reported as well the downsides that come with this stage. The last set-up used for the demonstrator will also be evaluated. Recommendations for further usage and development will be addressed.

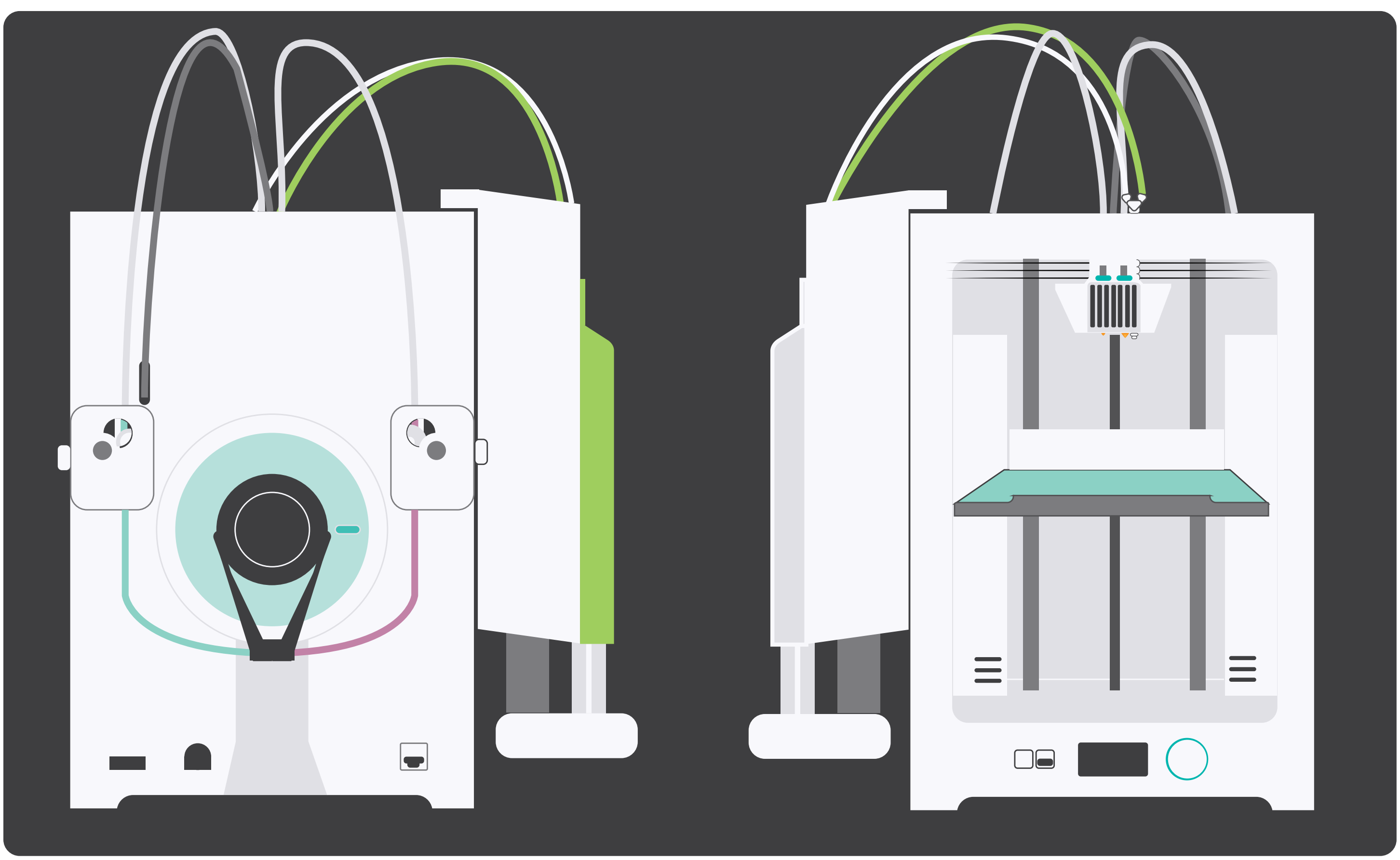
Flexcast (Ultimaker 3 + Flex3Drive + Ulticast)
Capable of printing flexible and solid molds which can be filled with two component silicones under low pressure.

Upside: Is capable of casting silicone products

Downside: Is limited to the usage of only one material for the mold. Smaller printing range.







Ultimaker3 + Large Filament guide + Ulticast Internal
Capable of printing both solid as well as flexible molds which can be filled with silicone after printing. Just like the previous model working principle is less buggy.

Upside: A more consistent flow of extruded material. Full printing range of the Ultimaker 3 available.

Downside: Flexible filament tends to buckle around the filament guide causing the print to fail. Second core not operational.

Ultimaker3 + Large Filament guide + Ulticast External
The final printing set-up used for the creation of the demonstrator. Capable of printing PVA molds and adding an extra component through the silicone or mold.

Upside: Capable of using three materials for deposition. Resulting in a broader range of products that can be designed.

Downside: Printing range is limited due to the rear mount of the nozzle. BB-core activation buggy, due to the placement of the early end stop.

RECOMMENDATIONS FINAL SET-UP

The final set-up now works upon the old design of the Ulticast system. This system has a few drawbacks

Flow
The flow while extruding isn't continuous as a result of the pressure build up in the system. Not only makes this the deposition volume hard to control, but also allows for oozing over the printed parts.

Mounting
The mounting position of the nozzle is at the back to save as much space as possible, while not being influenced too much by the heating elements of the nozzle. As a result, the printed size is reduced and the maneuverability of the printhead. As a result, the BB-core doesn't get retracted properly all the time, so it needs some manual overseeing while operating.

Tight Design
The current housing of the Ulticast components is to tightly designed. As a result of some part occasionally tend to jam. It is resulting in different extrusion values for the A and B component. A more spacious design should be considered.

Volume
The current systems are capable of only extruding 50ml of A and B component. Thus providing only the capacity to extrude 100ml of silicone within a mold. As a result, only small parts can be created with this set-up.

Tubing
With the usage of a disposable nozzle, due to the clogging the tubing on to the nozzle needs to be remounted several times. However, the silicone tubing used will wear and rupture over time causing leakages in the system. A more sustainable solution needs to be found.

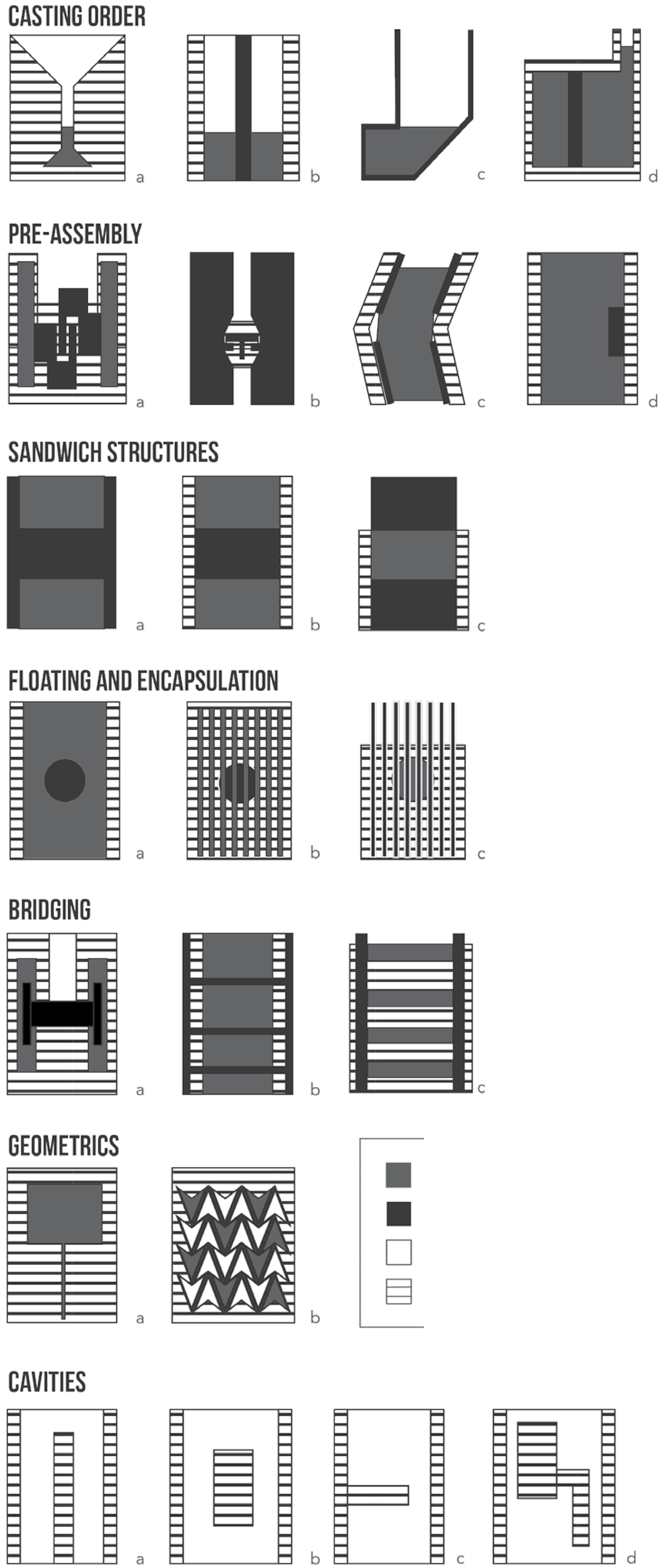
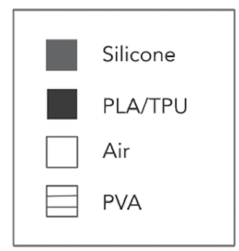


Figure 56:
Oveview of all the possibilities the new manufacturing set-up provides



3.3.5 THE POSSIBILITIES

After the design of the abstract prototype has been developed the second design cycle can be entered. Formulating the new potentials for the development of soft robotic parts. To gain insights of the added value such a set-up can create an overview was created of all the new added values such a system might bring.

First off is the ability to cast while printing the part. This can prove to be an added value for all sorts of issues. The casting order overview provides visual representations of the possible advantages. A) shows the ability to fill cavities through narrow channels, which normally would be unreachable as a result of the van der Waals forces. B) displays the possible advantages by using the early cast silicone as support against tumbling of high parts. This is also true in C) where big overhangs can be created without support due to the center of mass that is low in the product. D) Shows the possibility of filling of areas that else might have been closed due to rigid structures interrupting the flow of the material.

The second advantage makes more use of the multi-material aspects of the printer. A) makes use of the ability to anchor solid materials within soft materials in order to create flexible assemblies. B) makes use of the material properties of silicone that makes it nearly impossible for parts to adhere to it. Allowing for the easy creation of moving parts within the silicone. C) Shows the possibility of creating shells surrounding silicone shapes for local shape reinforcement whenever desired. D) Shows the possibility to integrate hard components within silicone parts in order to make sturdy connections between different components.

The third section poses the ability of the new system to create sandwich structures. This allows for the creation of alternating layers with different thicknesses. These sandwiches can be included in a total shape A) but also work without boundaries as shown in B) and C).

The fourth advantage the new set-up can provide is the ability to string or float objects within a certain matrix. A) shows an orb of solid material floating within a silicone cast. B) shows a solid orb which is captured in strings of silicone. C) uses the same principle but the materials are inverted.

The fifth advantage the set-up provides is the ability to bridge materials. Allowing the connection of two soft robotic parts by creating a solid connection with a hard material as shown in A). Other possibilities are the usage of strings or beams span across the parts as shown in B) and C).

The sixth section exploits the advantage of the 3D-printing technique allowing for really thin walled products as displayed in A). It can also provide complex mesostructures like auxetics as shown in B).

Besides these complex methods the seventh method shows the basic added value of having a soluble support material in order to create all sorts of complex cavities within a silicone matrix as displayed in A), B), C) and D).

3.3.6 CONCLUSION

For the implementation of the hybrid manufacturing system, several changes had to be made to the base building blocks that were already available. The biggest change was the mount of the nozzle externally.

In order to opperate all cores alongside the silicone nozzle. The nozzle had to be moved out side of the printhead. The placement required adjustments to the building volume of the printer. In addition, the slicer needed to be adjusted in order to slice three materials and keep the offset in mind.

For the implementation of the Flex3Drive a redesign has been proposed. During the usage of the system it seized to function due to the slack within the part. This has been improved in a redesign but hasn't been tested yet. It hasn't been tested as a solution was provided by Ultimaker in the form of a part replacement that reduced the amount of slack.

The final set-up now works upon the old design of the Ulticast system. This system has a few drawbacks**:**

- The flow while extruding isn't continuous
- The nozzle is at the back, as a result the printed size is reduced and the BB-core doesn't get retracted properly.
- The current housing is to tight causing parts to jam.
- The disposable nozzle needs to be replaced causing the silicone tubing to wear and rupture over time.

The new printer set-up can provide many new benefits for printing parts in general. Ranging from reducing the use of support up to create composite materials. In the concept phase, these possibilities will be further investigated and how they can be an added value in the field of soft robotics.

4.0 INTRODUCTION

The concept phase combined all the gathered knowledge and insights of the previous chapters with each other to create an overview of all the possibilities the newly developed hybrid manufacturing system brings. These possibilities have been carefully looked at and further developed into ideas. These ideas were carefully selected and developed into different main clusters. These main clusters than were carefully selected to set-up tests and from these clusters into feasible concepts.

The first chapter, Idea Generation, tries to provide answers to the question, in what areas can the new manufacturing system provide an outcome for soft robotics? The second chapter, Clusters, tries to structure the ideas generated and create an overview. In the Cluster Evaluation chapter, the clusters are evaluated on aspects like feasibility and novelty, but also on the added value, one cluster might provide to the further development of soft robotics.

After the evaluation, the Concepts Composites, Soluble Support and Hard Inserts each get their own chapter. This chapter is dedicated to research specified for each concept. For composites, answers have been searched for how fiber direction and material type might affect the properties of a soft robotic part. In the Soluble Support, chapter research was conducted in regards to how complex the internal cavities could be to still fully dissolve. The Hard Inserts chapter gathers insight of how much pressure an actuator with a hard insert can withstand before the seal ruptured or popped-out of the actuator.

The final chapter of the concept phase takes into account all of the findings for each concept. With these design guidelines, a demonstrator has been designed which clearly shows the added value of the new hybrid-manufacturing set-up. This design is the starting point for the next segment of this report. The Detailing Phase.

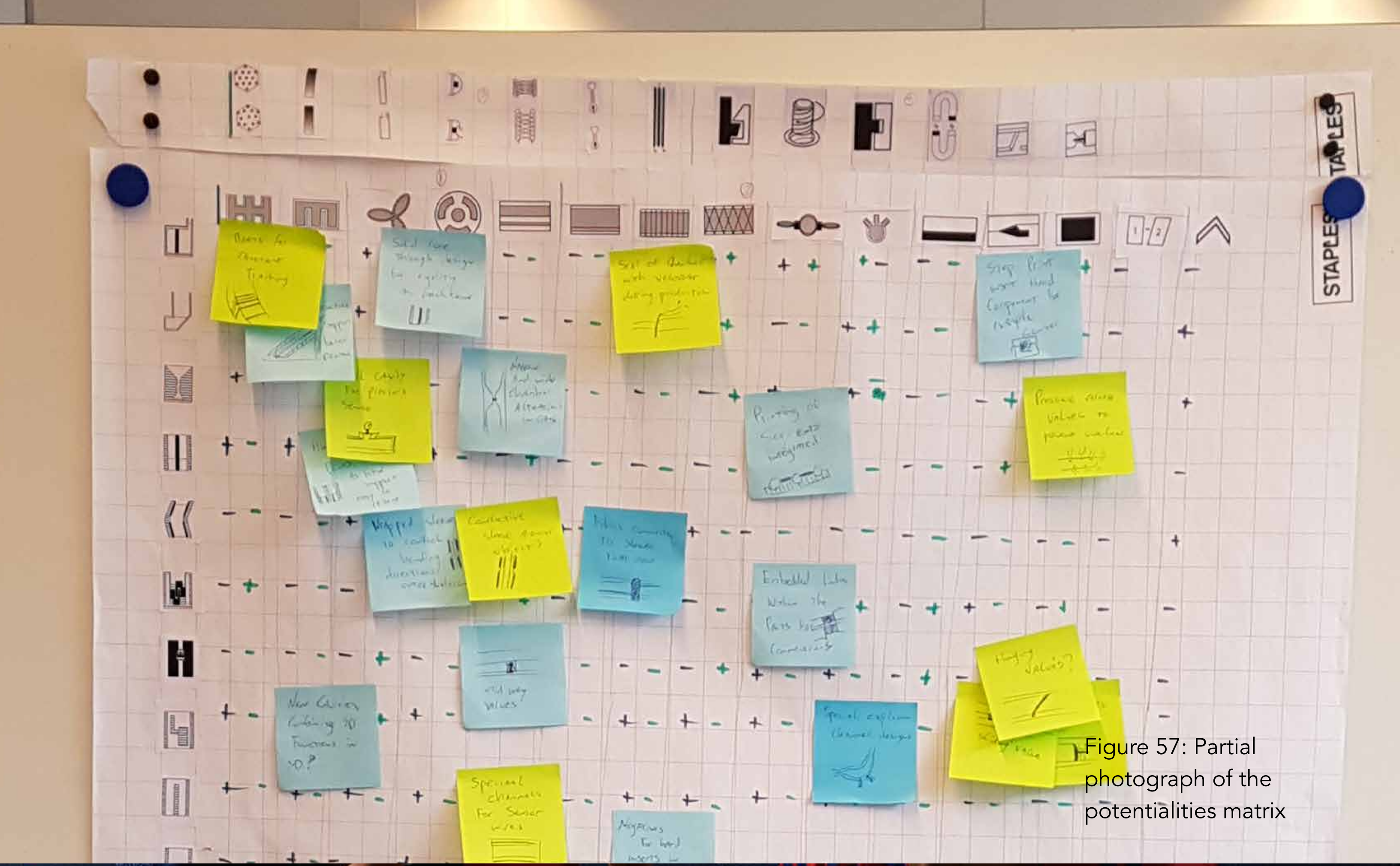


Figure 57: Partial photograph of the potentialities matrix

Figure 58: Impression photograph of the creative session.

4.1 IDEATION

During the research phase, an overview was generated of all the soft robotic actuators, sensors and connections up to date. To find out on what aspects the MultiCast might provide an outcome a function analysis was conducted to analyze what functions the parts fulfill and how these functions are achieved in the parts. This function analysis can be found in Appendix 8.2. This analysis formed the basis of the functionalities.

In chapter 3.3.5 the new possibilities of the MultiCast are analyzed and summarized. These formed the basis of the potentials of the printer.

By combining the functionalities of the soft robotics and the potential of the new set-up a matrix was created in which search areas could be found. Since the matrix consisted of over 500 possible combinations each of these combinations had been checked individually whether it showed potential for an idea. See figure 57. After all the cells had been checked the plusses were looked after and the first ideas were generated providing solutions for the possible combinations.

To come up with a broader range of solutions a creative session had to be hosted with other designer acquainted with soft robotics. A description of the method used during the creative session can be found in Appendix 8.3 and 8.4. The creative session resulted in a broad range of solutions, to create valuable insights out of these solutions clusters were generated. The following chapter will discuss each of the clusters created.

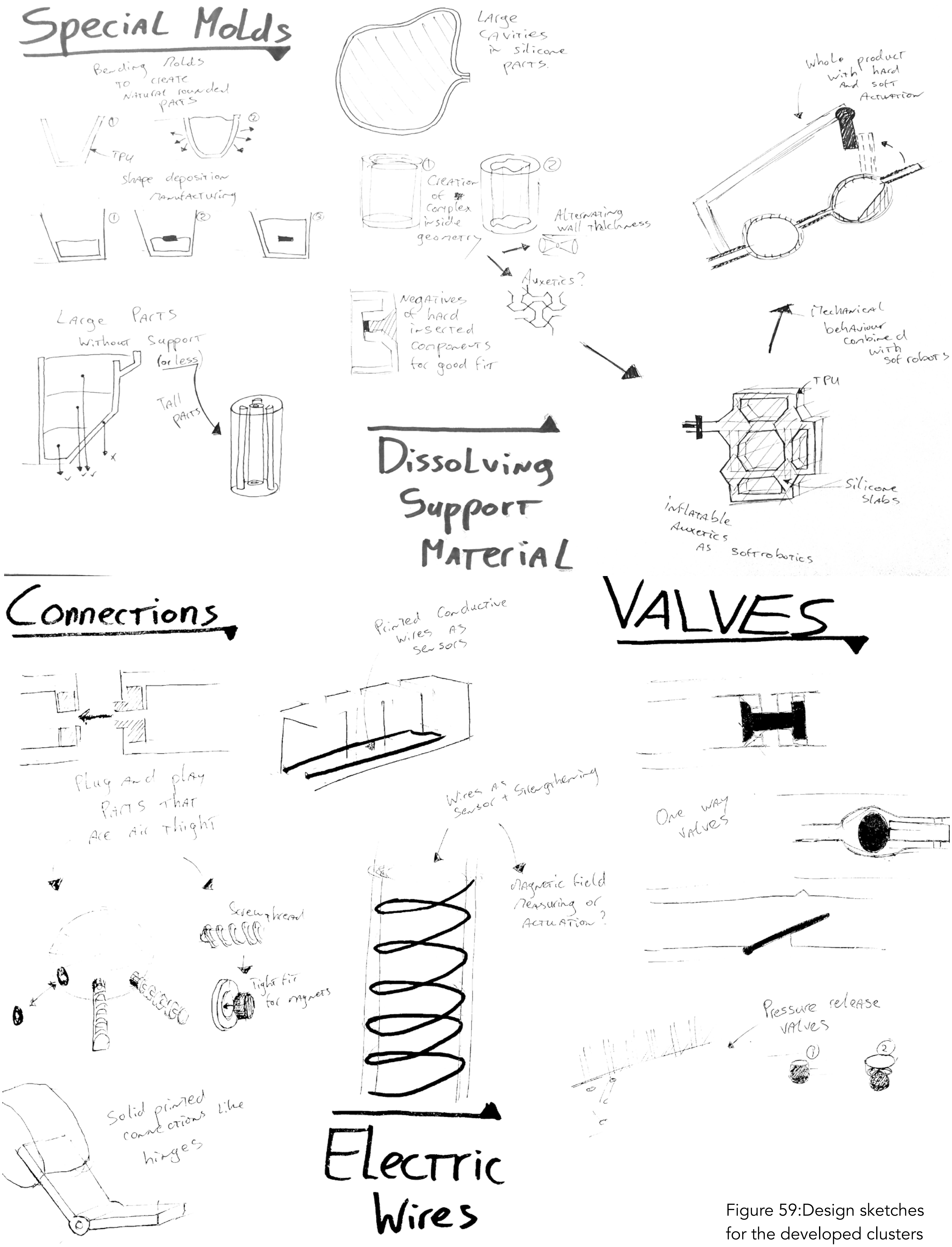


Figure 59:Design sketches for the developed clusters part 1

4.2 CLUSTERS

During the creative session, clusters were generated, by matching ideas with the main theme. All ideas that could fit within a certain theme had been added to the cluster until no loose ideas were left. This chapter discusses all the generated clusters briefly.

Special Molds

This cluster aims at the reduction of the use of support material. There are several ways proposed to do so like making use of the weight of the pre-casted silicone to prevent the parts from tumbling. This can be achieved by using the silicone infill as a counterweight to the moment of inertia that the part would normally have and tumble over. Another way is to increase the accuracy to prevent tall parts from moving with the nozzle what normally would require a support tower. Additionally, flexible molds could be considered which, collapse under the weight of the casted silicone, which could result in a uniquely shaped product. Lastly, this set-up is also suitable as an SDM production facility.

Visual Indicators

The sensing cluster is all about the increase of visual tracking of the part. This can be achieved via multiple ways by embedding visual trackers in the form of gradients, bars or dots. These visual trackers will change their conformation in relation to each other which can be measured to determine the actuated position of the part.

Sleeves

The sleeves section is composed out of two ideas. The first is based upon reducing the complexity of the parts that have to be designed for different types of actuation. By shifting these design issues the silicone part can be kept simple. Allowing for quick alterations in shapes and functions of the same part. The second idea is using the sleeves as a place holder for sensors. Different types of sensors could be used to fit within the sleeves to measure deformations within the actuator. An example could be a sensor that would measure how far the silicone would bulge out of the sleeve.

Stringing

The stringing cluster contains parts that are primarily made of silicone but locally contain strings of another material suspended through the part. By pushing and pulling the suspended wires conformations within the part can be altered. This result for example in the control of valves within the part.

Embedded Mechanisms

The previous group is a small example of a specific embedded mechanism. However, interlocking mechanisms and hinges could also be implemented. This could be interesting for soft robotics to mimic, for example, bone structures. By implementing hinges within a soft robotic finger, the way a bending actuator deforms might get a closer resemblance to that of a real human finger.

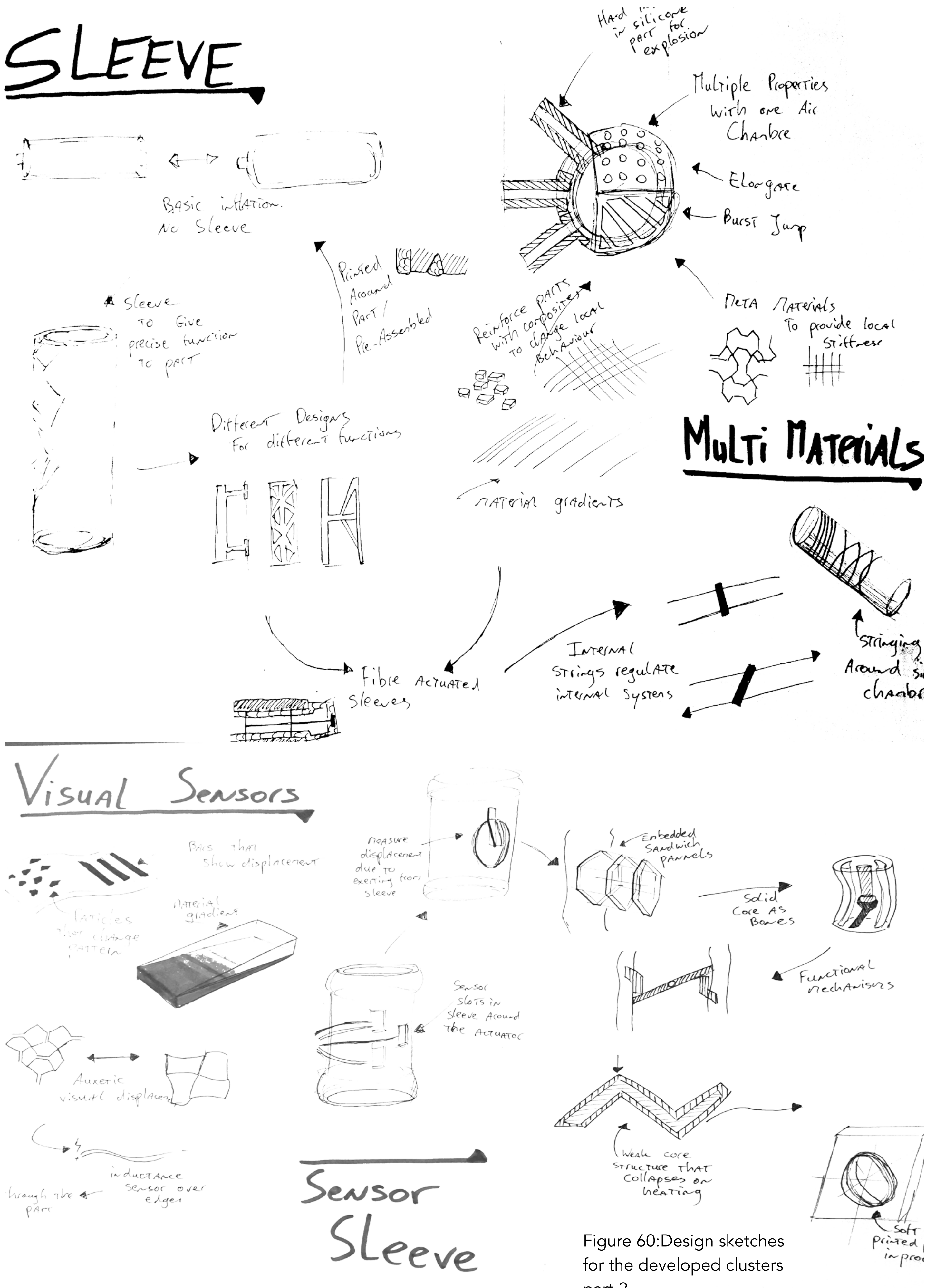


Figure 60:Design sketches for the developed clusters part 2

Composites

The cluster of composites is based on the principle of using printed fibers as local reinforcement of parts. By doing so anisotropic behavior within one part can be achieved. Additionally, since all the fibers are printed there is absolute control over density and direction of the fibers allowing for the creation of gradients within the composite. An example could be a balloon that contains a hard gradient, where one side will expand rapidly while the other side of the balloon remains in the same place unaffected by the extra pressure.

