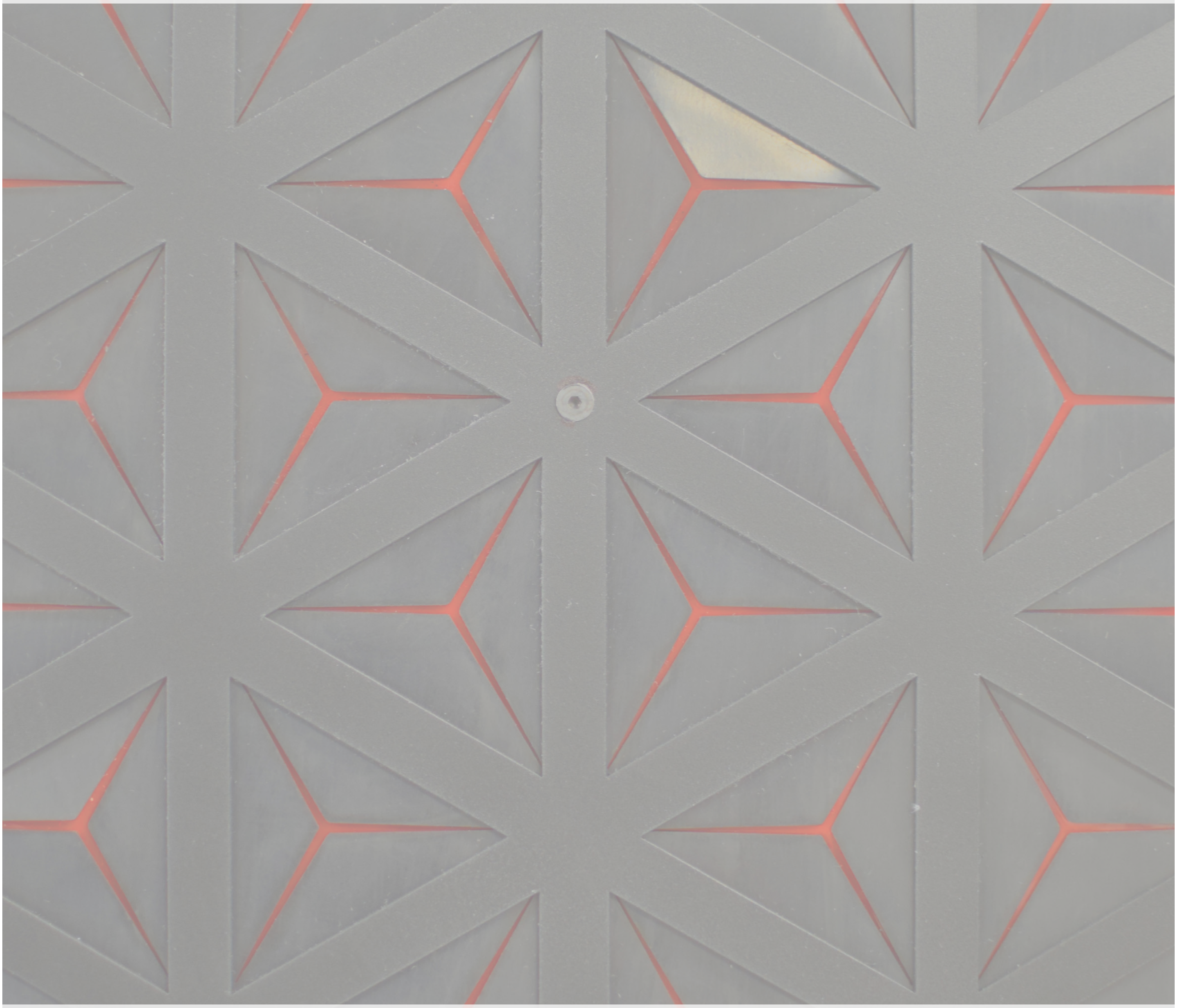
MIMICKING THE APPEARANCE CHANGING ABILITIES OF CEPHALOPODS WITH A PNEUMATIC MECHANISM

MASTER THESIS BY TIJMEN AMORY



Delft University of Technology
Faculty of Industrial Design Engineering
Master Integrated Product Design
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MIMICKING THE APPEARANCE CHANGING ABILITIES OF CEPHALOPODS WITH A PNEUMATIC MECHANISM

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Supervisory team:

Chair: Dr. ir. Doubrovski, E.L.

Mentor: Dr. ir. Elkhuizen, W.S.

Mentor: Ir. Minnoye, A.L.M.

Graduation date:

April 6, 2021

Faculty of Industrial Design Engineering
Delft University of Technology
Landbergstraat 15
2628CE Delft
The Netherlands

TU Delft

T.J. Amory

4373383

tijmenamory@gmail.com

PREFACE

This thesis was written in the context of the Master Integrated Product Design at the Faculty of Industrial Design Engineering at the Delft University of Technology. With this thesis, I complete my studies and thereby my days as a student has come to an end. I have always enjoyed studying Industrial Design and not only did I learn a lot, I also developed as a person.

With this project, I expressed my passion for creating novel and aesthetically pleasing designs, for developing these designs from sketches towards tangible products and for doing practical research by building and testing physical prototypes.

I am happy with the results and I hope you will enjoy reading this thesis!

ACKNOWLEDGEMENTS

During this project, I was assisted and supported by several people. Therefore, I would like to express my gratitude to these people, who helped me to get to the achieved results.

SUPERVISORY TEAM

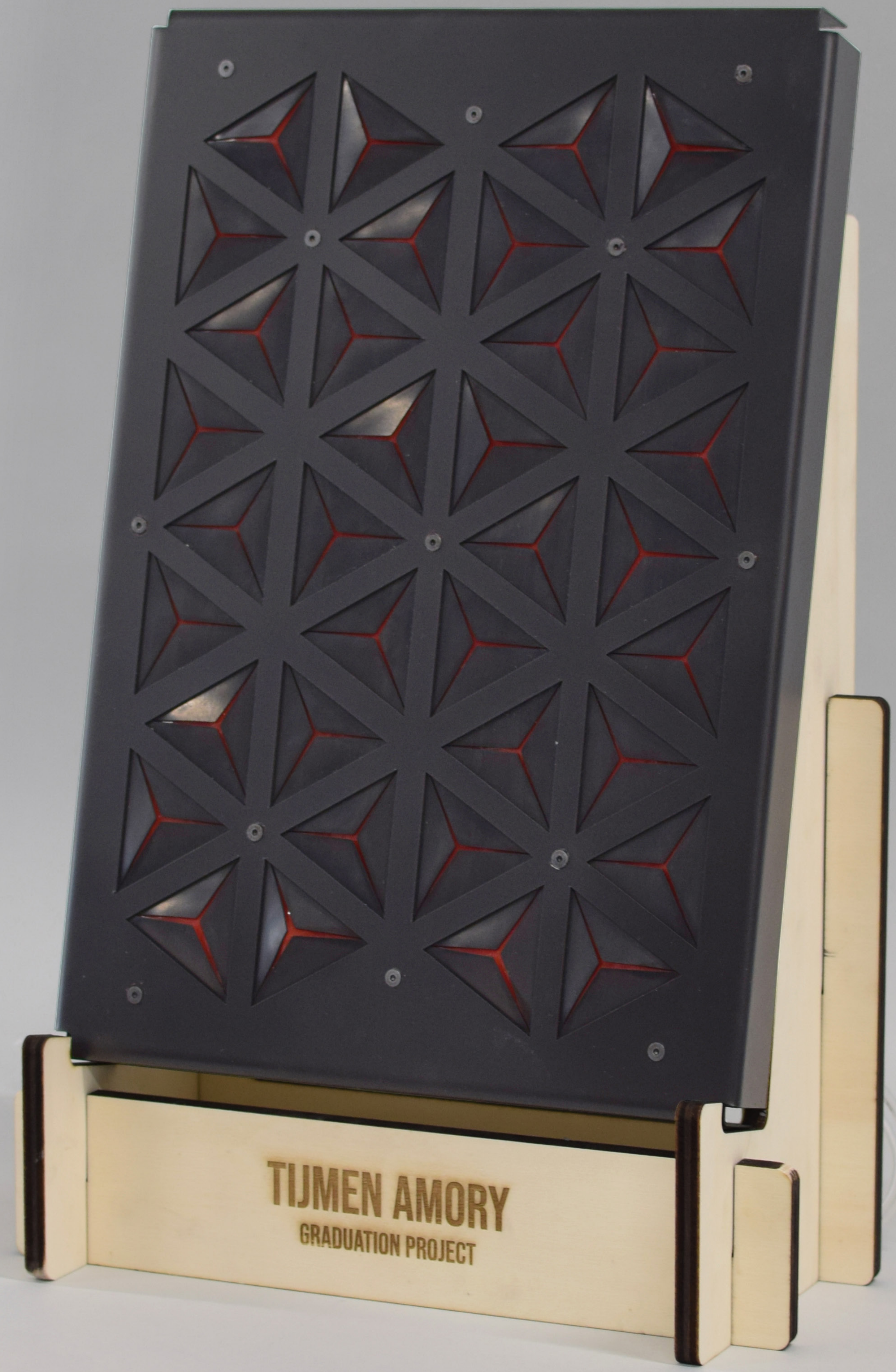
First of all, I would like to thank the supervisory team, consisting of Zjenja, Sander and Willemijn. Although the meetings were held online and were therefore not as efficient and natural as meeting in person, I still felt that they were always very inspirational and motivational. Furthermore, I would like to thank Sander in particular for stepping in halfway through the project. This transition in supervision went flawless and gave me new insights to the project.

PMB STAFF

I would like to thank the PMB staff for helping me building the many mock-ups and final prototype. Here, I would like to thank Wiebe in particular, as he spent a lot of time helping me prototyping and gave me new insights concerning the technical development of the project.

FRIENDS & FAMILY

Finally, I want to thank my friends and family who supported me during the project, as it did not always go off without a hitch and their support pulled me through the hard times.



EXECUTIVE SUMMARY

INTRODUCTION

Cephalopods (e.g. squids, octopuses, cuttlefish) are able to actively adapt their appearance in terms of color, texture or transparency. The idea of this project is to mimic this ability with a technical solution and apply this technology to a product or environment. Therefore, the following design goal was defined:

The goal of this project is to design and create a solution, applied to a product or environment, which enables an appearance transformation. Thereby creating an added value to this product or environment, by facilitating communication opportunities, enhancing interactions or enriching the user experience.

1: ORIENTATION & DEFINITION

In Part 1, an orientational research is given, concerning appearance changing animals and existing technology solutions. Furthermore, a generative session was held, which resulted in a mindmap of potential application possibilities. After this research and ideation phase, a scope definition was defined, in which the following focus points are defined:

- Change in color, texture or transparency
- 'Simple and low-tech' mechanical solution
- Fabricated with digital fabrication technology

2: MECHANISM & WORKING PRINCIPLE

In Part 2, a research concerning seven typical 'shape-changing mechanisms', is given. This reseach was used for an ideation session, including sketches and physical mock-ups. The numerous ideas were then clustered into five mechanism concepts. These were evaluated and compared, based on nine points of criteria and Harris Profiles, after which the following mechanism concept was chosen (see figure 1):

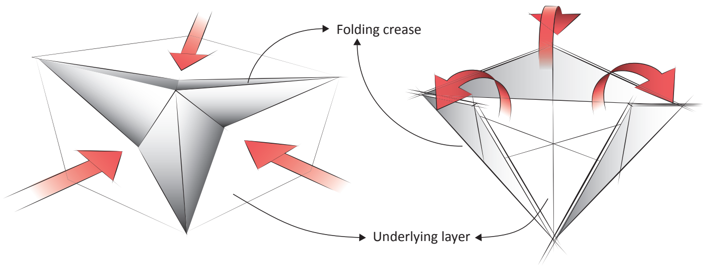


Figure 1: Chosen concept

3: ACTUATION & FABRICATION

In Part 3, a research is given, concerning potential forms of actuating and fabricating the chosen mechanism. Here, the decision was made to make use of soft pneumatic actuation, and to make use of either silicone casting, fabric sealing or 3D-printing as fabrication method.

4: CONCEPTUALIZING & ITERATIONS

In Part 4, an ideation session led to three potential solutions for operating the chosen mechanism with soft pneumatic actuation. These concepts were prototyped and tested during five iteration processes. Here, the three previously described fabrication processes were applied. This led to three final concepts which were evaluated and compared based on the previously described points of criteria and Harris Profiles. Finally, the following concept was chosen (see figure 2&3):

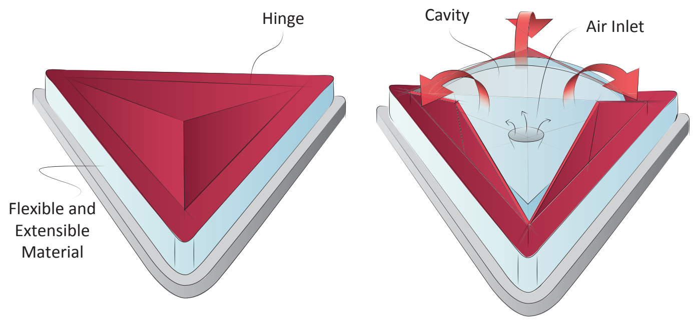


Figure 2: Chosen concept (sketch)

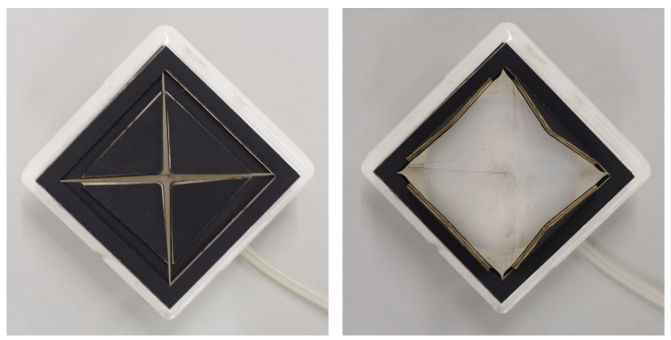


Figure 3: Chosen concept (prototype)

5: APPLICATION & DEISGN

In Part 5, the earlier created mindmap of potential application ideas was used to select five potential applications, based on how well they suit to the chosen concept's properties. Here the decision was made to apply the chosen mechanism to the inner or outer walls of public buildings and use them to communicate instructions or messages to users or passers of the buildings (see figure 4). The final design involves a panel with numerous mechanisms, consisting of five layers (see figure 5&6). Finally, a physical prototype was made to demonstrate the working principle of the design (see figure 7).

Figure 4: Chosen application

Figure 5: Final design

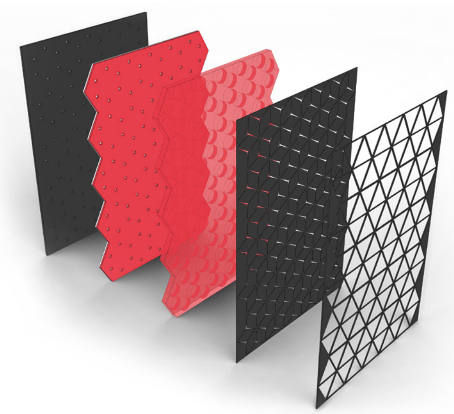


Figure 6: Exploded view of final design

Figure 7: Physical prototype before and after acutation

CONCLUSION:

When comparing the final results to the priorly defined design goal and scope, it can be concluded that the project was successful. This, as the final design and demonstrating prototype ensure a change of color and are applicable to an environment, for the purpose of communication. Also, the design offers a 'simple and low-tech' mechanical solution which is mainly fabricated with digital fabrication technology. When considering further development, it is recommended to reconsider the shape, size and materialization in order to optimize the performance, costs and ecological footprint. Also, the production process should be reconsidered to allow production on a larger scale. Furthermore, for the proposed application, it is required to produce and program a control panel. Finally, for a more legitimate validation, the product should be tested with potential users and its performance, costs and ecological footprint should be compared to competing technologies.

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INTRODUCTION

INTRODUCTION

Through evolutionary development, several animals have evolved their appearance in order to blend into their surroundings to hide for predators or to outwit their preys. This phenomenon is called camouflage and it comes in many varieties. A few animals have taken this phenomenon a step further: they evolved the ability to actively adapt their appearance in terms of color, texture or transparency, in order to blend into surroundings or to communicate to other animals. The most well-known animals which are capable of changing their appearance are cephalopods (e.g. squids, octopuses, cuttlefish) and chameleons.

At the same time, many products today are static in their appearance and if they are able to communicate, this is usually done through screens, lights or sound. With the rise of interactive and experience enriching products, the idea arose to develop a product which can adapt in appearance, similarly as cephalopods and chameleons (see figure 8&9). Thereby, the product itself becomes the actuator and by changing its appearance, the product is able to communicate and interact with the user, expressive the user's moods or emotions or respond to environmental factors.

Figure 8: Cephalopod (Getty Images, n.d.)

Figure 9: Chameleon (Wallpaperscraft, n.d.)

Prior to the start of the project, a design brief was defined. This description can be found in Appendix A. The assignment was created by Willemijn Elkhuizen and Zjenja Doubrovski, who came up with the idea of imitating the appearance changing capabilities of cephalopods and chameleons with a mechanical solution. They are both specialized in additive manufacturing and other forms of digital manufacturing technology. Therefore, in the search of a solution, the focus lies on this technology.

The assignment was offered through the 'Graduation Opportunities Platform' and directly caught my attention. This, because the assignment includes a technology driven design approach with a focus on digital manufacturing. Performing a technology driven project was new for me and therefore felt as an interesting challenge. Also, digital manufacturing technology has always attracted me a lot and therefore, I wanted to develop my knowledge in this field. Furthermore, I felt that the assignment offered the opportunity to come up with solutions where the focus lies on aesthetics and product experience rather than functionality. This appealed to me a lot and fits well with my interest in technology driven art. Finally, I assumed that the assignment included a lot of physical prototyping which I always enjoy and gives me the most satisfaction out of a project.

DESIGN GOAL

The goal of this project is to design and create a solution, applied to a product or environment, which enables an appearance transformation. Thereby creating an added value to this product or environment, by facilitating communication opportunities, enhancing interactions or enriching the user experience.

DESIGN APPROACH

For this project, a technology driven design approach is executed. The design process is focused on the development of a technology and the outcome of the research is used as base for the conceptualizing of product solutions. This, instead of a conventional design process where one would begin with a problem, leading to the implementation of an applicable technology for solving the problem.

CONVENTIONAL DESIGN PROCESS

TECHNOLOGY-DRIVEN DESIGN PROCESS

DESIGN PROCESS & REPORT STRUCTURE

DESIGN PROCESS

The project involved a chronological and iterative process including multiple divergent and convergent phases, following up on each other. In the divergent phases, I explored and discovered numerous potential solutions. In the convergent phases, I evaluated the most promising options and chose one for further development. Figure 10 shows an overview of the entire design process.

REPORT STRUCTURE

The report is divided in five parts:

1: ORIENTATION & DEFINITION

In this part, an orientational analysis is done on appearance change occurring in nature and in existing technology solutions. Also, a generative session with four participants was exectued in the search of potential applications. The outcomes of the research and ideation is used as inspiration for the remaining project and to determine the 'knowledge gap', which explains where there is room for new solutions. Finally, a 'scope' is defined, in which the design goal is clarified and narrowed down.

2: MECHANISM & WORKING PRINCIPLE

The goal of this part was to find a mechanism and working principle whereby an appearance change can be achieved. This was done through a combination of literature research on shape-changing mechanism, ideation on suitable solutions and practical exploration of mechanisms, materials and fabrication methods. The ideas were converged into five potential directions and one direction was chosen for further development.

3: ACTUATION & FABRICATION

In this part several possibilities for actuation of the chosen mechanism are discussed and evaluated, after which one form of actuation is chosen. Thereafter, potential fabrication methods for the production of the mechanism are discussed, which are conceptualized and tested in the next part.

4: CONCEPTUALIZING & ITERATIONS

For this part, the goal is to combine the chosen mechanism concept with the intended form of actuation and to determine the exact working principle, materialization and fabrication method of the mechanism. Therefore, an ideation process was executed and physical protypes were modelled, tested and evaluated. The process of numerous prototyping iterations resulted in three final concepts. These were then evaluated and compared in terms of performance, feasibility and applicability, after which one concepts was chosen.

5: APPLICATION & DESIGN

The goal for this part is to select a suitable application for the chosen mechanism, and to create a final design and demonstrating prototype. This was done by selecting five application ideas from the generative session of Part 1, and elaborate them towards application proposals. Here, one was chosen as most desirable and suitable application. Finally, a final design and demonstrating prototype were created.