Auxetics

By making use of Auxetics, a new way of actuation could be achieved. By pressurizing one room, special buckling behavior could be created in other rooms or vice versa. Also, the expansion could be controlled, by locally reducing or increasing the Poisson's ratio of the walls. This results in unique parts.

Conductive Wiring

The conductive wiring cluster involves the embedding of all sorts of conductive filament. By printing such a filament electromagnetic properties can be easily integrated into a soft robotic part. If for example the wires are coiled around an actuator they generate a magnetic field. This magnetic field can be used to interact with the environment. In addition, the magnetic field could be used to derive the current position of the finger, as the coil would deform during the transition from one position to another creating an interesting way of sensing the position of the actuators.

Valves

By exploiting the fact that silicones don't stick well to anything and can be printed upon, valves can be embedded within pneumatic actuators. It leaves room for the design of a pressurized system. Think for example of parts of an actuator that only start to actuate after a certain amount of pressure is mounted in the previous chamber.

Connections

The connections cluster focuses on using hard parts embedded within a flexible part to overcome the wear issues often found in soft robotic parts. Often this is an extra assembly step or just a big weakness in current designs. By printing a hard part within the silicone, a reliable and wear proof solution can be provided.

Complex Cavities

The last cluster identified is the usage of PVA to create complex cavities within a part. Since the material dissolves in water it is possible to create elaborate tunnel systems within a part. Removing the support should be less of an issue compared to for example parts printed with the Objet since it can be poured out as a liquid. Additionally, the usage of the more wear resistant Silicone might even help as it can be pressurized so the water can get anywhere.

All in all, there are loads of useful applications of the new MultiCast within the field of soft robotics. However, this project is limited in investigating all the possibilities, therefore, a selection has been made.

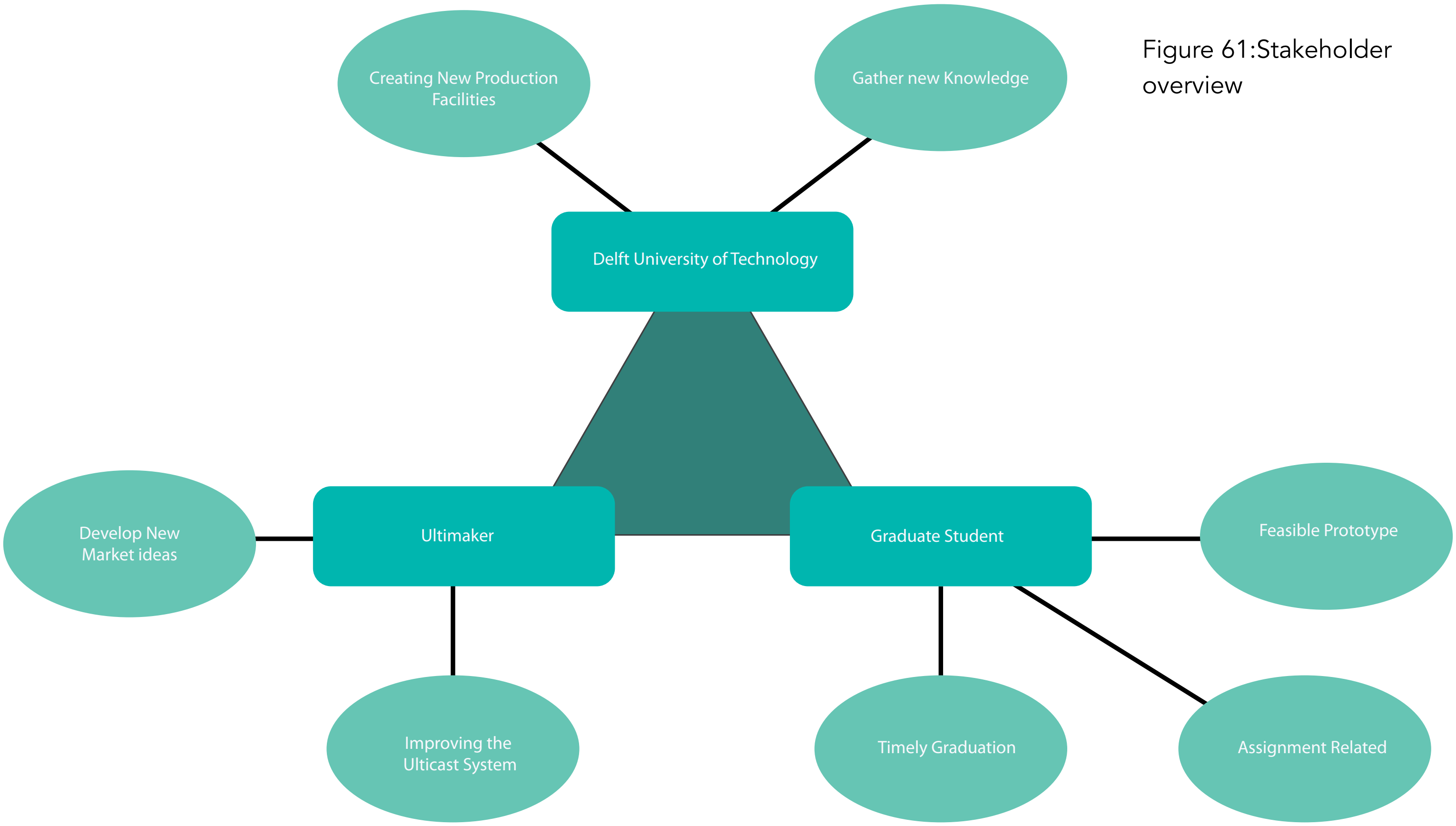


Figure 61:Stakeholder overview

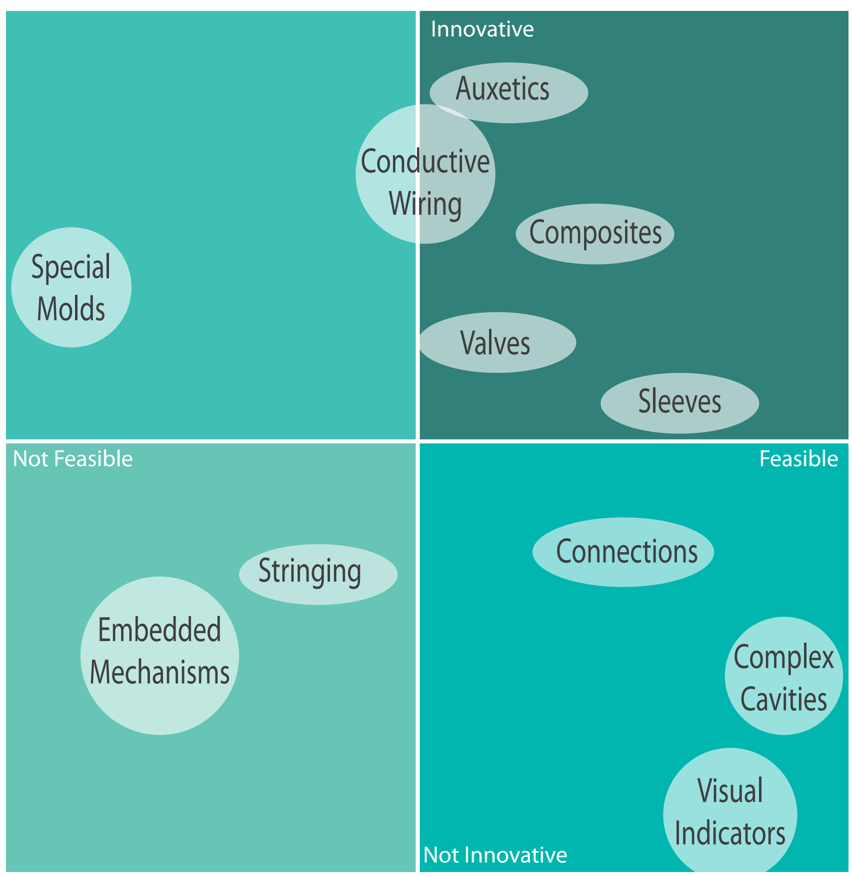


Figure 62: C-box selection method

4.3 CLUSTER EVALUATION

This project knows three main stake holders. All of these stake holders have their own desires. These stake holders and their desires have been mapped in figure 61.

Delft University of Technology

The first stake holder that is to be mentioned is the University of Delft. The University of Delft could profit from the MultiCast on its own, as it can be applied in several projects. Since the scope of this project is focused on the development of a soft robotic demonstrator the research group of Soft Robotics will benefit the most. The Soft Robotics group would like to use this new production facility to create new and innovative soft robotic parts and solution. In addition, the low production intensity, cost and continuous quality of the parts is desired.

Ultimaker

The second stake holder is Ultimaker, although they only have an advisory role, it doesn't mean they don't have goals they want to accomplish. Ultimaker is interested in what potential lies within their new Ulticast add-on. Therefore, new ideas are sought after and an environment in which their set-up can be put to the test. The results of this are interesting demonstrators to show clients and to determine potential improvements in the design.

Graduate Student

The last stake holder is me. As a graduate student Integrated Product Design I want to graduate without having to postpone the graduation date more than necessary thus time is relevant. However, as a design student I would also like to close the project with a satisfying resutl. Additionally, the chosen design should be feasible to make.

All of these aspects have been looked into for the determination of the most feasible concept to work further with. The determination was two fold as there were eleven possible clusters to work with.

C-Box Evaluation

The first step in reducing this amount was by mapping all clusters in a C-box. This evaluation method is designed to gain insight of which new concepts are the best to work with. The used C-box is shown in figure 62. This gives a clear overview of the clusters that are feasible and innovative. The two aspects that are desired by both Ultimaker as well as me as a graduate student. There has been chosen only to continue with the evaluation of the feasible clusters.

Figure 63: Weighted Criteria Selection method

Criteria	Weight	Auxetics	Composites	Connections	Conductive Wiring
Design Freedom	25	4	7	9	6
Interactive	20	5	5	6	8
Customize	20	4	9	9	7
Production Cost	15	7	8	8	5
Production Speed	10	6	8	8	7
Humanlike	5	7	6	4	6
Comformability	5	9	7	3	5
Total	100	525	720	790	650

Criteria	Weight	Valves	Sleeves	Complex Cavities	Visual Indicators
Design Freedom	25	6	7	8	6
Interactive	20	6	6	6	8
Customize	20	7	9	8	6
Production Cost	15	9	8	8	7
Production Speed	10	8	6	6	7
Humanlike	5	7	4	8	6
Comformability	5	7	3	8	6
Total	100	695	690	740	665

Chosen Criteria

The second evaluation method that has been used is the weighted criteria method. The criteria used for this method have been derived from previous research. First off, the aspects of Design Freedom, Production Cost, and Production Speed are derived from the preliminary test of Chapter 1. These aspects are also in line with the desires of the Soft Robotics group, thus the University of Delft.

The other criteria are derived from the application areas for soft robotics. Often these fields shared common strengths. The most used aspects are the Interactive, Humanlike and Conformability qualities of the soft robotics. Further more, the Customization of specific soft robotic parts was also often mentioned. Resulting in the used criteria used for the cluster evaluation.

After filling in the list; Composites, Connections, and Complex Cavities show the most promising for the application in the soft robotics. The reasoning behind the attributed values will be briefly discussed in their named section.

Composites

Creating composites with a printer comes with the unique possibility to control the strength and stiffness of a part with a high precision. This results in easily customizable parts, that are mostly homogeneous in composition. As a result, a lot of design freedom is gained and different types of behavior can be mimicked. A downside however of this cluster that it isn't based around improving the interactivity.

Connections

By implementing a solid connection within the parts, a lot of design freedom can be created. Not necessarily in terms of freedom for a part design. But more for the development of entire soft robotic systems. These can be easily customized and reliably produced with hard inserts. However, by implementing a hard insert it will come at the cost of decreasing the resemblance to that of humans, as well as its conformability.

Complex Cavities

Making use of complex cavities will greatly increase the design freedom of the soft robotic parts. All over it would also decrease the production cost. As it would leave the valuable support material of the Objet printer obsolete. By creating complex cavities complex human structures could be mimicked. However, the usage of water soluble filament might not improve the production time, of the parts.

Conclusion

All three clusters looked promising in regards to being an added value in the development of soft robotic parts and have been continued during this project. These concepts still required a proof of concept and some further testing. The following chapters will validate the clusters and set-up design guidelines for the final demonstrator.

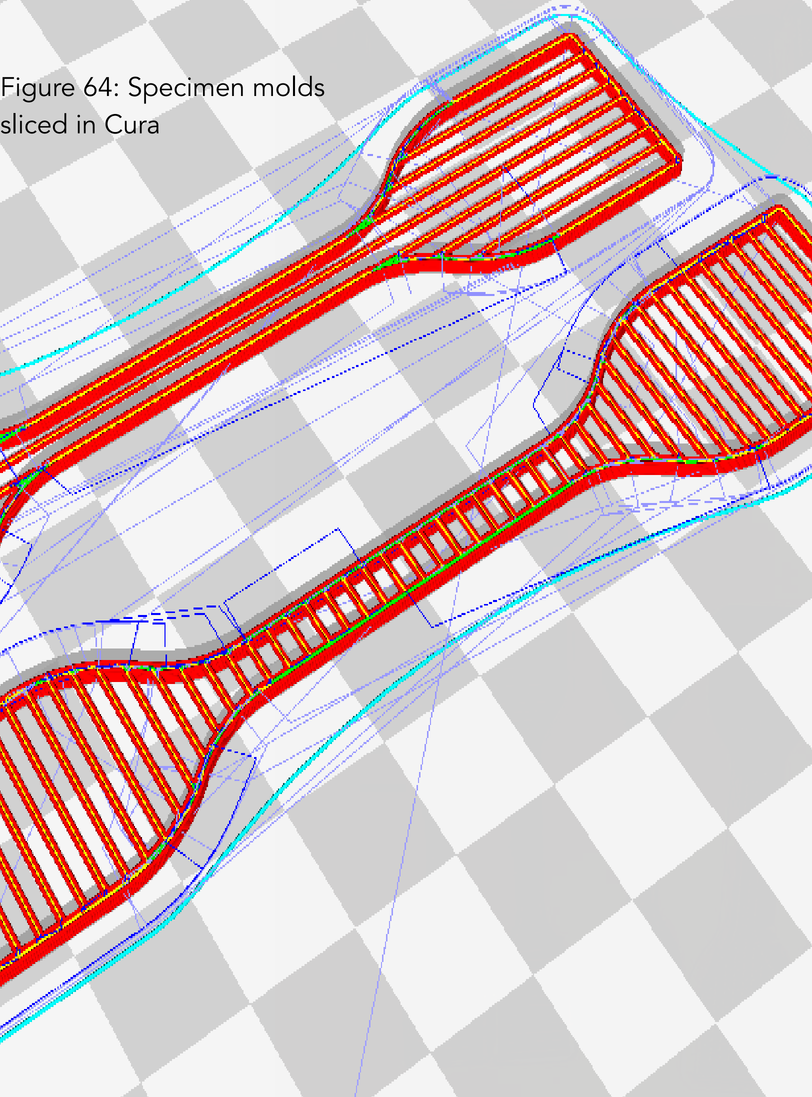


Figure 64: Specimen molds sliced in Cura


Figure 65: Finished 3D printed molds

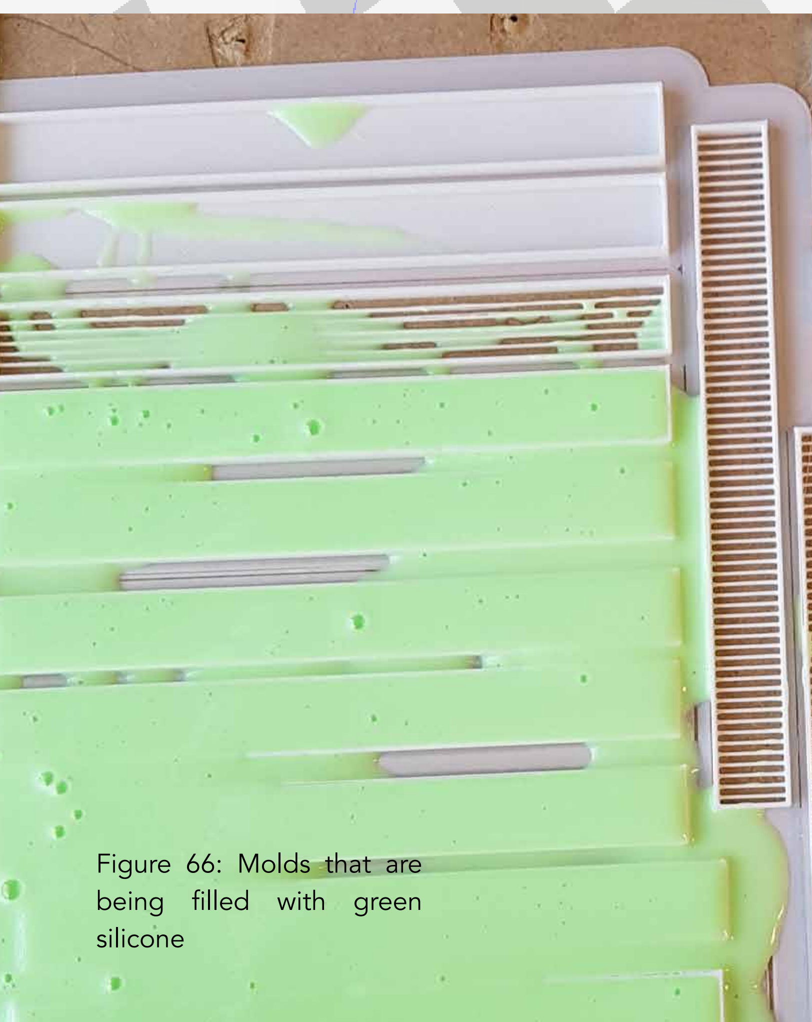
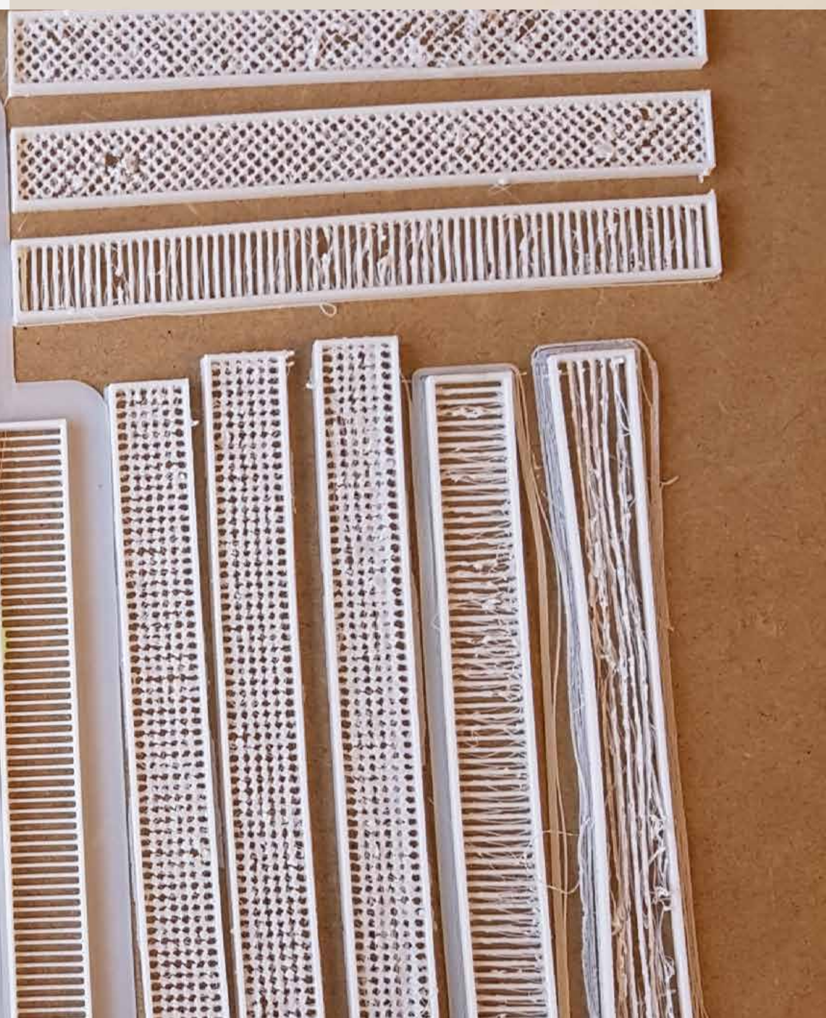


Figure 66: Molds that are being filled with green silicone



4.4 COMPOSITES

Main introduction

As a result from the concept choice, composites have been further investigated and developed. In the field of composites there are a lot of factors that can influence the parts. One of these is for example the bonding between fiber and matrix, as discussed in the composites section. To determine whether the usage of TPU and or PLA fibers can create a behavioural change in the silicone two tests have been conducted. A tensile test and a flexural test have been conducted. It is desired to change the behavior of silicone by means of 3D-printed composites as this would allow the user to fully control the material behavior at a Meso-level. Creating anisotropic behavior within one continuous part. The hypothesis of these tests was that the 3D-printed fibers would influence the parts.

Tensile Test

Introduction

The first test that had been conducted was the Tensile Test. This test has been conducted not only to determine whether the fibers would result in a change of material behavior, but also to determine how the matrix fiber bonding would be between the two components. Based up-on preliminary testing which have been discussed in the Testing chapter the hypothesis was that the bonding between PLA and silicone was less effective as that of TPU/Ninjaflex with silicone due to the high difference in young's modulus. Additionally, there was expected a change in material behavior.

Apparatus

In order to conduct the tensile test, a Zwick Z010 had been used. With the standard software delivered with it. Measurements have been done by scaling the displacement.

Specimens

One of the biggest challenges for this test was the creation of the specimens. In order to create all 55 specimens with the same dimensions, there had been chosen to 3D-print molds for casting, where the fibers were achieved by bridging. After the printing process, the specimens had been cast and cured for 24 hours. After curing the skirts of the molds had been cut off and a clean specimen was left. The following sections will provide some more detail upon the procedure.

Slicing

In order to print the specimens with fibers embedded in them, they had been created by means of bridging. In order to make sure that the layers of the fibers would be stacked in the same direction, the fibers were created as unique parts in Rhino. By merging the single parts in Cura into one complete part the fiber directions where saved and could print as intended. See Figure 64.

Casting

After the parts had been printed the molds had been placed on a flat wooden surface. A mixture of 50/50 Shore 30A green addition silicone was poured into and over the molds. To make the top parts flat, the prints were then covered with a heavy straight slab of Polystyrene. After 24 hours the wooden plate and slab of polystyrene had been removed. After the silicone had been cured the edges had to be removed. These have been simply cut away to leave the final specimens.

Dimensions

Although the production process for all the specimens was always the same, the final dimensions weren't. This wasn't concerned to be a big issue, as the test was designated to detect a significant difference in material behavior, and not derive exact measured values.

Procedure

The procedure used for testing the specimens was in accordance with the ASTM standards. The standards used for this test are ASTM D6746 (ASTM, 2017) and ASTM D412 (ASTM, Standard Testing Method for:, 2017). In ASTM D6746 is described that the preferred method for testing is the usage of specimen C from ASTM D412. However, for this experiment, there has been chosen to use specimen D. This in order to reduce the amount of displacement required to gain the critical stress and strain, as a result of the smaller cross-section of the specimens. It should be noted, that the data gathered with a tensile test with specimen D can't be directly compared to the data gained from a test with specimen C. Additionally, the test have been conducted with 5 specimen instead of the required 3, due to the big differences in geometry and quality of the specimen. This way the required data would be more reliable.