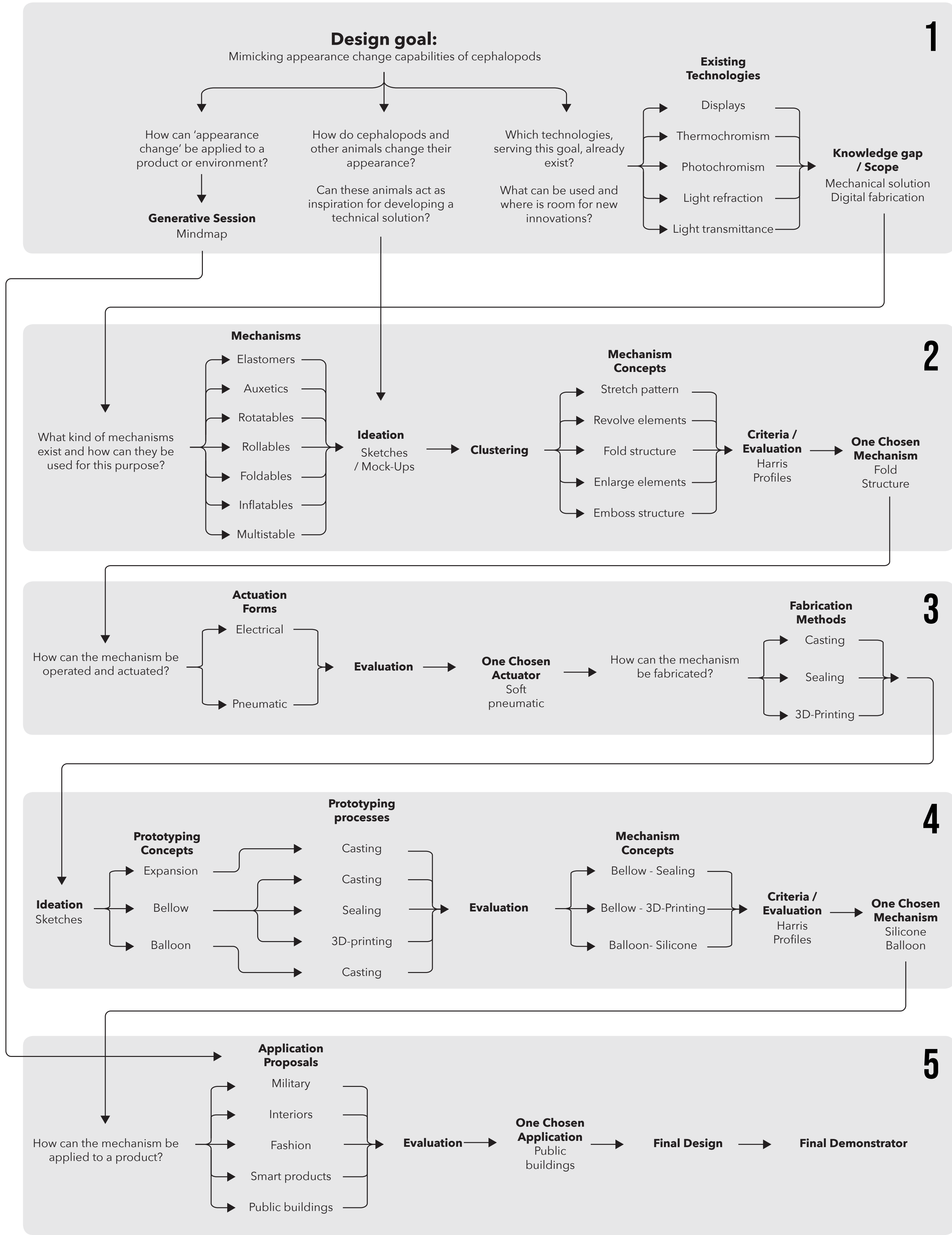

Figure 10: Overview of design process

PART 1

ORIENTATION & DEFINITION

INTRODUCTION

This phase focuses on the exploration of the topic 'Appearance Change'. The goal was to find out how an appearance change could be applied to a product or environment and to explore where and how appearance changing processes occur in the natural environment and in existing technology solutions. This, to get inspiration for the development of a novel solution, to see what already exists and to find unexplored fields where there is room for innovation. This was done through a generative session combined with literature research and has resulted in a mindmap and two overviews concerning appearance change in nature and in existing technology solutions. The latter overview was used to determine the 'knowledge gap' which explains where there is room for new solutions which are to be explored in this project. Finally, the conclusions of the chapter are used to redefine and narrow down the design goal in the form of a 'scope definition',

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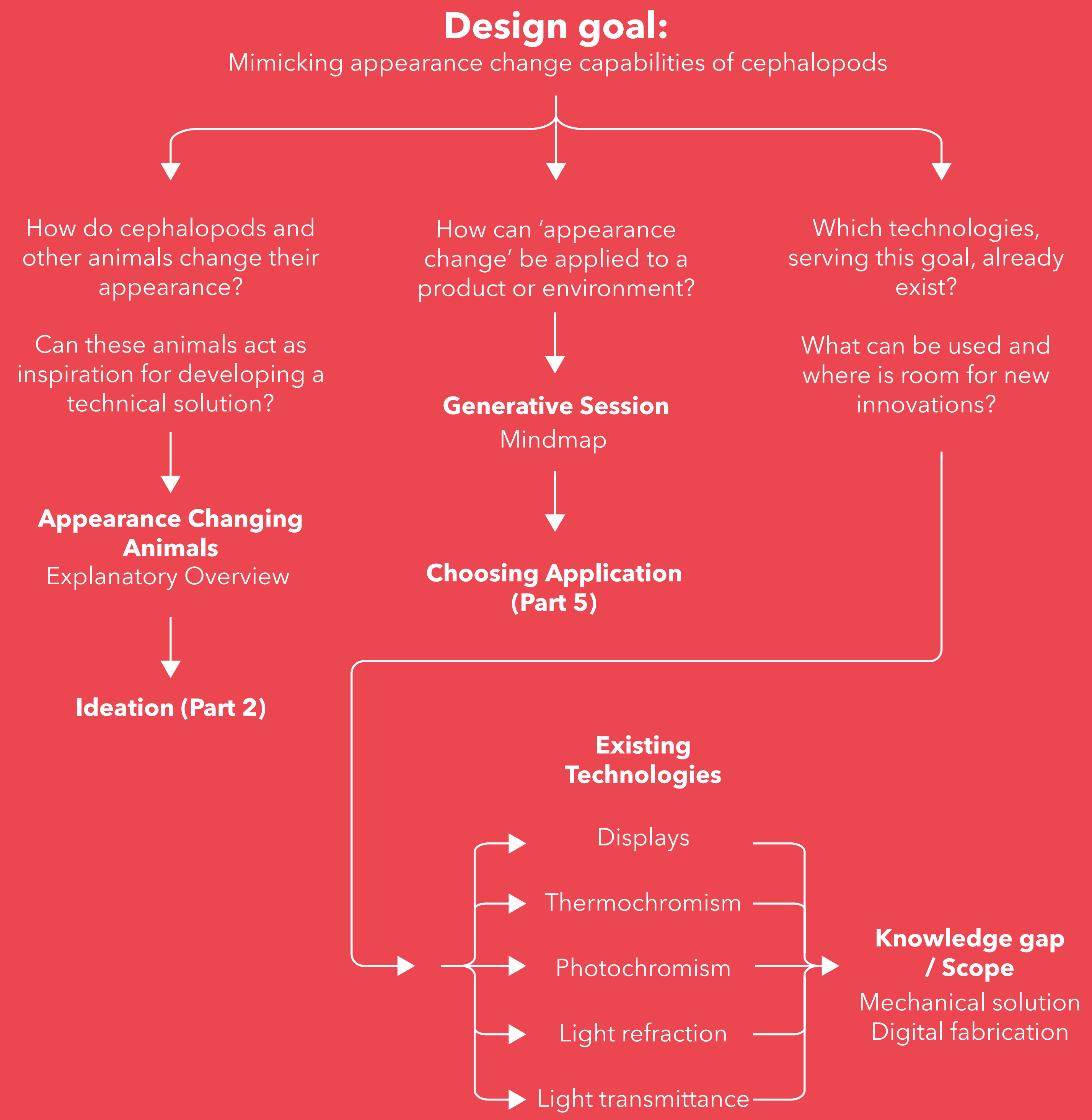

1.1 APPEARANCE CHANGE OCCURING IN NATURE

In this chapter, an analyzation was done on appearance changing animals. The chapter includes an explanatory overview while a more elaborate explanation is given in Appendix B. The gained knowledge is used as inspiration for ideation in the next part

APPROACH

In order to find out where and how appearance change occurs in the natural environment, I conducted a literature research and watched explanatory videos on the internet. To find the discussed information, I mainly used the following keywords in Google, Google Scholar and Youtube: Active camouflage, appearance changing animals, appearance change in nature.

OVERVIEW

An overview of the appearance changing ability of four animals is shown in figure 11. The overview shows the processes causing the appearance change, the purpose they use them for, and the changing features of the animals. Every (dotted) line represents one of the four analyzed animals and is connected to the elements of the overview that are relevant for that specific animal.

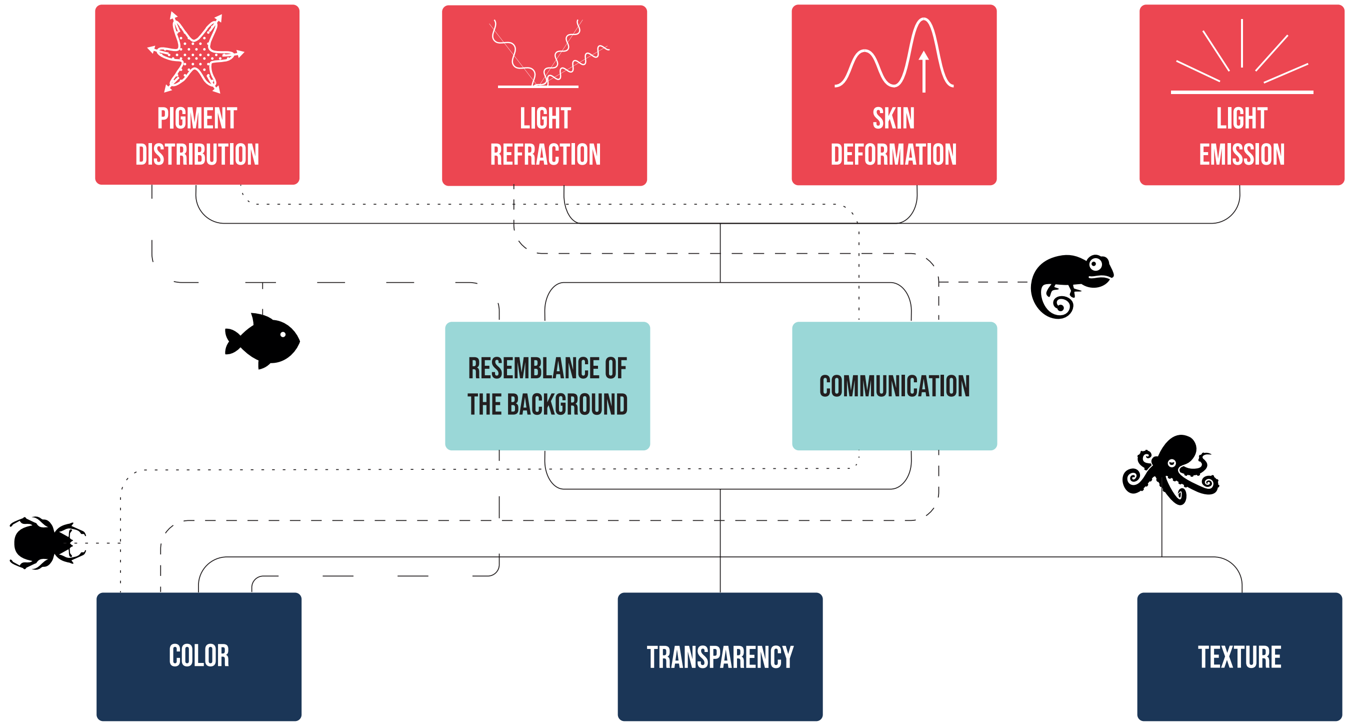

Figure 11: Overview of appearance change occurring in nature

1.2 POTENTIAL APPLICATIONS

A generative session was held to orientate on potential applications for the to be developed technology. This, to get an overview of the possibilities and to get inspiration for the development of the technology. The generative session resulted in a mindmap of numerous application ideas, divided into three categories. This mindmap will be used for choosing a suitable application later in the project when the working principle, materialization and visual effect of the technology are determined.

APPROACH

As the design goal states to find a suitable application, I organized a generative session with fellow Industrial Design students, with the aim of generating a large amount of application ideas. This session started with an open discussion, after which a 'Brainwriting' session was executed. This idea generation method involves a silent brainstorm where participants write down or draw ideas on pieces of paper, which are passed around among the participants (Heijne & Meer, 2019). This type of brainstorming increases fluency and allows to use each other's ideas as inspiration and steppingstone for new ideas.

GENERATIVE SESSION

The generative session was held with four participants and took approximately two hours. First, the participants were informed and instructed, after which two rounds of brainstorming were executed.

INSTRUCTIONS

Firstly, I described the assignment and the results that were achieved until that moment. Then, I explained my expectations and provided instructions concerning the generative session. I asked the participants to try to think 'outside-of-the-box' and explained that in this stage a large quantity of ideas is essential, and therefore all ideas are appreciated. The session started with an open discussion and was followed by a 'Brainwriting' session according to Heijne & Meer (2019)

OPEN DISCUSSION

The following questions were discussed during the open discussion:

- What comes to mind when hearing about this topic?
- What are your first intuitions?
- What kind of existing solutions can you name?

BRAINWRITING

In the 'Brainwriting' session, the participants were asked to draw and write as many ideas as possible on a piece of paper see figure 12). The session included eight rounds of 3 minutes. At the end of each round, the papers were passed on to the next participant. To induce creativity, the following questions were printed on paper and distributed among the participants:

Paper 1:
What kind of products (should) respond to environmental aspects?
...and what kind environmental aspects do/should these products respond to?

Paper 2:
What kind of products (should) respond to interactions?
...and what kind interactions do/should these products respond to?

Paper 3:
What kind of products (should) communicate a message to the user?
...and what kind of message do/should these products communicate to the user?

Paper 4:
What kind of products (should) communicate information to the user?
... and what kind of information do/should these products communicate to the user?

Paper 5:
What kind of products (should) communicate their state to the user?
... and what kind of state do/should these products communicate to the user?

Paper 6:
What kind of products (should) communicate instructions to the user?

… and what kind of instructions do/should these products communicate to the user?

Paper 7:
What kind of products (should) express the user's mood/emotion?
… and what kind of moods/emotions do/should these products express?

Paper 8:
What kind of products (should) express a certain occasion?
… and what kind of occasions do/should these products express?

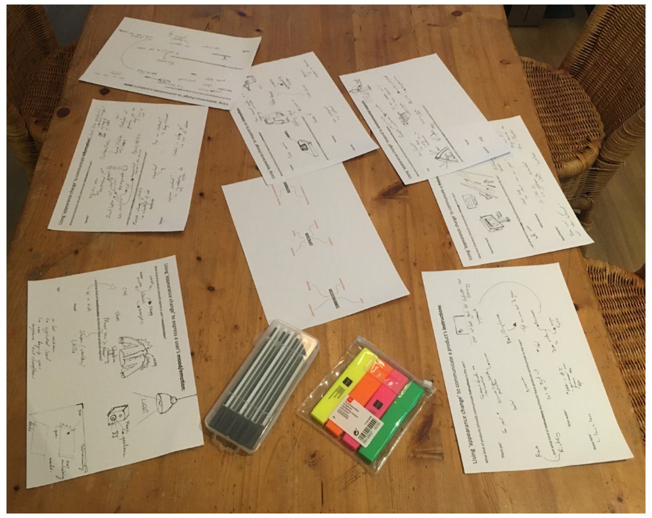

Figure 12: Papers full of ideas and drawings, as result of 'Brainwriting' session

MINDMAP OF GENERATED IDEAS

The following mindmap is the result of the individual brainstorm and the generative session:

Figure 13: Mindmap of generated ideas

1.3 EXISTING TECHNOLOGY SOLUTIONS

Humans have tried to mimic the ability to actively change in appearance for similar purposes as animals. For example to resemble an environment for camouflaging purposes, or for the purpose of communication or expression. Various research about this topic exists, which is set out in this chapter. The chapter starts with an explanatory overview of the gained knowledge, after which a more elaborate explanation is given per technology.

APPROACH

In order to get an overview of existing technologies, I conducted a literature research in which I searched for product solutions and scientific research on the topic of appearance change. I mainly used the following (combination of) keywords in Google and Google Scholar: Active camouflage, appearance change, color change, tunable color, tunable morphology, biomimicry, biomimetic, cephalopods and chameleon

Since the design goal is to create a similar appearance adaption as seen in nature, I focused mainly on solutions which achieved a similar form of appearance change as the animals discussed in Chapter 1.1. Therefore, I looked for solutions where a change in color, transparency or texture is achieved.

Furthermore, I looked for solutions which could be used for the purpose of environment resemblance, communication, interaction or expression.

OVERVIEW

An overview of all the found literature on the topic of existing technologies for achieving an appearance change is shown in figure 14. The overview shows five technology principles, the form of actuation they require and the specific appearance features that change due to the technology. Every (dotted) line represents one of the found technologies and is connected to the elements of the overview that are relevant for that specific technology.

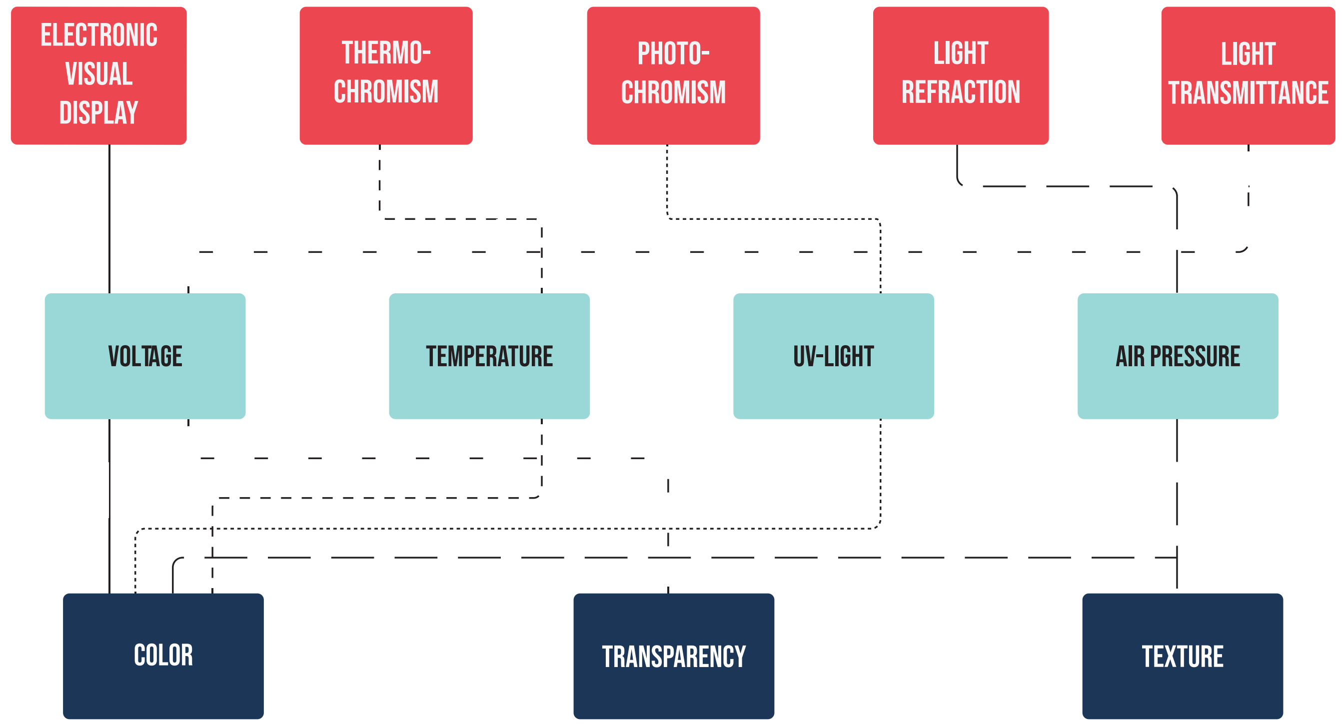

Figure 14: Overview of appearance change achieved with existing technology solutions

ELECTRONIC VISUAL DISPLAY

Electronic visual displays, informally known as 'screens', are devices which can present information in visual form after electronic input. A common example is LED technology which is for instance used for television screens. Another example is electronic paper (e-paper) technology known from e-readers. In contrary to most screens, this technology is based on reflection rather than emission of light. The screens consist of pigmented particles which are placed in a transparent fluid between two electrodes. By charging the electrodes, the pigmented particles either move up or down and thereby, the visual display can be modified (see figure 15) (Primozic, 2017).

For example, Pezeshkian et al. (2015) used e-paper technology for actively changing the appearance of a military vehicle, in order to resemble its background for camouflage purposes. This was done by displaying the image of the surroundings, recorded by cameras, on the e-paper screens (see figure 16) (Pezeshkian et al., 2015).

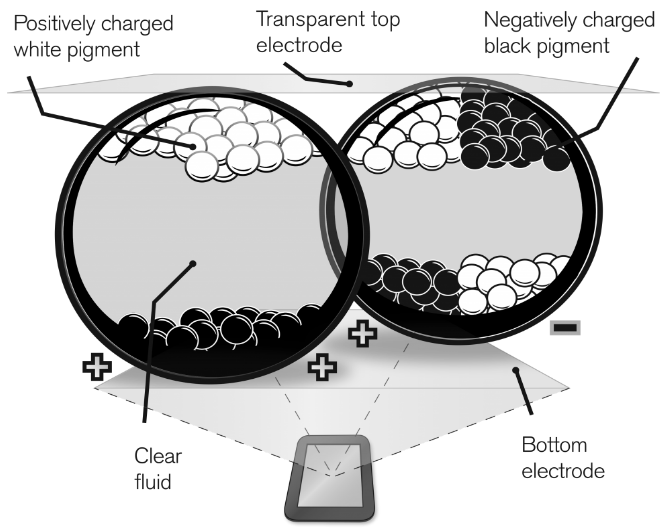

Figure 15: Electronic paper technology (Birsa, 2016)

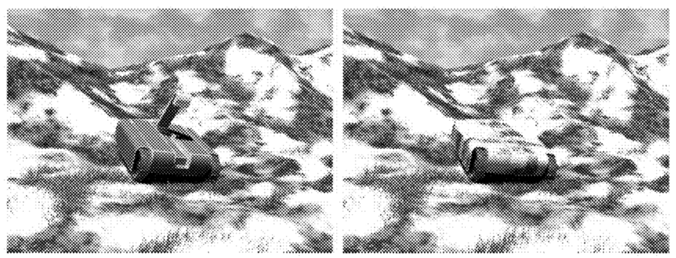

Figure 16: Military vehicle covered with electronic paper displays (Pezeshkian et al., 2015)

The disadvantage of electronic paper is that color filters or color-mixing layers are required to display full color images, which results in more complex devices. (Wang et al., 2016). Therefore, Wang et al. (2016) used plasmonic pixel display for the similar purpose of camouflaging a device (see figure 17) (Wang et al., 2016). Similar to e-paper, this technology is based on particals which are placed between electric fields. However, plasmonic pixels enable the display of any color by tailoring the reflection and absorbtion of light (Greybush et al., 2019).

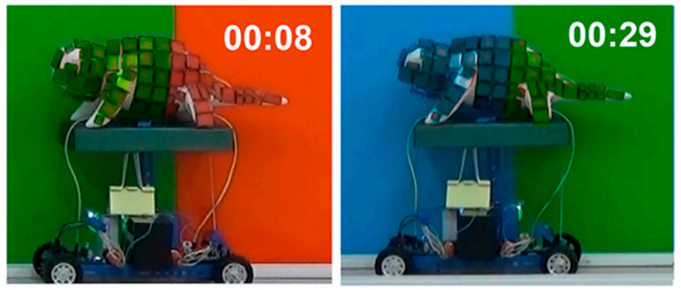

Figure 17: Mechanical chameleon covered with plasmonic pixel displays (Wang et al., 2016)

THERMOCHROMISM

Thermochromism is the property of a material to change color due to a change in temperature. This technology is used in various research on appearance change and active camouflage. For example, Karpagam et al. (2017) have performed a study in which they coated military uniforms with thermochromic colorants, enabling them to change color depending on temperature (see figure 18) (Karpagam et al., 2017). These uniforms turn from a jungle color motif (green-brown) to a desert color motif after being heated by an external heat source to 60°C for two minutes (see figure 18). Therefore, the uniforms are not limited to only one terrain.

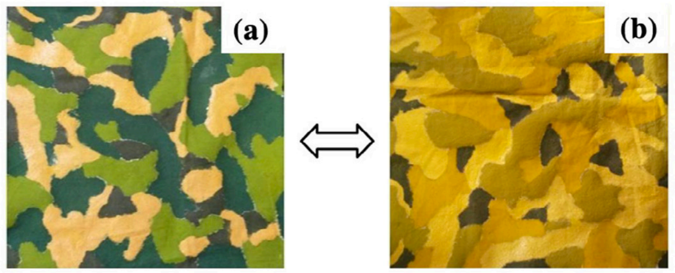

Figure 18: Military uniforms with thermochromic colorants (Karpagam et al., 2017)

Nemiroski et al (2012) used thermochromic dyes in liquids which were transported within a network of tubes within a silicone sheet. They placed this sheet on a soft robot and by regulating the temperature of the liquids, enabled the robot to change color, contrast, pattern, apparent shape, luminescence, and surface temperature. Therefore, the robot is able to camouflage itself by matching its appearance to the background or communicate a message by displaying certain color or pattern (see figure 19) (Nemiroski et al., 2012)

Lee et al. (2020) and Yu et al. (2014) used thermochromic material in a structure of cells within a flexible sheet (see figure 20). The cells can change color individually by locally adjusting the temperature within the cell. The flexibility of the sheet enables it to be used as wearable, and in combination with photodetectors, they can be used to resemble the surroundings which could be used for military purposes (Lee et al., 2020) (Yu et al., 2014).

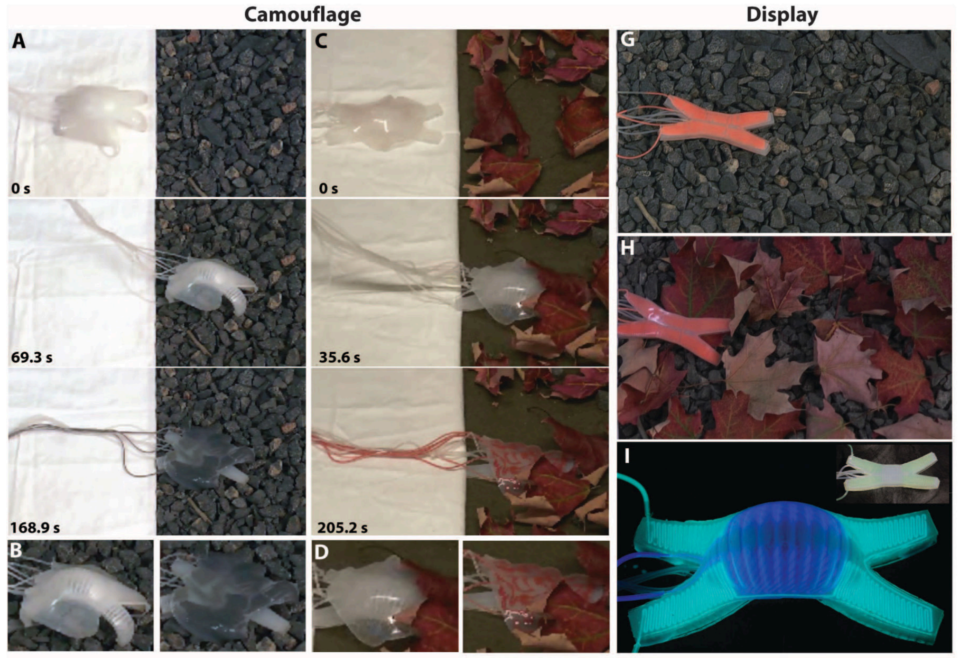

Figure 19: Color adaptive soft robot (Nemiroski et al., 2012)

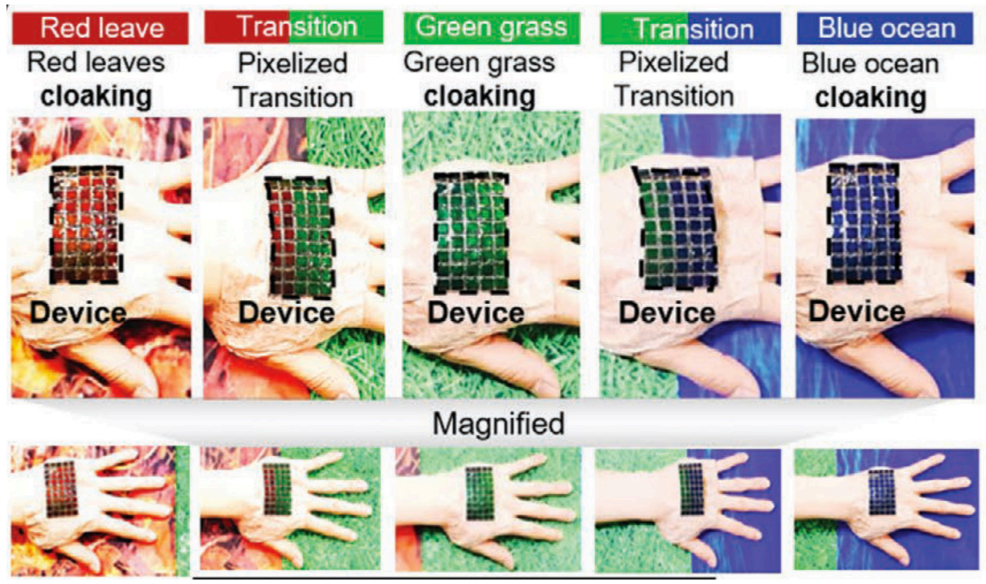

Figure 20: Sheet with dyed cells (Lee at al., 2020)

PHOTOCHROMISM

Photochromism is the property of a material to change color after illumination. This technology is mainly used in sun glasses or windows, which darken after being exposed to the ultraviolet radiation of sunlight (see figure 21)(UKEssays, 2018). The technology can also be used to dye textiles which change color after being exposed to sunlight (see figure 22)(Morsümbül & Akçakoca Kumbasar, 2018).

Figure 21: Photochromic sunglasses (Morsümbül & Akçakoca Kumbasar, 2018)

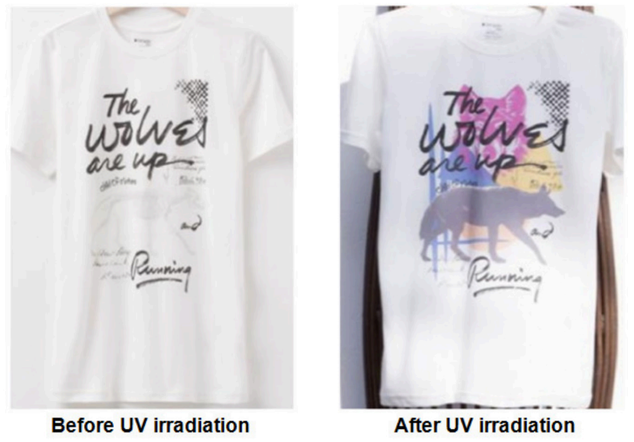

Figure 22: Photochromic textiles (Morsümbül & Akçakoca Kumbasar, 2018)

LIGHT REFRACTION

Light refraction is the bending of light waves with for example a prism or lens. This phenomenon can be used to make something appear differently from different angles. Kamrava et al (2019) used this to built a mechanism for tailoring the color and morphology of a surface, with a biomimetic scale system (see figure 23). On each scale, a combination of lenticular image and lens is placed. Lenticular lenses display only a part of the underlying image, depending on the viewing angle, while lenticular images are graphics consisting of different images or colors (see figure 23). The perceived color is dependent on the angle in which the scales are observed. By controlling the angle in which the scales are positioned, the overall perceived appearance can be modified (see figure 24&25) (Kamrava et al., 2019).

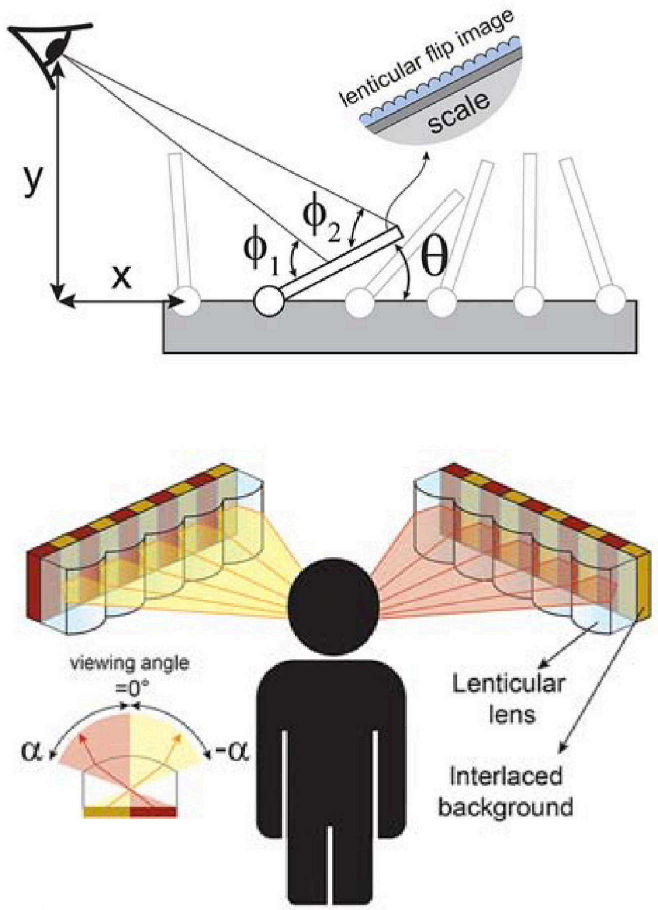

Figure 23: Working principle of lenticular image and lens (Kamrava et al., 2019)

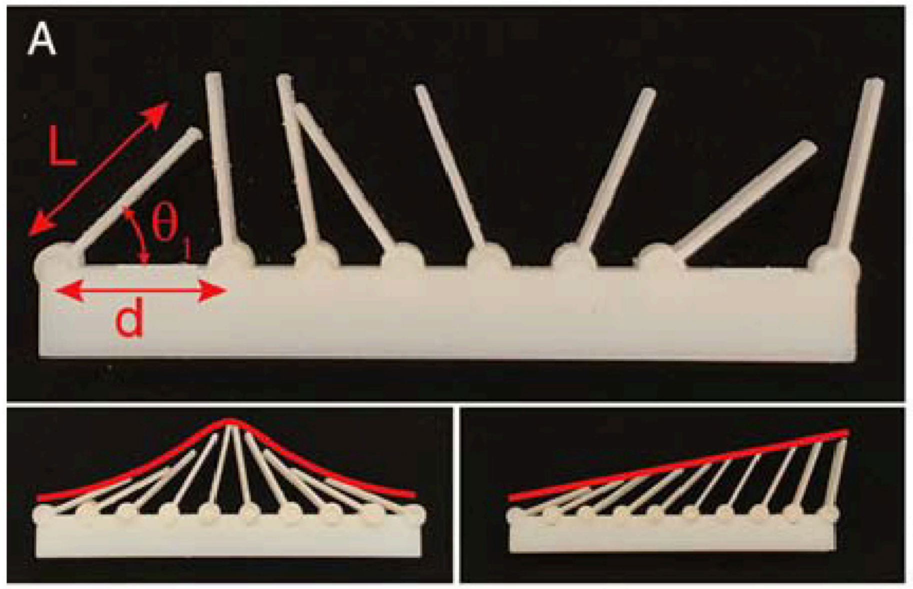

Figure 24: Biomimetic scale system for tailoring surface morphology (Kamrava et al., 2019)

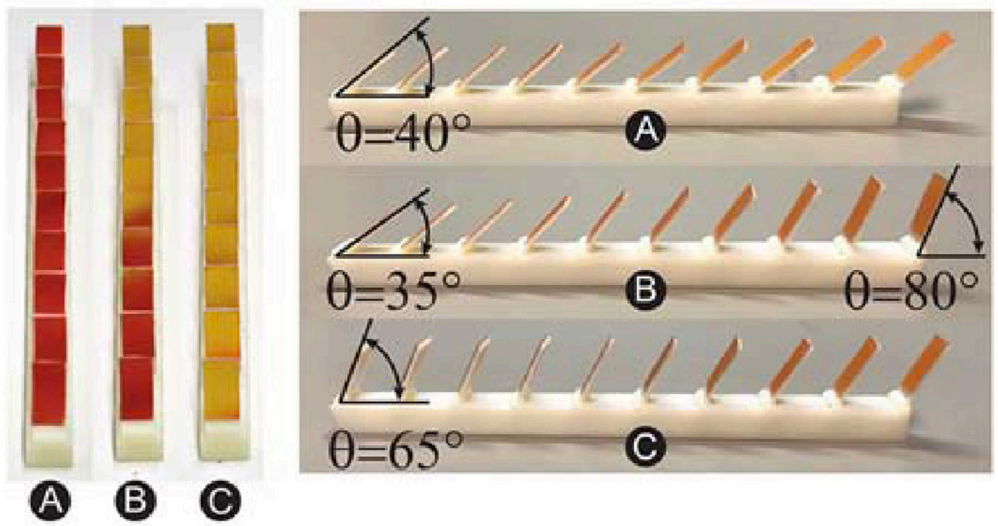

Figure 25: Perceived color depended on viewing angle (Kamrava et al., 2019)

LIGHT TRANSMITTANCE

By expanding chromatophore cells in their skins, cephalopods regulte the amount of light which transmits through their skin and thereby adjust their transparancy. Various researchers haven found inspiration in this and have tried to mimic chromatophore cells to adjust the transparency of a material. For example, Xu et al. (2020) sandwiched an dielectric elastormer layer between two layers of highly conductive membranes. After actuation, the layers spread out which makes them thinner and assures a more flattened smooth surface. Both result in an increased transparency (see figure 26&27) (Xu et al., 2020).

Rossiter et al (2012) used a similar technology to create an opposite effect. They also used layers of compliant electrodes and electroactive polymers which compress after electric actuation. However, In between the layers, they placed a pigmented fluid. The fluid spreads out due to the compression which reduces the transparency, similarly as chromatophores spread out in cephalopod skin (see figure 28)(Rossiter et al., 2012).

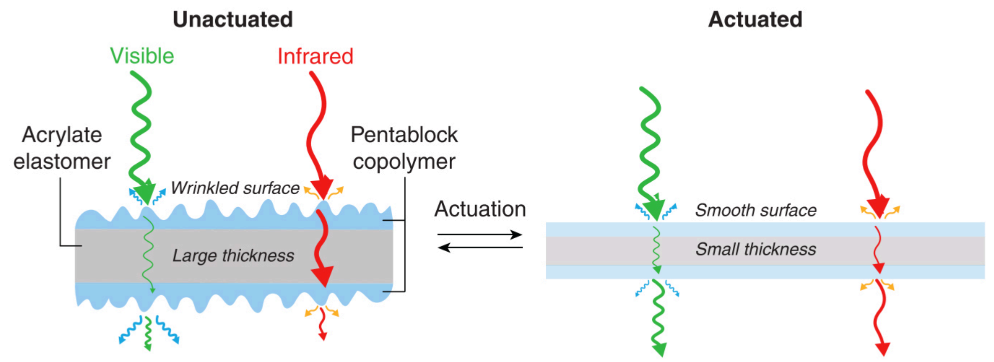

Figure 26: Dielectric elastomers spreading out after actuation (Schematic - Sideview) (Xu et al., 2020)

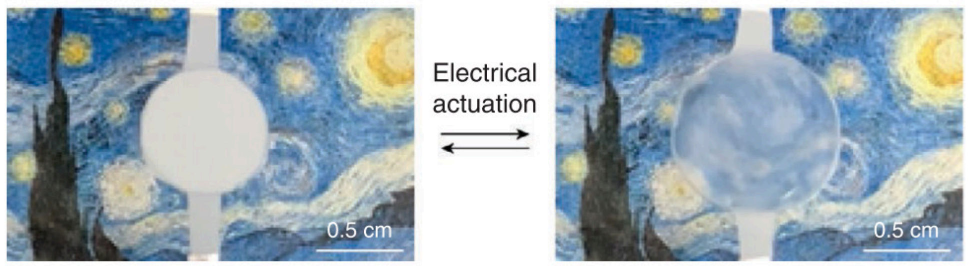

Figure 27: Dielectric elastomers spreading out after actuation (Photograph - Topview) (Xu et al., 2020)

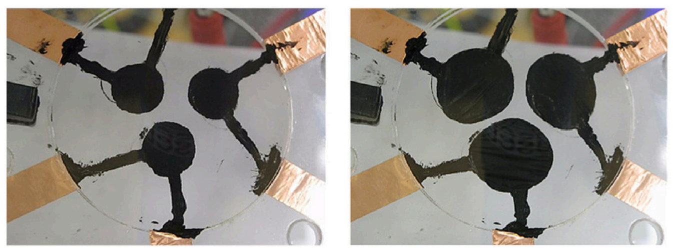

Figure 28: Pigmented fluid spreads out due to compression (Rossiter et al., 2012)

1.4 KNOWLEDGE GAP

Existing solutions for active appearance change often require complex technologies, involving state-of-the-art materials, chemical processes and advanced forms of actuation. Only little research exists on achieving an appearance change with a 'simple' mechanical solution, involving a mechanism which deforms and thereby achieves an appearance transformation.

At the same time, current research often only shows proof-of-principle results, which are still (far) removed from the application of these technologies in actual products or industries.

With the development of a new solution for achieving appearance change, a new and unexplored field arises. This offers the opportunity to come up with interesting implementation solutions which could enhance product interactions, enable new forms of communication and expression or enrich the product's experience or aesthetic value.

1.5 DESIGN GOAL & SCOPE

After analyzing existing solutions and defining of unexplored fields where there is room for new solutions, a revised design goal is stated in the form a 'Design Scope' in which the general aims and focus points of the project are described.

REVISED DESIGN GOAL

- To achieve an appearance transformation by the development of a simple and 'low-tech' mechanism which dynamically changes in shape and thereby changes the appearance of the product.
- To find a suitable application to which the developed technology can be applied to.
- Thereby creating an added value to this product or environment, by facilitating communication opportunities, enhancing interactions or enriching the user experience.

SCOPE

- With the mechanism, I will focus on an alteration of color, transparency or texture, as this occurs in nature.
- For the fabrication of the mechanism, I will focus on digital fabrication technologies such as 3D-printing and laser cutting, as these technologies are accessible, and offer the opportunity to create customized, complex geometries with high precision and consistancy, while minimizing manual labor.
- For the material used to fabricate the mechanism, I will focus on materials that are suitable for shape changing mechanisms and are processable with digital fabrication such as plastics, elastomers, fabrics and metals
- For the actuation of the mechanism, I will focus on electrical and pneumatic actuators as they require relatively simple and durable technology and thereby fit with the 'Revised Design Goal'.

PART 2

MECHANISM & WORKING PRINCIPLE

INTRODUCTION

The previous phase concluded with a revised design goal to achieve an appearance transformation with a simple and low-tech, shape-changing mechanism. Therefore, the goal of this phase was to find an ideal mechanism to achieve that goal. This was done through a combination of literature research on shape-changing mechanism, ideation on suitable solutions and practical exploration of mechanisms, materials and fabrication methods. Finally, the ideas were converged into five potential directions and one direction was chosen for further development.

CONTENT

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2.2	IDEATION	24
2.3	EXPLORATION	25
2.4	CLUSTERING	26
2.5	MECHANISM CONCEPTS	27
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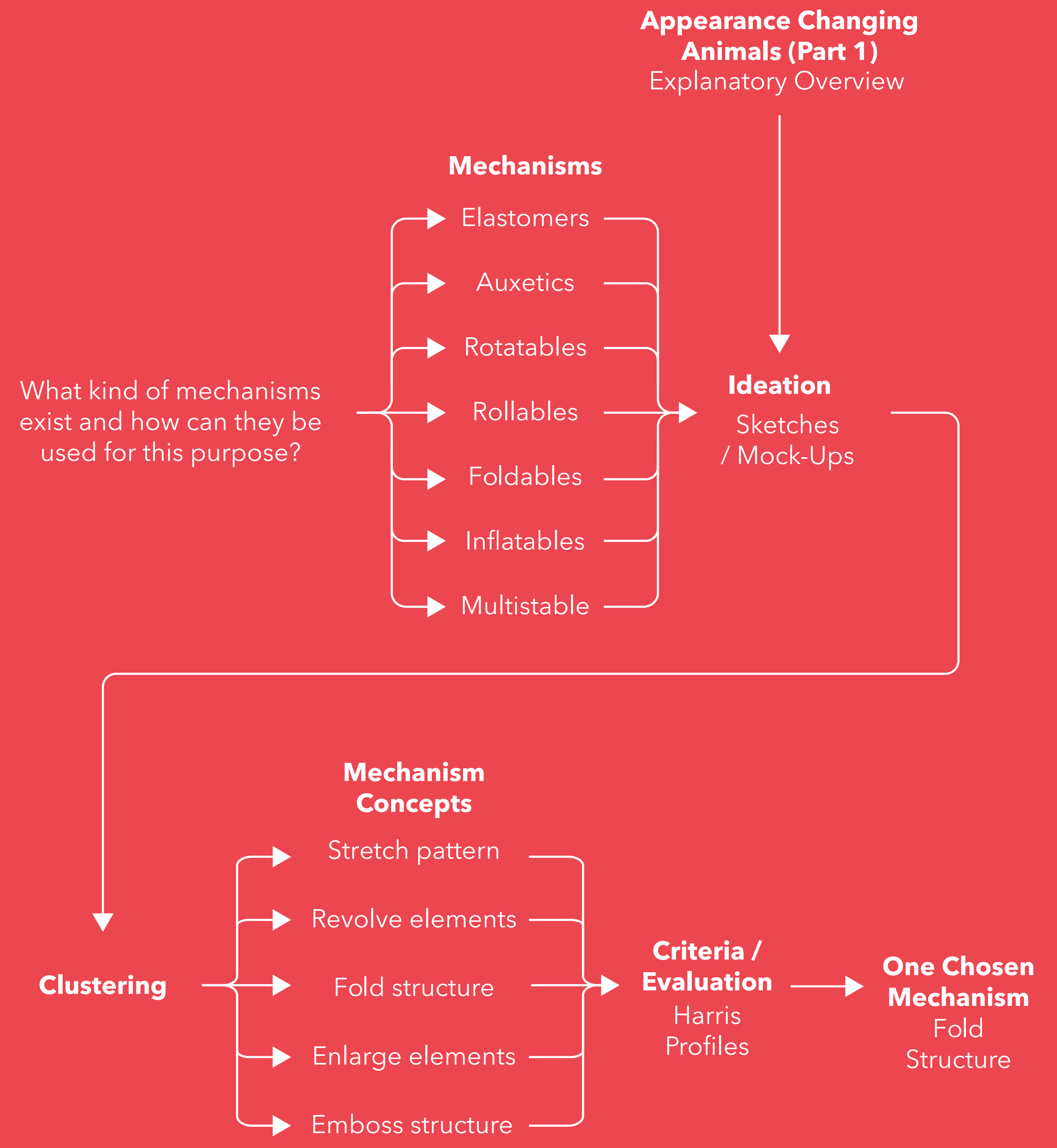


2.1 SHAPE CHANGING MECHANISMS

The goal for this project is to achieve an appearance change due to a mechanism which transforms in shape. Therefore, an overview of potentially suitable shape-changing mechanisms was created. The chapter includes an explanatory overview of the gained knowledge. A more elaborate explanation, including typical applications for each mechanism, is given in Appendix C.

APPROACH

In order to get an overview of existing mechanisms and to find an ideal mechanism which can deform and thereby ensure an appearance transformation, I searched for literature on Google and Google Scholar concerning shape-changing mechanisms. In addition, I searched on image sharing platforms such as Pinterest for mechanism applications and watched explanatory videos to get a better idea of the working principle of various mechanisms. To get to the obtained information, I mainly used the following keywords: Shape-changing mechanism, dynamic mechanism, appearance changing mechanism, color changing mechanism, texture changing mechanism and transparency changing mechanism.

As a result, I found various papers concerning this topic, of which two were found to be particularly informative and insightful for this project. These papers from Thill et al. (2008) and Qamar et al. (2018) list categories and examples of shape changing mechanisms used in respectively aircrafts and human-computer interfaces.

I have used most of their categories as guidance for the overview and complemented them with a new category: rotatable structures. This category does not fit perfectly with the others, but it involves many solutions that are suitable for the purpose of appearance change.

Furthermore, I listed examples and typical applications in which the mechanisms are currently used, which can be found in Appendix C. Finally, for each category, I described how I think they can be used to achieve an appearance adaption of a product surface and in some cases support this with examples from literature.

OVERVIEW

An overview of the potential solutions for appearance transformation is shown in figure 29. The overview shows the seven shape changing mechanism categories, the three ways to achieve the appearance transformation with a mechanism and the specific appearance features that change.

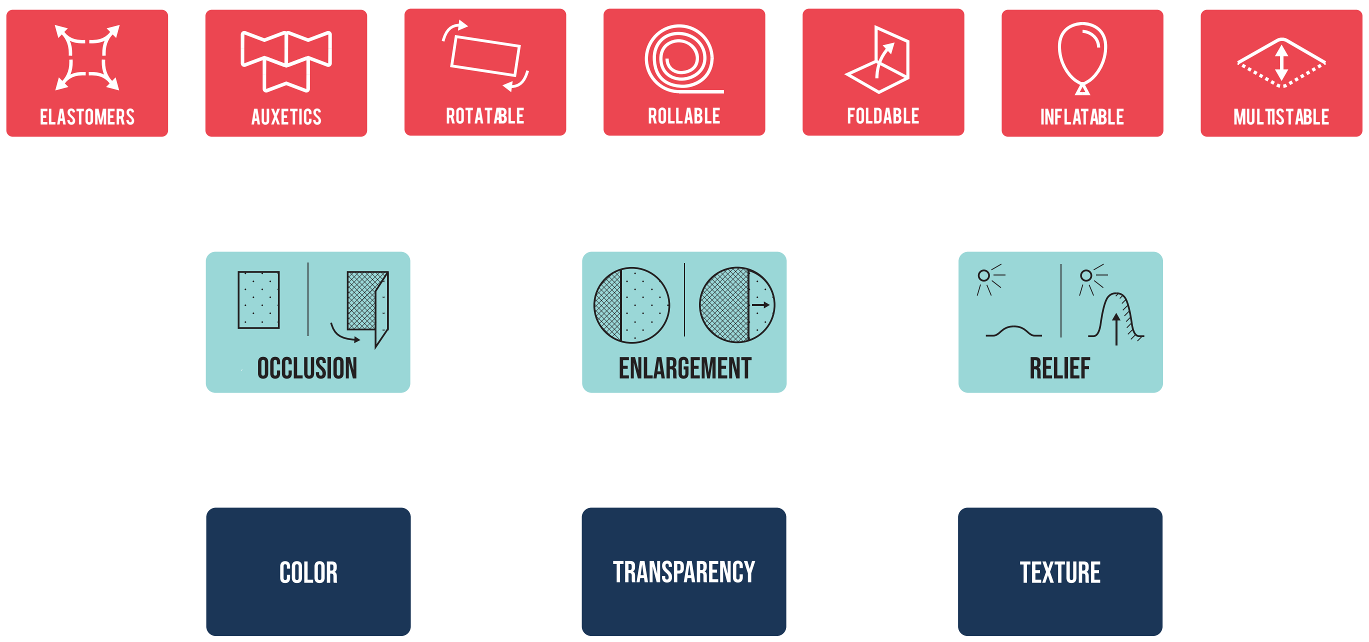


Figure 29: Overview of potential solutions for achieving appearance change with a shape-changing mechanism

SHAPE CHANGING MECHANISM

ELASTOMERS

Elastomers (or rubbers) can be stretched or compressed and thereby increase or decrease in area. Elastomers are polymers with a low elastic modulus (Young's modulus, a material's resistance to being stretched) which enables them to undergo large deformations without deforming permanently (Thill et al., 2008) (Qamar et al., 2018).