Figure 67: Stress Strain Curves of the Specimens

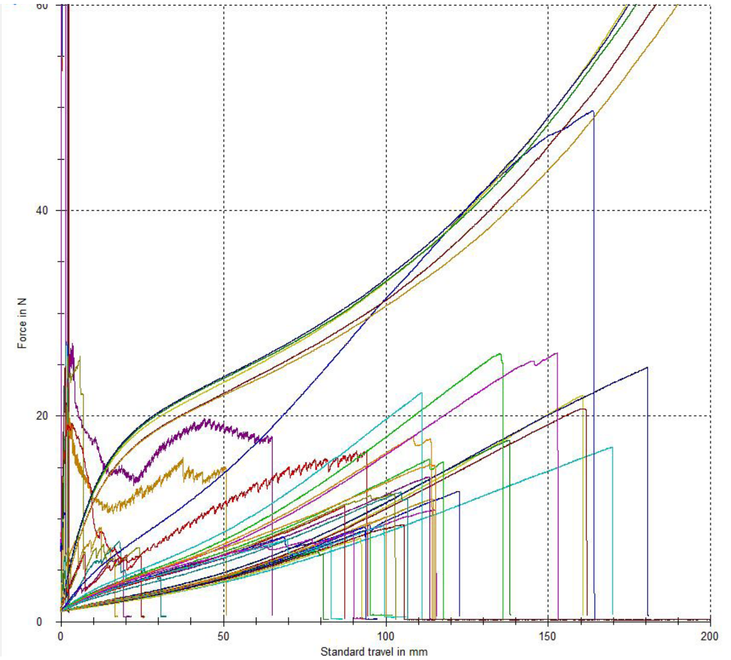
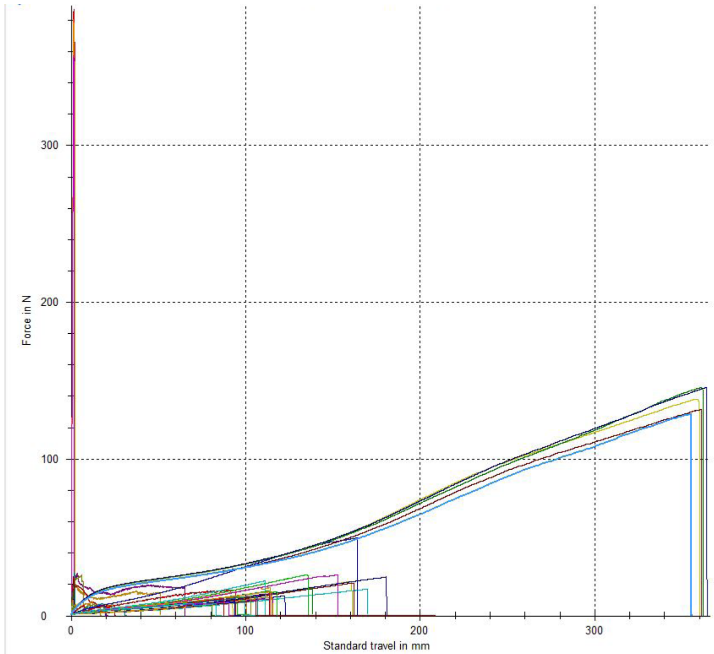


Figure 68: Zoomed-in Stress Strain Curves of the Specimens



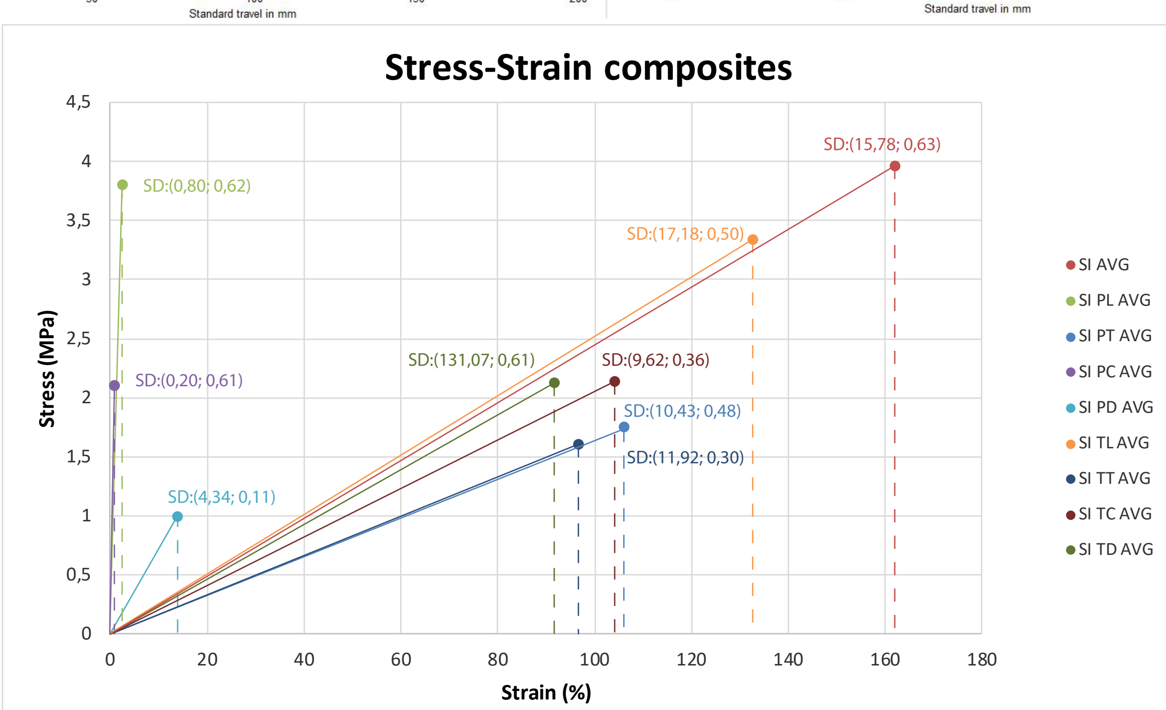


Figure 69: Avera Stress and Stra values plotted one graph.

Calculation

For the determination of the stress, strain and young's modulus, the following formulas have been used.

$$\varepsilon = 100\,[L - L_0]/\,L_0$$

ε The strain in percent (%)

L The observed distance between the benchmarks on the extended specimen (mm)

L_0 The original distance between the benchmarks (mm)

$$E = \frac{\sigma}{\varepsilon}$$

E The young's modulus MPa

σ The stress on the Specimen during the elastic stage (MPa)

ε The strain of the Specimen in the elastic stage

$$\sigma = \frac{F}{A}$$

σ The stress on the Specimen at a specific point (MPa)

F The force on the Specimen on a specific point (N)

A Surface Area of the Specimen (mm²)

Discussion

When looking at the results it can be noted that there are significant changes in the material behavior of the created composites. The following section will try to elaborate on the material changes and try to give an explanation why the material behaves in such a manner. The full overview of the results can be found in Appendix 8.5.

The tensile tests have been conducted from composites composed out of three main materials. All of these individual materials have been tested to gather insight about their individual behavior. The most noticeable peaks are the once from pure PLA. This material has a high yield strength but a very low strain compared to the other materials, which is in line with the expectations of a thermoplastic as can be seen in figure 67.

The material with the second largest yield strength is TPU, not only has this material a high yield strength but also the highest strain up to 706%. Leading up lengths for this type specimen up to 360mm.

The peaks of pure silicone are harder to find. They show high levels of strain, although not as high as TPU, at around 285% resulting in lengths of 160mm. The average maximum force applied on the samples is 20N resulting in a maximum stress of 3,95 MPa. This indicates that the expected value of the yield strength provided by silicones and more of 5MPa (Silicones&more, 2017) is not achieved.

To make a more clear distinction between the different composites, the graph of figure 67 is zoomed in and displayed in figure 68. The most noticeable peaks are the ones from the composite which contains PLA fibers in the Longitudinal direction of the load (Si PL). The stress, leads up to 20N and then dropping a bit and altering around a base value. The alternation can be explained by the PLA fibers, slipping through the silicone up until the point that the silicone finally breaks. This indicates that the fibre-matrix bonding between the PLA and Silicone is limited. Although this was not the expected outcome, the finding can still prove to be use full, as the material still performs well up to the maximum stress of 3,95MPa which is close to the maximum stress found for silicone at 3,79 MPa. Also it displays an increased young's modulus compared to pure silicone.

The PLA composite with Cross-linked fibers (Si PC) shows a similar behavior as that of the Si PL. However, the maximum stress is significantly lower with a value of 2,10MPa. Also the strain of the material is lower. The lower strain is a result of the higher filling, of PLA throughout the specimen leaving less silicone for slipping through the material. The alternating force curve is again the result of the fibers slipping through the silicone.

All the other composites show stress-strain curves similar to that of pure silicone. However there are still two samples that show an increased young's modulus compared to pure silicone. These are the samples of the Diagonally cross-linked PLA (Si PD) and the composite with TPU fibers in the Longitudinal direction of the load (Si TL). The Si PD sample has a greatly reduced maximum stress and strain of 0.98MPa and 27,36% strain, but this results in a higher all over young's modulus for the material. The Si TL sample also has lower values for its stress 3.35MPa and strain 243,18%. It has a higher young's modulus and the values are the closest to that of pure silicone.

All the other materials, display a decrease in stress, strain and young's modulus. Although, it is not a positive change in behavior it is a change in behavior what could be use full in some applications.

In the data used for the analysis, the samples with big air pockets have been left out resulting in slightly different values and a lower number of specimens on which the values are based. For this test this is not a big issue as it intended as a guideline and a comparison of the composites. However, it should be noted that the results only provide an indication but are not fully conclusive.

Figure 70: Stress Strain Curves of the Specimens

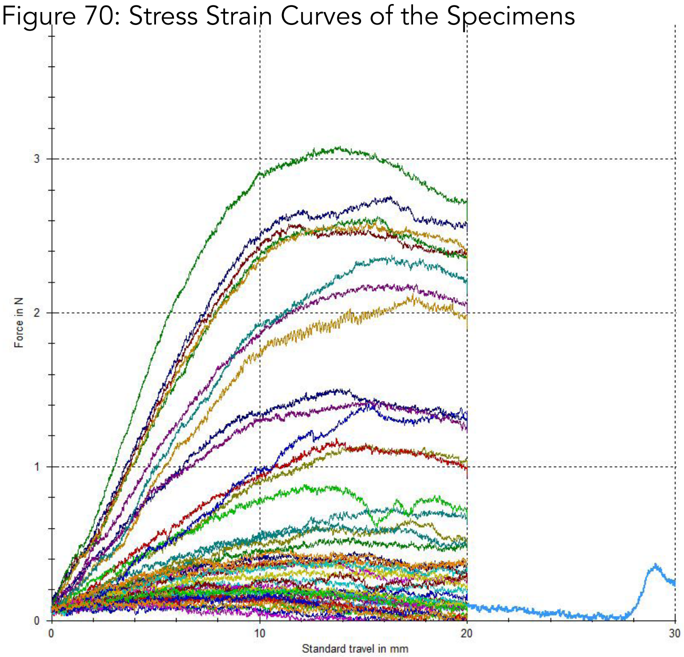
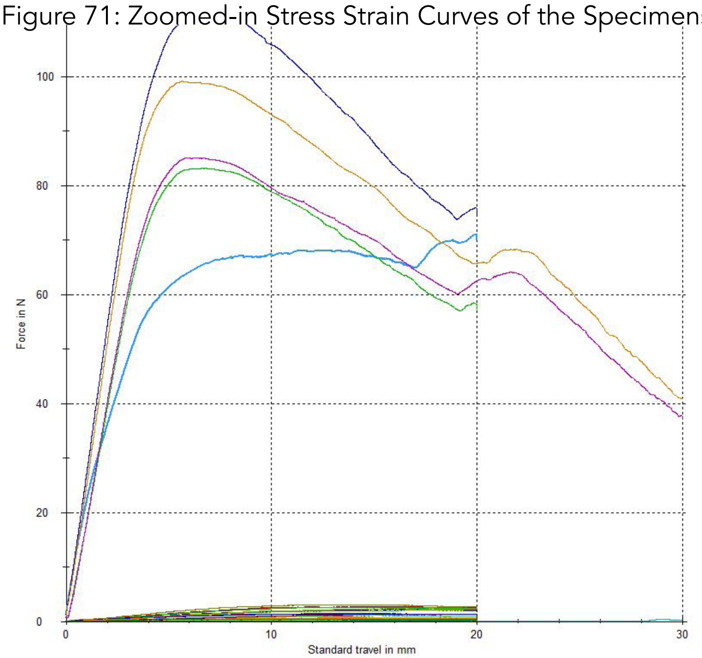


Figure 71: Zoomed-in Stress Strain Curves of the Specimens



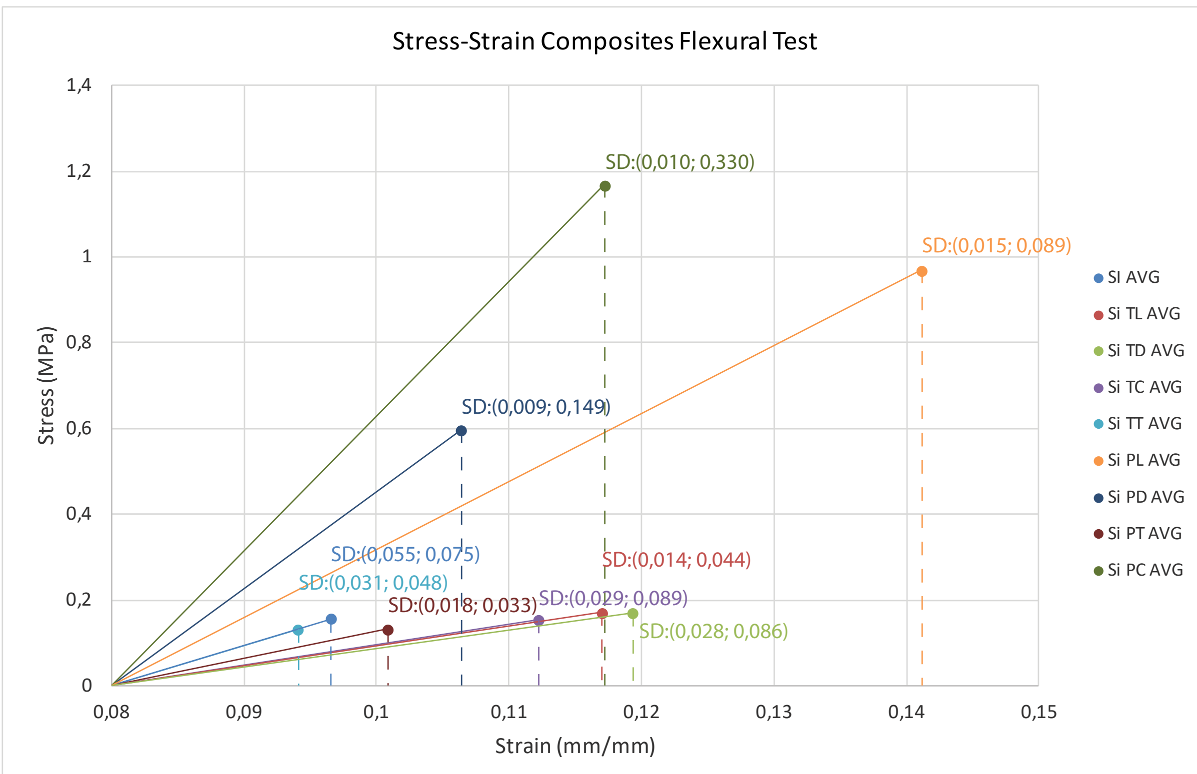


Figure 72: Avera
Stress and Stra
values plotted
one graph.

For the determination of the Stress, Strain and Young's modulus the following formulas have been used.

Discussion

$\sigma_f = 3PL/2bd^2$

σ_f	Stress in the outer fibres (MPa)
P	The load on the specimen (N)
L	Support span (mm)
b	Width of the specimen (mm)
d	Depth of the specimen (mm)

$\varepsilon_f = 6Dd/L^2$

ε_f	Strain in outer surface (mm/mm)
D	Maximum deflection in (mm)
L	Support span in (mm)
d	Depth of the specimen (mm)

$E = \frac{\sigma}{\varepsilon}$

E	The young's modulus MPa
σ	The stress on the Specimen during the elastic stage (MPa)
ε	The strain of the Specimen in the elastic stage

Flexural Test

Introduction

After conducting the tensile test there was still information lacking, as a soft robotic receives loads in the transverse as well as the longitudinal direction of the part. The previous test provided insight in the material behavior of the composites when loaded in the longitudinal direction. The transverse direction however is relevant for bending purposes. This test aims at finding answers, on how the composites effect the bending behavior of the material. The hypothesis is yet again that the fibers effect the behavior. However, this time the influence of fibre-matrix bonding should be less noticeable, as the load isn't capable of dragging the fibers.

Apparatus, Specimens, Procedure

The apparatus used for this set-up is yet again a Zwick Z010 with the accompanied software. However, to accommodate the bending, a 3-point bending bridge was used and a load bar clamped into the Zwick.

The procedure for the creation of the samples was done in a similar way of that of the Tensile Stress test.

The procedure used for this test are in line with the ASTM D790 guidelines (ASTM, Standard Testing Methods for:, 2017). For the support span, the value was calculated once and used for all specimens. In addition the amount of specimens used for testing was again 5 instead of the prescribed 3. This has been done due to the big difference in quality of the specimens.

Calculation

Since the flexural test was only done up to a distance of 20mm, the stress strain curves of the specimen don't show much difference. The only exception is the curve of PLA which can be seen in figure 70. All the other specimens didn't receive a critical load thus the curvatures look very similar see figure 71. The non-continues nature of the lines is due to the silicone slipping over the connection points.
As a result of the limited loads, the values gathered for the stress and strain at the deflections are also not at the materials limits. This still allows for comparison of the measured values and the thereby relative increased or decreased stress, strain and modulus. In comparison to the tensile stress test, there are big notable differences for the material behavior.

For pure silicone the calculated maximum stress was 0.15MPa and the calculated strain at the maximum stress was 9,66%. All most all composites showed improvement in terms of strain. Only the TPU transverse composite (Si TT) performed worse. With a lower stress of 0.12MPa and strain of 9,41%.
Furthermore, there were three big noticeable to be seen in figure 72. The first one is the peak of the Crosslinked PLA (Si PC). This composite displays a maximum stress of 1.16MPa and a strain of 11,73% resulting in the highest Young's modulus calculated for this test. Also, it should be noted that these specimens all showed signs of permanent deformation after the test.

The material with the second largest Young's modulus is the Diagonal crosslinked version of the PLA composite (Si PD) with a maximum stress of 0.59MPa and a strain at the maximum stress of 10,65%. The other peak is that of the composite with PLA fibers in the Longitudinal direction (Si PL). Displaying the second highest value for the maximum stress with 0.96MPa and the highest strain of 14,12%. Resulting in the third best Young's modulus.

All the TPU composites show an increase in the maximum strain, with exception of the Transverse specimen (Si TT). Their maximum stress is in line with their pure silicone counterpart leaving them all with lower Young's modulus than the base material.

The findings are in line with the hypothesis that the fiber, matrix bonding is less relevant for these type of loads. Additionally, big differences in material behavior can be detected.

Figure 73: Photograph of the conducted Tensile Stress test

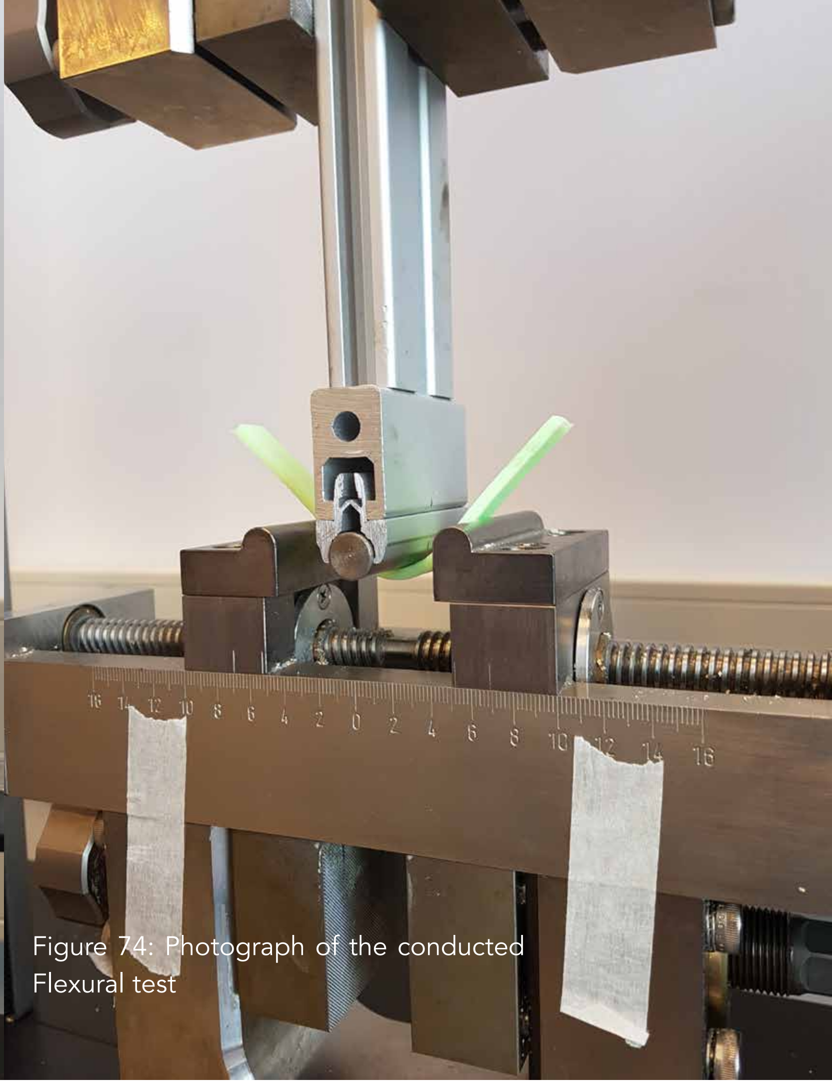


Figure 74: Photograph of the conducted Flexural test

Figure 75: Normalized overview table of the Tensile Stress and Flexural Test

	Stretch			**Bend**			High Bend Resist	High Bend Resist
Materiaal	*E(MPa)*	*σ(Mpa)*	*ε(%)*	*E(MPa)*	*σ(MPa)*	*ε(%)*	Low Elong resist	High Elong Resist
Si	0,00	0,05	1	0,06	0,08	0,57	0,0553	0,0554
Si PL	**0,0612**	**0,0494**	0,0108	0,0152	0,0890	1,0715	-0,0460	**0,0764**
Si PT	0,0002	0,0134	0,6540	0,0175	**0,0333**	0,4041	0,0174	0,0177
Si PC	0,0514	0,0195	**0,0000**	0,0104	**0,3296**	**3,1227**	-0,0410	0,0617
Si PD	0,0077	**0,0000**	0,0801	**0,0089**	0,1489	1,1492	0,0013	**0,0166**
Si TL	0,0001	0,0413	**0,8186**	0,0139	0,0438	0,3303	0,0138	0,0140
Si TT	**0,0000**	0,0108	0,5947	**0,0312**	0,0479	**0,2907**	**0,0312**	0,0312
Si TC	0,0001	0,0202	0,6409	0,0293	0,0894	0,4003	0,0292	0,0295
Si TD	0,0003	0,0199	0,5633	0,0278	0,0856	0,4128	0,0276	0,0281

Discussion

Normally a flexural test is conducted until there are signs of fracture, or until a maximum strain is achieved by 5%. This test hasn't been conducted in such a manner, as the displacement would be so little and would result in less reliable results. By pushing the extremely flexible materials further the difference became more visible.

Conclusion

To be able to apply the gathered knowledge of these composites an overview has been created in image . It is displaying the normalized values of all the tested specimens. By normalizing the values the changes of the material behavior from both tests can be compared to each other in order to pick materials with desired behaviors.The finding of this research is all in line with the hypothesis that the introduction of fibers into a silicone material provides a change in material behavior. With the overview created in image . It is possible to select specific composites for certain functions. In the case of a bending actuator, the most important factor is the strain. For the bottom layer, it is important to have a low value for the strain in both the stretch and bending direction. For the top layer, the stretching should be high while the bending should remain low as well. All the measurements and calculations can be found in Appendix 8.5 and 8.6