AUXETICS

Auxetics are structures or materials which have a negative Poisson's ratio. When stretched or compressed, these structures become respectively wider or narrower in perpendicular direction of the applied force. This is due to an internal 'honey-comb' structure of cells which can deform because of their hinge-like architecture (Kolken & Zadpoor, 2017).

ROTATABLES

Rotatable structures rotate around a central point or axis. Hereby, the shape itself stays the same but its position within a space changes (Khan Academy, n.d.). Thereby, a structure of rotating elements can transform in both shape and appearance.

ROLLABLES

Rollable structures roll out by a combination of rotation and translation. Hereby, their area expands, and their shape transforms from a cylinder to a flat sheet(Qamar et al., 2018).

FOLDABLES

Foldable structures fold in or out and thereby, turn from a flat sheet into a three-dimensional structure or shape. By folding, they can increase or decrease in area (Qamar et al., 2018).

INFLATABLES

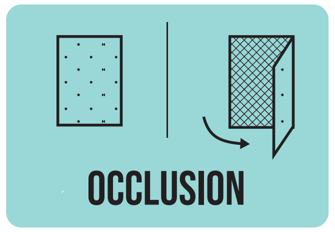
Inflatables structures can be inflated with gas or air and thereby increase in size, strength and stiffness. Their advantages are their low weight and production costs, their ability to pack into small volumes and their ability to deploy into almost any shape (Qamar et al., 2018).

MULTISTABLES

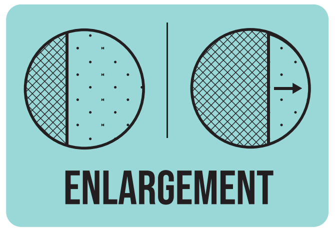
Multi-stable structures deform rapidly from one stable state to another. Typically, only low actuation forces are needed to generate large deformations and the mechanisms can hold their positions without power input. (Qamar et al., 2018).

USAGE OF THE MECHANISMS

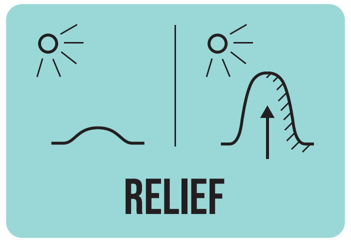
When analyzing the shape changing mechanism categories, I found that there are three main ways to achieve an appearance transformation while using (a combination of) these mechanisms:



OCCLUSION
By operating the mechanisms, it is possible to expose a visual element, while elimination another. Thereby achieving a change of color and/or transparency.



ENLARGEMENT
By operating the mechanisms, it is possible to enlarge a visual element, while reducing another. Thereby achieving a change of color and/or transparency.



RELIEF
By operating the mechanisms, it is possible to emboss a surface to create brilliance and shading. Thereby achieving a change of color and/or texture.

2.2 IDEATION

Several idea generation sessions were performed in order to find solutions for the design goal to achieve an appearance adaption with a shape changing mechanism.

APPROACH

With the gained knowledge and insights about shape-changing mechanisms and how they could be used to achieve an appearance transformation, I made numerous sketches. Here, I looked for answers to the following question:

'How can a mechanism achieve an appearance transformation to a product?'

In order to organize the ideas, to find similar principles and to fulfill unexplored fields, I made an overview in which the sketches were placed. This overview includes the mechanism categories and types of appearance change.

OVERVIEW

An overview of the generated ideas is shown in figure 30.

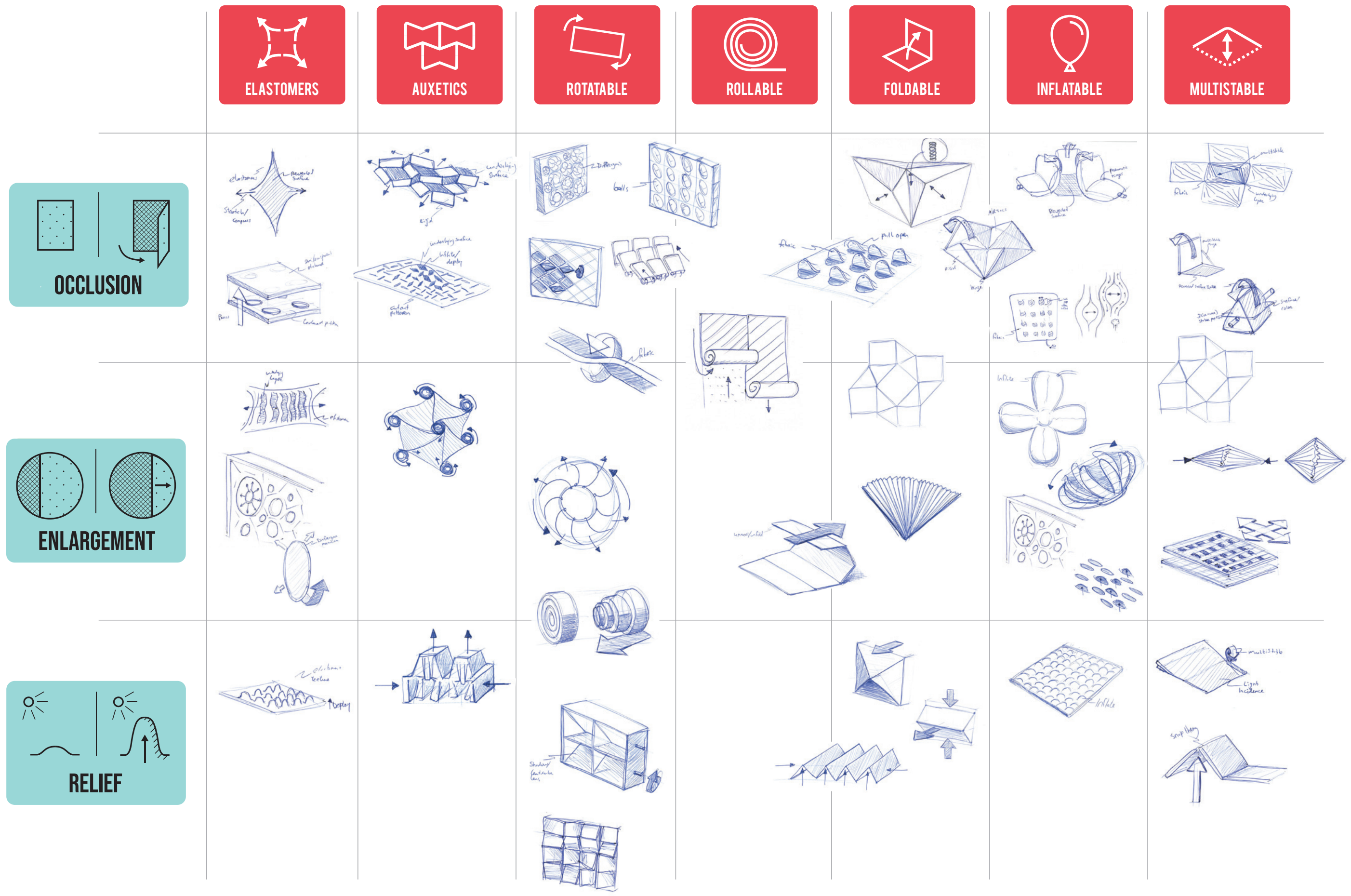


Figure 30: Overview of generated ideas

2.3 EXPLORATION

In order to find an ideal mechanism, an exploration of working principles, materials and fabrication processes was performed with physical prototypes.

APPROACH

In order to test the working principle of the generated mechanisms, and to explore suitable materials and fabrication processes for these mechanisms, I made physical prototypes. For example, I laser cut paper, cardboard and wood and explored various foldable, rotatable and auxetic structures by creating hinges with pins, tape and rubber bands. I casted silicone in a mold and sealed TPU coated nylon with a flat iron to explore inflatable structures. Furthermore, I explored the potential of fabrics such as felt and nylon and other soft materials and used them to explore various mechanisms.

Finally, I put the physical prototypes in the same overview as the idea generation, to organize them and to find unexplored fields.

OVERVIEW

An overview of the explored working principles of mechanisms, materials and fabrication processes is shown in figure 31.

Figure 31: Overview of explored working principles, materials and fabrication processes

2.4 CLUSTERING

The generated solutions were converged into five clusters in order to make a preliminary selection and to get an overview of the potential directions for further development.

APPROACH

Firstly, I looked for matching working principles among the potential solutions. Subsequently, I made a preliminary selection in which I eliminated some of the solutions. This selection was based on an evaluation in which I rated the ideas and prototypes in terms of their (assumed) performance, feasibility and applicability.

I made assumptions on how well the solutions would succeed in the goal of active appearance adaption, if they would be producible within the given time with the available resources and if they would be suitable for the application to a product.

As a result, I clustered the solutions into five potential directions for further development. I supported each direction with two sketched mechanism solutions which best describe the direction and a collage to show the potential appearance transformation, achieved by the mechanism.

OVERVIEW

An overview of the clusters is shown in figure 32.

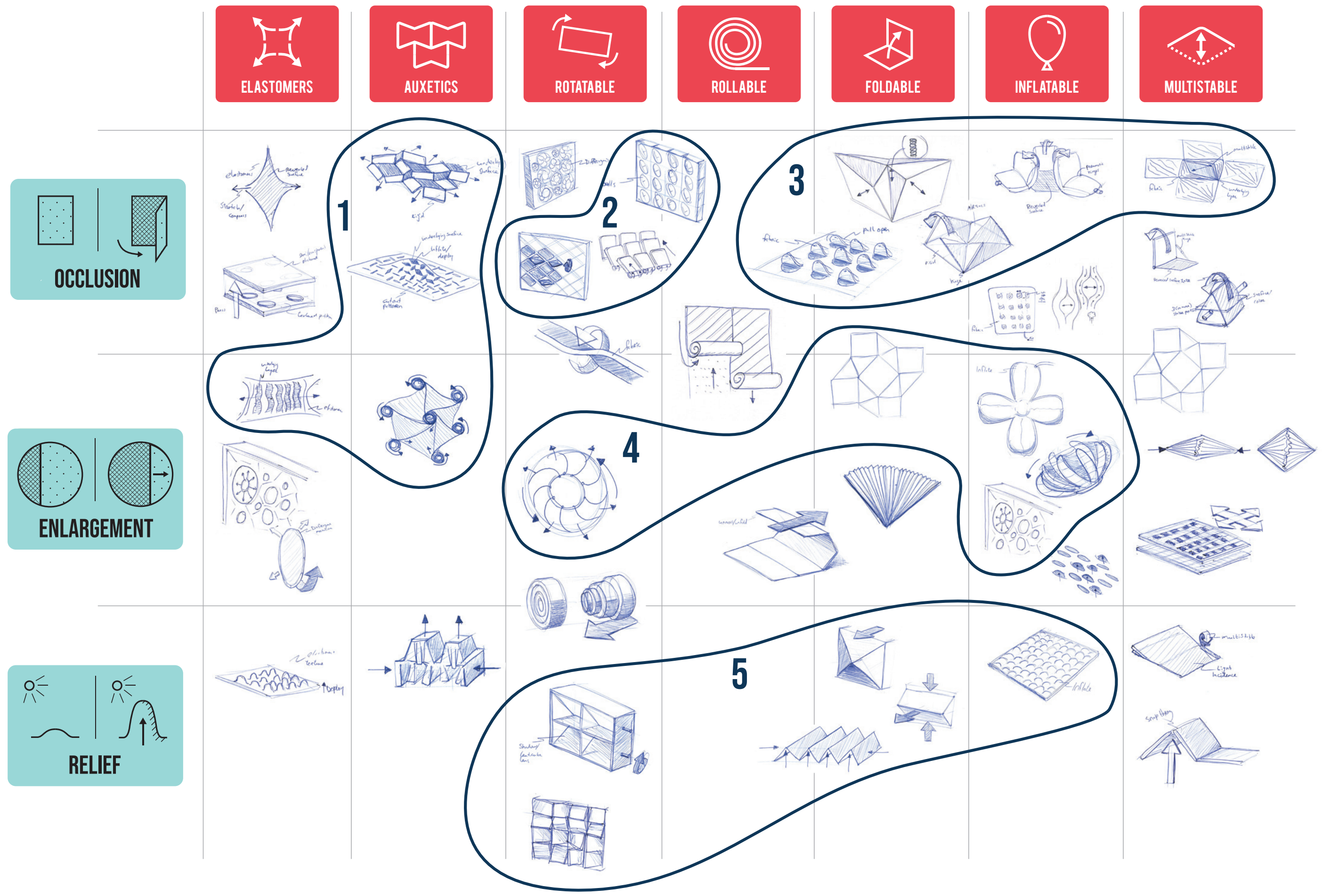
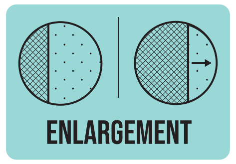


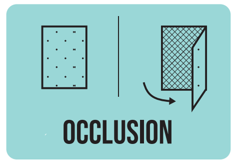
Figure 32: Overview of generated clusters

2.5 MECHANISM CONCEPTS

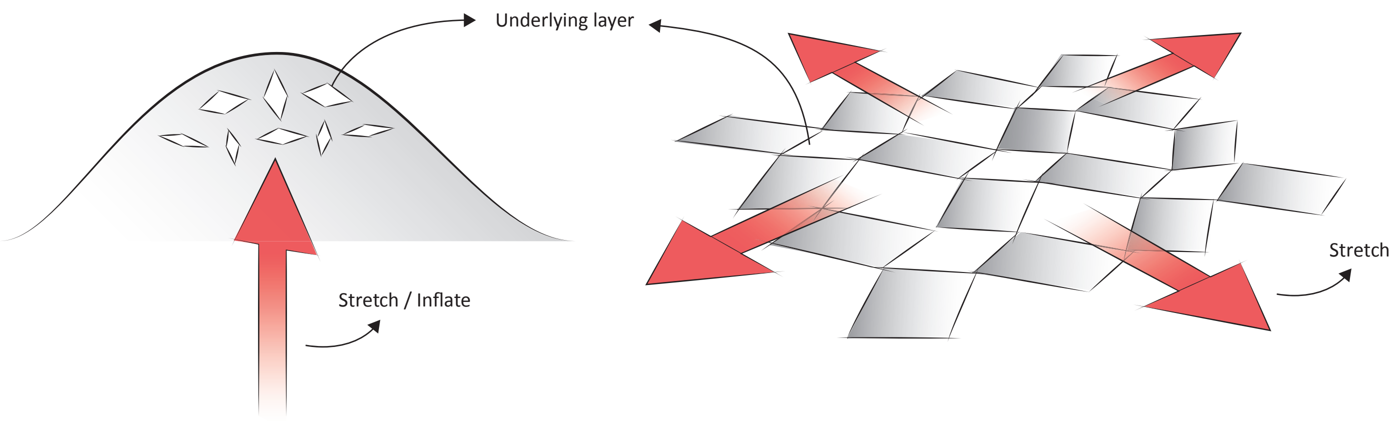
The five mechanism clusters were translated to five mechanism concepts which act as potential directions for further development. For each concept, two potential working principles are given, and inspirational collages with explementary mechanisms or applications are added to show the potential visual effect that the mechanisms could create. Finally, for each concept is indicated how appearance change is achieved.

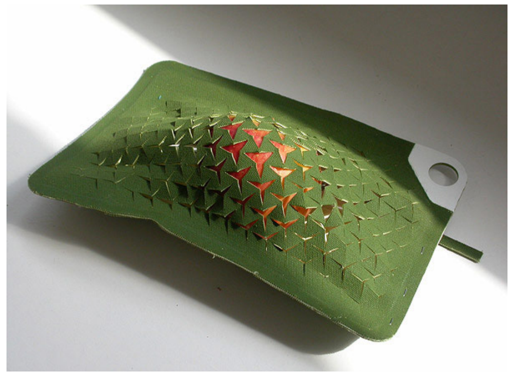
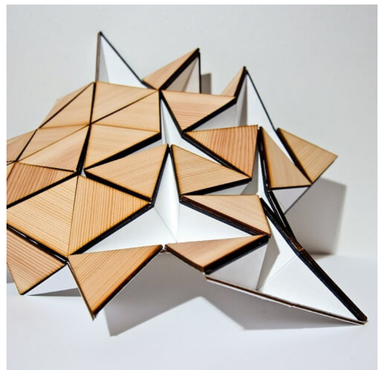
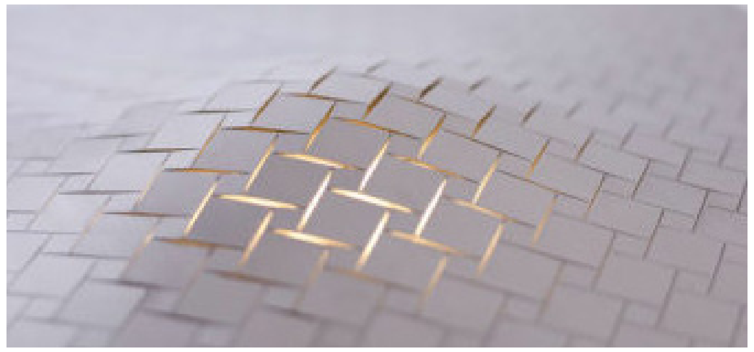
CONCEPT 1
STRETCH PATTERN



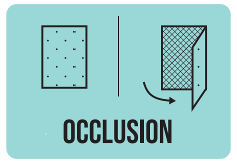


Stretching out a patterned surface to show an underlying layer

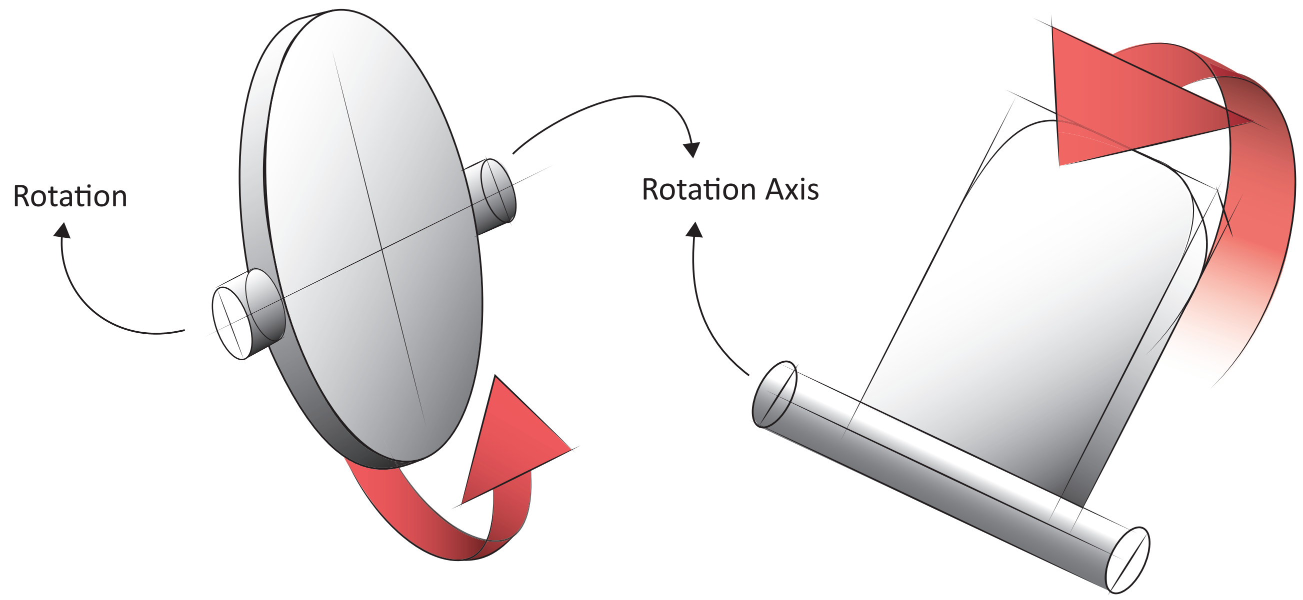


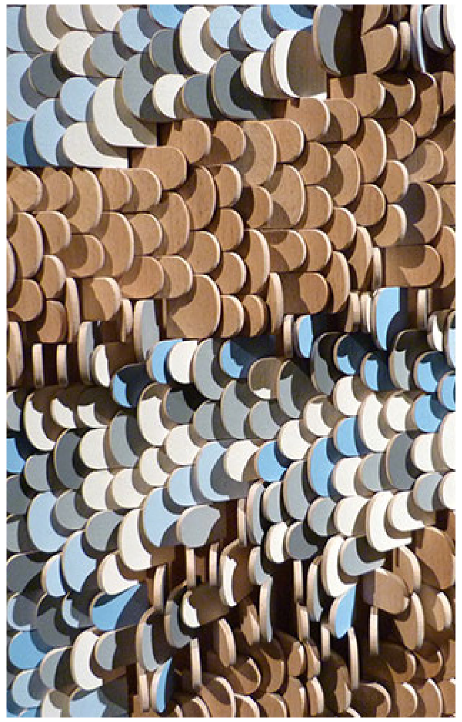
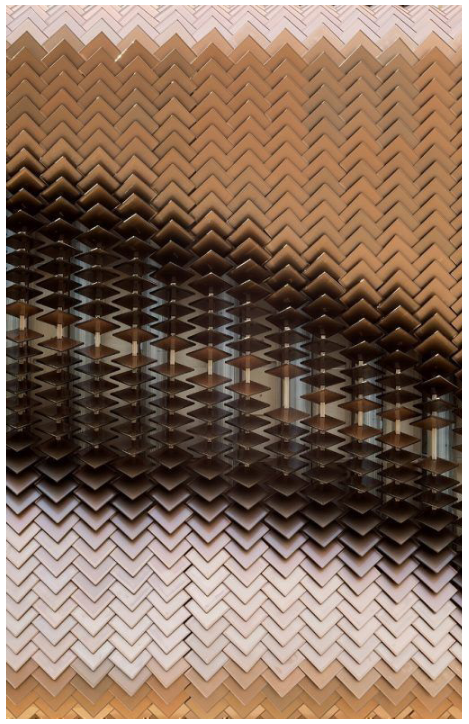
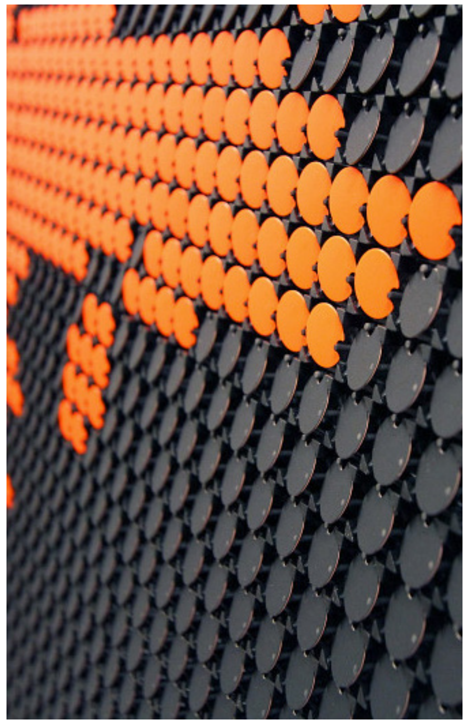





CONCEPT 2
REVOLVE ELEMENTS



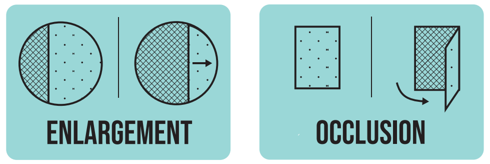
Rotation of discs or flaps over an axis to show an underlying layer or the backside of the element



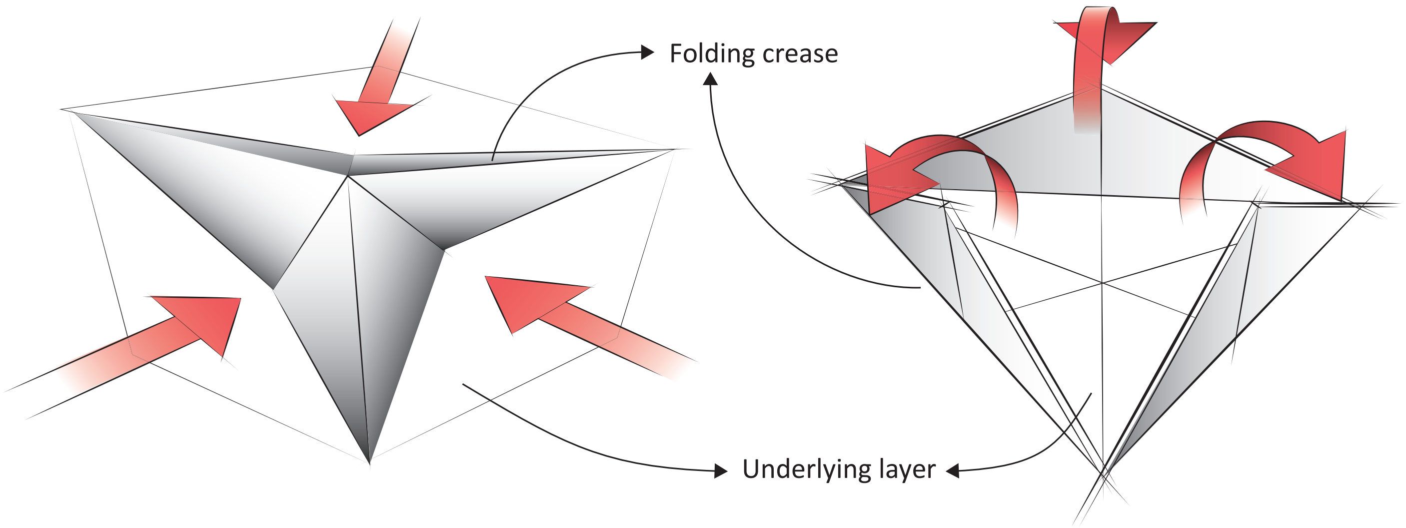




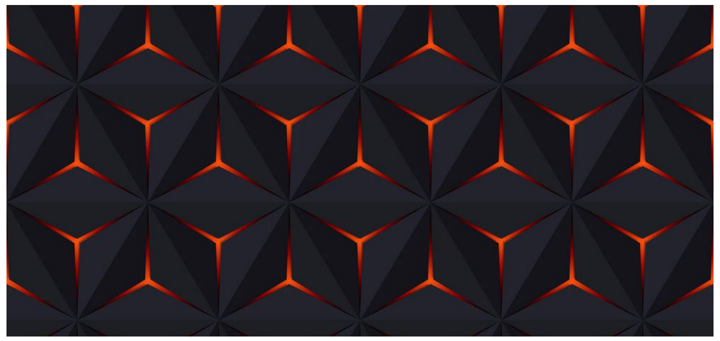
CONCEPT 3

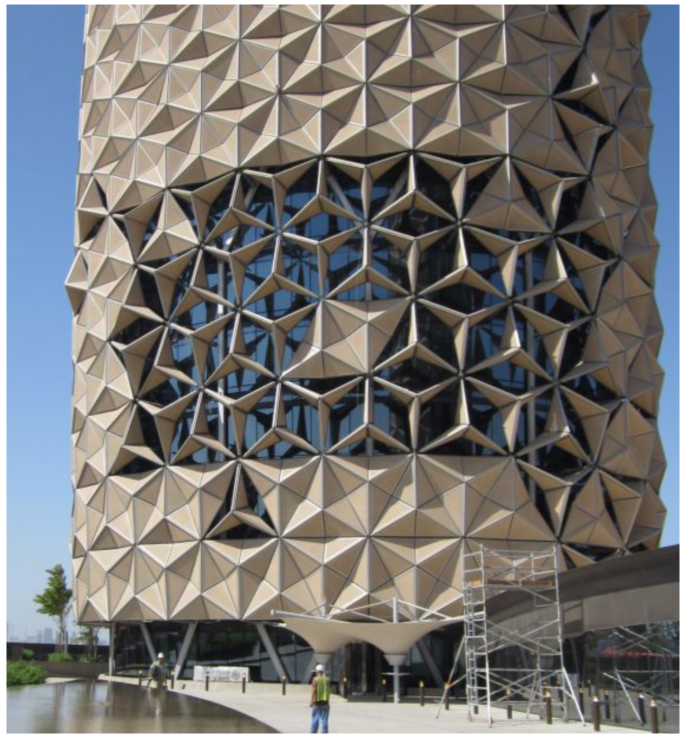
FOLD STRUCTURE



Folding over a pattern of creases to show an underlying layer

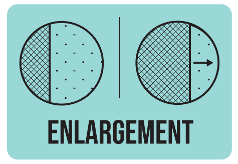




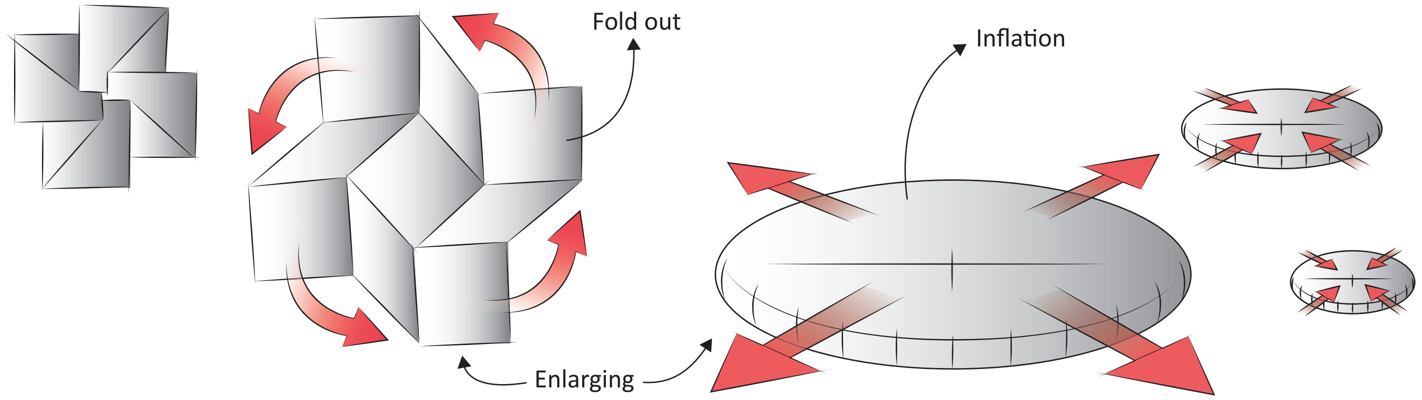


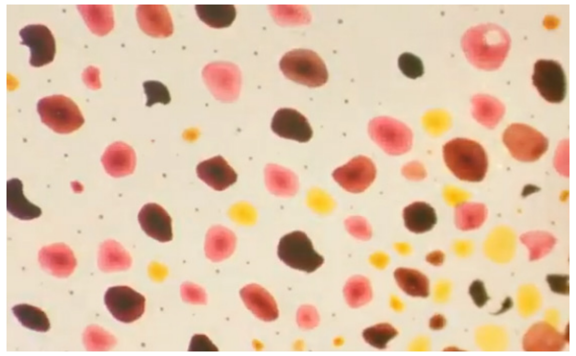
CONCEPT 4

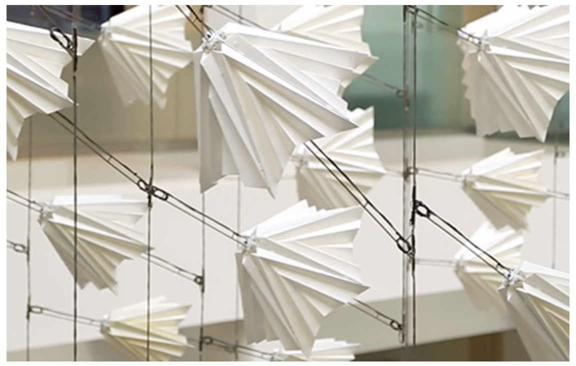
ENLARGE ELEMENTS



Enlarging elements to make them more visible or to cover an underlying layer

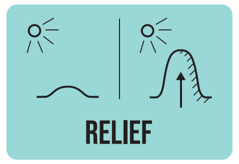


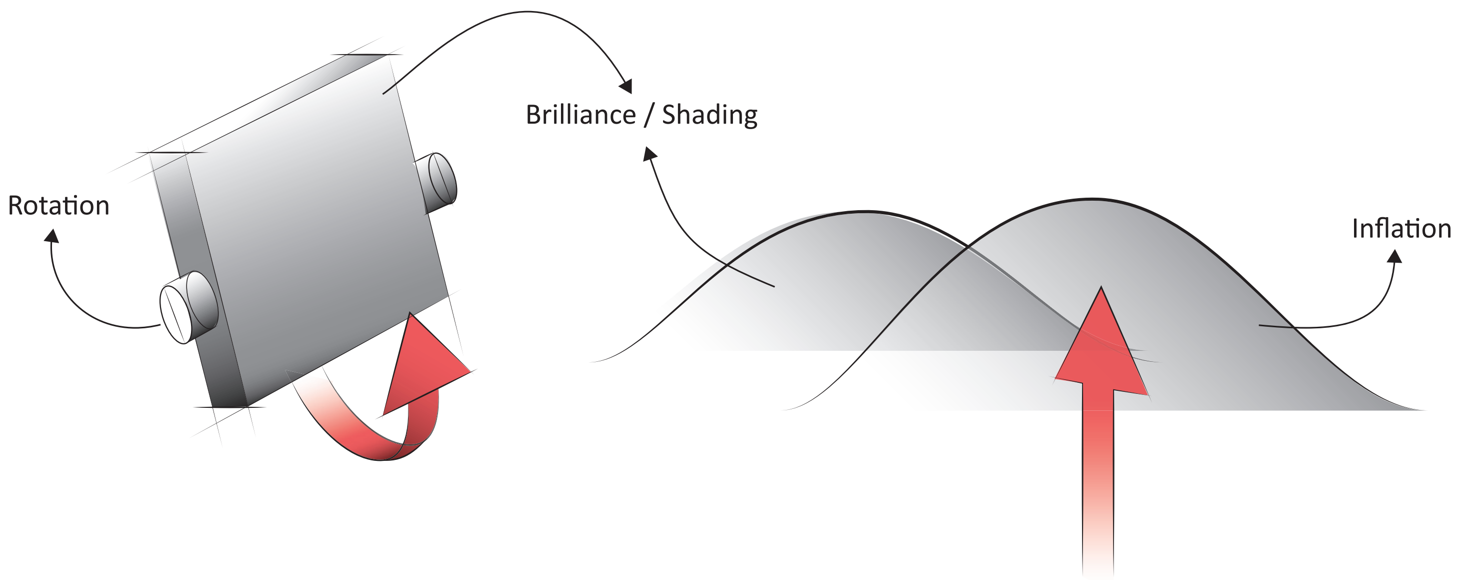




CONCEPT 5
EMBOSS STRUCTURE

Embossing a texture to modify the brilliance and shading of the surface





2.6 CONCEPT EVALUATION

The five potential directions were evaluated by means of nine points of criteria and one direction was chosen for further development.

APPROACH

In order to choose the most promising direction, I started with formulating nine requirements in terms of performance, feasibility and applicability. I formulate them in such way that they are concrete and testable. I used Harris Profiles to evaluate and compare the directions. Harris Profiles give a graphical representation of the evaluated concepts, as they provide a rating on all requirements in a graphical four-point scale. Thereby, the profiles clearly show the overall score for each concept in a visual way (Boeijen et al., 2014). I mainly rated the requirements as comparison to each other and in some cases the rating is a subjective assumption, as the requirements were not always testable. However, the profiles helped me to choose the direction with the most potential and to substantiate this decision.

CRITERIA

PERFORMANCE:
How well does the mechanism succeed in the goal of active appearance change?

1: The mechanism provides a clear change of appearance by changing from one color to another or from opaque to transparent, *to ensure that the effect is noticeable and that it can therefore be used for the purpose of interactivity, expression, communication or response*

2: The mechanism enables a spectrum of appearances instead of only a few states, *which broadens the possibilities for using the mechanism for the purpose of interactivity, expression, communication or response*

3. The mechanism enables the possibility of local appearance change, *which broadens the possibilities for using the mechanism for the purpose of interactivity, expression, communication or response*

FEASIBILITY:
Is it possible to build the mechanism within the given time with the available resources?

4. The mechanism can be actuated with simple mechanical or pneumatic actuators, *in order to fulfill the goal of keeping the solutions simple and 'low-tech'*

5. The mechanism can be fabricated, assembled and actuated with many at the same time or together as one part, *allowing quick and effortless production on a larger scale.*

6. The mechanism can in total, or to a large extent, be fabricated with digital fabrication technology, *assuring high precision and consistency while minimizing manual labor.*

APPLICABILITY:
How suitable is the mechanism for the application to a product?

7. The mechanism is applicable to any surface or shape, *and can therefore be applied to products of any shape*

8. The mechanism keeps the overall contour or shape of the surface intact during the transformation, *and thereby keeps the product's functionality intact*

9. The mechanism keeps the product's surface rigid without loose or fragile parts, *and is thereby suitable for contact and interaction*

HARRIS PROFILES

PERFORMANCE
1: The mechanism provides a clear change in appearance
2: The mechanism enables a spectrum of appearances instead of only a few states
3: The mechanism enables the possibility of local appearance change
FEASIBILITY
4: The mechanism can be actuated with simple mechanical or pneumatic actuators
5: The mechanism can be fabricated, assembled and actuated with many at the same time or together as one part
6: The mechanism can in total, or to a large extent, be fabricated with digital fabrication technology
APPLICABILITY
7: The mechanism is applicable to any surface or shape
8: The mechanism keeps the overal controur or shape of the surface intact
9: The mechanism keeps the product's surface rigid without loose or fragile parts

STRETCH

	--	-	+	++		
1			■		PERFORMANCE	Addition of a color/change in transparency
2		■				Only original color and the added element
3			■			Possible with locally stretching/inflation
4			■		FEASIBILITY	Mechanical stretching/Inflation
5			■	■		One patterned sheet (+underlying surface)+ Actuators
6			■	■		Laser cut/3D-print with fabrics/elastormers/plastics
7		■			APPLICABILITY	Shaping the sheet would stretch it out
8		■				Stretching changes the contour and shape of the surface
9			■			No loose or fragile parts

REVOLVE

	--	-	+	++		
1			■	■	PERFORMANCE	One color to another/change in transparency
2			■	■		Different elements can show different colors
3			■	■		Elements can be actuated individually
4			■	■	FEASIBILITY	Mechanical rotation, electromotor
5	■	■				Many parts and actuators needed
6			■	■		Laser cut/3D-print with plastics or metals
7			■		APPLICABILITY	Possible but not easy
8			■			Revolving the discs changes the surface morphology
9	■	■				Many loose and fragile parts making it inconvenient for interaction

FOLD

	--	-	+	++		
1			■	■	PERFORMANCE	One color to another/change in transparency
2			■			Different elements can show different colors
3			■	■		Elements can be actuated individually
4			■		FEASIBILITY	Mechanical bending/Inflation
5		■				One patterned sheet (+underlying surface)/Many parts and actuators
6			■	■		Laser cut/3D-print with fabrics/elastormers/plastics/metals
7			■	■	APPLICABILITY	Structure built up of triangles can easily be shaped
8			■			Unfolding changes the surface morphology
9			■			No loose or fragile parts

ENLARGE

	--	-	+	++		
1			■		PERFORMANCE	Elements become more visible, no elimination/change in transparency
2			■	■		Different elements can show different colors
3			■	■		Elements can be actuated individually
4			■		FEASIBILITY	Mechanical rotation/Inflation
5	■	■				One patterned sheet/Many parts and actuators needed
6			■			Laser cut/3D-print/sealing/casting with fabrics/elasomers / plastics
7			■		APPLICABILITY	Possible but not easy
8			■			Enlargement changes the surface morphology
9	■	■				Many loose and fragile parts making it inconvenient for interaction

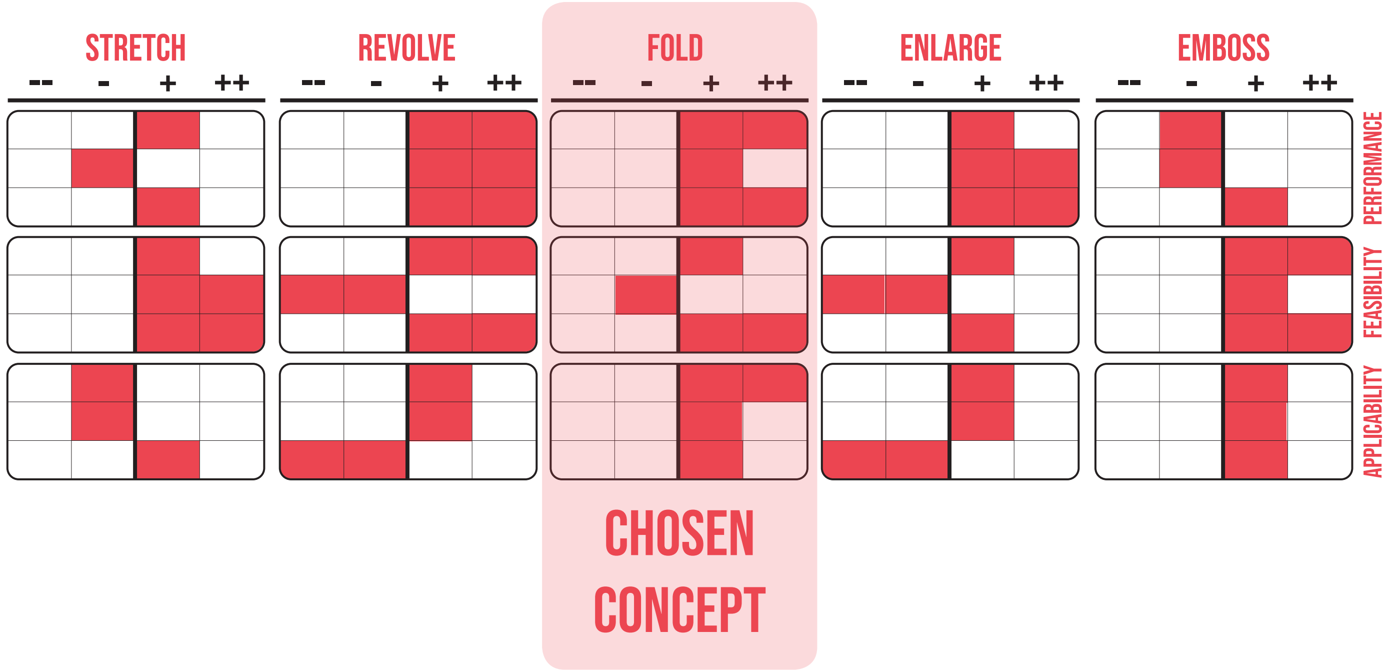
EMBOSS

	--	-	+	++		
1		■			PERFORMANCE	Only a change in texture and change inbrilliance and shading
2		■				Only brilliance and shading
3			■			Possible by embossing locally
4			■	■	FEASIBILITY	Mechanical bending/Rotating/Inflation
5			■			One patterned sheet (+underlying surface)/Many parts and actuators
6			■	■		Laser cut/3D-print/sealing/casting with fabrics/elasomers/plastics
7			■		APPLICABILITY	Possible but not easy
8			■			Embossment changes the surface morphology
9			■			No loose or fragile parts

CHOOSING DIRECTION

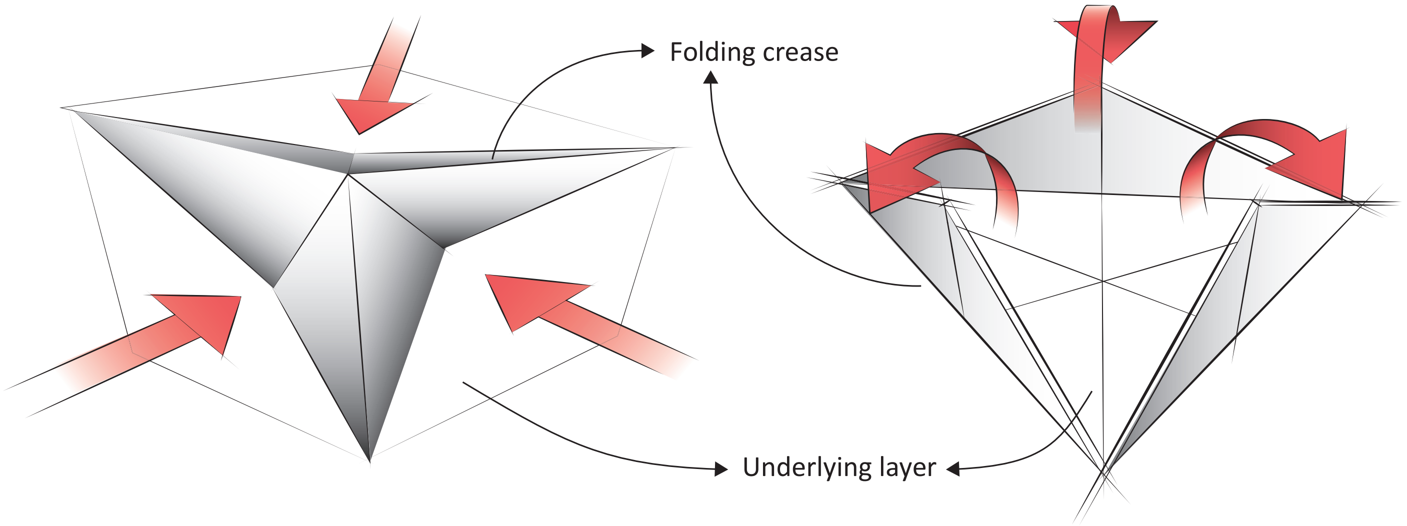
When placing the five profiles next to each other, they can be compared to each other and one can be chosen for further development. This is done by looking at the Harris Profiles and seeing which one is rated most positively. Here, the upper points of criteria are prioritised over the lower ones. After comparing the concepts, It can be concluded that the 'Fold Structure' has the best overall score.

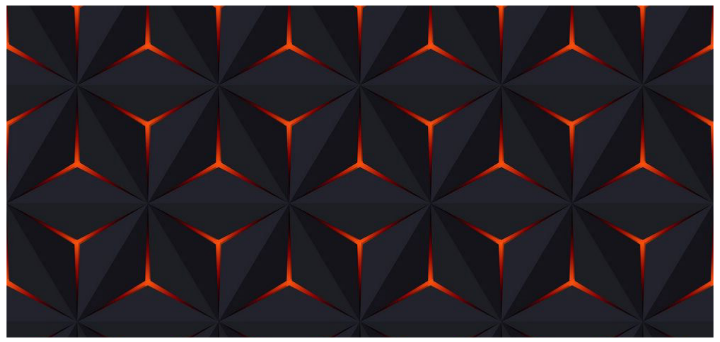
Although the concept is outscored by other concepts in terms of performance and feasibility, it has the best score in terms of applicability and has the least negative ratings. Therefore, this direction is chosen for further development.