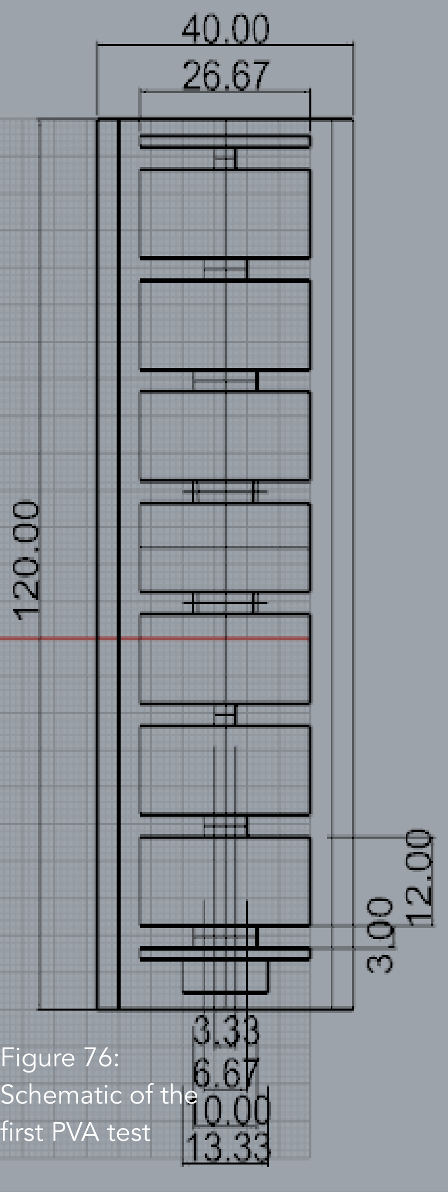


Figure 76:
Schematic of the first PVA test

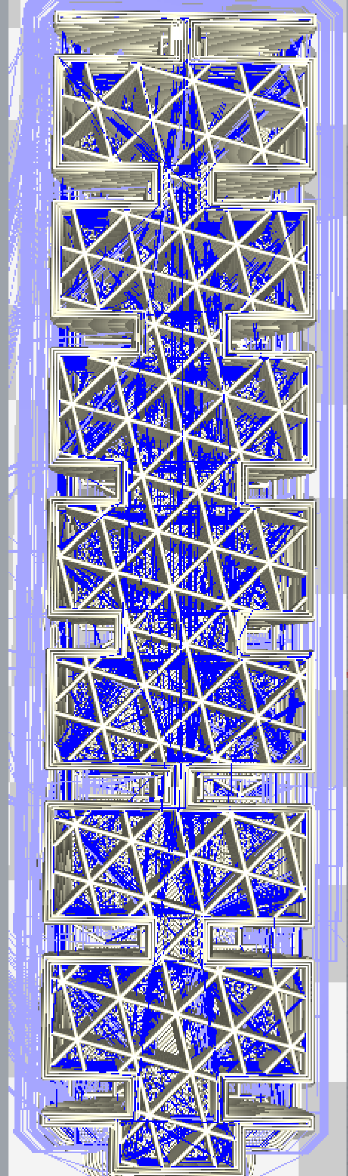


Figure 77:
Dissolve test sliced in Cura

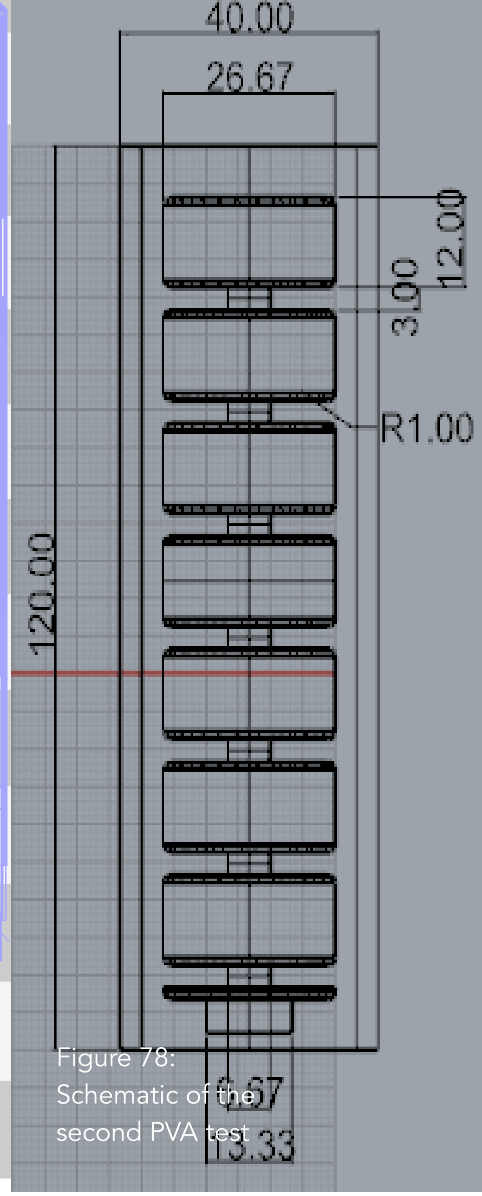


Figure 78:
Schematic of the second PVA test

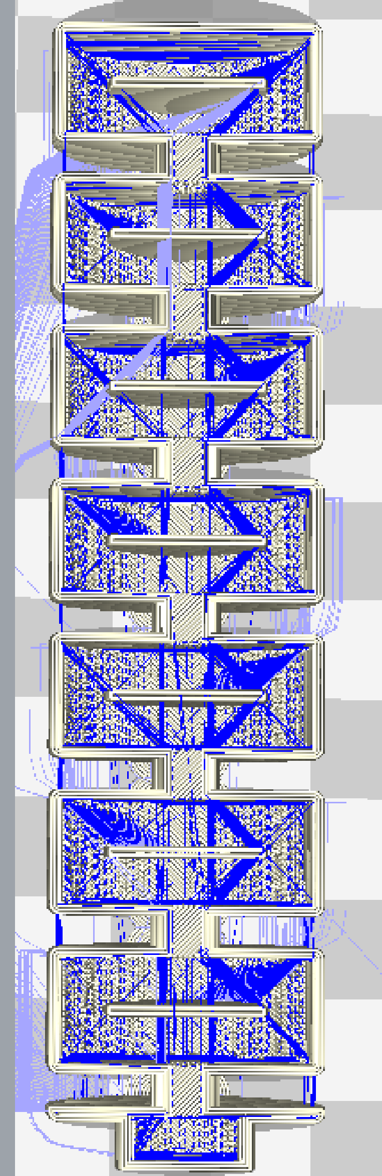


Figure 79:
Second dissolve test sliced in Cura

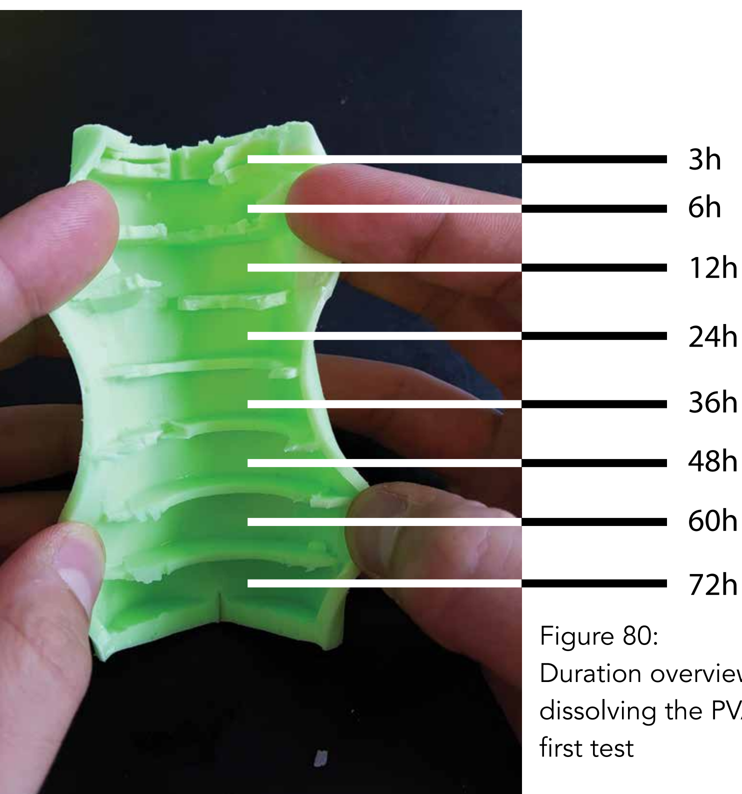


Figure 80:
Duration overview of dissolving the PVA for first test

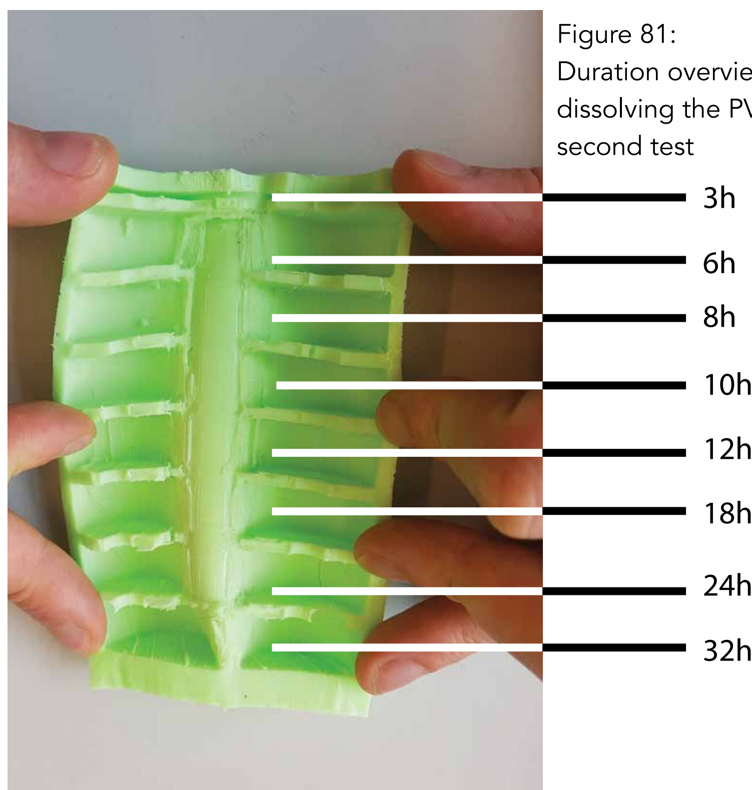


Figure 81:
Duration overview of dissolving the PVA fo second test

4.5 COMPLEX CAVITIES

Introduction

The final concept tested within this thesis is the usage of PVA for the creation of complex cavities. In theory, the PVA should be capable of creating the most elaborate and complex shapes within a part and still dissolve. However, this would require an undefined amount of time. To see if this assumption was right a test was conducted to verify this. The test also aimed at setting up guidelines to reduce the time that was required to dissolve the support material out of complex cavities. This is especially relevant for pneumatic actuators as they often rely on complex air bellows.

Specimens

For the test, a special bellow design was made. It can be seen in figure 76. The design consisted out of a 120mm long rod with staged alternating diameters ranging from 3.33mm up to 26.67mm. The outer shell was just a rod with a constant diameter of 33.33mm. Both parts had been printed separately in PVA. The slicing was done by Cura with a triangular infill for the rod of 20% see figure 77. After printing, the rod was inserted into the shell and liquid green silicone shore 30A was poured into the mold. After letting the silicone cure for 24 hours the specimen was ready for testing to see figure 82.

Procedure

The test was conducted by submerging the created part, including the mold, into a bucket of water. For the first 6 hours, the part was checked every hour to check the progress. After that, every 6 hours the part was checked, washed and massaged a bit to improve the dissolving.
Results

Results

After 72 hours the support material was fully dissolved. This is a relatively long time for the support material to dissolve it proves that the complexity of cavities shouldn't be a limitation when designing a part. The downside was that due to the massaging of the specimen some ruptures occurred within the specimen causing damage. The question is how well the support material would dissolve without massage the part so no internal damage is caused.

In order to reduce the time required for dissolving support material multiple hypotheses were formulated to test with a second specimen. The specimen was designed with a long rod with altering diameters like the previous specimen. However, the smaller diameter was kept at a constant value of 6.67mm. In addition, the edges were rounded off so the transitions would be more smooth allowing for a better flow around the rod. Also in the production procedure, some settings had changed in Cura. The support structure was changed to concentric, allowing the fluid to flow through the part. In addition, the infill was reduced to 10%. See figure 79. The resulting specimen was then treated the same way as the previous sample with one difference: instead of massaging the specimen, there was a flow created in the bucket with an air pump see image figure 83.

The result was a major improvement of the time it took to dissolve the support material. The previous specimen took 72 hours while this specimen only took 32 hours to fully dissolve. What should be noted was after opening some highly viscous fluid was still present in the corners. This might be the result of the rounded edges, as this locally increased the density of the support see figure 81.

Conclusion

This led to the following conclusions: The support material should have a geometry that allows the creation of a water flow within the part. Decreasing the infill lowers the time required to dissolve the support material. Adding rounded edges in a part doesn't decrease the time it takes for support to fully dissolve. Putting the printed mold in a bath with a continuous flow improves the rate at which the PVA dissolves.

Figure 82:
Finsihed test sample

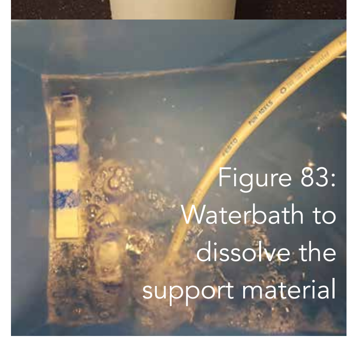


Figure 83:
Waterbath to dissolve the support material

Figure 84: Photograph of the conducted pull test

Figure 85: The silicone deforming out of the hard insert due to its deformation.

Figure 86: Plot of the stress required to pull out the insert vs the contact area

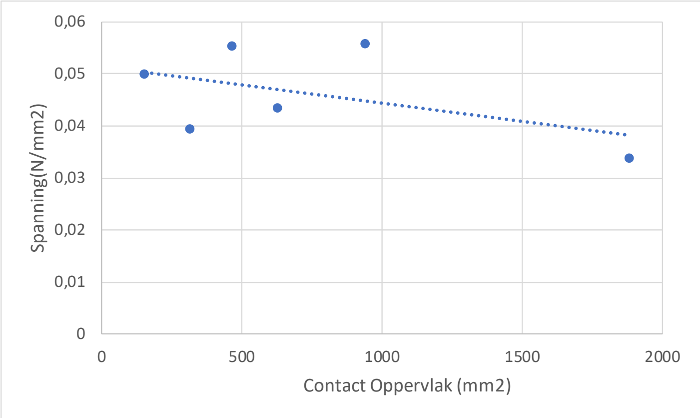


Figure 87: FBD of the forces on the hard insert

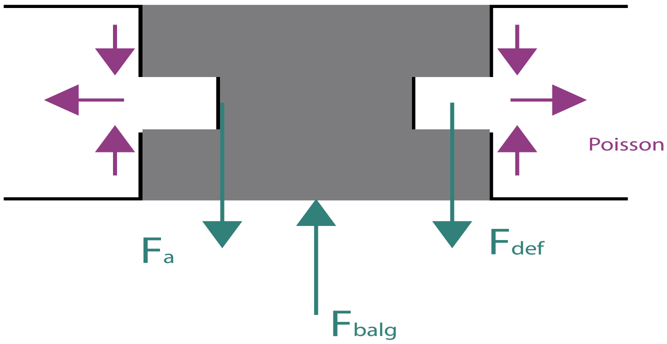


Figure 88: Table with surface area in contact with the silicone and calculation s made of the stress applied on the part.

Pully	**Area (mm²)**	**Area (m²)**	**Fmax(N)**	**Pi(N/m2)**	**Pi(N/mm2)**	
Klein K	152,32343	0,000152323	7,610057354	49959,86076	0,049959861	1
Middel K	314,159269	0,000314159	12,36421585	39356,52095	0,039356521	2
Groot K	628,318538	0,000628319	27,22224426	43325,54686	0,043325547	4
Klein G	466,48271	0,000466483	25,79207802	55290,53374	0,055290534	3
Middel G	942,477808	0,000942478	52,48603439	55689,41141	0,055689411	5
Groot G	1884,95562	0,001884956	63,70180511	33794,85673	0,033794857	6
Gemiddelde				**46236,12174**	**0,046236122**	
SD					*0,008121974*	

4.6 HARD INSERTS

Introduction

The second concept that would be further investigated was the usage of hard inserts. This concept has many applications as it allows the integration of components within a silicone matrix. For this project in specific, it could useful to create connections and seals with PLA that allow for reassembly of parts. As the silicone often wears out over time. In the preliminary tests, there was already shown that the bonding between, PLA and silicone isn't well as a result of the big difference in the elasticity modulus of the materials. By increasing the surface area this effect could be countered. The hypothesis was that embedding hard components is possible, as long as the load wasn't too high upon the insert and preferably the materials would have a matching elasticity modulus.

Pull Test

In the FBD of figure 87 is an overview of the acting forces upon a hard insert that is pressurized. The method used to determine the friction coefficient is by means of pulling a mass of a material over another surface with a spring-balance. The coefficient can then be easily calculated by dividing the mass of the block by the force required to move the mass. This method doesn't work for elastic materials. For inelastic materials, the actual surface area that is in contact with each other can be simplified to three points touching the surface. While an elastic material actually has more contact points and thus the contact surface area can't be neglected in the equation. Resulting in a way more complicated determination of the friction coefficient. To overcome this issue another test was conducted. Where printed parts with different measurement were inserted in uncured silicone and left to cure. After curing the parts were pulled out and the force required was measured. The hypothesis was that by increasing the surface area the required force would increase and an altering value of the required stress would be found. For this test, the Zwick 010 used to pull out the parts.

Specimens

In Rhino cylinders were designed with on top of the cylinder a grip on which the inserts could be pulled out. After designing the parts, they were printed with Ninjaflex. After printing, two component silicone was mixed and poured out over the specimens. After 24 hours of curing the parts were ready to be tested. The surface area in contact with the silicone is shown in figure 88.

The procedure used was clamping the block with silicone and insert into the Zwick at the bottom and in the upper clamp, the grip was clamped. When the part was fully clamped the grips would separate until the insert was fully pulled out of the silicone. The maximum force required to do so was measured. After measuring the maximum stress the part could take was calculated by dividing the maximum force with the surface area of the insert.

Results

When plotting the result of the test it was clear that there was no clear linear behavior for the required stress to pull out the insert and the surface area that was in contact with the part. However, all the values seemed to be close in range of one another. Therefore, the average value of the maximum stress has been calculated which was 0.046 N/mm² with a standard deviation of 0,008. For future calculations, the force that the part was capable of withstanding has been determined by the average value minus the standard deviation to be on the safe side.

To test this hypothesis a second insert was printed. This insert was calculated that it would withstand the force with an internal over pressure of 1 bar within the bellow. The formulas used for this calculation were:

$$\Sigma F=0$$
$$F_{(balg)}=-F_{(A)}-F_{(def)}$$
$$F_{(balg)}=P_{(balg)}*A_{(balg)}$$
$$F_{(A)}=\sigma_{gem}*A_{contact}$$
$$F_{(def)}=\sigma_{max}*A_{overlap}$$

Discussion and Conclusion

What should be noted in these equations was that the effect of the deformation of the silicone wasn't taken into account. During testing, the silicone deformed too much and started leaking air around the insert See figure 85. Although the insert wouldn't fully rupture out of the bellow at 1 bar over pressure. Therefore, the previously set-up guidelines didn't provide the hoped outcome. Requiring a redesign for the insert for the final demonstrator, that tries to decrease the deformation of the silicone around the part, and increases the contact area.

Criteria	Weight	Complex Cavities	Composites	Connections
Design Freedom	25	8	7	9
Interactive	20	6	5	6
Customize	20	8	9	9
Production Cost	15	8	8	8
Production Speed	10	6	8	8
Humanlike	5	8	6	4
Comformability	5	8	7	3
Total	100	740	720	790

Figure 89: Weighted improvements of the concepts on the soft robotic strengths

17

26

18

18

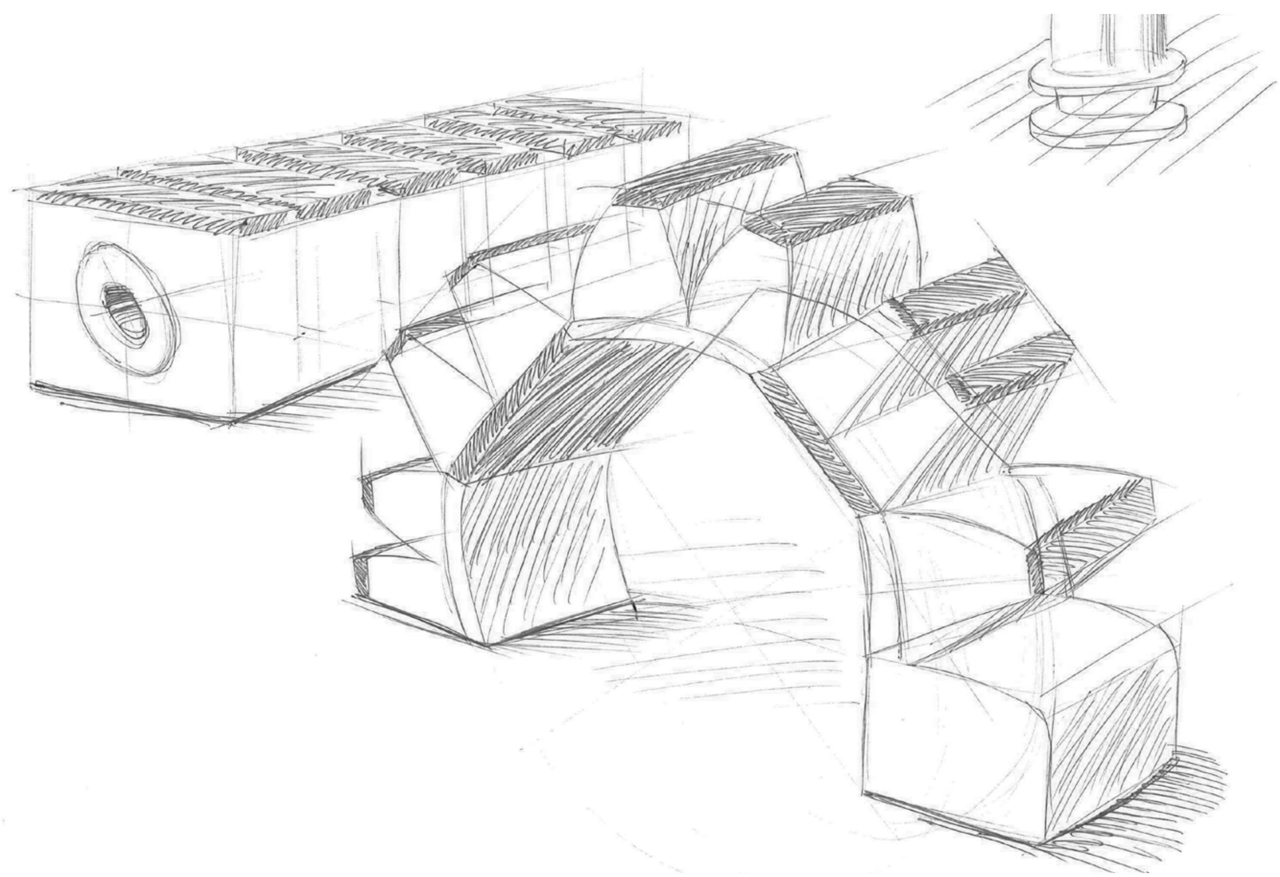


Figure 90: First sketch of the proposed demonstrator

4.7 DEMONSTRATOR

Selection Method

After the main concepts have been explored and some design guidelines had been set-up the next steps towards a demonstrator could be taken. In the chapter about possible applications for soft robotics, there are multiple possible applications that could be fullfilled by the demonstrator. However, not all of them would suit equally well as the concepts all contribute to the improvement of different factors. To make a good decision, the weighted criteria method results are again taken into account. This time, the improvement on each of the soft robotics aspects is looked at see figure 89.

The values attributed to the factors; Interactive, Customizability, Human likeliness and conformability have been added up to a final improvement score as the result of the applied concepts. It shows that with the incorporation of these concepts the customizability of the soft robotic parts is improved the most. Now that the improvement per aspect has gained value, the total increased value for certain applications can be calculated.

Conclusion

After evaluation, the groups Prosthetics, Orthosis, and Human Simulation robots would benefit the most of applying these concepts. Therefore it would make sense to choose a final demonstrator which would also fit within one of these groups. Besides the found application areas a new opportunity were also found during the course of this project. Conveying the possibilities and applications of soft robotics to other people is a hard task. This is the result of a lack of understanding. Designing a demonstrator that allows people that are not familiar with soft robotics to learn the basics could also be a valuable application.

Eventually there has been chosen to further develop a demonstrator that could function as both a prosthetic as well as an orthosis: namely a pneumatic bending actuator. There has been chosen not to further develop a human simulations robot and a learning kit as this would be too elaborate to fit within the time span for this project. Also making use of a new pneumatic bending actuator would allow for a final comparison between the original bending actuators and the newly created one with the set-up.

Field of Application

The proposed demonstrator is a pneumatic bending actuator that was created in an automated production process with the new MultiCast. This allowed the incorporation of hard inserts which allowed for a reliable and easy (dis) assembly of the actuator to its pneumatic source or other parts. Additionally, the behavior would be manipulated with composites to create anisotropic behavior of the part. The first rough sketch of the part can is shown in figure 90.

The anisotropic behavior is a valuable addition to the current pneumatic bending actuator as it allows the mimicry of the knuckles in a finger. In contrast to the current fingers that follow a continuous curvature as a result of their isotropic behavior. This allows the creating a more realistic approximation of a human hand that grasps around an object. The benefits of such an actuator not only creates a more realistic approximation of the human finger but also allows grippers to grasp objects that require more clamping than the current bending actuators can provide.

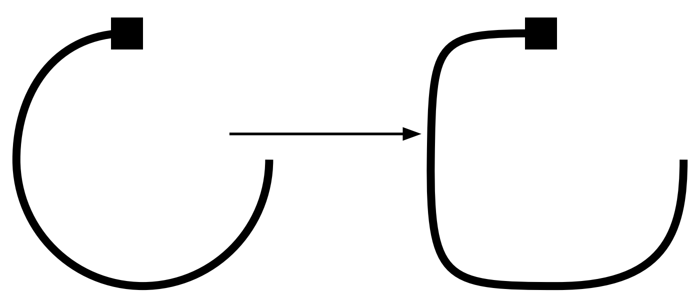


Figure 91: Schematic representation of the anisotropic bending behavior

5.0 INTRODUCTION

This section contains the last steps taken in this project. First off the demonstrator was designed in more detail. A choice has been made in regards to the size, and type of the insert required to fulfill its function. Secondly, the fiber types used within the part and their positioning are elaborated on.

After the design, the production process is explained. Providing insights of what steps have to be taken in order to reproduce the parts made. Also, it can be used as a basis for creating new prints.

The next chapters contain optimization steps. For the set-up, this meant mainly the improvement of the adhesion of the next layers on top of the silicone. While for the demonstrator some adoptions had to be done in the redesign.

This section closes with a nice overview of the final demonstrator created for this project.

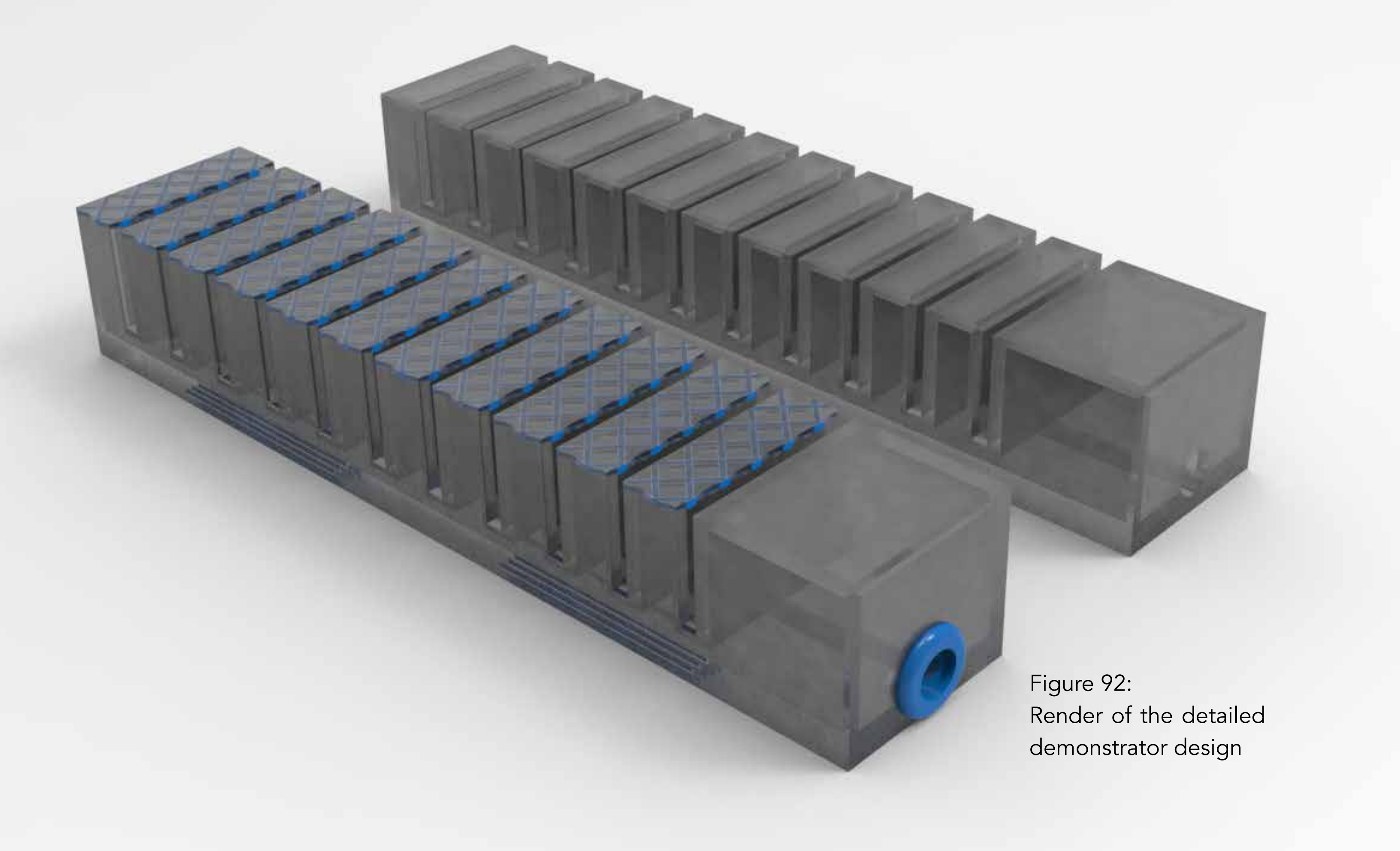


Figure 92:
Render of the detailed demonstrator design

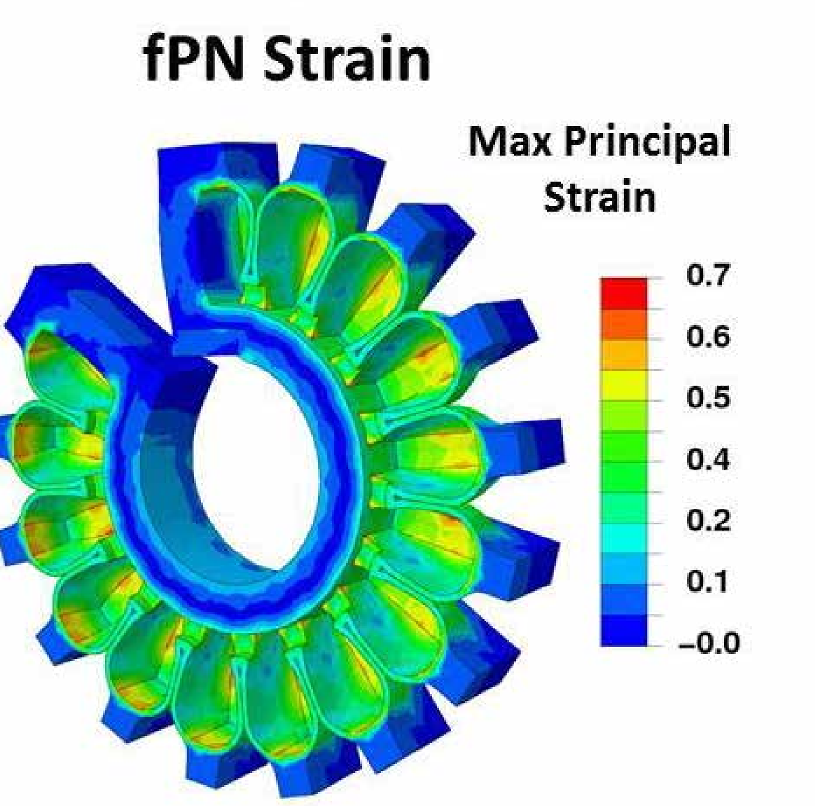


Figure 93:
Stress induced on a pneumatic bending actuator as a result from internal air pressure. Polygerinos 2013

Figure 94:
Overview of the support build up for round and square shapes

5.1 DEMONSTRATOR DESIGN

In chapter 4.7 a quick introduction to the demonstrator has already been given. This chapter explains the reasoning behind the design and will provide more details on the design.

Main geometry

First off, the shape of the demonstrator is squared and composed out of hard edges. This has multiple reasons. The first reason is the result of the conclusion of chapter 4.5. Rounded corners for the support material would leave a viscous paste. The second reason is that making rounded shapes with silicone as support material requires multiple casting operations after one and another in order to support the layers see image Figure 94. Making the production process more complicated. Finally embedding the fibers would also become more complicated as it would require bent fibers, of which the effects and the production haven't been investigated during this project.