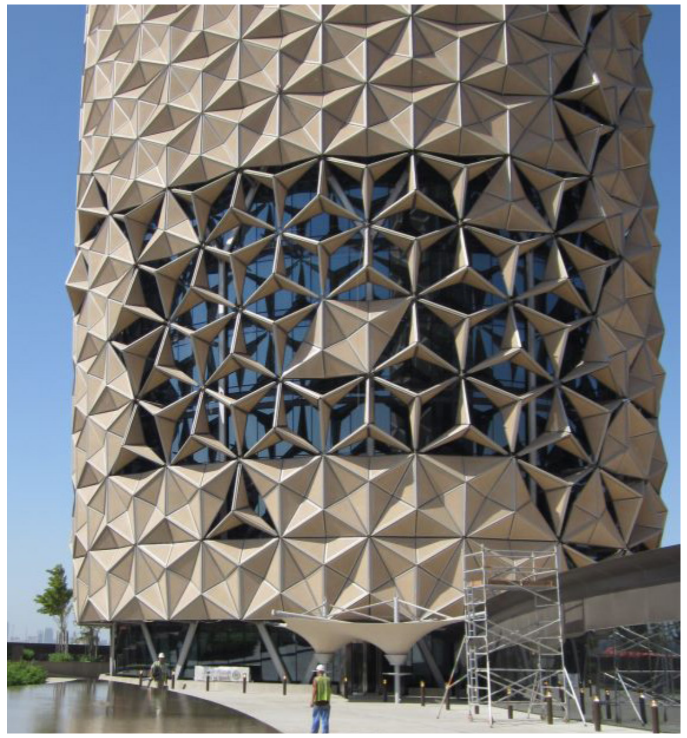


CHOSEN CONCEPT

FOLD STRUCTURE







PART 3

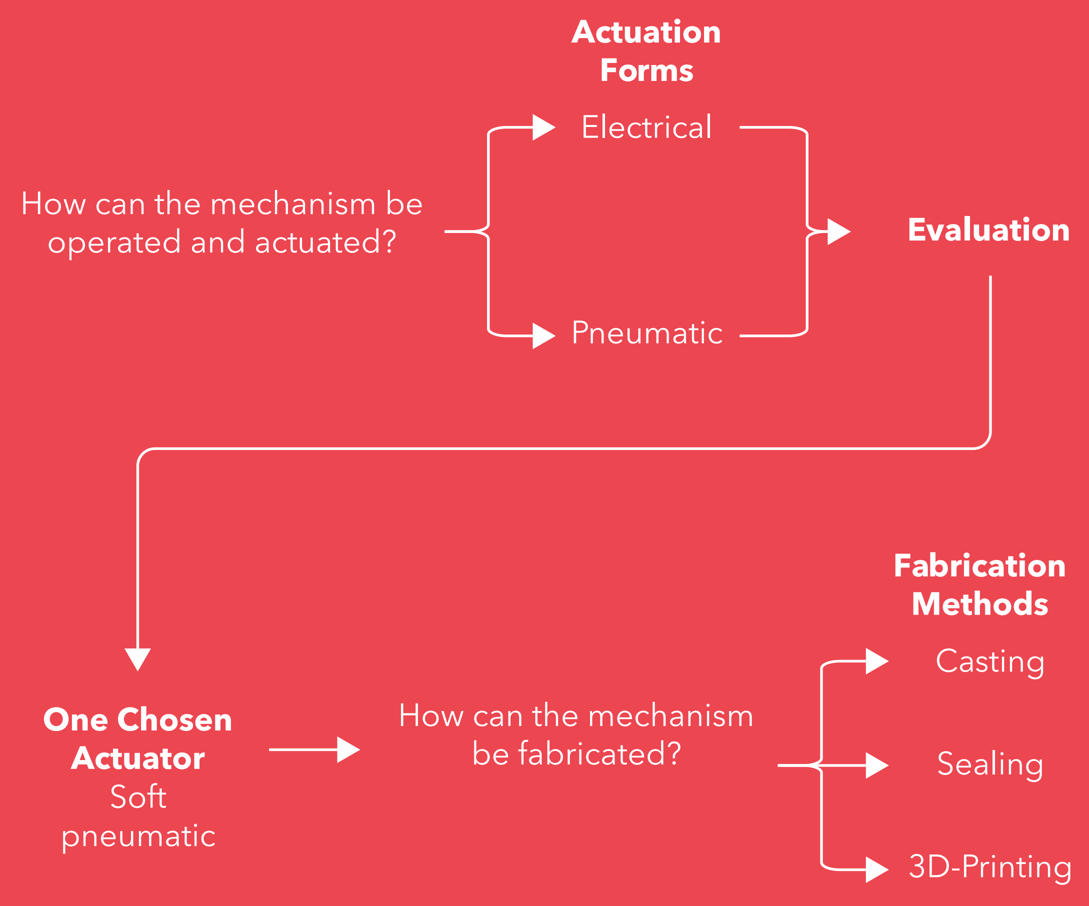
ACTUATION & FABRICATION

INTRODUCTION

The previous part concluded with the decision to proceed the design process with the ‘Fold Structure concept’ as working principle for achieving the appearance transformation of a product. In order for this mechanism to fold open, it requires an angular displacement of certain elements within the structure, for which actuation is needed. In this part several possibilities for actuation are discussed and evaluated, after which one form of actuation is chosen. Thereafter, potential fabrication methods for the production of the mechanism are discussed, which are conceptualized and tested in the next part.

CONTENT

3.1	ACTUATION	**39**
3.2	FABRICATION	**40**



3.1 ACTUATION

In order to find an ideal form of actuation, several actuation possibilities were analyzed, evaluated and compared after which one was chosen for further development. This chapter includes the evaluation of the analyzed actuators. A more elaborate explanation of the actuators is given in Appendix D.

APPROACH

I conducted research on potential actuators. I mainly focused on 'low-tech' electrical, pneumatic and thermal actuators which could be used to achieve the required angular displacement of the 'Fold Structure' mechanism. I used Google to find actuation possibilities and Youtube to discover the working principle of these actuators. Here, I searched for the following (combination of) keywords: actuator, angular displacement, rotary actuator, electronic rotary actuator, electronic hinge, electrostatic rotary actuator, electrostatic hinge, pneumatic rotary actuator, pneumatic hinge.

I compared the actuators and then chose a direction for further analyzation based on how well they fit to the 'Fold Structure' mechanism, and to the design goal and scope.

EVALUATION

After comparing the options for the actuation of the 'Fold Structure' mechanism, soft pneumatic actuation was chosen for further development. Soft pneumatic actuators (or soft robotics) are made of soft and flexible materials and consist of cavities, pouches or air channels, which deform after being inflated with gas or pressurized air. These actuators are shaped in a way, that their deformation caused by inflation, generates movement (see figure 33). They are mainly used to create soft actuators such as grippers, used to handle fragile products or interfaces which allow safe interactions with humans (Y. Sun et al., 2013).

This form of actuation was chosen because soft pneumatic actuators are generally low costs and easy to fabricate and conrtol. Also, they offer high customizability, high degree of freedom and a high power to weight ratio (Y. Sun et al., 2013)(Khin et al., 2017). Therefore, they suit well to the design goal of a simple and low-tech solution.

Furthermore, soft pneumatic actuators are very compatible with digital fabrication technology. This allows to construct complex and customizable geometries, offering enhanced possibilities in the design phase.

Finally, instead of adding additional actuators to a mechanism, using soft pneumatic actuation makes it possible to integrate actuation into the mechanism. This offers the opportunity to produce and actuate numerous mechanism units at once, which can be desired for the production of a surface consisting of many of these units.

Figure 33: Soft gripper (Wyss Institute, 2018)

3.2 FABRICATION

In the previous chapter, the decision was made to use soft pneumatic actuation to operate the chosen 'Fold Structure' mechanism. Thereby, the focus lies on achieving an angular displacement in order to create an appearance transformation. In this chapter, three possibilities for the fabrication of pneumatic actuators are discussed: casting silicone, heat sealing sheet material, and 3D-printing with flexible material.

APPROACH

In order to get an overview of potential fabrication methods for the production of soft pneumatic actuators, I searched for literature on Google and Google Scholar. Here, I specifically looked for solutions where soft pneumatics actuators where used to achieve an angular displacement and which could therefore be integrated with the 'Fold Structure' mechanism. I mainly used (a combination of) the following keywords to obtain the gained information: pneumatic rotary actuator, inflatable actuator, soft pneumatic actuator, soft robotics, self-folding, pouches, bellows, fabric actuator, silicone actuator and 3D-printed actuator.

CASTING SILICONE

Silicone is a stretchable material which deforms after being inflated with gas or air. Before curing, silicone exist as two separate liquids which have to be mixed together in equal amount, and then degassed to avoid air bubbles. The liquid mixture can then be casted in a mold after which it cures and becomes a flexible and elastic material. As the molds can be created with 3D-printing, silicone casting allows high customizability and form freedom. The molds can be used to create air channels and pouches within the silicone shapes, which can be inflated with air, after which the material expands and the shape deforms. When an inextensible layer, such as a fabric or hard plastic surface, is applied to a section of the casted part, the material cannot expand in that direction anymore. This given can be used to control the deformation of the silicone part and thereby accomplish an angular displacement (Y. Sun et al., 2013).

Numerous research in this field exists. As for instance, Y. Sun et al. (2013) present two silicone actuators where inflation causes angular movement. Both actuators consist of a combination of a casted shape with integrated air chambers and inextensible layers which close off the air channels and contribute to the controlled deformation of the actuators (see figure 34&35&36). After inflation, the first actuator deforms from straight to curved while at the second actuator, inflation causes an increased angular movement (see figure 34&35&36).

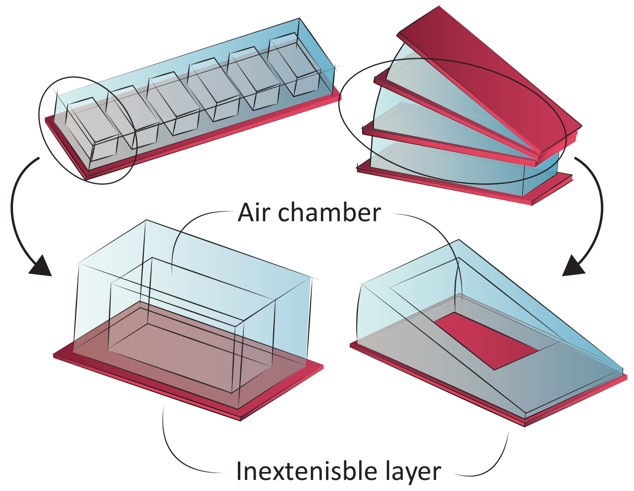


Figure 34: Schematics of the build up of two silicone actuators (Y. Sun et al., 2013)

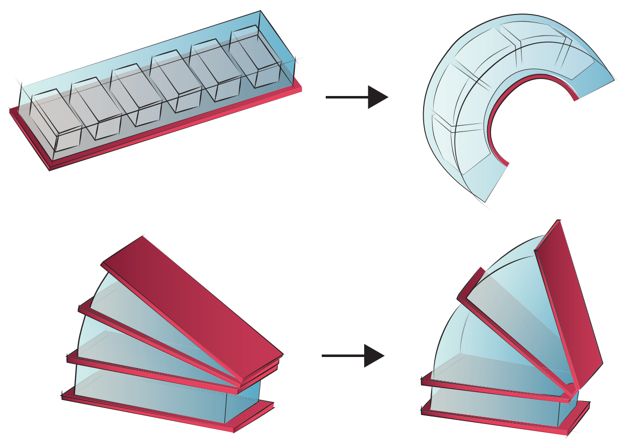


Figure 35: Schematics of the working principle of two silicone actuators (Y. Sun et al., 2013)

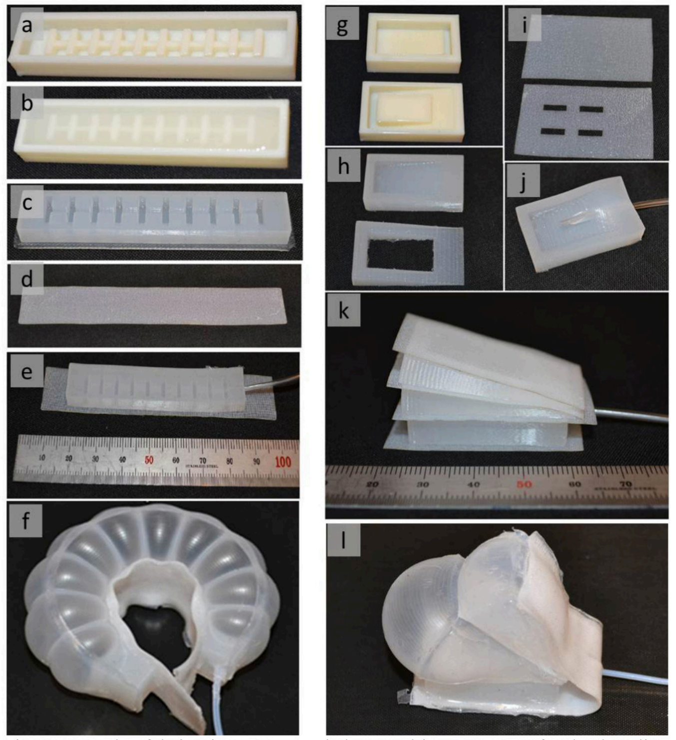


Figure 36: Photographs of the production process and working principle of two silicone actuators (Y. Sun et al., 2013)

BONDING TO INEXTENSIBLE LAYERS

Silicone does not bond well to other materials. However, two (cured) silicone parts can be connected to each other with additional silicone mixture or a silicon adhesive. The inextensible layers should therefore first be laminated with silicone mixture before they can be connected to the casted part (Y. Sun et al., 2013). Furthermore, Rossing et al. (2020) developed a technique to bond silicone with thermoplastics by means of an interlocking structure within a 3D printed mold. This interlocking structure consist of a 3D-printed grid of vertical walls and horizontal crossover beams (see figure 37&38).

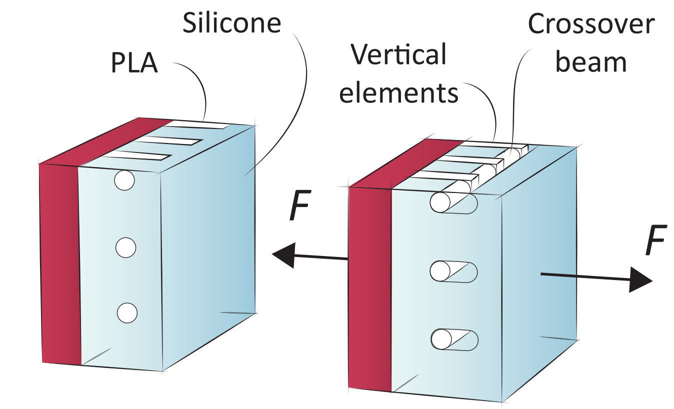


Figure 38: Schematic of interlocking grid and silicone (Rossing et al. 2020)

After a silicone mixture is poured over this grid, the liquid flows and spreads out within the grid. After the mixture is cured, the silicone interlocks with the grid, resulting in a strong connection (see figure 38) (Rossing et al., 2020).

REINFORCEMENT FIBERS

Inflating silicone parts results in an isotropic expansion of the material, meaning that these parts become spherical like a balloon after inflation. As mentioned before, inextensible layers can be used to control the deformation of the part. In addition to these layers, Jiralerspong et al. (2018) and Fras et al. (2017) developed a technique to prevent this 'ballooning effect', assuring deformation in one desired direction. This technique includes the addition of inextensible 'reinforcement fibers' to the extensible section of the silicone part (see figure 39).

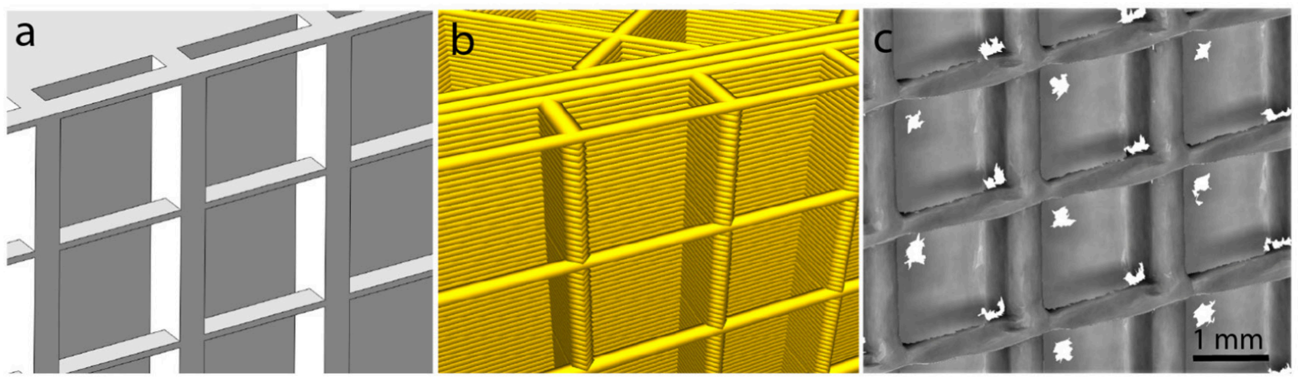


Figure 37: Interlocking grid in (a) SolidWorks model (b) Cura model and (c) 3D scan (Rossing et al., 2020)

These fibers, consisting of for instance polyester threads, prevent the silicone to expand in, for instance, horizontal direction, thereby redirecting the expansion to only the vertical direction. Finally, the addition of a hinging element then assures the angular displacement (see figure 40&41) (Jiralerspong et al., 2018)(Fras et al., 2017).

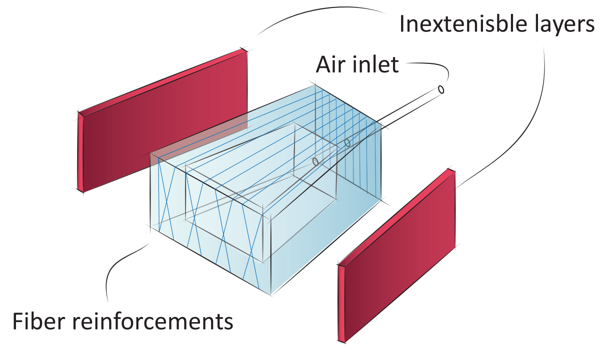


Figure 39: Schematic of silicone actuator with inextensible layers and reinforcement fibers (Jiralerspong et al., 2018)

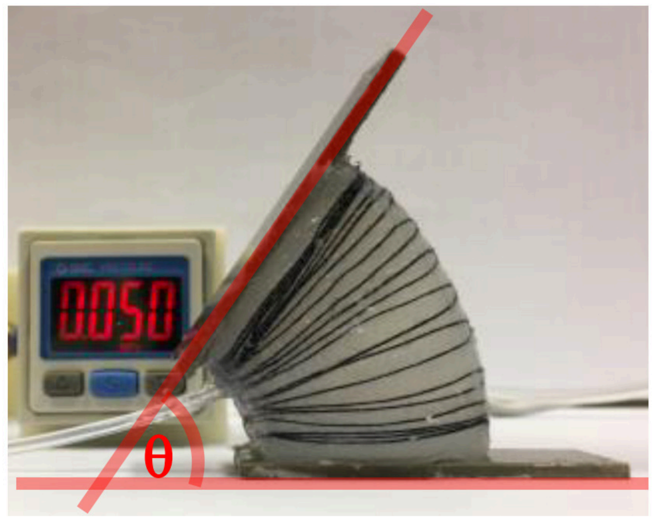


Figure 40: Silicone actuator with reinforcement fibers and angular displacement without ballooning effect (Jiralerspong et al., 2018)

Figure 41: Silicone actuators with reinforcement fibers, showing the effect of the density of the fibers on the ballooning effect(Fras et al., 2017)

HEAT SEALING SHEET MATERIAL

This fabrication method is based on bonding layers of sheet material together in a certain pattern and thereby creating air-tight pouches which can be filled with air. The bonding of the sheet material is done by a combination of applying heat and pressure. This can be done through three processes: manual sealing, heat press sealing and robotic sealing. The sheets can be made from paper, plastic or fabric, coated with sealable film material, as for example TPU (Ou et al., 2016). Apart from creating closed pouches, folding creases can be created, which act as hinge after inflation. Thereby, self-folding structures can be created (see figure 42) (Ou et al., 2016).

Figure 42: Self-folding structure (Ou et al., 2016)

The structure folds as follows: Inflating an airbag made of inextensible material tends to become spherical like a balloon. Since an inextensible material is used, inflation causes the shape to lift in the upper direction and thereby shorten at the sides. This results in an angular displacement of the structure (see figure 43). The direction in which the structures bends after inflation is depended on the side from which the material is sealed (see figure 43). (Ou et al., 2016).

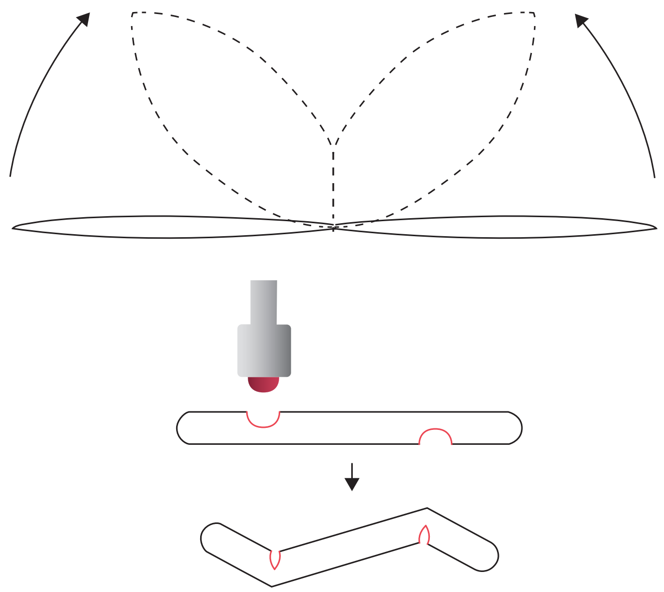


Figure 43: Schematics of the working principle of self-folding structure (up) and the fold direction due to sealing side (down) (Ou et al., 2016)

Furthermore, Khin et al. (2017) presents a fabric-based rotary actuator which consists of two sheets of TPU coated fabric, sealed together in a V-shaped fold. As the structure is inflated, the fabric in the inner folds expands and thereby folds open (see figure 44). When the actuator is deactivated, the structure returns to its original shape. In order to accelerate this process, a C-shaped frame is placed inside the structure. This frame is 3D-printed with a flexible filament and acts as endoskeleton of the actuator (see figure 45) (Khin et al., 2017).

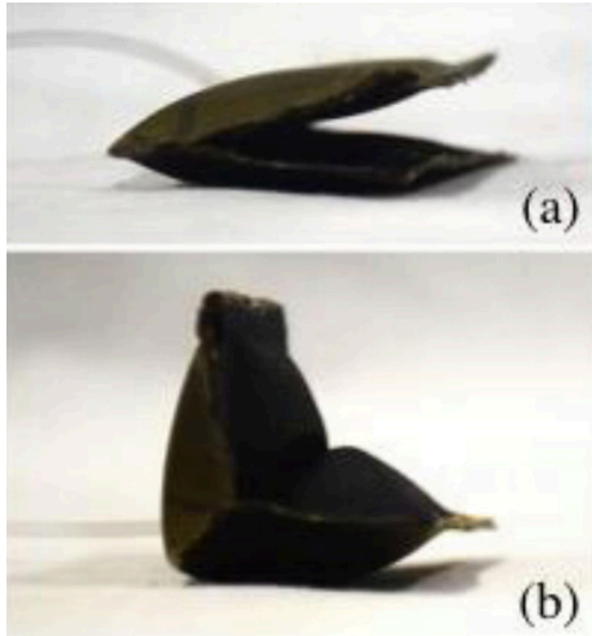


Figure 44: Fabric rotary actuator folds open due to inflation (Khin et al., 2017)

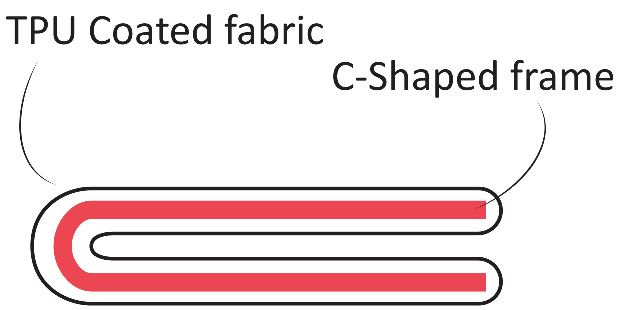


Figure 45: Schematic of rotary actuator, including the C-Shaped frame (Khin et al., 2017)

3D-PRINTING FLEXIBLE MATERIAL

For the fabrication of air-tight and inflatable pouches, it is also possible to make use of 3D-printing technology. However, in order to use these pouches as part of a rotary actuator, the pouches should be deformable. It is therefore required to make use of a flexible material for the fabrication of the pouches, which is possible with both Fused Deposition Modeling (FDM) and PolyJet printers. The difference between these printers is that FDM printers heat a thermoplastic filament which is then layered, after which it cools down and cures. This, while PolyJet printers make use of liquid polymers which are jetted onto a printer bed and then cured with UV-light (Laserlines, 2020).

As the flexible material used with this technology is usually not as elastic and expansible as silicone or other elastomers, it is required to make use of bellows for the shape of the pouches. Bellows include a folded geometry which enables an increased expansion and assures deformation in only one direction instead of the isometric expansion occurring with elastomers (De Volder & Reynaerts, 2010).

As for example, Lau (2019) constructed a bellow-shaped pouch while making use of Stratasys Agilus30 filament. This material is flexible and strong and can be printed with a PolyJet printer. Inflation of the actuator results in a significant angular deflection (see figure 46) (Lau, 2019).

Figure 46: 3D-printed actuator (Lau, 2019)

Furthermore, Anver et al. (2017) used a combination of thermoplastics and thermoplastic elastomers as filament for a FDM 3D-printer, to create a pneumatic ‘finger’ consisting of multiple air chambers and an inextensible layer (see figure 47). Inflation causes the air chambers to expand, resulting in a bending motion (see figure 48) (Anver et al., 2017).

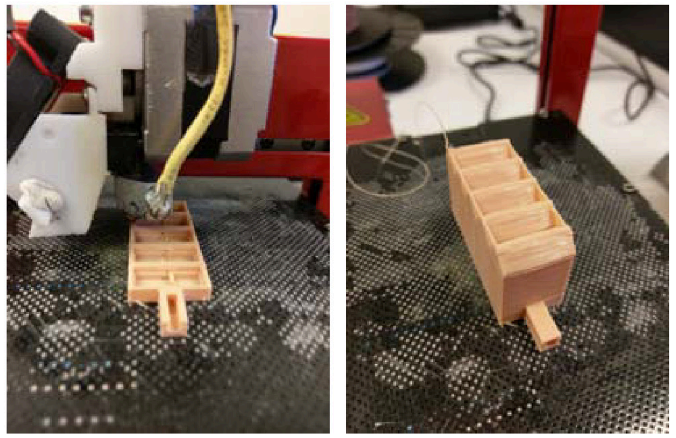


Figure 47: Printing process of 3D-printed actuator (Anver et al., 2017)

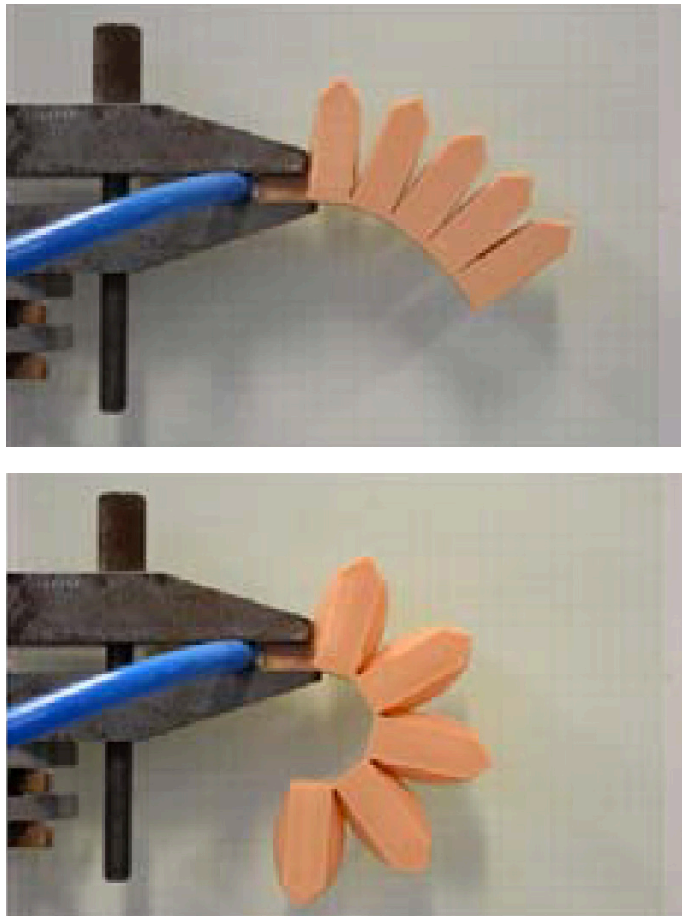


Figure 48: 3D-printed actuator (Anver et al., 2017)

CONCLUSION

There are several possibilities for the production of soft pneumatic actuators, of which three were discussed in this chapter. Numerous examples exist in literature where these fabrication methods were used to produce soft pneumatic actuators, capable of achieving an angular deflection. However, from the analyzation of the literature alone cannot be determined which fabrication method is most suitable for the realization of an appearance change. Therefore, the next part includes experiments with the three discussed fabrication methods, in the form of physical mock-ups, which are iterated towards a final concept.

PART 4

CONCEPTUALIZING & ITERATIONS

INTRODUCTION

In Part 2, the decision was made to create a mechanism which can fold open and thereby reveal an underlying layer with a different appearance. In order to achieve this folding motion, actuation is required. Therefore, in Part 3, several forms of actuation were evaluated after which the decision was made to use soft pneumatic actuation as this is low-tech and suitable for digital fabrication technology. Also, an analyzation on potential fabrication methods was executed. In this part, the goal is to combine the 'Fold-Structure' mechanism concept with the intended form of actuation and to determine the exact working principle, materialization and fabrication method of the mechanism. To reach this goal, an ideation process was executed and physical protypes were modelled, tested and evaluated. The process of numerous iterations resulted in three final concepts which were evaluated and compared in terms of performance, feasibility and applicability. Eventually, one concepts was chosen and thereby the working principle, materialization and fabrication were defined.

CONTENT

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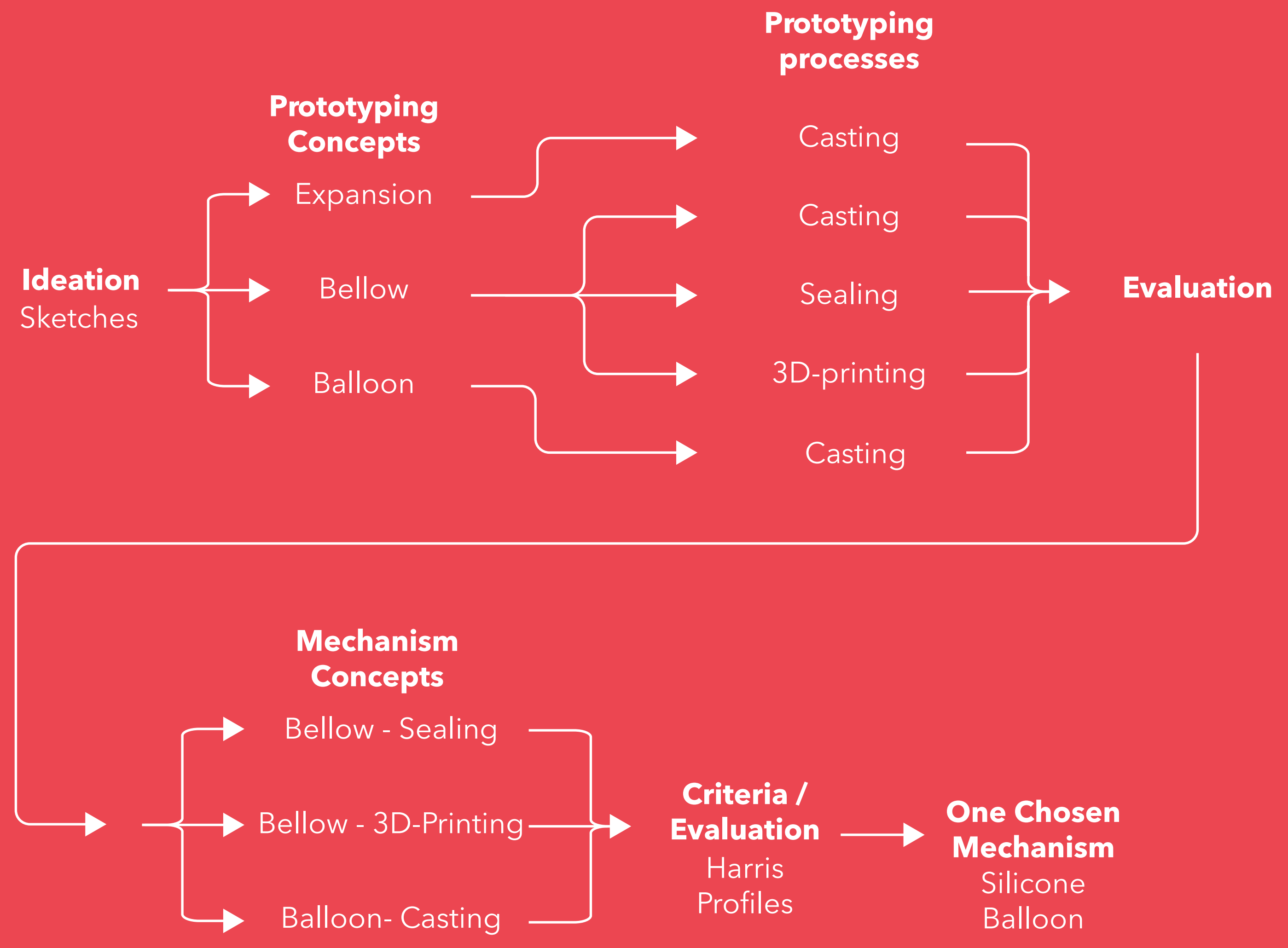


4.1 IDEATION

An ideation session was executed after which three potential working principles were selected and illustrated.

APPROACH

In order to achieve the goal of creating a mechanism which folds open due to inflation, I performed an ideation session. I made sketches of potential working principles, based on research executed in previous parts. I focused on solutions which could be fabricated with silicone casting, sealing fabrics and 3D-printing with flexible material. For each idea, I sketched two forms: the original state and the assumed state after actuation.

After the ideation session, I evaluated the ideas and chose three working principles based on their expected performance, feasibility and applicability. These three working principles were furtherly developed towards three concept illustrations, including a more elaborate plan for materialization and fabrication.

OVERVIEW

An overview of the generated ideas is shown in figure 49.

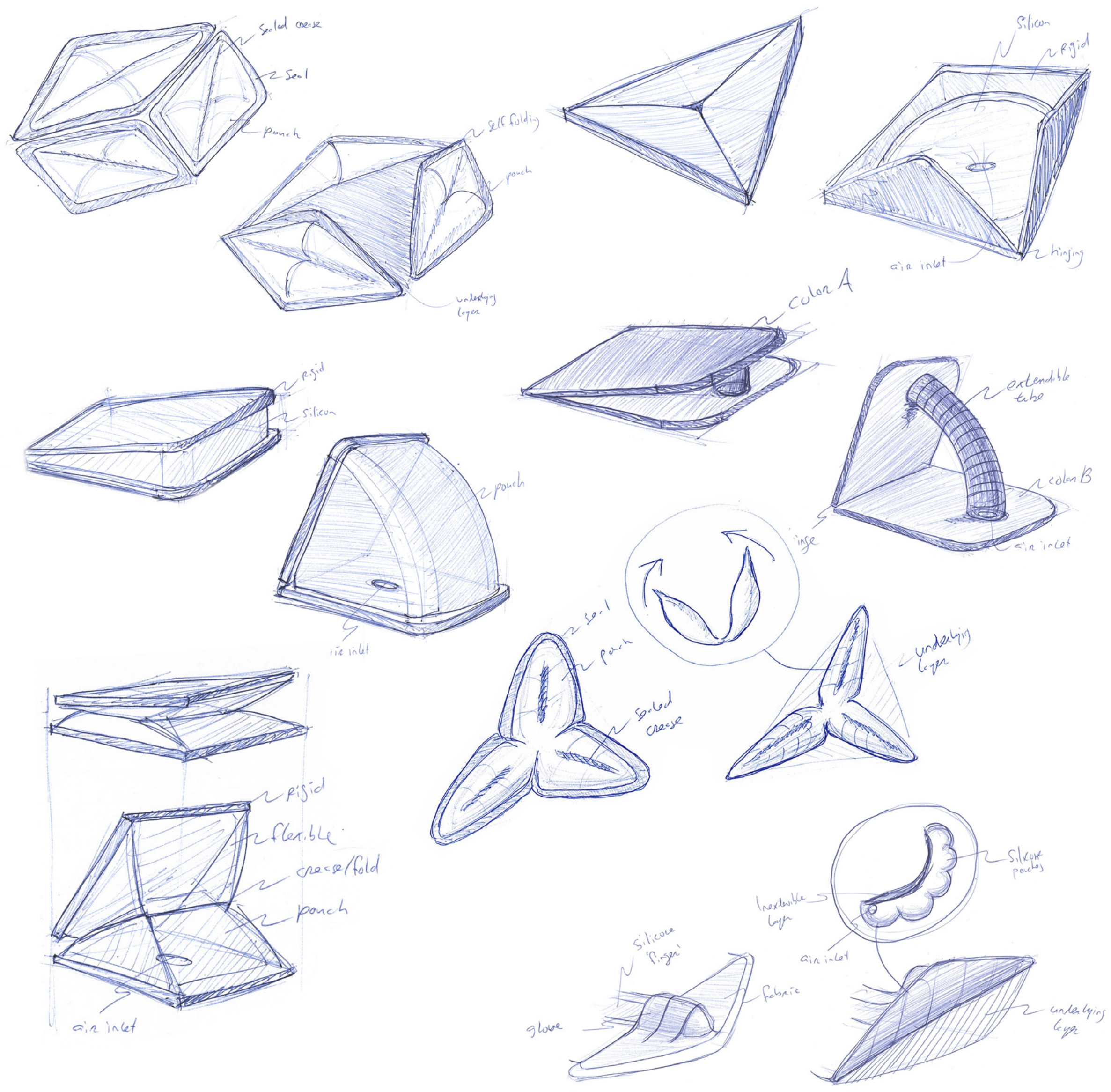


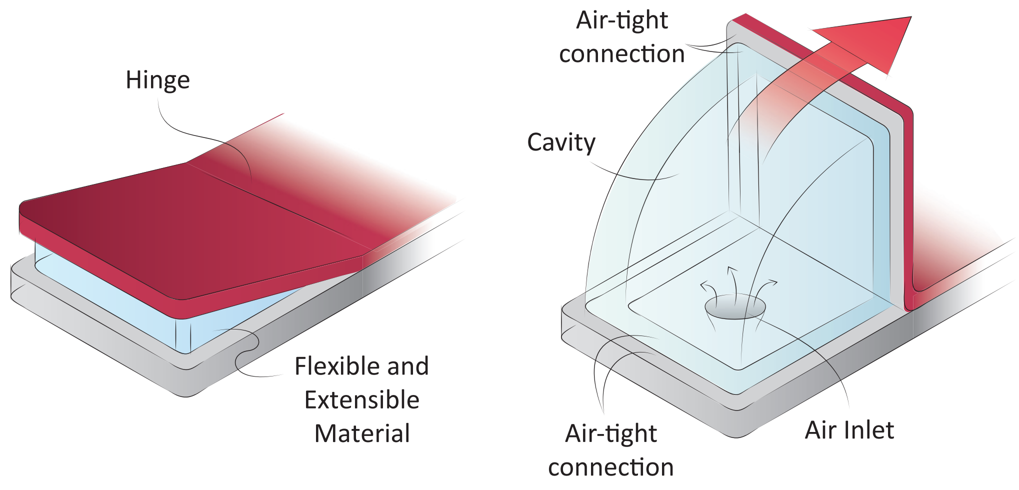
Figure 49: Overview of ideation session

CONCEPT 1

THE 'MATERIAL EXPANSION'

The idea of this concept is that inflation would ensure that the material used for the pouch, stretches out and the shape expands. This should result in an angular displacement of the top layer, due to the presence of a hinging element and inextensible layers on the top and bottom of the model. After the top layer has folded open, the differently colored inside is revealed and thereby an appearance change is achieved.

As the working principle for this concept is based on the expansion of the material used for the pouch, a flexible and extensible material is required. Therefore, this concept should be fabricated with silicone, using silicone casting as fabrication method.

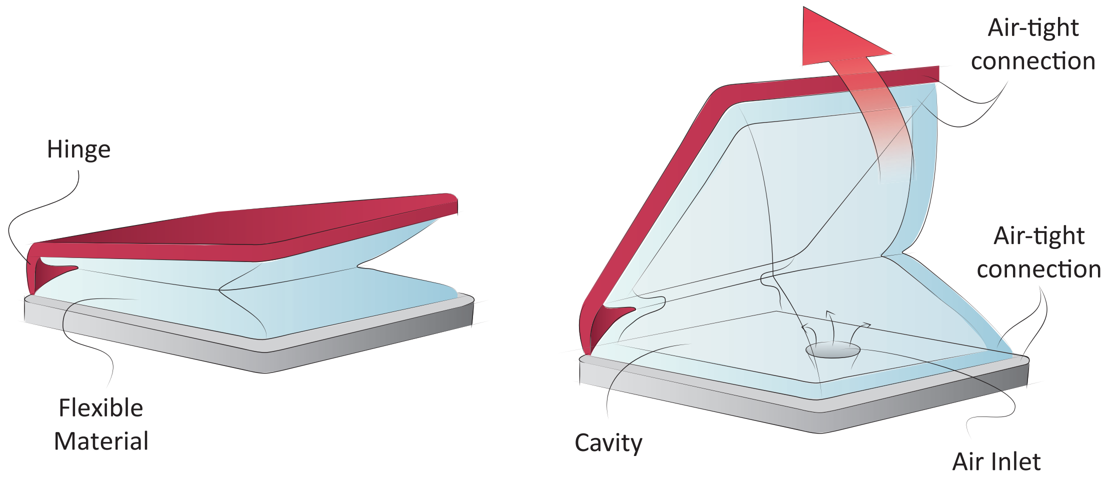


CONCEPT 2

THE 'BELLOW-SHAPE'

The idea of this concept is similar is to the previous concept. However, in this case the expansion of the shape comes from using a bellow-shaped pouch. Due to the presence of a dent, acting as folding crease, this shape itself is capable of expanding and compressing without expansion of the pouch material. Similar to Concept 1, inflation would ensure an angular displacement of the top layer, after which the differently colored inside is revealed and thereby an appearance change is achieved.

Since the working principle for this concept is based on the expansion of a bellow-shaped pouch, it is not necessarily required to make use of an extensible material. However, the used material should be flexible enough to enable the deformation of the shape. Therefore, this concept could be fabricated with all three previously described fabrication processes: 3D-printing with flexible material, sealing fabrics and silicone casting.

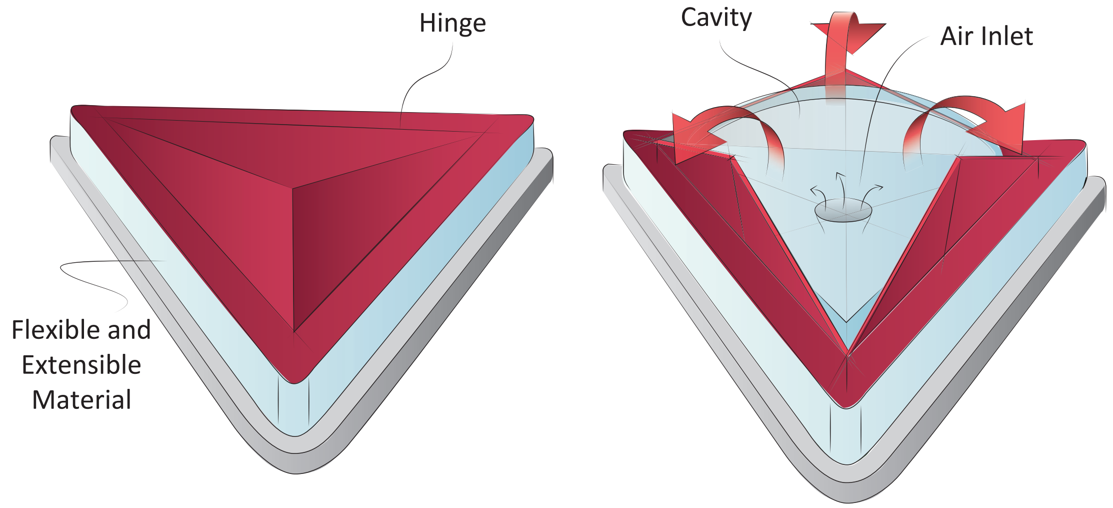


CONCEPT 3

THE 'CENRAL BALLOON'

The idea of this concept is that inflation would ensure the expansion of a pouch which then bloats as a balloon. Hereby, multiple lids, placed on top of the pouch, are pushed away. As these lids are connected to a hinging element, they fold open after inflation, revealing the differently colored inside and thereby achieving an appearance change.

Similar to Concept 1, the working principle for this concept is based on the expansion of the material used for the pouch. Therefore, this concept should also be fabricated with silicone, using silicone casting as fabrication method.



OVERVIEW

Figure 50 shows an overview of the three proposed concepts and their potential form of fabrication.

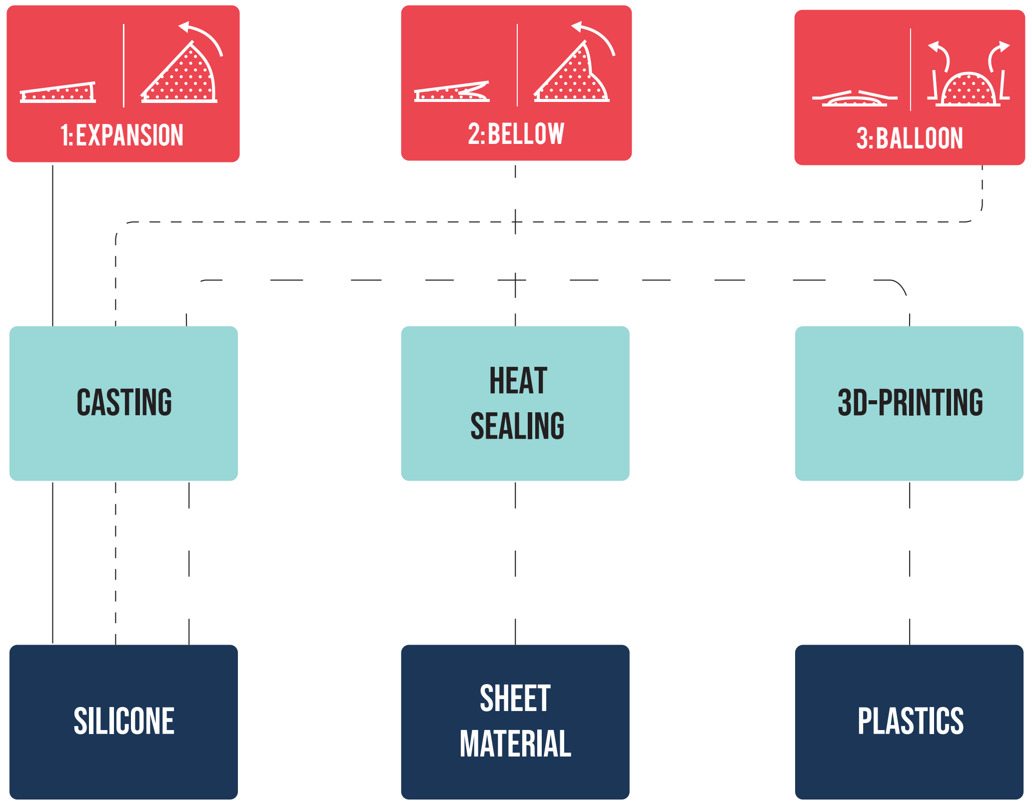


Figure 50: Overview of fabrication methods

4.2 PROTOTYPING & ITERATIONS

The three proposed concepts were fabricated with physical prototypes, using three fabrication methods: casting silicone, heat sealing sheet material and 3D-printing with flexible material. This resulted in five iterative prototyping processes.