Main material

For the production of the demonstrator, transparant silicone has been used. By doing so the inserts and fibers stand out. Thereby putting the emphasis on the extended capabilities of the MultiCast.

Composites used

The fiber reinforcement has been placed in the positions that require the strain limiting the most. At the top of the air chambers of the pneumatic actuator and at the bottom of the actuator. As shown in figure 93 these positions required the most strain limiting. However, the fibers used on the top and bottom are not the same.

The fibers at the top of the air chamber should allow the chamber to elongate while preventing the air chamber to expand in the top direct (expanding). By doing so the pneumatic actuator would increase in length more, without having to add more silicone on top of the finger to accomplish the same behavior. From the table in chapter 4.4 can be found that the composite with PLA fibers in the longitudinal directions is the most suitable. So the top of the air chambers has been covered with PLA fibers which are positioned in the same directions as the bending direction.

The fibers positioned in the strain limiting layer had a different purpose than that of the fibers at the top of the air chambers. Not only was the elongation in the longitudinal direction limited to enhance the bending. Also, the bending was limited to locally create a stiffer part. Resulting in a more human like finger. To accommodate this the most suitable fiber composite would be PLA fibers crosslinked in a diagonal direction. As shown in the table of chapter 4.4.

Hard Insert

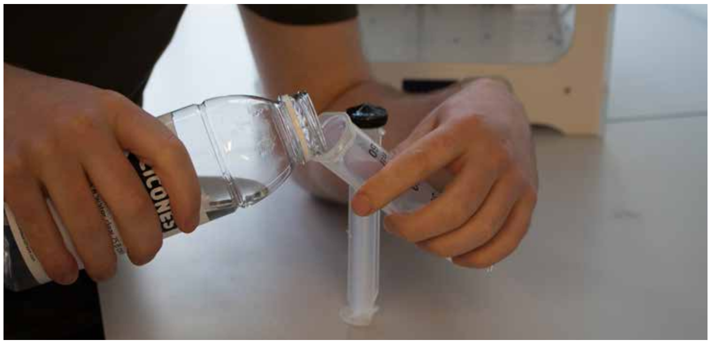
Silicone actuators are prone to rupture as a result of wear of connecting them to different air inlets. To prevent this from happening the air inlet is improved by creating a stationary insert. All the friction and insertion force of a new air connection is on the insert. By designing the hard insert in such a manner that there is a lot of contact area between the insert and silicone. The forces can be better absorbed by the silicone part. To create the best adhesion between the silicone this part is preferably made from TPU. In the demonstrator design, this part has been made from PLA. This has two main reasons.

The first reason being that the composites need to be produced from PLA, and the set-up is limited to using only three materials. Of which the PVA and Silicone are already in use. It would have been possible to switch materials midway to TPU with a material change and increasing the nozzle temperature. But since there are a few layers that require printing both fibers and insert makes this impossible.

The second reason for not printing the part out of TPU is the reliability of the set-up. As mentioned in chapter 3.3.2 the feeder can still buckle the TPU preventing it from extruding. Leaving the 12-hour print a failure.

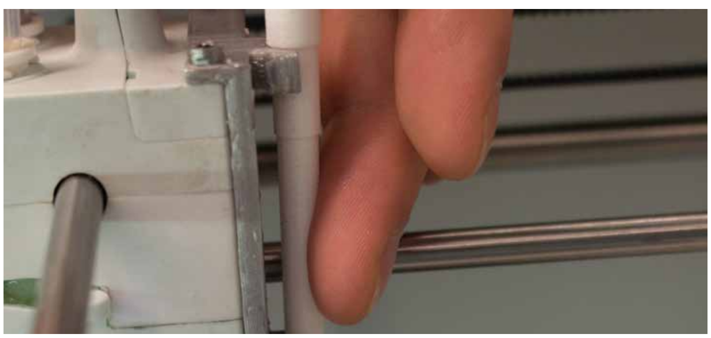
It should be noted that the usage of PLA instead of TPU would decrease the bonding of the insert with the Silicone. The effects of this have been evaluated in chapter 6.3.

5.2 PRODUCTION PROCESS

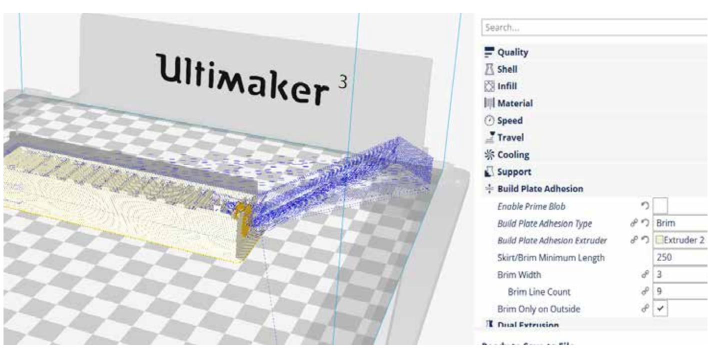


Step 1: Load the Silicone in the Ulticast. The easiest way to do so is by removing the syringes and pour in the compounds. While in the mean while returning the pushing rods to their starting positions

Step 2: Mount the tubes to the nozzle. Slide the A and B tubes over the two ends of the nozzle.



Step 3: Mount the nozzle on the printhead. This is mounted to the back and can be easily clicked in.



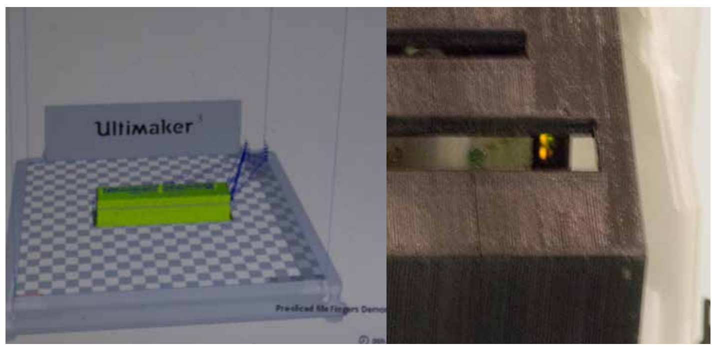
Step 4: Slice the part for production. This can be done like normal in Cura.

```
T1

G0 Z70
G1 F1500 E48
M104 T1 S100
M190 S40

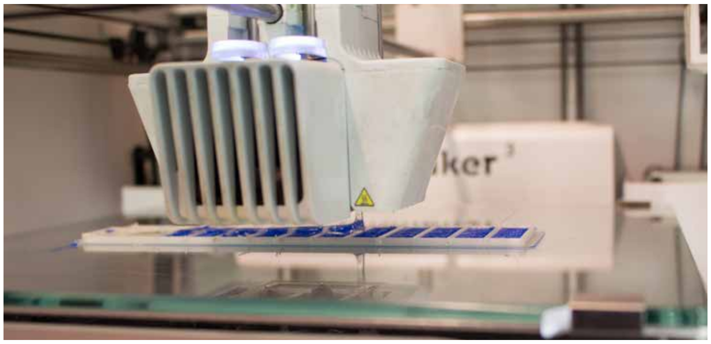
;priming
G92 A0 B0
G0 F5000 Z100
G0 F5000 X175 Y25
M107
M400
G111 A-20 B-20 F25
M400
G4 P10000
;priming
```

Step 5: Edit the g-code to insert the casting commands. The command for casting is G111 where the A and B compounds can be controlled with A-XX and B-XX for extruding materials. positive values retract material. The position of the nozzle in the X-direction is in line with that of the T1 nozzle thus is the easiest to start the code with. The Y-offset is 40mm.

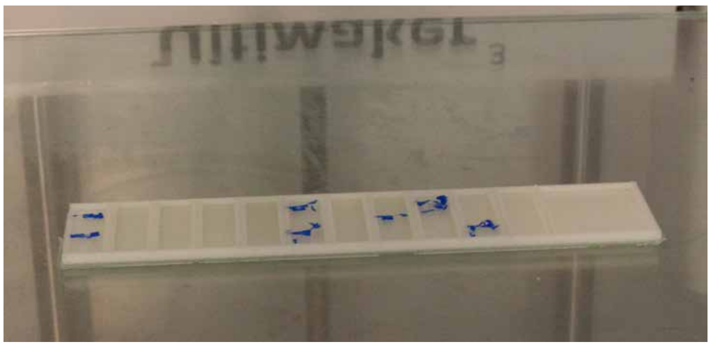


Step 6: Load the edited code to the printer. G-code can be directly loaded in Cura and previewed, however not edited. When doing so make sure that the orange light is blinking, which indicates that the Ulticast Set-up is linked with the Ultimaker. Start the print like a normal print, and wait for the casting part to commence.

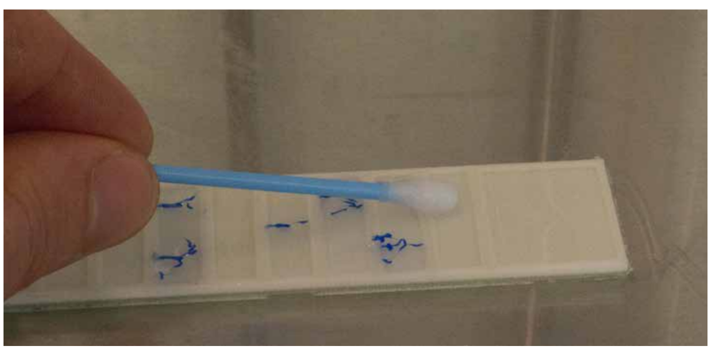
Step 7: Prime the nozzle. This part is already incorporated in the code. However, it can be handy to place a cup under the priming position to prevent silicone pouring over the entire print bed. In Appendix 8.7 is an example of a full casting cycle. While priming the nozzle it is recommended to decrease the temperature of the print bed to 30 degrees to prevent the silicone from curing while casting.



Step 8: Cast the silicone in the printed mold. If the code is written correctly. This process should be automated.

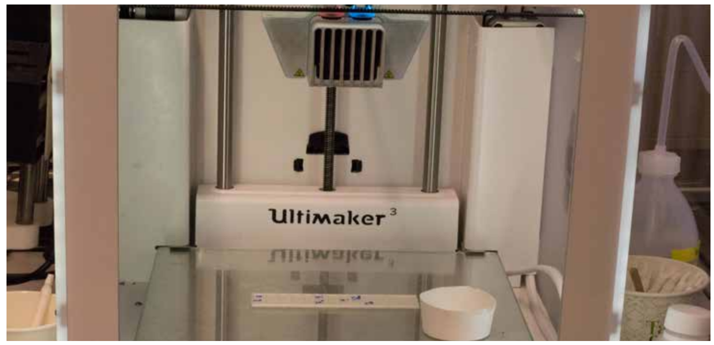


Step 9: Wait to let the silicone cure. To reduce the curing time the print bed should be heated back up again. The used silicone for the demonstrator needed 10minutes to cure. To implement this waiting time a pause command can be added in the code or the printer can be paused manually.

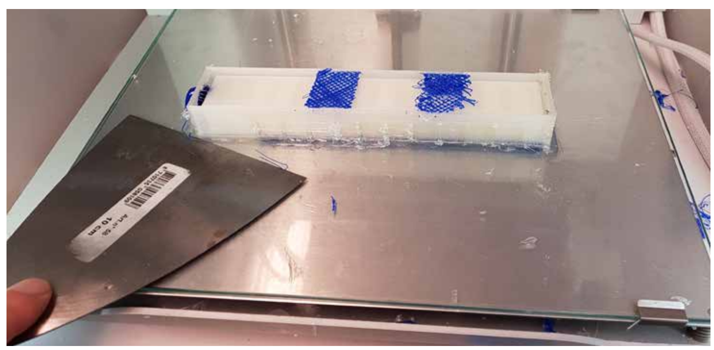


Step 10: Prime the cured silicone with the silicone primer. This should be done manually with a small cotton stick. After 15 minutes the primer is cured enough to print over it. If the primer is on the silicone for longer than 30 minutes it doesn't work properly anymore.

Step 11: Continue the printing process. Depending on the way the pause was introduced this is automated.



Step 12: If needed repeat steps 7 up until 10 until the part is finished. If the time between second casts is over 1.5 hour. it is recommended to replace the nozzle with the help of steps 2 and 3. To prevent clogging of the nozzle due to the cured silicone.



Step 13: Remove the final product from the printing bed and place it in a water bath to dissolve the support material.

Figure 95:
Overview of heat exchanges for the silicone during a print

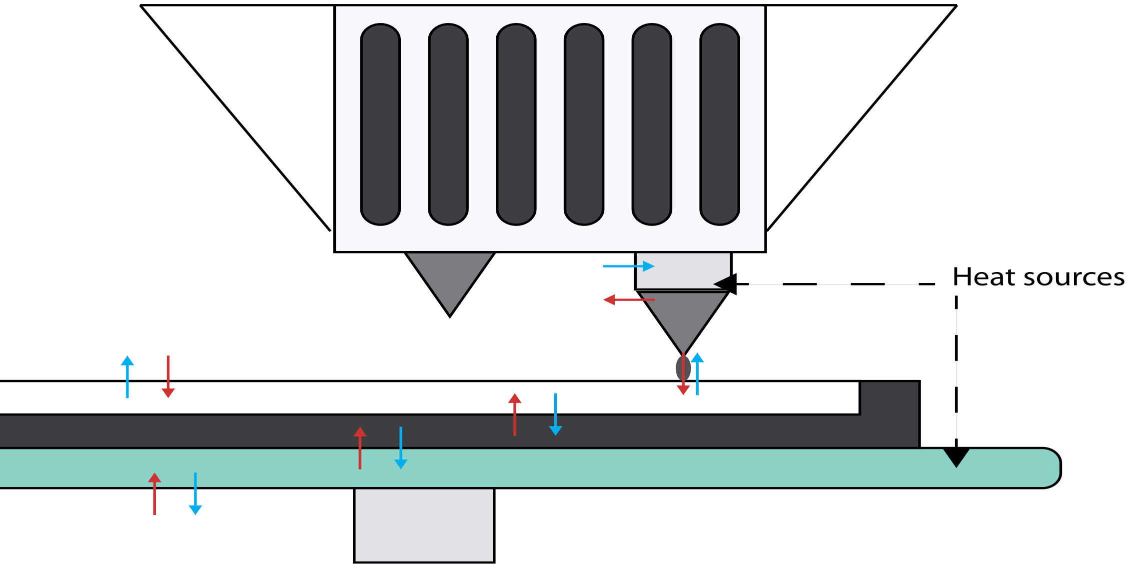


Figure 95:
Overview of heat exchanges for the silicone during a print

Figure 96:
Test for printing PVA and PLA in curing silicone

Figure 97:
Test for the bonding of PVA on hardened silicone after several surfacetreatments

5.3 PRODUCTION OPTIMIZATION

During the production process of the demonstrator, several flaws appeared in regards to the production process. This chapter will focus on the flaws in the production process and will try to elaborate on the solutions if they were found.

Sticking the first layer of Silicone

The biggest issue that arose was the continuation of the print on top of the silicone. During the first printing tests, it succeeded multiple times. There are many influential factors that affect whether the newly extruded material will stick to the silicone. So during the testing, in a relatively short time, the ideal circumstances had been achieved. However, it was over looked how complex this process could turn out.

So why did it succeed the first time? In the first tests, the ideal viscosity was achieved by letting the additive silicone cure up to the ideal point. When this was achieved, the new layer was printed on top of the silicone. Resulting in a well-bonded print with a messy first layer, which would be compensated in the following layers. To achieve this ideal point, only little was needed since the dragon skin shore 2A silicone would be hardened within 12 minutes. This wasn't the case for the green and transparent additive silicones. The green silicone required 6 hours to harden and the transparent needed 20 hours.

To speed up this process the reaction rate could be increased by increasing the temperature of the silicone mixture. As a result, the hardening times could be reduced to less than 10 minutes. This also had a downside. By increasing the temperature the reaction rate would be increased in such a manner, that when the temperature would be lowered, later on, it wouldn't have an impact on the reaction rate anymore. Resulting in curing times which were hard to estimate.

The second problem was that the heat transfer to the silicone was also different for every part designed. The heat is transferred from the heat bed to the PVA mold on to the silicone. So the mold size and thickness would also impact the rate at which the heat would be transferred to the silicone. Additionally, for casts conducted at a higher level, the heat transfer of all previous layers and materials need to be taken into account. Finally, the nozzle which extrudes the material also is a source of heat. Causing local heating on the parts as well. Which effects locally the curing time. An overview of all the influential factors can be seen in figure 95:

It can be concluded that in theory and practices it actually is possible to print on top of silicone as shown in figure 96. However, since there are so many variables that have to be taken into account it is very hard to set-up standard guidelines or rules for printing on top of silicone. Every part needs to be calculated and tweaked on its own.

To overcome this issue, alternatives have been looked after. It would be preferable to print on top of hardened silicone. As it was easy to let it cure quickly. In addition, most silicones stick well to previously cast and hardened silicones. To find out what would work the best for printing on top of hardened silicone some tests were conducted. The results can be seen in figure 97.

Printing on top of hardened silicone didn't work as the printed first layers wouldn't stick resulting in a PVA mess. Sanding the surface showed some improvement but not enough to be feasible.

Putting the first layer of printed PVA on top of the hardened silicone resulted in a better adhesion. However, the friction between the first layer and silicone was too low. Resulting in the print being dragged over the silicone. To over come this issue the first layer was put into hardening silicone. The result was a better print. The only downside was that the mold would move around the print bed as the friction of the mold on the build plate turned out to be too low.

The solutions that showed the most promise were glue and primer. Both resulting in well-printed models on top of the silicone without any movement, resulting in successful prints. The difference between primer and glue was that glue wouldn't stick only improve the friction, where the primer would bond the surfaces together. Therefore this problem has been solved by putting primer on top of every layer of hardened silicone.

Figure 98:
Photograph of a test print with spilled silicone and badly bridging fibers

Early end-stop issues.
While switching materials the printer wasn't capable of running all the way back to pull the lever of the BB-core. This was the result of the early end-stop installed to prevent collisions with the rear mount of the nozzle and the printer casing. To solve this issue an extra bracket was printed and mounted parallel to the other bracket. Allowing the printhead to be shifted while still being able to pull the lever.

While printing parts there was always a shift in the first layer. As the firmware wasn't adjusted to accommodate this change. The printhead would collide with the webcam mount in front of the printer when switching to PVA filament. To overcome this layer shift the webcam mounting has been removed solving the issue.

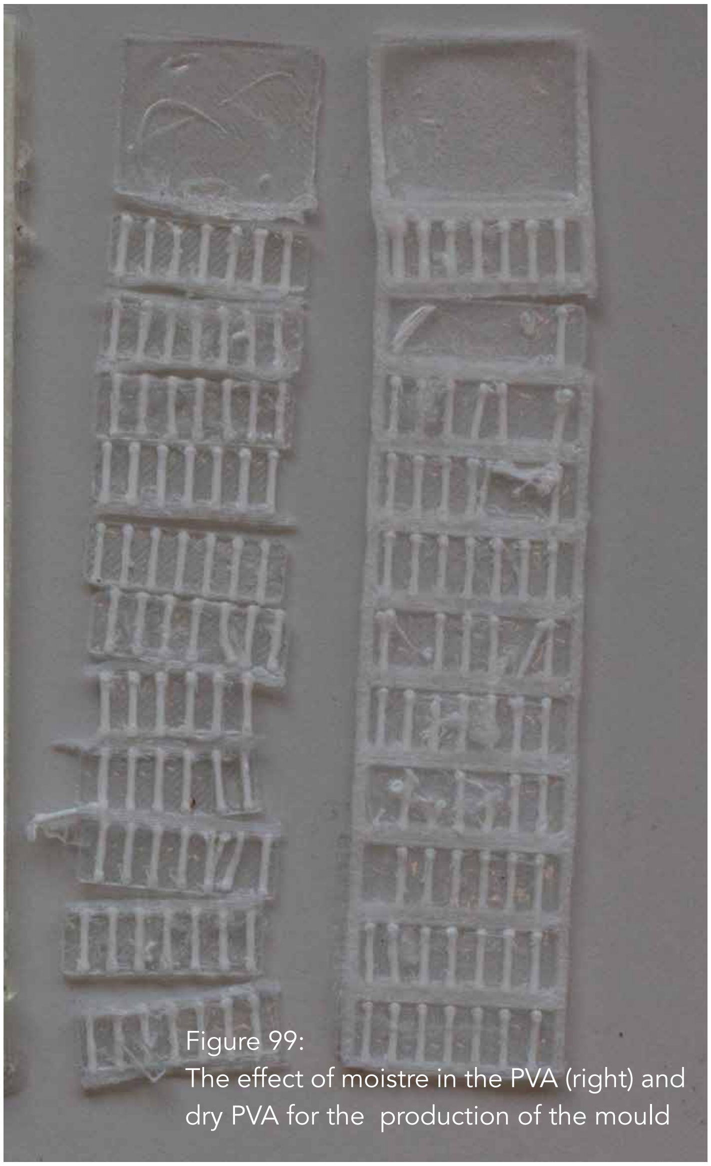


Figure 99:
The effect of moistre in the PVA (right) and dry PVA for the production of the mould

Silicone Extrusion Control

Another big issue that arose during the production process, even after solving the biggest adhesion issues, was the control over the amount of deposited silicone. This was a big issue as the deposited volume inside the mold would directly influence the layer height of the silicone. Additionally, unintended spills of silicone on top of printed layers would ruin the adhesion of future layers deposited on top of it.

The reason for this issue is the high viscosity of the silicone used. The high viscosity causes a delay in the pumping system. So pressurizing the system firstly results in pressurized silicone within the tubes. When the maximum pressure is achieved to push the silicone through it starts flowing. The same thing happens when retracting the silicone resulting in delays in the system.

For big casting operations, this isn't much of an issue as the delay only affects a small portion of the extruded volume. For small volumes the issue becomes more significant. The number of steps needed for the extrusion of 1ml can be found in Appendix 8.8.

To solve these issues two solutions have been applied. The first solution is increasing the amount of volume that is used to prime the nozzle and to retract the silicone from the nozzle. By doing so the delay would be reduced when the real casting operations would commence. It is worth to note that retraction shouldn't be increased to much as it could result in mixed silicone running up in the A and B tubes clogging them.

The second solution was to merge multiple mini casting operations together decreasing the extrusion delay even more. The downside of this was that sometimes silicone would be poured over the mold leaving a thin layer of silicone. The best way to work around this was to prime this silicone as well and remove this thin layer in the final product.

All in all, this solution improved the control over the volume. However, the issue still isn't fully solved the impact has only been reduced.

Low-Quality Molds

During the printing of the molds, there was a difference in quality to be noted. Sometimes the density was higher than in previous prints. This had all to do with the amount of moist within the PVA.

If there was moist in the PVA it would evaporate during extrusion resulting in a porous layer which would, in turn, create a porous mold, allowing the silicone go towards unintended areas.

To overcome this the PVA was put in an oven at 60 degrees Celsius over the course of 6 hours evaporating all the excess moisture. By drying the filament, silicone tight molds could be created. It is advised to give the PVA such a treatment after every print and store it preferable in a vacuum bag to prevent it from becoming moist again.

Bridging

To reduce the amount of casting operations, there has been chosen to make use of bridging the fibers over the mold. The issue that arose with the bridging of the fibers, was a lack of adhesion and the fibers leaning on the bottom of the mold. To over come these issues a mesh overlap was applied and the retraction for PLA was turned off. Additionally, the print temperature and speed were lowered. Resulting in a higher quality of fibers through the part.

Synchronisation

The final issue that needs to be addressed is the loss of synchronization of the Ulticast set-up with the Ultimaker 3. Resulting in the print performing only the movements, but not the casting operations, potentially failing a print.

To prevent this from happening, the casting times needed to be calculated. Around those times the printer needed to be attended to check the synchronization. If it was lost the printer needed to be turned off during the casting operations and rebooted. Regaining the synchronization. In order to complete the print the code needed to be reloaded to the printer, but starting from the casting operation.

During the project, it was unclear why the synchronization was lost from time to time. There were no clear correlations identified. Lars Rossing reported that is set-up at Ultimaker tended to do the same and was hoping to solve this issue in a future Firmware update.

Figure 100:
Different hard insert designs

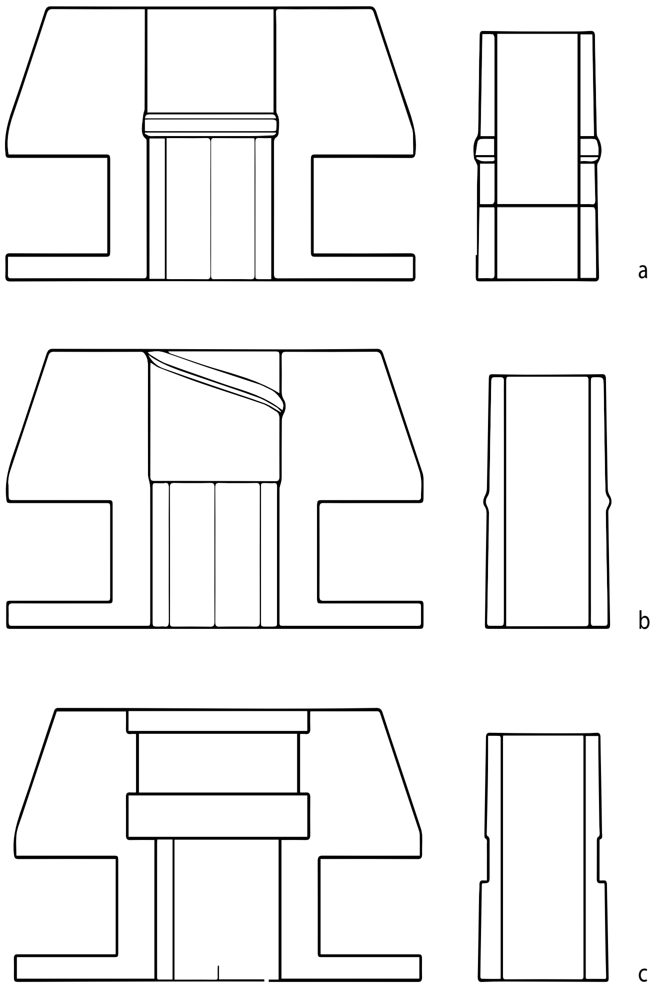


Figure 101:
Iterations made for the actuators from top to bottom: First to small, second no hard insert, third PVA not dissolving, fourth wrong PVA, fith hand casted.

Figure 102:
Hard insert prototypes

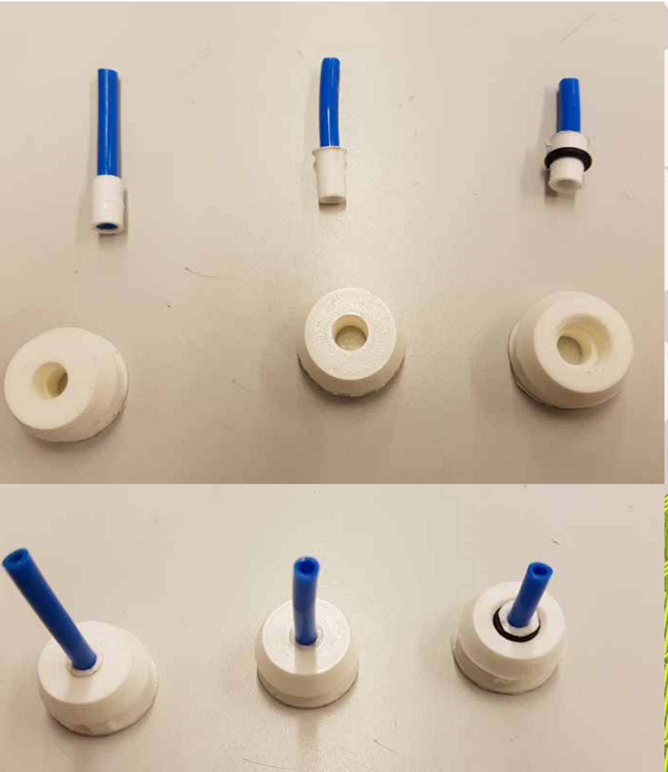
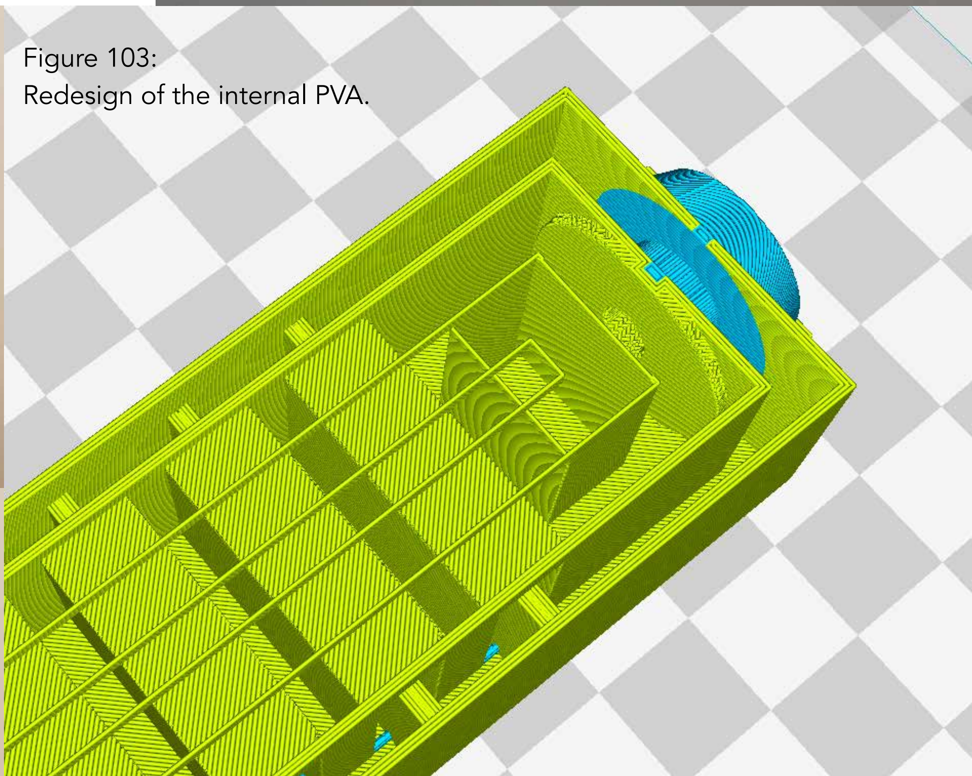


Figure 103:
Redesign of the internal PVA.



5.4 DESIGN OPTIMIZATION

During the production and testing of the Pneumatic Actuator, several issues arose. This chapter will discuss the issues and solutions that have been found during the design process.

Size

One of the first issues that arose during the production process, was the quality of the printed molds. Due to the small size of the casted parts they where of low quality. This was the result of an oozing nozzle. In addition, the small sizes led to narrow cavities which made it a lot harder for the PVA to dissolve as only limited amounts of water could enter the part.

By increasing the size of the actuator the negative effects of oozing PVA was overcome. It also resulted in a mold where the internal system would dissolve slightly better. In addition, to solve these issues it also made it easier for the printer to bridge the fibers as the bridging movement was more of a continuous movement.

Support Design

As indicated in the previous section the issues of the support material, not fully dissolving was solved only up to a limited extent. To make further improvements the support was sliced in such a manner, that once the first membrane was dissolved, water could flood the entire part in one go. As can be seen in image Figure 103.

Hard Insert Design

The part of the Pneumatic actuator that has seen the biggest changes is the hard insert, which is positioned at the front. The original design was only created with the idea in mind of reinforcing the connection. However, as a result, the art plastic part lead to air leakage. To get the most out of this insert a redesign has been made, that would also make the connections more flexible.

The key criteria for creating the hard insert where the following:

- The insert should be re-attachable.
- The insert should be air-tight.
- The insert should prevent the silicone from rupturing as a result of the mounting forces.

The considered designs are shown in Image Figure 100.

Type A) makes use of a snap fit. The advantage of this part is that it is fully 3D-printed and is a reliable way of mounting and dismounting a part.

Type B) makes use of a bayonet mount. Also, this design can be fully 3D-printed. The benefits of such a mounting type are that the amount of force required to mount the part is less.

Type C) is a snap fit where the snapping finger is a rubber seal. This rubber ring is mounted on top of the male part of the connection. The advantage of this connection is that it is fully air tight.

All types have been tested and evaluated by means of a prototype. The mount used for the latest iteration of the pneumatic actuator was type C.

During the testing, there was concluded that the force of making the connection, might negatively influence the bonding of the silicone with the insert. To improve this bonding the wall thickness at the connection was increased. Hoping to decrease the deformation of the silicone around the part and increasing the frictional forces.

Iterations

As a result of the issues, with the printer and support material not dissolving inside the actuator. Only 3 iterations have been made. An overview of the itterations is shown in figure 101. The final iteration has been evaluated in chapter 6.3.

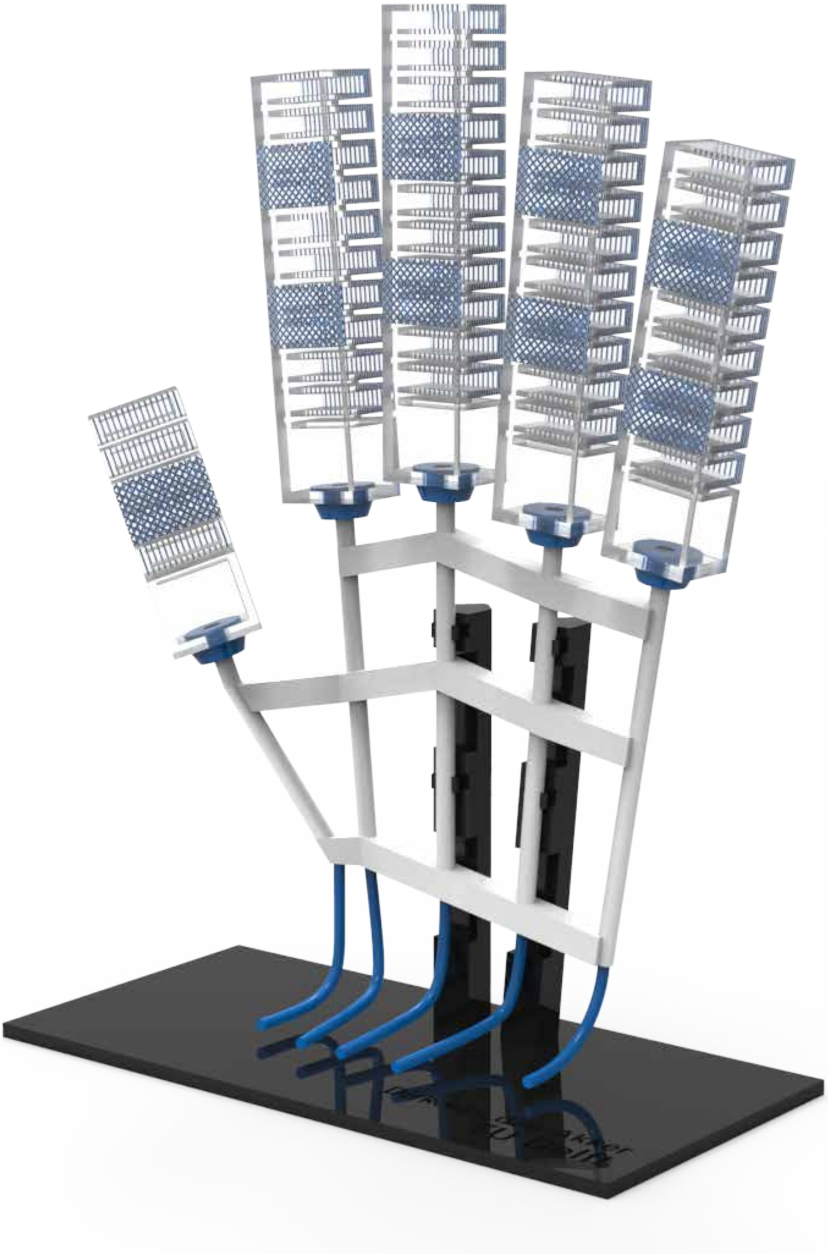


Figure 104:
Soft Robotic Hand Design

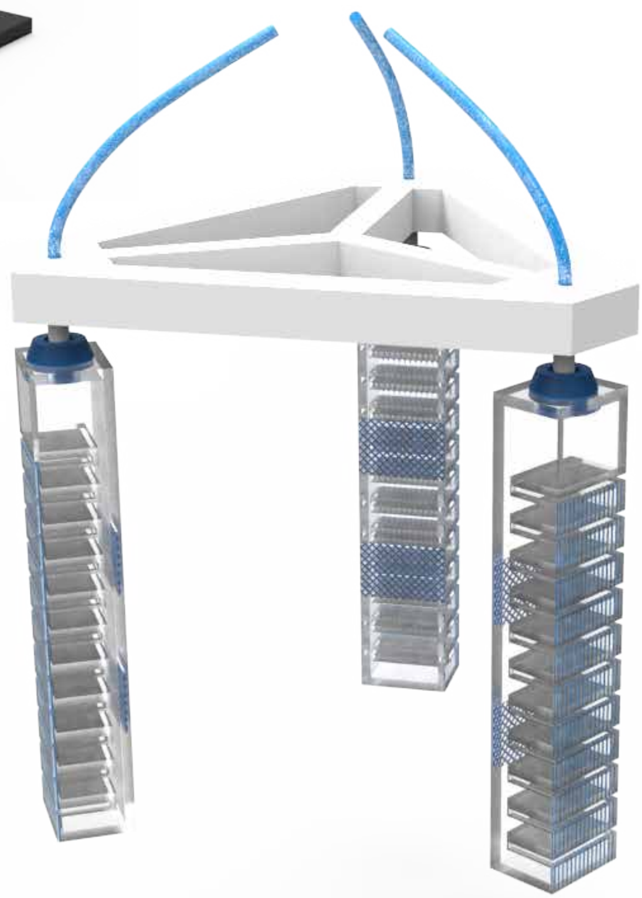


Figure 105:
Soft Robotic Gripper Design

5.3 FINAL DESIGN

On its own, the Pneumatic Actuator isn't interesting to look at or to show its capabilities. To make the newly designed actuator stand out two mounting types have been designed. The mount gives the bending actuator a function. Raising the part to a functional product.

There has been chosen to design two mounting types in order to demonstrate the added flexibility of the actuators as a result of the hard inserts with integrated snap fits.

Hand

One of the designs created is a Pneumatic Hand. This is the main design. The design has been made in such a manner that the focus is on the actuators. This is achieved by creating a simple, transparent frame. The basis of the frame is the hard inserts. They connect to the pneumatic actuators providing the pressurized air. To draw the suggestion of a hand the top and bottom bars are added. Serving a double function both closing the shape visually as well as providing stiffness to the frame and keeping the tubes in place.

As can be seen in figure 104. The finger has also been altered in size to accommodate a more realistic representation of the used fingers. The number of chambers has been reduced, and where required the layers have been shifted in position.

By pressurizing the chambers movements could be made, allowing the hand to perform simple tasks. There can be thought of movements like waving, grasping and crawling. Although this would require some extra research in solenoid valves and programming them. This is beyond the scope of this project.

The hand on its own would not be interesting being placed upon a table. To make the hand more interesting to look at when in rest, a complementary plinth has been designed. This plinth is equipped with four snap fits, grasping the back of the hand to keep it in place.

Gripper

The second design created is that of a gripper. This gripper is basically a triangular frame. This frame has room to mount three pneumatic actuators on. The purpose of this design is mainly to show the flexibility and the possible applications a pneumatic actuator could serve. Again the frame is designed based upon a framework and kept as simple as possible. Allowing the beholder to focus upon the pneumatic actuators.

6.0 INTRODUCTION

This final chapter evaluates both the final production set-up as well as the demonstrator. First, the production set-up will be discussed. The up and downsides will be discussed of the set-up and a comparison shall be made with the previously available production methods. Additionally, the final advantages and disadvantages are summed up.

After the production set-up, the demonstrator will be evaluated. How did all the concept perform within the pneumatic actuator? And how did the demonstrator perform compared to a normal pneumatic bending actuator?

After the parts have been evaluated future recommendations will be provided for both the demonstrator as well as the production set-up.

Since this set-up has many applications that couldn't be explored during this project. Further research is needed. In addition to the exploration of other applications, that set-up would also benefit from improvements. Therefore a roadmap has been created to provide some guidance for future projects with this hybrid manufacturing set-up.

This chapter closes with an evaluation of the entire project.

6.1 SET-UP EVALUATION

The goal of this project was to develop a hybrid manufacturing system that would be a feasible alternative to the current production methods of soft robotic parts. To determine the success of the current production system the manufacturing system has been evaluated using the criteria used in chapter 2.1. See Figure 106.

In terms of production speed, the set-up performs like the hand casting process. This is the result of the combination of production methods used. The printing of the mold takes just as long as it would for the hand cast. In addition, there are more waiting themes introduced in order to print on top of the hardened silicone. Finally, the time required to dissolve the PVA adds also a lot of production time.

Although the time required has increased a lot the intensity for the e production steps has decreased. The actions required are only 5 minutes at set times. Also, the dissolving of the PVA requires little intervention simply because this doesn't increase the speed that much.

With the new set-up, a whole array of new possibilities opens up for the field of soft robotics. In addition, all previously constructed shapes can be created. Making the MultiCast the best production set-up for design freedom.

The material used in the MultiCast is also silicone with local reinforcements of PLA. This didn't have a negative effect on the durability of the parts compared to hand casted parts. Leaving them at a tie.

In terms of Material Flexibility, there hasn't much changed either. Of course, there can be stated that at some points the material loses flexibiit due to the fibers. However, this is intended to alter the behaviour.

Finally, the production cost of the part is relatively low as it uses normal base compounds. However, it is more expensive than FDM as it requires more different materials. Also, it is slightly more expensive in terms of materials than hand casting, however this balances out at the labor costs which should be lower for this kind of parts.

In conclusion, there can be stated that the MultiCast shows great promise for the development of soft robotic parts. The material properties combined with the form freedom make it a viable production method. However, the production speed and intensity should be improved in further development steps.

Over the course of this project, the set-up has seen several changes, as has been documented in chapter 3.3.4. The final set-up used during the creation and development of the demonstrator has its benefits and disadvantages. These will be discussed in this section. The disadvantages were the basis for the recommendations that are discussed in the similairly named chapter 6.4.

Criteria	FDM (Ninjaflex)	Material Jetting (Agilus)	Hand Cast (Silicone)	MultiCast (Silicone + PLA)
Production Speed	++	+	- -	- -
Production Intensity	++	-	- -	+
Design Freedom	- -	+	+	++
Material Durability	++	- -	+	+
Material Flexibility	-	+	++	++
Production Cost	++	-	+	+

Figure 106:
Final set-up evaluation table

ADVANTAGES

One system
The biggest advantage of this set-up is that it functions as a fully integrated system. By sending a single g-code all the desired commands are processed. A small downside however that should be noted is that the current slicers don't support casting g-code yet. Leaving the final user to program their own code for the casting commands.

Extra mounting point
As a result of the external mounting point, a lot of the issues from previous casting configurations have been resolved. The nozzle is less likely to clog as the heat of the print scores isn't affecting the reaction rate of the blended silicone at the tip of the nozzle. Additionally, the mounting outside allows exploiting the capabilities of the MultiCast to the fullest.

Reliable Casting of Silicone parts
The add-on has been designed with the purpose of creating silicone parts by low-pressure casting. The current set-up is still more than capable of performing such an operations. This makes the printer a valuable asset for the Manufacturing Lab for all sorts of projects.

Creation of Complex parts
By combining the filament from the AA-core, the soluble support material from the BB-core and the static mixing nozzle from the casting set-up. The most complex parts can be created, especially when altering between the different materials within one print. Like for example, printing on top of the hardened silicone.

DISADVANTAGES

Synchronisation
Unfortunately, the MultiCast set-up isn't perfect and still has a few downsides. The biggest downside is the loss of synchronization of the casting set-up with the Ultimaker3. Forcing the user to be present at the casting times to make sure the print casts. If this was not the case the user had to switch off the printer and send a shortened g-code to the printer. As indicated in chapter 5.3 Ultimaker is currently looking into this issue.

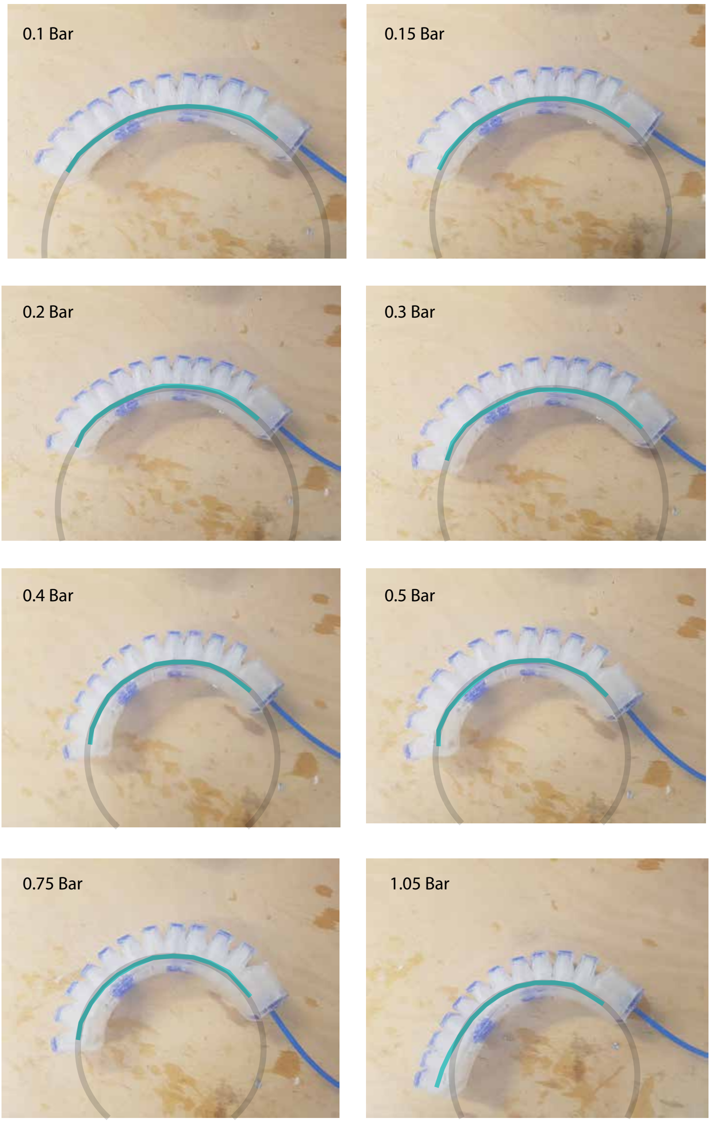
Tubing
Another important issue to mention of the current set-up is the way the nozzles are replaced. Due to the clogging of the nozzles, they need to replaced after every casting operation. After disposing of the nozzle a new one needs to be mounted in the tubes. However, each time a new nozzle has been used the tubes are being stretched. Resulting in leakages and ruptures in the tubing.

Capacity of Silicone
The current set-up can only store up-to 110ml. During this project, this was only considered an issue due to the number of times the set-up needed to be refilled. In the future, this might affect the number of parts that can be created in one go or the volume of these parts.

Flow Control
As discussed in chapter 5.3 the amount of volume that is extruded isn't always constant. During this project, there has been worked around this issue. However, in the long run, to smoothen the production process this downside needs to be addressed.

Bad Layer Adhesion
As a result of the PVA-filament not sticking properly to the Silicone, layers primer needs to be applied. Making the production process not fully automated. This is a big issue that needs to be addressed in the future since the goal was to create a fully autonomous hybrid manufacturing set-up.

Flexible Filament
During the development of the hybrid manufacturing system, the need of a flex-drive emerged. Although not used in the final demonstrator, it still remains relevant for creating composites that require better bonding between fiber and matrix. However, the set-up as it is currently operating is not reliable in the usage of flexible filament.



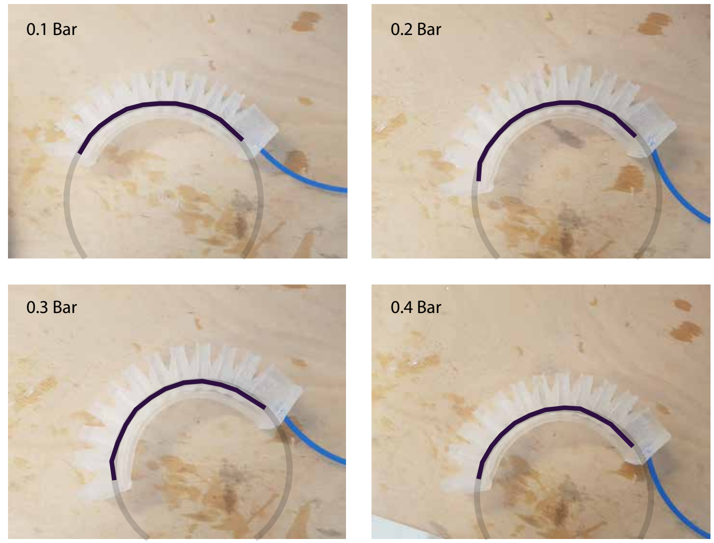


Figure 107:
Bending behavior of the fibre reinforced actuator compared to the behavior of a normal silicone bending actuator

PVA mold design

With the new design, there has been some improvement in dissolving the support material. All areas could be reached in one go which weakened the support. The time needed to dissolve the support is still very long. This is due to the fact that the support material doesn't get washed away in the cavities. To make the water flow through the part some manual labor was required. For the pneumatic actuator shown in Figure 109, not the standard Ultimaker PVA was used but the 123-3D home brand. This type of PVA functions worse than the Ultimaker version, as it expands into a paste within the actuator. Resulting in a viscous paste that blocks the in and output of fresh water. All over there can be concluded that there has been taken some steps in improving the rate at which the support material dissolves. However, the process of removing the support material is still far from ideal for this pneumatic actuator.

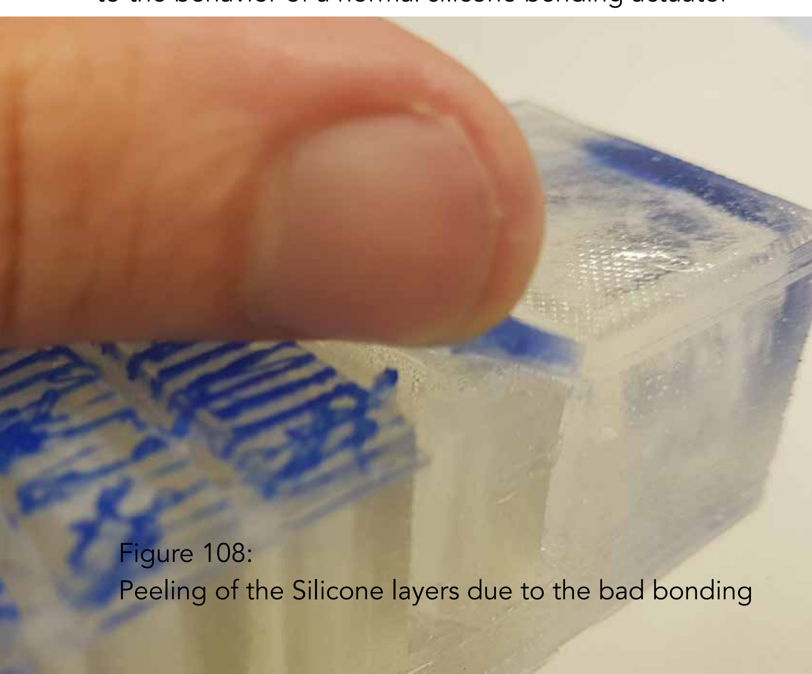


Figure 108:
Peeling of the Silicone layers due to the bad bonding

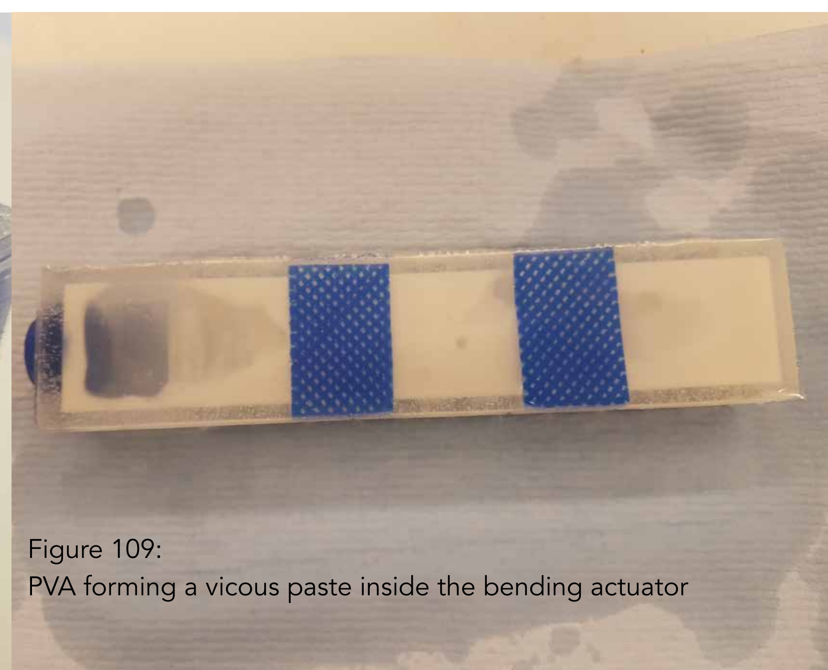


Figure 109:
PVA forming a vicous paste inside the bending actuator

6.2 DEMONSTRATOR EVALUATION

After this issues with printing had been overcome the demonstrator could be tested on multiple aspects. The questions this chapter tries to answer are the following. Did the redesign of the PVA mold help in removing the support material? Is the bending behavior of the pneumatic actuator adjusted? How does the redesign of the hard insert function?

Bending Behavior
The main goal of this bending actuator was to alter the bending behavior of the actuator. To be able to compare the actuator with a normal actuator a copy without all the PLA inserts has been hand cast. Unfortunately the PVA didn't dissolve in time to test the actuator that had been printed. To overcome this issue the actuator with fibers has also been hand cast. This has the advantage to compare that the effect of the fibers on the actuator can be directly monitored without the influence of the production process.

In Figure 107 the bending paths are shown with the accompanying pressures. Unfortunately the pure silicone actuator started leaking at 0.4Bar. So for higher pressures, no comparison could be made.

There are two things that could be observed from the images. First off, the fiber reinforced actuator required a higher pressure to achieve the same curvature. Secondly, the bending of the fiber reinforced actuator was disturbed by the fibers. This was the most apparent at the pressures of 0.2bar and 0.4bar. The actuator bent only slightly where the fibers had been inserted. Another effect that could be observed was that the actuator showed a sharper rate of bending at the chambers that were between the two fiber reinforced areas. This is probably due to the fact that the effect of the fibers needed to be compensated somewhere else.

Bonding of Silicones
During the testing of the pneumatic actuator, one of the issues that arose was the peeling of the silicone composite layer from the later cast silicone layer see figure 108. The reattachment could be achieved by gluing them together with uncured silicone. The reason that the bonding between these layers is bad, is probably due to the effects of the primer. As of to date, the hypothesis is that the primer creates a weaker bonding. During the washing of the PVA, the primer dissolves. Leaving a fragile layer bonding between the two silicone parts.

Hard Insert
When tested the hard insert didn't act as was intended. Due to the snap fit, with the rubber ring, some force was required to insert the connector. However, the silicone would deform under the pressure of trying to snap the fitting. Eventually resulting in ruptures on the sides. Around the insert. Therefore there can be concluded that amount of force required to close the fitting is still too high. To overcome this there needs to be looked into a combination of the bayonet mount with a rubber seal.
Although, some of the ruptures can be contributed to the force exerted on the insert. Another aspect needs to be addressed as well. The transparent silicone used for the demonstrator wasn't as wear proof as the green silicone used in previous phases of the project. In addition, the material has a lower yield strength and shore hardness. Resulting in a lower quality actuator than what could have been achieved with the tested green silicone.

Conclusion
In conclusion, there can be stated that all the individual concepts didn't perform as well as expected. However, the aspects show promise and could perform as intended with some more iterations. In regards to the performance of a normal actuator: the behavior of the pneumatic bending actuator is affected which shows that it is possible to alter the material behavior by locally applying composites.

6.4 RECOMMENDATIONS

As the deliverable of this project was two fold so are the recommendations. One list of recommendations are formulated for the manufacturing set-up whilst the other is for the demonstrator and their displayed advancements.

SET-UP

Flexdrive

During this project, a Flex3Drive prototype has been created. Although it eventually has been replaced with a new feeding wheel from Ultimaker the system still isn't capable of reliably printing flexible filaments. In order to do so, it is recommended to either further develop the proposed Flex3Drive system and splitting the steps from the two feeders in the firmware. Or further decreasing the amount of slack in the feeder with the Ultimaker feeding wheel.

Tubing

The disposable nature of the nozzle requires the tubing to be attached and detached multiple times causing ruptures. This should be overcome by making better connections between nozzle and tubing. A good example could be the connections used for the air connections designed by Festo. Another option would be to redesign the nozzle so it is no longer disposable. This can be achieved by flushing the nozzle or even inhibiting the chemical reaction from happening inside the nozzle. The last way seems the most interesting as it would require the least amount of user intervention, as well as it is a more sustainable solution.

Volume

The capacity of silicone that can be used for casting operations is currently quite small. In the future this should volume should be increased to reduce the number of refills required. In addition, this would allow for the creation of even bigger or multiple silicone parts in one print.

Flow control

The printer in its current state doesn't have a full control of the deposited volume of silicone extruded. For more precise applications and smaller parts, this control needs to be improved. There are two possible ways of addressing this issue. One is to look at ways to reduce the delay in the system as much as possible. Another option would be re-evaluating the way the system is actuated and come up with a design, which is less prone to delays.

Layer adhesion

One of the issues that has been addressed during this project is the adhesion of other layers on top of the hardened silicone. It was redeemed unfeasible to print with constant quality on top of unhardened silicone so a primer has been used. This primer improves the layer adhesion between the silicone and PVA but ruins the adhesion between the silicone and silicone. In the future, a solution needs to be found to optimize the adhesion between all types of layers on hardened silicone. In addition to finding the right adhesive, the application needs to be automated to make the set-up a fully autonomous system.

Housing

The 3D-printed housing used to host all the parts of the Ulticast set-up requires a redesign. This has multiple reasons. The first reason being the casing is too tightly packed. Leaving very little play for parts to move around the casing. This led to random jamming of the moving parts affecting the extrusion rate. In addition, the current housing isn't capable of fully extruding the syringes. With the redesign, the full capacity can be extruded of 120ml. Finally, the mounting of the housing should be redesigned. The add-on is leaning on the Ultimaker 3 with a strip. This makes the entire set-up hang skew which makes it look messy.

Printing area

As a result of the externally mounted printing nozzle, the printing area has been decreased. On its own, this isn't much of an issue. However, the layer shifts and the nozzle switch commands need to be revised in the Firmware to solve the collision issues. This could be done in the .json files and afterward recalibrate the positions on the printer.

Expanding Capabilities

After improving all the previously addressed issues the system should be reliable. After the system is reliable the capabilities could be expanded. Think of the usage of silicones that would alter their material properties as a result of their mixing proportions. This set-up could easily create different mixtures, expanding the capabilities of the set-up.

DEMONSTRATOR

Material usage
During the testing of the pneumatic actuator, the transparent silicone proved to be inferior to the green silicone. Therefore, it is recommended to further investigate the which additive silicone has the best properties to function as a pneumatic bending actuator.

Insert Bonding
The hard insert used was a snap fit with a rubber ring. As this design put to much pressure on the system it is recommended to use another fit. The proposed system that could be used as a bayonet mechanism with a rubber seal added to it. Decreasing the force required, while sealing the pneumatic actuator air tight.

Fibers usage
During this project, only fiber composites composed out of TPU and PLA have been tested. However, there is a wider range of materials to extrude from an Ultimaker to create composites from. Also, the stacking of composite layers in a sandwich structure hasn't been tested during the course of this project. It could also be interesting to investigate this further.

For the actuator in specific; the behavior of the fibers has only been evaluated up to a limited extent. It seems like the fibers affected the part as desired. Unfortunately, this effect is not up to the extent that was desired. To improve this behavior some more iterations have to be made in order to get a better understanding of the composites behavior in the pneumatic actuator.

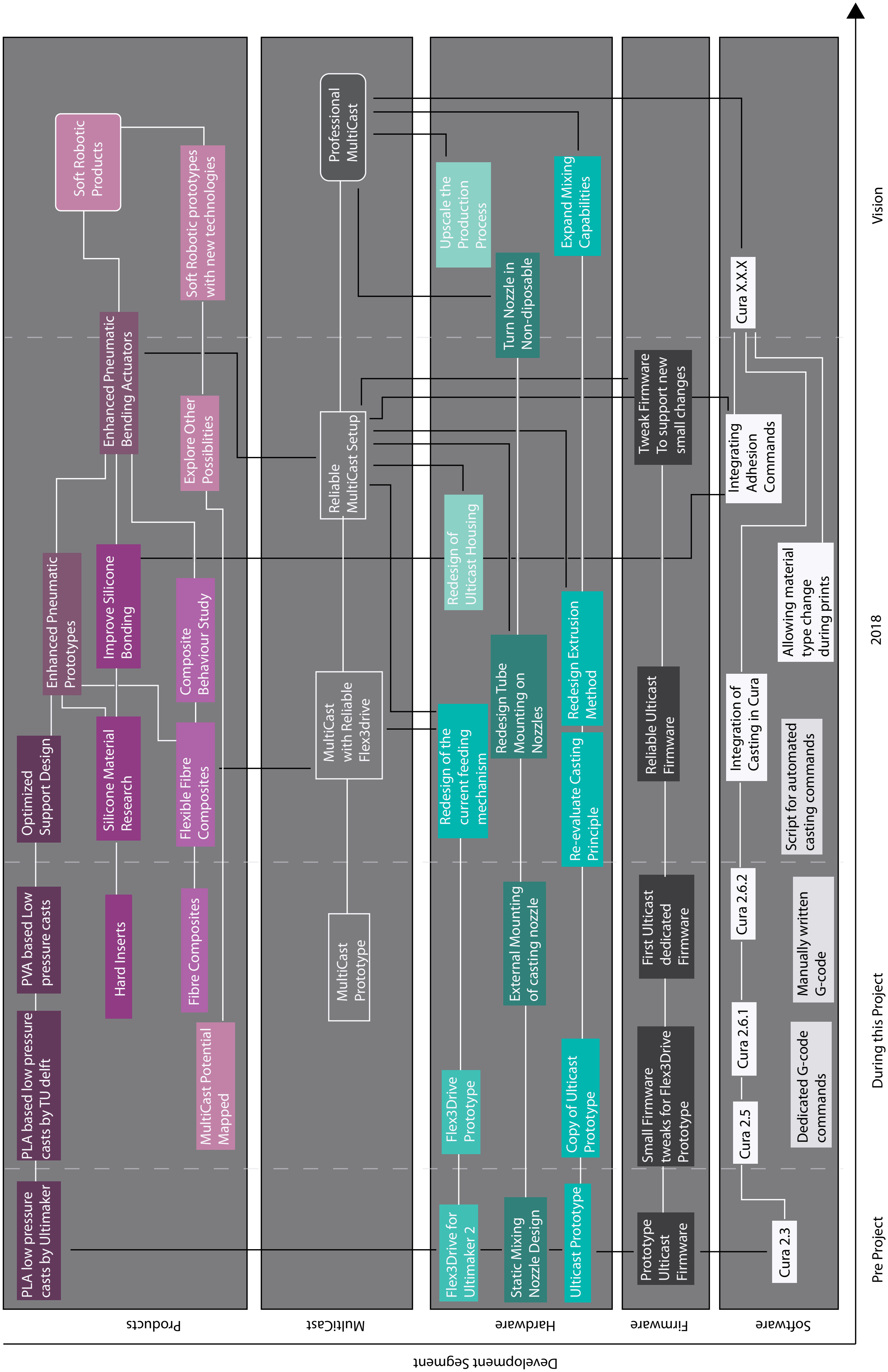
PVA design
Over the development of the Pneumatic actuator, the support material remained an issue. It is recommended to redesign the bottom cavity and the strain limiting layer. This way the production intensity of the pneumatic actuator as well as the production time can be reduced. An option to do so could be, creating an extra hard insert so the part can be fully flushed.

Optimization
Another aspect that should be looked at in the future is the usage of the demonstrator as a real gripper or hand. In order to perform such a tasks, a right balance of air pressure applied vs the gripping force needs to be found. To determine this the ideal morphology of the finger needs to be determined, as well as the ideal positioning of the fibers.

Possibilities
The last thing that hasn't been addressed yet in this chapter is the possibilities that haven't been explored in this project. In Chapter 4.2 several other possible applications have been mentioned. It is recommended to further investigate these possibilities in order to optimize the set-up as well as extending the production capabilities. Also, new developments could be created in the field of soft robotics by exploring these concepts.

All of the recommendations have been taken into account for the development of the roadmap.

Figure 110: Technology roadmap



6.5 ROADMAP FOR THE FUTURE

To provide an overview of what point require attention and how the development relates to one another. This roadmap has been created. The roadmap has been split into two main categories, the pneumatic actuator, and the MultiCast. To gain a better overview of the individual issues and components the MultiCast has been split up into its three main domains, Software, Firmware, and Hardware. The expectation is that the improvement suggested should be feasible to implement within approximately one and a half year.

At the start of this project, only a working prototype was in use at Ultimaker. The prototype was capable of performing small casting operations and had limited support from the software and firmware.

Over the course of this project, the set-up has been expanded. Improving the flexibility extrusion capabilities, moving the nozzle outside of the printhead and the possibilities have been mapped. A few of these possibilities have been researched and led to a few improvements and recommendations for the set-up.

In the further development, the biggest hurdles will be the volume control of the system. As this issue sits at the core of the design of the casting set-up. Additional high priority issues that need to be addressed are the replacement of the static mixing nozzle and the way the g-code is created. Currently all the work is done manually a great deal of time can be won by integrating this part within Cura or another slicer. When these issues have been addressed it should improve the reliability of the system, making it easier to conduct reliable research on the effects of the suggested pneumatic actuator improvements.

The long-term vision of this project is to enable the development of all sorts of soft robotic parts. In turn, this can lead to the integration of soft robotic parts into consumer products.

For the set-up, the developments will lead to a MultiCast set-up that can be sold on the consumer market with a wide range of applications.

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APPENDIX

8.1 LIST OF REQUIREMENTS SET-UP

List of requirements Hybrid Manufacturing Set-up

1. *Performance*
    - *1.1. The product has to cast silicone*
    - *1.2. The product has to print multi-materials thermoplastics*
    - *1.3. The product should be able to print flex materials*
    - *1.4. The casting volume should be 110 mL*
    - *1.5. The casting process should be done with a precision of 0.5 mm*
    - *1.6. The maximum print time shouldn't exceed 24 hours*
    - *1.7. The printable parts should be at least be 200x180x180mm*

2. *Environment*
    - *2.1 The different printing nozzles can't be contaminated by material from other nozzles.*
    - *2.2 The silicone shouldn't clog the nozzle due to the heat of the print bed*
    - *2.3 The product should work with an Ultimaker 3*

3. *Life in Service*
    - *3.1 The product should be able to run every day for 6 hour.*
    - *3.2 The product should function without fatal errors for 5 years*

4. *Maintenance*
    - *4.1 The end user should be able to maintain the product by him/herself*
    - *4.2 The user should be able to switch the nozzles*
    - *4.3 The user should be able to switch the cartridges*
    - *4.4 The user should not have to access any other components of the system*
    - *4.5 The maintenance of the system should be done via the Ultimaker 3 system*

5. *Target Production Cost*
    - *5.1 The production cost of the system shouldn't exceed 5000 euro*
    - *5.2 The production cost of one part shouldn't exceed 50 euro*

6. *Transport*
    - *6.1 The main components should be delivered to the client*
    - *6.2 The nozzle should be printed by the client*
    - *6.3 The Silicone should be transported as a separate system*

7. *Packaging*
    - *7.1 The silicone should be packaged as a dual package*
    - *7.2 The set-up should be sent in a box with an instruction manual*
    - *7.3*

8. *Quantity*
    - *8.1 The amount of products produced should be at least 1*
    - *8.2 The production of the parts should be done in batches of 1*

9. *Production Facilities*
    - *9.1. The parts that make up the product should be composed of Ultimaker parts.*
    - *9.2. The production of the packaging should be Internal or External?*

10. *Size and Weight*

10.1 The product dimensions shouldn't exceed: 342 x 508 x 300 mm 0.5xSetup
10.2 The weight of the add on shouldn't exceed: 5kg 0.5xSetup

11. *Aesthetic, appearance and finish*
    11.1 The product should fit the house style of Ultimaker

12. *Materials*
    12.1 The product should be completely skin safe in use
    12.2 The product should be food safe at the printing area

13. *Product life span*
    13.1 The product should be produced for at least 5 years
    13.2 The product should last for at least 5 years

14. *Standards rules and regulation*
    14.1 The product should not create any toxic gasses in the production process

15. *Ergonomics*
    15.1 The product should be operational without a manual
    15.2 Products regarding the depositing material should be solvable by the consumer
    15.3 The product should be easy to operate for users from 16 till 67 years old

16. *Reliability*
    16.1 The product should not get hardware issues during it's operational years
    16.2 Material issues are allowed to occur as a result of tweaking the system
    16.3 The system should be 99% reliable for easy prints

17. *Storage*
    17.1 The storage of the product requires the material to be airtight sealed
    17.2 After longterm storage the user needs to be able to clean the product for smooth operation

18. *Testing*
    18.1 Basic hardware tests should be conducted by the company
    18.2 Basic casting tests should be conducted by the company
    18.3 Complicated tweaking should be done by the community

19. *Safety*
    19.1 The product should not explode as a result of clogging
    19.2 The casts shouldn't ooze through the printer
    19.3 The printer isn't allowed to create unhealthy fumes as a result of production

20. *Product policy*
    20.1 The product should be easy to tweak with for the users to explore possibilities

21. *Societal and Political Implications*
    21.1 The product mustn't be associated with a sex toy factory

22. *Product Liability*
    22.1 The company shall not be held liable for hardware tweaks
    22.2 The company should be liable for extreme settings in Cura

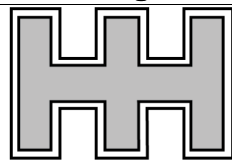
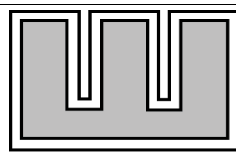
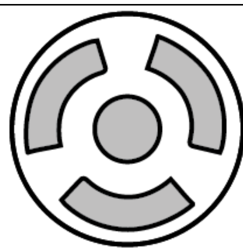
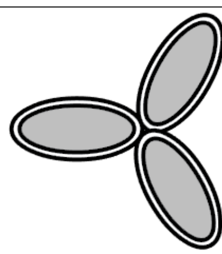
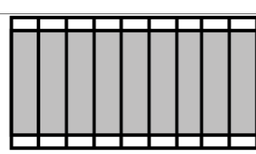
23. *Installation and Initiation of use*

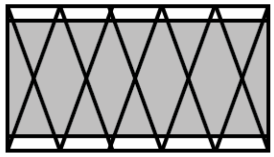
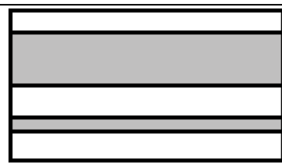
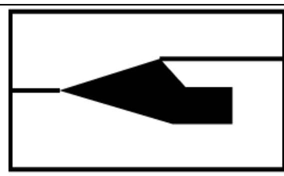
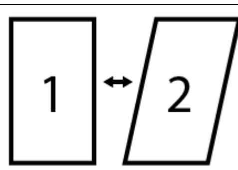
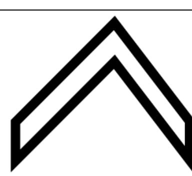
23.1 The user should install the material at home
23.2 The user should install the software at home
23.3 The user needs to link the product to the Ultimaker
23.4 The hardware should be delivered as a whole package

24. *Reuse Recycling*
    24.1 The cartridges containing the material should be recycled
    24.2 The nozzle and tubing should be replaceable

8.2 FUNCTION ANALYSIS

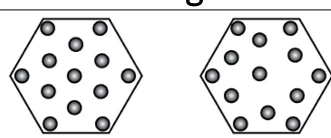
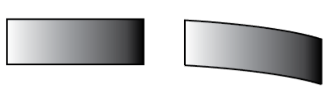
Actuators

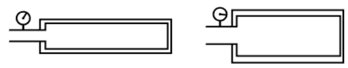
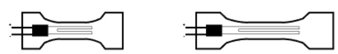
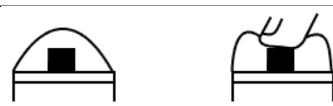
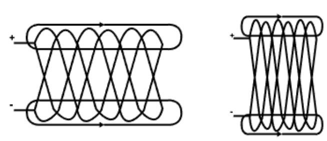
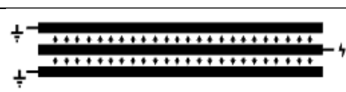
Type	Design	Function
PneuNet: Push and Pull Actuator		• Elongation in the longitude • Strain Limitation on the top segments of the finger • Thin walled design • Function achieved by means of geometry
PneuNet: Bending Actuator		• Bending over the z-axis • Strain limitation on the top and bottom of the finger • Thin walled design • Function achieved by means of geometry
PneuNet: Multi-module various stiffness manipulator		• Multi-direction bending control • Stiffness control with middle section • Strain limitation in the core the rest remains flexible • Complex channel design • Function achieved by means of geometry
PneuNet: Torsion Actuator		• Torsion Actuation • Rotation from the base of the shape • Strain limitation in the longitude • Thin walled design • Function achieved by means of geometry
Fibre Reinforced: Longitudinal Tensile Actuator		• Bending over the z-axis • Increased strain through fibre pull • Function achieved by means of though fibre running through main shape
Fibre Reinforced: Transverse Tensile Actuator		• Compression of the finger over the y-axis • Increased strain through fibre pull • Function achieved by means of multiple fibres running through the main shape

Fibre Reinforced: Woven Fibre Shell Actuator		• Shortening and widening of the part • Strain limitation in the z and x direction • Function achieved by means of fibres running around the main shape
Pneumatic Artificial Muscles		• Creation of a Bi-directional motion • One muscle to move the load other to stop the motion • Strain limitation by other air chamber • Thin walled designs • Function achieved by geometry
Shape Deposition Manufacturing		• Embedding of hard components within a flexible part • Integration of complex parts in one part • Function achieved by the inserted component • Often alternating rigid structures with flexible bridges
Di-electric Elastomer Actuator		• Contraction in the thickness • Elongation in the plane direction over entire sheet • Function achieved by means of material selection
Shape-memory Alloys and Polymers		• Perform a pre-defined motion • Return to the base position • Function achieved by material selection • Deformation over entire shape
Wax Coated Structure		• Collapsing a rigid structure to provide motion • Function achieved by wax material coating • Deformation over the entire shape

Thermal expandable Core Actuators		• Creating expansion similar to an increase of air-pressure based upon heat • Structure composed of filled thin walled shells • Function achieved by material composition
Tunable Segmented Soft Actuator		• Elongation in the longitudinal direction • Use of different elasticity moduli to exploit PV=nRT • Function achieved by material and or geometry, by altering the pressure needed to inflate or deflate • Structure consists of alternation of hard shells and elastic balloons
Combustion Driven Actuator		• Impulse driven motion actuator • Three functional channels; exhaust, fuel and ignition • Designed with a thin wall chamber • Function achieved by ignition from one chamber in thin specific geometry

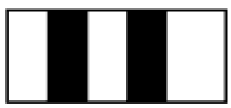
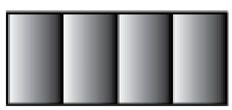
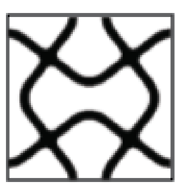
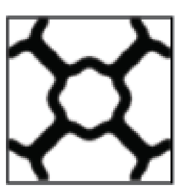
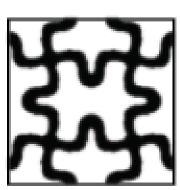
Sensors

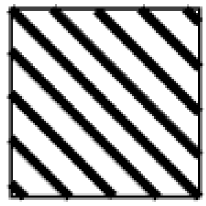
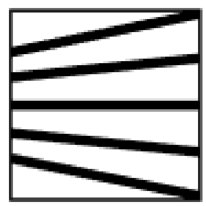
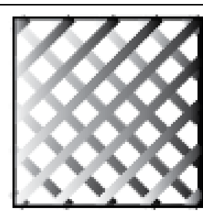
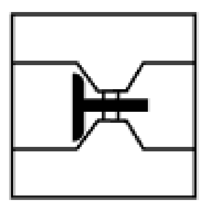
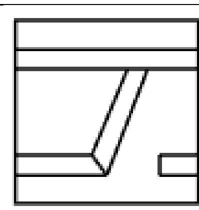
Type	Design	Function
Visual Displacement Sensor Static Points		• Measuring displacement of parts static • Checking position due to displacement • Function achieved by material composition of specific coloration
Visual Displacement Sensor Dynamic		• Measuring displacement of parts dynamic • Prediction of movement due to trackers

		• Function achieved by material composition
Pneumatic Deformation Sensor		• Measuring pressure • Prediction of movement due to pressure profiles • Function achieved by means of an external barometer
Eutetic Indium Gallium Alloy		• Measuring resistance • Prediction of movement due to change in resistance • Function achieved by measuring the resistance of imbedded conductive wires
Takktile Sensors		• Rubber casted MEM-barometers for integration in parts • Prediction of movement due to pressure profiles • Function achieved by means of an internally placed barometer
Smart Braids		• Measure the change in magnetic field • Prediction of the movement due to magnetic field fluctuations • Function achieved by wires running around the object
Piezo Sensors		• Measuring stretch, bending and pressure in electrical capacitance • Determining the movement due to changes in electrical capacitance

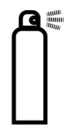
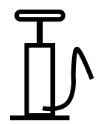
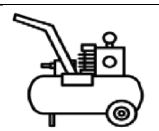
		• Function achieved by two piezo sheets lain on top of the object

Structural Control

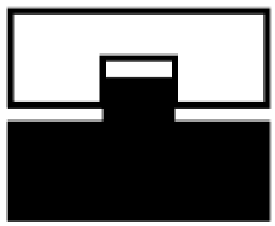
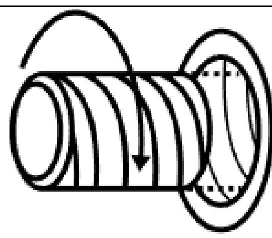
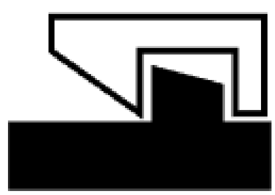
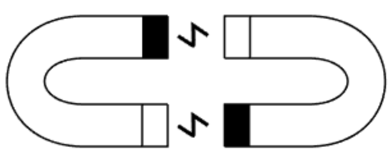
Type	Design	Function
Mono Material		• Create strength and stiffness with the help of wall thickness variations • Functions achieved by means of geometry
Multi Material, Local reinforced		• Creating local increase in strength and stiffness due to multi-materials • Functions achieved by means of material usage
Multi Material, Gradients		• Creating transitions of strength and stiffness due to local gradients • Functions achieved by means of material usage
Auxetic Material Poisson Ratio -0.8		• Expansion when being put under tension • Geometry based material behaviour
Auxetic Material Poisson Ratio 0		• No change in material thickness due to tension • Geometry based material behaviour
Auxetic Material Poisson Ratio +0.8		• Extreme buckling-in when put under tension • Geometry based material behaviour

Fibre Reinforced Material		• Random fibre reinforcements to provide light weight solution to stress and strain issues • Multi-material behaviour
Fibre Reinforced Material in Strain Direction		• Specific fibre reinforcements to provide a light solution to stress/strain issues • Multi-material behaviour
Multi-material Gradient through composites		• Combining multi-materials in stress and strain solutions • Multi-material behaviour
Valve Type 1		• Limiting and regulating pressure divides in parts • Exploit material behaviour of embedded components
Valve Type 2		• Limiting and regulating pressure divides in parts • Exploit material behaviour of embedded components

Power Sources

Type	Design	Function
Pneumatic Container		• Limited air pressure supply full motion freedom • Provide pulsated pressure to other components
Pneumatic Pump /Manual		• Unlimited air pressure supply limited motion freedom • Provide pulsated or continuous pressure to components
Hydraulic Pump		• Heavy duty system of previous air systems
Electricity Continuous		• Powering actuators and sensors to provide and measure motion changes • Unlimited amounts of electricity limited motion freedom • Provides pulsated or continuous electricity to components
Electric Batery		• Powering actuators and sensors to provide and measure motion changes • Limited amounts of electricity unlimited motion freedom • Provides pulsated electricity
Combustion		• Short term powering of actuators • Provides pulsated motion

Connections

Type	Design	Function
Form Fit		• Limit degrees of freedom of locked in part • Function achieved by geometry
Screw		• Temporary rotational bonding mechanism • Function achieved by geometry
Snap Fit		• Limit degrees of freedom by using one-way elasticity • Function achieved by geometry
Magnetism		• Temporary bonding due to magnetic fields • Function achieved by material

8.3 CREATIVE SESSION

INFORMATIE

1. **Kennismaken Line-up**
2. **Los komen met Association game** **5 min**
3. **Introductie** **10 min**

- Bezig met afstuderen Ontwikkelen Hybride Productie Proces voor Soft Robotica
- Huidige productie processen zijn vrij gelimiteerd, snelheid, betrouwbaar en vrijheid
- Onderzoek gedaan naar de potentialen en functies
- Die gaan we vandaag verder verkennen en combineren voor ideeën generatie
- Klusteren & Concepten genereren

Kaartjes Doornemen **15min**

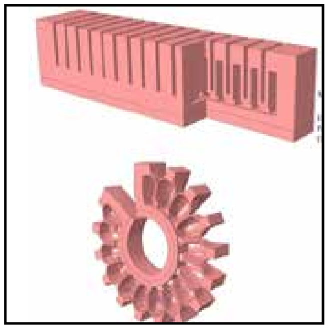
BRAINSTORM
Combineren van potenties met een groep
Actuators 1 **15 min**
Actuators 2 **15 min**
Sensors 1 **15min**
Connections 1 **15min**

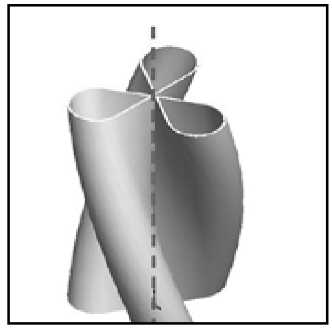
CLUSTEREN **30 min**

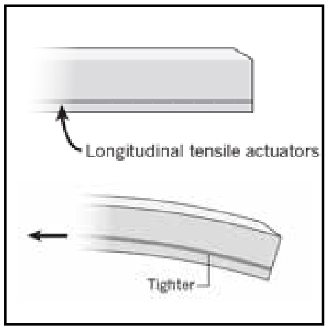
CONCEPTEN **30 min**
Individueel een concept generen uit een of meerdere clusters

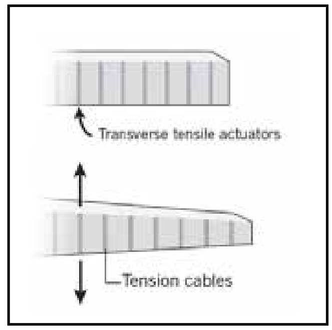
Methodes:
- Met z'n allen tegelijk op een groot vel + Post-it iedereen eigen kleur (FFA)
- Aflopen met HKJ 1 min
- Forced Fit method

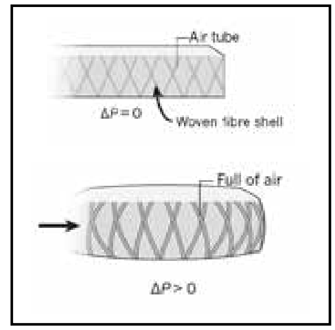
8.4 CARDS FOR CREATIVE SESSION

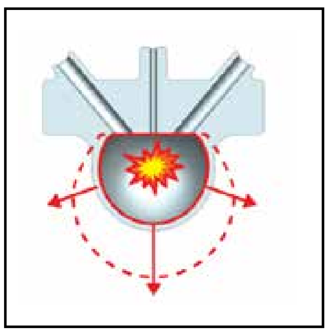


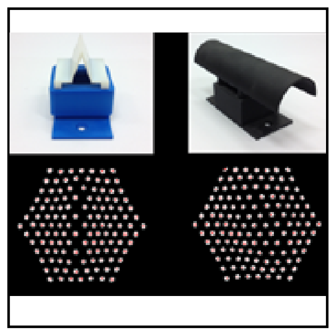


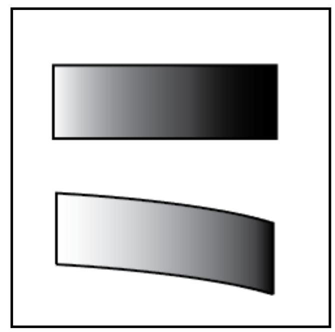


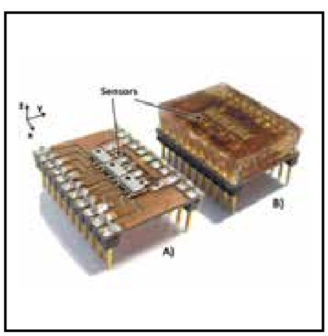


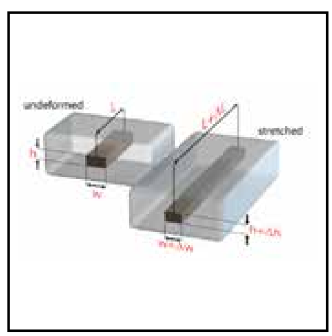


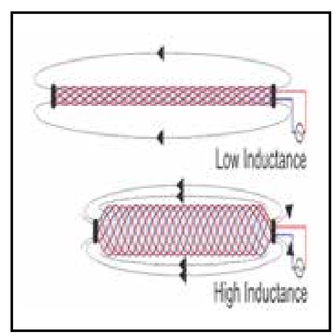


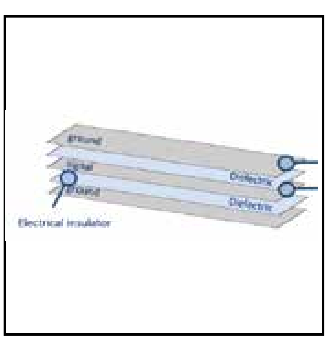


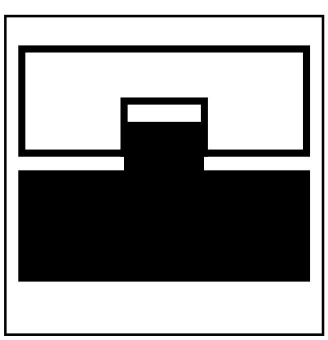


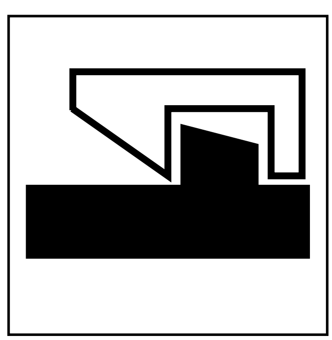


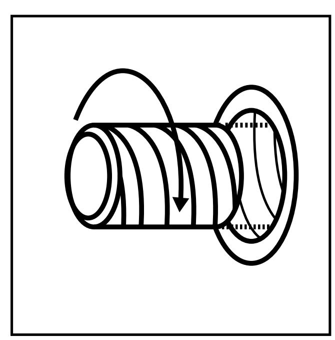












8.5 TENSILE TEST RESULTS

	Specimen	σ_Y	ε_Y	h	b	A_0	Peak detec	$L_{0\ CH}$
		MPa	mm	mm	mm	mm²	N	mm
PLA 1	1			2,067	3,03	6,26301	386,8208	49,83948
PLA 2	2			2,1	3,2	6,72	368,418	52,64624
PLA 3	3			2	3,25	6,5	373,0629	55,48934
PLA 4	4			2,03	3,1	6,293	380,424	53,58449
PLA 5	5			2,1	3,1	6,51	357,2073	54,28873
PLA AVG				**2,0594**	**3,136**	**6,457202**	**373,1866**	**53,16966**
SI 1	6			1,33	2,7	3,591	16,9709	57,18262
SI 3	8			2	2,7	5,4	20,71397	57,38158
SI 4	9			2,06	2,85	5,871	17,6375	55,84124
SI 5	10			2	2,9	5,8	24,74593	56,73325
SI AVG				**1,8475**	**2,7875**	**5,1655**	**20,01707**	**56,78467**
SI PL 1	11			2,27	2,95	6,6965	20,87392	51,15775
SI PL 2	12			2,03	2,9	5,887	27,04411	52,01672
SI PL 3	13			2,2	2,95	6,49	27,24686	50,75657
SI PL 5	15			2,1	2,8	5,88	19,30153	50,71123
SI PL AVG				**2,15**	**2,9**	**6,238375**	**23,61661**	**51,16057**
Si PT 1	16			2,47	3	7,41	8,992145	56,31208
Si PT 2	17			2,27	2,5	5,675	12,67692	56,67688
Si PT 3	18			2,4	2,7	6,48	10,17929	55,85424
Si PT 4	19			2,33	1,95	4,5435	10,8611	57,75391
Si PT 5	20			2,2	3,2	7,04	9,357503	58,23608
SI PT AVG				**2,334**	**2,67**	**6,2297**	**10,41339**	**56,96664**
SI PC 1	21			2,56	3	7,68	15,26743	50,63623
SI PC 2	22			2,73	3	8,19	24,79806	50,62791
SI PC 3	23			2,53	3	7,59	15,7208	50,4774
SI PC 5	25			2,53	3	7,59	9,945332	50,62391
SI PC AVG				**2,5875**	**3**	**7,7625**	**16,4329**	**50,59136**
SI PD 1	26			2,23	3,1	6,913	6,090803	51,25323
SI PD 2	27			2,36	3,1	7,316	7,814156	50,40289
SI PD 3	28			2,23	3	6,69	7,482965	50,68839
SI PD 4	29			2,23	3,3	7,359	6,514455	50,87056
SI PD AVG				**2,2625**	**3,125**	**7,0695**	**6,975595**	**50,80377**
SI TL 1	30			2,43	3,1	7,533	26,04869	53,81423
SI TL 4	33			2,36	2,85	6,726	26,11154	55,30259
SI TL 5	34			2,46	3,4	8,364	22,29005	54,7474
SI TL AVG				**2,416667**	**3,116667**	**7,541**	**24,81676**	**54,62141**
SI TT 1	35			2,24	2,55	5,712	8,124786	63,92091
SI TT 2	36			1,9	2,7	5,13	9,407359	61,52159
SI TT 3	37			2,18	2,4	5,232	6,872133	62,3549
SI TT 4	38			2,36	2,77	6,5372	8,848538	62,51291
SI TT 5	39			2,38	2,41	5,7358	11,92985	60,96725
SI TT AVG				**2,212**	**2,566**	**5,6694**	**9,036533**	**62,25551**
SI TC 1	40			2,03	2,7	5,481	14,08006	54,2909
SI TC 2	41			2,41	2,7	6,507	12,64086	55,97623
SI TC 3	42			2,26	2,85	6,441	12,42561	54,97391
SI TC 4	43			2,45	2,71	6,6395	11,19457	54,7249
SI TC 5	44			2,34	2,64	6,1776	15,80359	54,04559
SI TC AVG				**2,298**	**2,72**	**6,24922**	**13,22894**	**54,80231**
SI TD 2	46			2,19	2,56	5,6064	15,28063	54,94792
SI TD 4	48			2,09	2,53	5,2877	7,980795	54,46791
SI TD AVG				**2,14**	**2,545**	**5,44705**	**11,63071**	**54,70791**
TPU 1	49			1,86	2,88	5,3568	138,1196	50,79054
TPU 2	50			1,99	2,81	5,5919	131,6018	50,87307
TPU 3	51			1,98	2,84	5,6232	145,5368	50,69024
TPU 4	52			1,94	2,87	5,5678	145,5555	51,12773
TPU 5	53			2	2,81	5,62	128,4655	51,07885
TPU AVG				**1,954**	**2,842**	**5,55194**	**137,8558**	**50,91209**

E_t MPa	σ_M MPa	ε_M mm	ε_M %	Em	σ_B MPa	ε_B mm	ε_B %	$E_{t\ (\%\ increase)}$	$\sigma_{M\ (\%\ increase)}$	$\varepsilon_{M\ (\%\ increase)}$	$E_{M\ (\%\ increase)}$	
2748,041	61,76277	1,423566	2,856302	43,38595	21,35781	2,310739	4,636361					
2836,167	54,8241	1,298466	2,466397	42,22222	18,38844	2,095016	3,979422					
2970,014	57,39429	1,336218	2,408063	42,95278	19,85039	2,163984	3,89982					
3007,787	60,45193	1,328196	2,478695	45,51431	20,91802	2,061781	3,84772					
3072,478	54,87055	1,330474	2,450736	41,24136	20,36785	1,494139	2,752209					
2926,897	**57,86073**	**1,343384**	**2,532039**	43,07088	**20,1765**	**2,025132**	**3,823106**	**1,000000**	**1,000000**	**0,002209**		
1,480929	4,725954	169,5437	296,4952	0,027875	4,651847	169,7803	296,909	**0,179672**	**0,634358**	**15,778989**		
1,08901	3,83592	160,6077	279,8941	0,023884	3,766537	161,7878	281,9507					
1,049181	3,004172	137,6544	246,5104	0,021824	2,998524	138,0978	247,3044					
1,063713	4,266539	180,5577	318,2572	0,02363	4,245866	180,5979	318,3282					
1,170708	**3,958146**	**162,0909**	**285,2892**	0,024419	**3,915693**	**162,566**	**286,1231**	**0,000012**	**0,052221**	**1,000000**	**-0,006802**	**E(mm)= 25**
172,4854	3,117139	2,264888	4,427262	1,376289	2,199783	50,88821	99,47311	**16,464393**	**0,617024**	**0,799842**		
204,6899	4,59387	3,607179	6,934653	1,273535	3,053463	64,90883	124,7845					
159,9282	4,198284	1,658083	3,266736	2,53201	3,813466	2,135559	4,207453					
183,9554	3,282572	3,381328	6,66781	0,970794	2,522697	94,19292	185,7437					
180,2647	**3,797966**	**2,72787**	**5,324115**	1,392283	**2,897352**	**53,03138**	**103,5522**	**0,061225**	**0,049404**	**0,010803**	**-0,001974**	**E(mm)= 0,25**
1,292302	1,213515	95,13219	168,9374	0,012756	1,207017	95,15302	168,9744	**0,297827**	**0,477752**	**10,432845**		
1,728454	2,233819	122,4959	216,1303	0,018236	2,138255	122,5169	216,1673					
1,493891	1,570878	100,0555	179,1368	0,0157	1,567628	100,1392	179,2867					
2,086433	2,39047	114,6712	198,5515	0,020846	2,323603	115,4064	199,8243					
1,306471	1,329191	99,36234	170,6199	0,013377	1,194789	99,63506	171,0882					
1,58151	**1,747574**	**106,3434**	**186,6752**	0,016433	**1,686258**	**106,5701**	**187,0682**	**0,000152**	**0,013352**	**0,653965**	**-0,006830**	**E(mm)= 10**
158,2543	1,987946	0,849761	1,678168	2,339418	1,949709	0,86061	1,699593	**28,832197**	**0,611938**	**0,200099**		
190,9965	3,027846	1,332162	2,63128	2,272881	2,866696	1,378991	2,723777					
145,8216	2,071252	0,905624	1,794118	2,287099	2,065768	0,915676	1,814031					
110,4219	1,31032	0,862235	1,703218	1,519678	1,198267	0,882339	1,742929					
151,3736	**2,099341**	**0,987446**	**1,951696**	2,126032	**2,02011**	**1,009404**	**1,995083**	**0,051350**	**0,019537**	**0,000000**	**0,000615**	**E(mm)= 0,25**
9,933633	0,881065	17,41318	33,9748	0,050598	0,852133	15,7888	30,80547	**12,101116**	**0,106593**	**4,340070**		
39,69074	1,068091	17,97147	35,65563	0,059433	0,86881	1,283819	2,547114					
30,59679	1,11853	13,06894	25,78291	0,085587	0,906257	2,892974	5,707371					
14,05457	0,885236	7,137244	14,0302	0,124031	0,880822	7,25138	14,25457					
23,56893	**0,988231**	**13,89771**	**27,36088**	0,071107	**0,877006**	**6,804243**	**13,32863**	**0,007667**	**0,000000**	**0,080136**	**-0,006637**	**E(mm)= 1**
1,462128	3,457943	134,8831	250,6457	0,025637	3,156017	136,0189	252,7564	**0,086517**	**0,504454**	**17,175464**		
1,647406	3,88218	152,8271	276,3471	0,025402	3,019906	152,9239	276,5221					
1,465674	2,664999	110,9007	202,5679	0,024031	2,626575	111,0162	202,7789					
1,525069	**3,335041**	**132,8703**	**243,1869**	0,0251	**2,934166**	**133,3197**	**244,0191**	**0,000133**	**0,041264**	**0,818622**	**-0,006800**	**E(mm)= 20**
1,104793	1,422407	92,3636	144,4967	0,0154	1,411207	92,42637	144,5949	**0,096353**	**0,303090**	**11,921894**		
1,243648	1,833793	105,058	170,766	0,017455	1,812026	105,6987	171,8074					
1,228208	1,313481	79,08923	126,8372	0,016608	1,303608	79,25721	127,1066					
0,977178	1,353567	93,44031	149,4736	0,014486	1,247576	93,77649	150,0114					
1,124549	2,079893	114,0576	187,0801	0,018235	2,064181	114,6877	188,1136					
1,135675	**1,600628**	**96,80173**	**155,7307**	0,016535	**1,56772**	**97,16929**	**156,3268**	**0,000000**	**0,010768**	**0,594738**	**-0,006830**	**E(mm)= 20**
1,765717	2,568885	113,4045	208,8831	0,022652	2,370035	113,5827	209,2114	**0,158091**	**0,360074**	**9,617891**		
1,349977	1,942656	104,7081	187,0582	0,018553	1,78454	106,6925	190,6033					
1,570618	1,929143	102,447	186,3557	0,018831	1,793684	102,8671	187,1198					
1,426483	1,686056	87,18687	159,3185	0,019338	1,658039	87,26066	159,4533					
1,703699	2,558208	113,4208	209,8614	0,022555	2,518185	117,7257	217,8267					
1,563299	**2,136989**	**104,2335**	**190,2954**	0,020502	**2,024897**	**105,6257**	**192,8429**	**0,000146**	**0,020199**	**0,640868**	**-0,006816**	**E(mm)= 20**
1,964856	2,725569	113,8232	207,1474	0,023946	2,622103	115,2195	209,6886	**2,255826**	**0,608128**	**131,065790**		
1,825927	1,509313	69,63542	127,8467	0,021675	1,48131	69,65643	127,8853					
1,895392	**2,117441**	**91,72931**	**167,4971**	0,023084	**2,051707**	**92,43798**	**168,7869**	**0,000260**	**0,019855**	**0,563252**	**-0,006807**	**E(mm)= 20**
7,103765	25,78397	358,0557	704,9655	0,072011	7,647703	360,0658	708,923					
6,436325	23,53436	360,8034	709,2227	0,065228	9,140487	361,2836	710,1668					
6,87392	25,88148	360,9862	712,1414	0,071697	10,17808	361,9197	713,983					
7,05017	26,14237	363,8565	711,6618	0,071848	10,13726	364,2647	712,4602					
6,400813	22,85864	354,4945	694,0142	0,064482	8,794868	355,5475	696,0757					
6,772998	**24,84016**	**359,6393**	**706,4011**	0,06907	**9,179679**	**360,6163**	**708,3217**					**E(mm)= 25**

8.6 FLEXURAL TEST RESULTS

	F_{max} N	dL at F_{max} mm	a_0 mm	b_0 mm	S_0 mm^2	ε_f mm/mm	σ_f Mpa	E_f MPA	ε_f (% increase)	σ_f (% increase)	E_f (% increase)
PLA 1 (BAD)	70,93331	19,88043	3,29	12,56	41,3224	0,1497	40,071	267,668			
PLA 2	83,27133	6,795107	3,2	12,43	39,776	0,04977	50,2442	1009,55			
PLA 3	112,1797	6,960587	3,25	12,76	41,47	0,05178	63,9232	1234,58			
PLA 4	99,16044	5,633806	3,28	12,64	41,4592	0,04229	56,0022	1324,09			
PLA 5	85,15517	6,667135	3,28	12,52	41,0656	0,05005	48,5535	970,054			
PLA AVG	**90,14**	**9,187414**	**3,26**	**12,582**	**41,01864**	**0,068719**	**51,75879**	**961,1878**	**1**	**1**	**1**
Si 1	0,37151	29,07359	3,06	12,54	38,3724	0,20363	0,24299	1,19333	**0,0553556**	**0,0753714**	**0,5748281**
Si 2	0,12964	10,92633	3	12,4	37,2	0,07503	0,08921	1,18913			
Si 3	0,112025	8,242446	3,02	12,59	37,2	0,05697	0,07493	1,31512			
Si 4	0,175562	7,622346	3,09	12,57	38,8413	0,05391	0,11234	2,08391			
Si 5	0,394637	13,03319	3,14	12,54	39,3756	0,09367	0,24513	2,61704			
SI AVG	**0,236675**	**13,77958**	**3,062**	**12,528**	**38,19786**	**0,09664**	**0,152922**	**1,679705**	**1,4062995**	**0,0029545**	**0,0017475**
Si TL 1	0,288338	11,50371	3,89	12,39	48,1971	0,10242	0,11811	1,15317	**0,0139005**	**0,0437606**	**0,3302929**
Si TL 2	0,382623	11,75112	3,95	11,96	48,1971	0,10624	0,15747	1,48224			
Si TL 3	0,411508	14,78575	4,06	12,39	48,1971	0,1374	0,15474	1,12625			
Si TL 4	0,539088	14,52568	3,68	12,85	47,288	0,12235	0,23792	1,94458			
Si TL AVG	**0,405389**	**13,14156**	**3,895**	**12,3975**	**47,96983**	**0,117102**	**0,167061**	**1,426562**	**1,7040621**	**0,0032277**	**0,0014842**
Si TD 1	0,450403	14,55649	3,85	11,38	43,813	0,12827	0,20507	1,59871	**0,027828**	**0,0856402**	**0,4128469**
Si TD 2	0,189445	9,304426	3,88	11,33	43,9604	0,08263	0,0853	1,03233			
Si TD 3	0,183086	12,27245	3,84	11,13	42,7392	0,10786	0,08568	0,7943			
Si TD 4	0,736459	16,6132	4,17	11,3	47,121	0,15856	0,28785	1,81534			
Si TD AVG	**0,389848**	**13,18664**	**3,935**	**11,285**	**44,4084**	**0,119332**	**0,165973**	**1,310171**	**1,7365023**	**0,0032067**	**0,0013631**
Si TC 1	0,661996	17,26842	3,89	12,12	47,1468	0,15375	0,27721	1,80302	**0,029306**	**0,0894415**	**0,4002935**
Si TC 2	0,216614	9,993678	3,96	12,72	50,3712	0,09058	0,0834	0,92074			
Si TC 3	0,216445	10,37768	3,9	11,9	46,41	0,09264	0,09184	0,99142			
Si TC AVG	**0,365018**	**12,54659**	**3,916667**	**12,24667**	**47,976**	**0,112322**	**0,150818**	**1,238395**	**1,6344933**	**0,0029139**	**0,0012884**
Si TT 1	0,23038	10,05763	3,86	11,45	44,197	0,08886	0,10371	1,16716	**0,031239**	**0,0479136**	**0,2906809**
Si TT 2	0,41987	14,00973	3,86	11,89	46,41	0,12377	0,18202	1,47059			
Si TT 3	0,118898	4,289082	3,72	11,13	46,41	0,03652	0,05929	1,62345			
Si TT 4	0,40518	11,60906	3,88	11,23	46,41	0,1031	0,18406	1,78536			
Si TT 5	0,330923	12,1671	4,24	12,05	46,41	0,11808	0,11732	0,99359			
Si TT AVG	**0,30105**	**10,42652**	**3,912**	**11,55**	**45,9674**	**0,094065**	**0,12928**	**1,408029**	**1,368819**	**0,0024977**	**0,0014649**
Si PL 1	2,57913	11,94584	4,08	12,34	50,3472	0,11155	0,96427	8,64392	**0,0152004**	**0,0890338**	**1,071526**
Si PL 2	2,62844	15,6677	4,04	12,14	49,0456	0,14488	1,01877	7,03202			
Si PL 3	2,758713	16,27327	4,09	11,82	48,3438	0,15234	1,07153	7,03387			
Si PL 4	2,589508	15,58103	4,06	12,53	50,8718	0,14479	0,96289	6,65031			
Si PL 5	2,188172	16,48383	4,04	12,78	51,6312	0,15242	0,80565	5,28565			
Si PL AVG	**2,548792**	**15,19033**	**4,062**	**12,322**	**50,04792**	**0,141196**	**0,964623**	**6,929153**	**2,0546756**	**0,0186369**	**0,0072089**
Si PD 1	0,63669	13,79187	3,28	12,59	41,2952	0,10354	0,36101	3,48664	**0,0089232**	**0,1488524**	**1,1491985**
Si PD 2	1,141733	15,29043	3,28	12,11	39,7208	0,11479	0,67303	5,86313			
Si PD 3	1,185899	13,69846	3,3	12,12	39,996	0,10347	0,69005	6,66931			
Si PD 4	0,881892	12,14988	3,34	12,58	42,0172	0,09288	0,48262	5,19605			
Si PD 5	1,412965	15,26237	3,37	12,52	42,1924	0,11772	0,76318	6,48284			
Si PD AVG	**1,051836**	**14,0386**	**3,314**	**12,384**	**41,04432**	**0,10648**	**0,593977**	**5,539594**	**1,5494917**	**0,0114759**	**0,0057633**
Si PT 1	0,461535	10,94712	3,88	12,35	47,918	0,09722	0,19065	1,96107	**0,0175426**	**0,0333317**	**0,4041385**
Si PT 2	0,252928	11,9659	3,61	11,53	41,6233	0,09887	0,12927	1,30752			
Si PT 3	0,220041	10,89903	3,96	11,7	46,332	0,09879	0,09211	0,93238			
Si PT 4	0,2276	8,571119	3,96	9,48	37,5408	0,07769	0,11758	1,51353			
Si PT 5	0,317319	13,88102	4,16	12,49	51,9584	0,13217	0,11275	0,85306			
Si PT AVG	**0,295884**	**11,25284**	**3,914**	**11,51**	**45,0745**	**0,100945**	**0,128472**	**1,313513**	**1,468949**	**0,0024821**	**0,0013666**
Si PC 1	3,085132	13,87963	3,37	12,42	41,8554	0,10706	1,67978	15,6904	**0,0103515**	**0,3295905**	**3,1227077**
Si PC 2	1,507206	13,72374	3,36	12,58	42,2688	0,10554	0,81503	7,72239			
Si PC 3	2,127573	17,38036	3,34	12,4	41,416	0,13287	1,18122	8,89026			
Si PC 4	1,426757	15,31985	3,33	12,21	40,6593	0,11676	0,8093	6,93101			
Si PC 5	2,373846	16,36701	3,32	12,39	41,1348	0,12437	1,33495	10,7337			
Si PC AVG	**2,104103**	**15,33412**	**3,344**	**12,4**	**41,46686**	**0,11732**	**1,164057**	**9,993544**	**1,7072354**	**0,02249**	**0,0103971**
TPU 1	0,179955	7,2844	1,82	12,59	22,9138	0,03034	0,3314	10,9214			
TPU 2	0,177219	7,920539	1,82	12,14	22,0948	0,03299	0,33846	10,2582			
TPU 3	0,221013	9,938303	1,68	12,24	20,5632	0,03821	0,49134	12,8572			
TPU 4	0,180885	10,3584	1,85	12,16	22,496	0,04386	0,3338	7,61046			
TPU 5	0,139025	4,841132	1,68	12,21	20,5128	0,01862	0,30983	16,6438			
TPU AVG	**0,179619**	**8,068556**	**1,77**	**12,268**	**21,71612**	**0,032806**	**0,360966**	**11,65822**			

8.7 G-CODE FOR CASTING COMMANDS

```
T1

G0 Z70
G1 F1500 E48
M104 T1 S100
M190 S40

;priming
G92 A0 B0
G0 F5000 Z100
G0 F5000 X175 Y25
M107
M400
G111 A-20 B-20 F25
M400
G4 P10000
;priming

;retraction
M400
G111 A-10 B-10 F200
M400
G111 A-5 B-5 F25
M400
G4 P3000
;retraction

;extrusion
G111 A-15 B-15 F200
G92 A0 B0
G0 F5000 Z100
G0 F5000 X34.5 Y70
G0 F5000 Z15
G4 P1000
G0 F100 Z8.75

G111 A-6.22625 B-6.22625 F50
G1 X42
M400
G111 A-10.4525 B-10.4525 F25
G1 X62
M400
G111 A-14.67875 B-14.67875 F25
G1 X82
M400
G111 A-18.905 B-18.905 F25
G1 X102
M400
G111 A-23.13125 B-23.13125 F25
G1 X122
M400
G111 A-27.3575 B-27.3575 F25
G1 X142
M400
G111 A-31.58375 B-31.58375 F25
G1 X162
M400
G111 A-35.81 B-35.81 F25
G1 X172
M400
G4 P10000
;extrusion

;retraction
M400
G111 A0 B0 F200
G0 F5000 Z100
G0 F5000 X175 Y25
M400
G111 A-5 B-5 F25
M400
G4 P3000
;retraction

M190 S60
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8.8 CALIBRATION VALUES

Silicone Extrusion

A:B Feedrate		Steps	Silicone (ml)	ml/step		ml required	steps
	25	21	5	0,238095		8,05	33,81
						54,46	228,732
Max Steps		1500					
	1	4,22625	4,22625		19,375		
	2	4,22625	8,4525				
	3	4,22625	12,67875				
	4	4,22625	16,905				
	5	4,22625	21,13125				
	6	4,22625	25,3575				
	7	4,22625	29,58375				
	8	4,22625	33,81				