APPROACH

In order to determine the ideal working principle, materialization and fabrication method of the intended mechanism, I made physical prototypes of the three proposed concepts. Here, I experimented with the previously described fabrication processes for the fabrication of soft pneumatic actuators: casting silicone, heat sealing sheet material and 3D-printing with flexible material. For the production of Concept 1 and 3, I mainly used silicone casting while for Concept 2, I experimented with silicone casting, heat sealing and 3D-printing. In total, I conducted five iteration processes.

All the created prototypes were based on examples from literature and were focused on achieving a significant angular deflection after inflation with air, with the purpose of achieving a clear appearance transformation. In most cases, I started with replicating an existing actuator, described in research papers, after which I modified the prototype towards the intended shape and functionality. I mainly used a trial-and-error approach where I would produce and test a physical prototype and improve it by means of its flaws and errors. In order to do this in an organized way, I kept a journal in which I kept notes and pictures of the conducted process, the achieved results, the flaws and errors and the learning points of each iteration. Also, I asked for consult from experts in the PMB workshop and Applied Labs of the Industrial Design Faculty. With their experience with the intended forms of fabrication, they helped me to accomplish the intended results.

CASTING SILICONE

For casting silicone, I created molds in SolidWorks, after which they were 3D-printed with Ultimaker 2+ FDM 3D-printers (see figure 51). I used Ecoflex® 00-30, Smooth-On Inc silicone (see figure 52), purchased from www.formx.nl, as this type is commonly used for the fabrication of silicone actuators (Agarwal et al., 2016)(Jiralerspong et al., 2018) (Larson et al., 2016) (Pikul et al., 2017) (Sun et al., 2013). The silicone comes in two separate parts, which are ought to be mixed together in a 1:1 ratio. In order to achieve this ratio accurately, I used a lab scale with a precision of 0,1 g (see figure 53). After mixing thoroughly, I used a vacuum machine to degas the mixture and thereby remove air bubbles within the mixture (see figure 54). For casting of silicone within the molds, I used disposable paper cups and wooden sticks (see figure 55). Finally, I let the casted shape cure for at least one day before demolding (see figure 56).

HEAT SEALING SHEET MATERIAL

For the sealing of sheet material, I used both sealable fabrics and film material (see figure 57). In general, sealable fabrics are coated with a sealable material on one side only, while sealable film can be sealed from both sides. I used TPU-coated nylon as sealable fabric, as this material is commonly used for the production of fabric actuators (Ou et al., 2016)(Khin et al., 2017). I experimented with two different TPU coated nylon fabrics, which were both purchased from www.extremetextil.de. Furthermore, I used TPU film material, which was provided by a researcher from the Applied Labs of the faculty. In order to seal the materials and create air-tight pouches, I used a flat iron used for ironing clothing (see figure 58). Finally, I used copper tape and baking paper in order to dissipate the heat of the flat iron and thereby protect the materials and to keep the intended air-chambers unsealed.

3D-PRINTING WITH FLEXIBLE MATERIAL

For 3D-printing inflatable and deformable pouches, I constructed CAD-models in SolidWorks. I created separate parts for both the rigid and flexible parts of the intended shape and arranged them securely, in order to ensure that the separate parts are positioned well in relation to each other. I consulted experts about the created CAD-models, as they are more experienced and can therefore foresee potential flaws and errors before printing. After approval, the parts were printed with a 'Stratasys 735' PolyJet 3D-printer (see figure 59). This 3D-printer can print multiple materials at once, including the flexible material 'Agyllus30', which was used for this project. Finally, the support material in and around the printed part was removed by hand and with a waterjet (see figure 60).

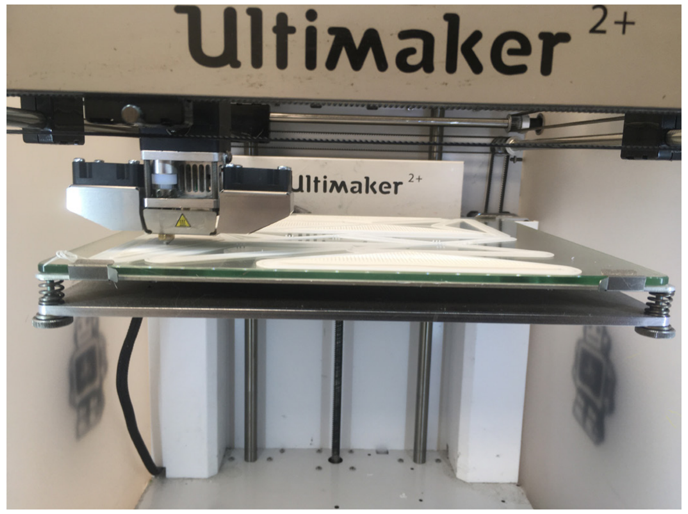


Figure 51: 3D-Printing molds with Ultimaker 2+

Figure 52: Ecoflex 00-30 Silicone


Figure 53: Weighing silicone to obtain 1:1 ratio

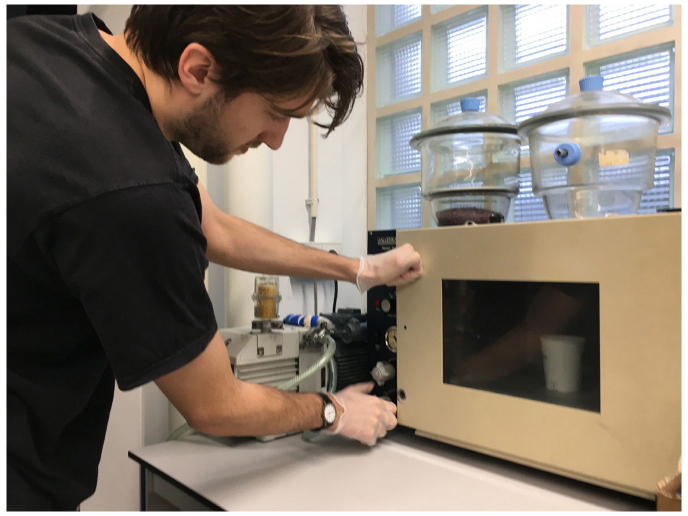


Figure 54: Degassing silicone mixture


Figure 55: Casting silicone into a mold

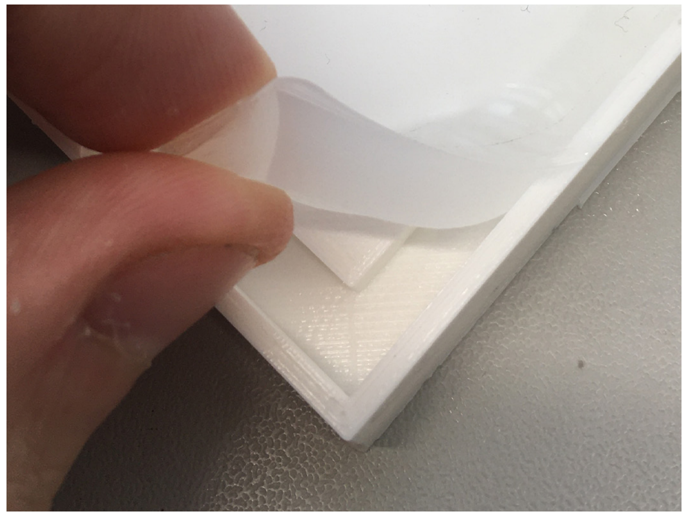


Figure 56: Demolding after silicone has cured

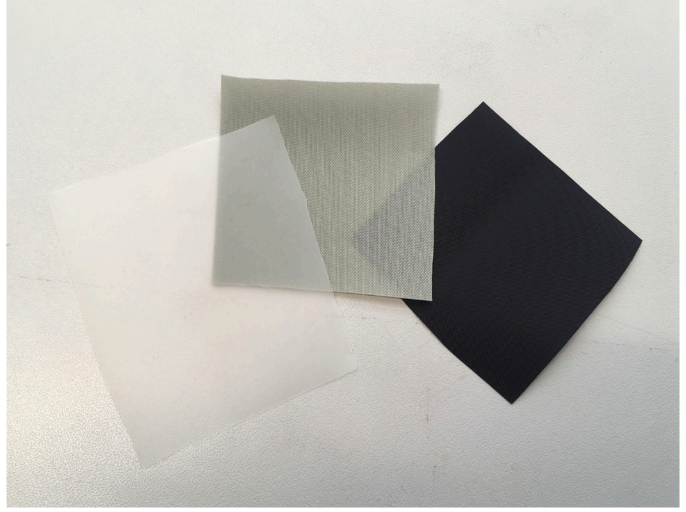


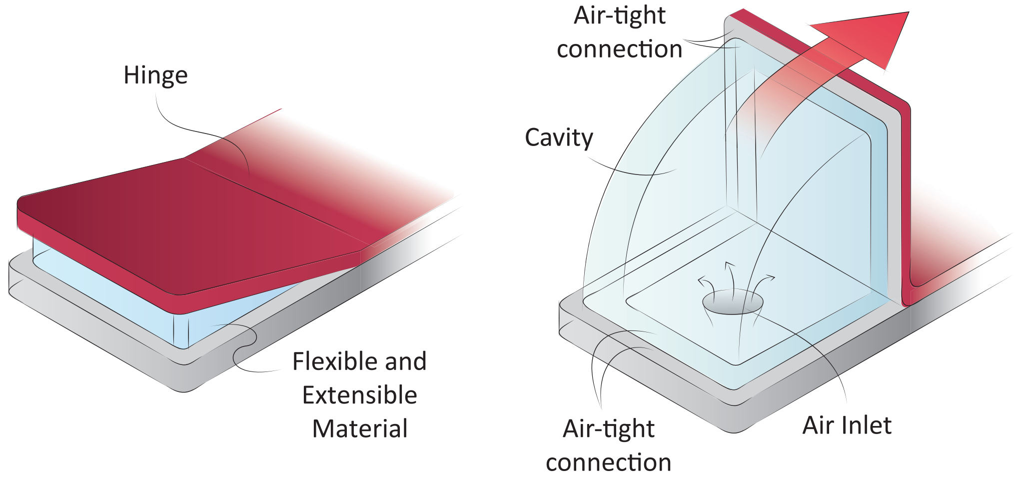
Figure 57: Sheet materials


Figure 58: Heat sealing with flat iron

Figure 59: Stratasys J375 PolyJet 3D-printer

Figure 60: Waterjet for removing support material

CONCEPT 1
THE ‘MATERIAL EXPANSION’



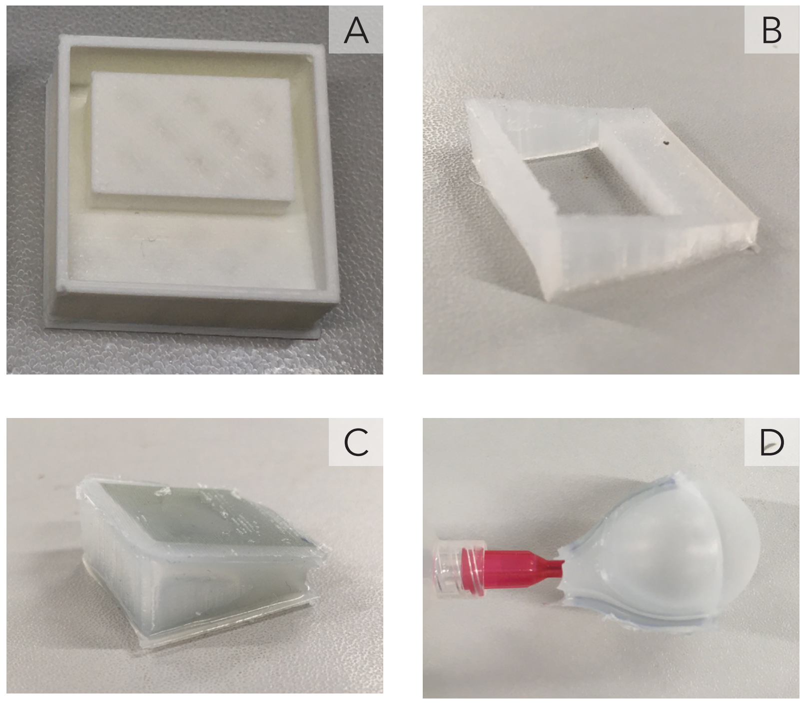
For the first silicone prototype, I tried to mimic the silicone rotary actuator from Y. Sun (2013), described in the previous part. Here, the goal was to explore the material and to achieve an angular displacement due to expansion of the material after inflation. I casted a silicone mixture into a rectangular shaped mold, which I modelled in SolidWorks and fabricated with an FDM 3D-printer (see figure 61-A). The mold included a rectangular shaped cavity which acts as inflatable air chamber. To induce an angular deflection, I used an increased wall thickness on one of the sides, which acts as hinge for rotation (see figure 61-A&B). In order to furtherly control the deformation, I used laminated fabric as inextensible layers on the top and bottom of the casted shape (see figure 61-C). Finally, I repeated the entire process with a triangular shaped mold, since patterning triangles allows filling a surface entirely (see figure 61-E&F&G).

Although inflation led to an angular displacement, the achieved deflection was only slight and insufficient for the realization of an appearance change. Also, instead of pushing away the top layer, most of the material’s expansion resulted in a ‘balloon-blowing effect’ on the sides of the shape (see figure 61-D&H). Therefore, I found that in order to avoid the ‘balloon-blowing effect’ and direct the material’s expansion in only one intended direction, it is required to make use of reinforcement fibers.

ITERATION 1

In order to avoid the ‘balloon-blowing effect’ appearing in the previous mock-up, I wrapped both the rectangular and triangular shape with inextensible threads and bonded the threads to the material by spreading additional silicone mixture over them (see figure 62-A&B). This process was done similarly as the silicone rotary actuator from Jiralelerpsong et al. (2018), discussed in the previous part. The threads should assure that after inflation, the material cannot expand on the sides and will therefore only expand in vertical direction.

However, the addition of the threads did not result in an increased rotational movement and a ‘balloon-blowing effect’ still occurred between or below the threads (see figure 62-C). This often resulted in tear of the bonding material between the separate parts, after which the inflated air leaked out. Also, spreading additional silicone mixture over the threads did not result in a strong bond between the threads and the casted shape, after which the threads would sometimes fall off. Therefore, I found that instead of wrapping the threads around a cured part and bonding them with additional silicone mixture, they should be placed inside the mold before casting. I also found that the current inextensible layers were too flexible, allowing to bend and make space for a ‘balloon-blowing effect’, holding back the desired rotational movement. Therefore, the inextensible layers on the top and bottom of the model should be made from a more rigid material.



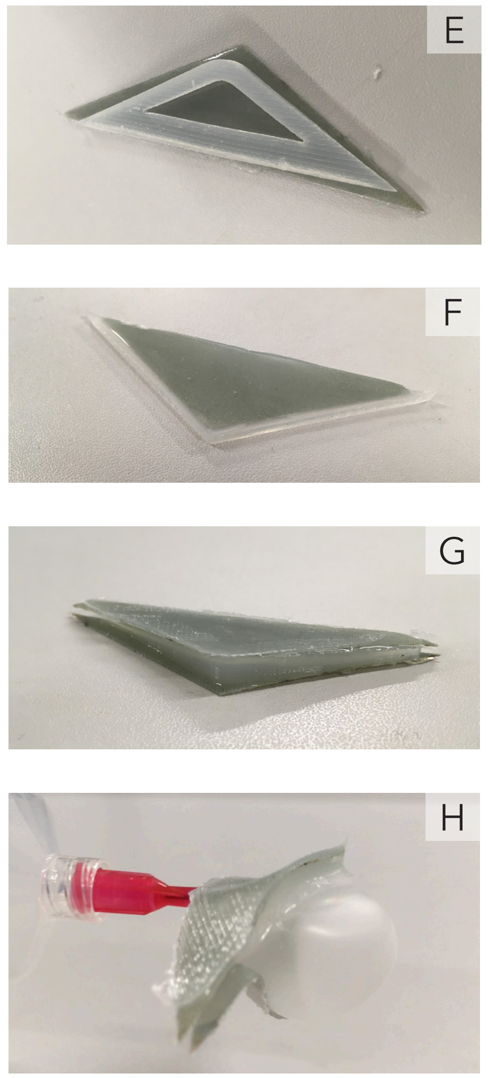


Figure 61: The ‘Material Expansion’ Concept - Prototyping process - **A:** 3D-Printed Mold. **B:** Casted silicone shape. **C:** Casted shape with inextensible layers, bonded on the top and bottom. **D:** Prototype after inflation, resulting in balloon-blowing effect. **E:** Casted triangular shape on top of inextensible layers before bonding together. **F:** Inextensible layer. **G:** Casted triangular shape with inextensible layers, bonded on the top and bottom. **H:** Triangular prototype after inflation, resulting in balloon-blowing effect.

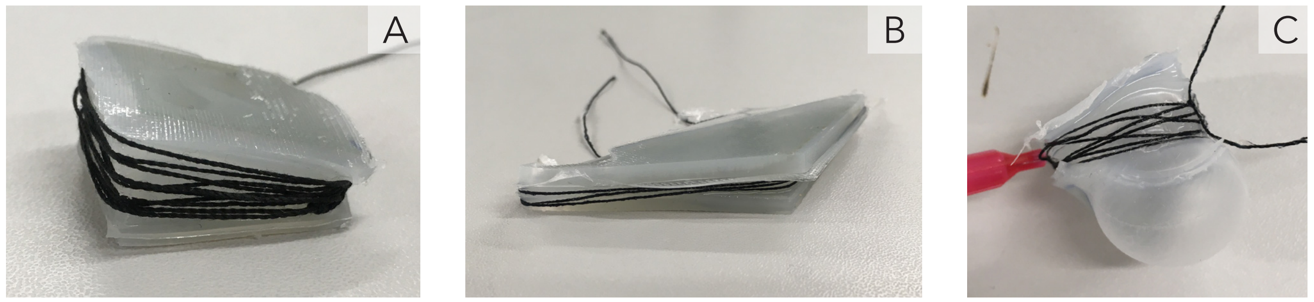


Figure 62: Iteration 1: Prototyping process - **A:** Prototype with threads wrapped around **B:** Triangular prototype with threads wrapped around **C:** Prototype after inflation, resulting in balloon-blowing effect

ITERATION 2

For this prototype, I used 3D-printing to fabricate rigid, rectangular panels, which are used as inextensible layers on the top and bottom of the model (see figure 63-A). In order to bond these thermoplastic panels with the casted silicone, I made use of an interlocking grid on top of the panels. Here, I replicated the grid and its dimensions from research by Rossing et al. (2020), discussed in the previous part. Furthermore, I included a mechanical hinge to connect the two panels, by including open cylinders to one side of the panels. A metal nail was stuck through the cylinders and thereby acted as rotation axle for the rotation of the hinge (see figure 63-A&E).

For the silicone part, I used a 3D-printed, three-part mold (see figure 63-B). This, to induce a more careful demolding process and thereby avoid tear due to demolding. The mold consisted of two halves and a central block, responsible for the air chamber within the silicone shape. The three parts were held together with rubber bands (see figure 63-C). I casted silicone mixture into the mold and onto the interlocking grids on the 3D-printed panels. After everything was cured, I bonded the parts together with additional silicone mixture (see figure 63-E).

After testing, I found that the additional hinge does not contribute to the rotational movement of the prototype. This, because the casted shape already includes a thicker wall, acting as hinge. Furthermore, since I did not make use of reinforcing fibers, inflation resulted in a 'balloon-blowing effect' and only a slight rotational movement (see figure 63-F). However, this was expected and therefore neglected for this prototype.

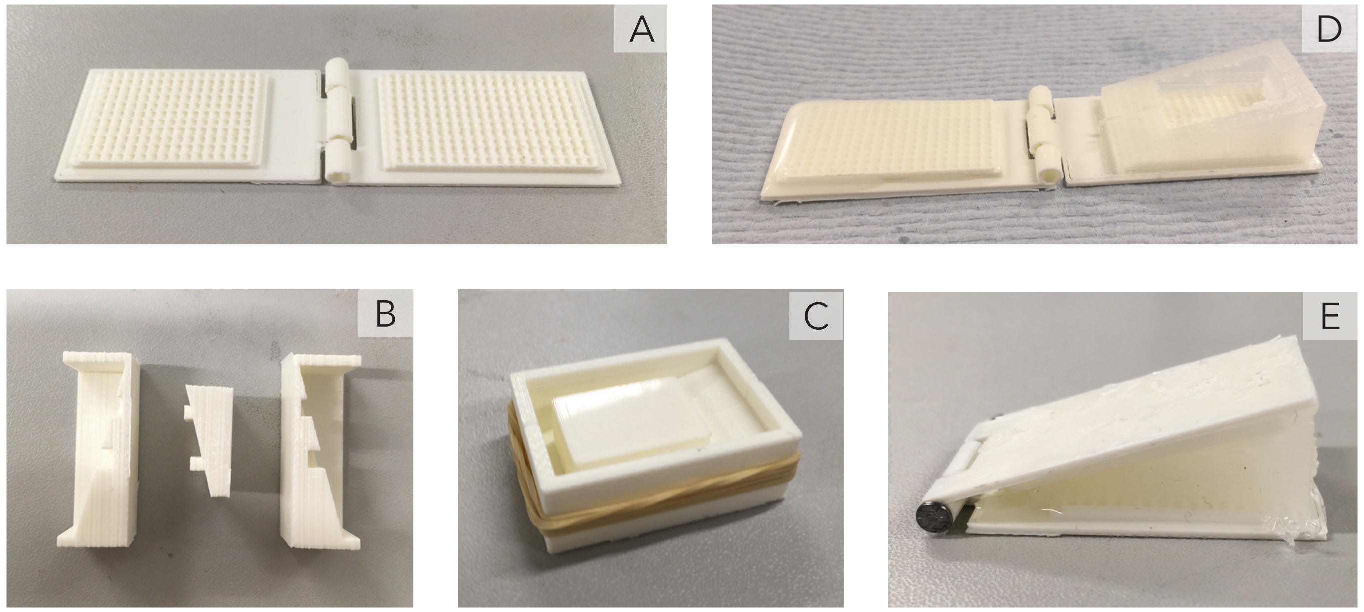


Figure 63: Iteration 2: Prototyping process - **A:** 3D-Printed three-part mold. **B:** Three-part mold held together by rubber bands. **C:** 3D-printed inextensible layers with interlocking grid. **D:** Casted shape bonded together with inextensible layers. **E:** Casted shape on top of inextensible layers before bonding together. **F:** Prototype after inflation, resulting in balloon-blowing effect.

ITERATION 3

In order to avoid the 'balloon-blowing effect' appearing in previous prototypes, I placed inextensible threads within the mold before casting with silicone (see figure 64-A). I tried this with various, previously used molds, and used rigid, 3D-printed panels as inextensible layers (see figure 64-B&C). Here, I included an interlocking grid on each panel, in order to assure a strong bond between the parts. After inflation, the reinforcement fibers assured a decreased 'balloon-blowing effect' and an increased angular displacement for some of the shapes (see figure 64-D). However, since a flexible thread was used as reinforcement, it was difficult to create equally sized spacings between the wraps. In some cases, there was still room for the material to expand horizontally, resulting in an undesired 'balloon-blowing effect'. This often resulted in tear of the bonding material between the separate parts, followed by leakage of the inflated air. Therefore, I found that it is required to make use of a more rigid reinforcement structure.

ITERATION 4

For the purpose of creating equally sized spacings within the integrated reinforcement structure and thereby eliminate the reoccurring 'balloon-blowing effect', I constructed rigid, 3D-printed triangles which can be placed within a triangular mold (see figure 65-A). The triangles include vertical spacers to keep the triangles apart from each other and assure equally sized spacings between them. I stacked three triangles in a mold while casting layers of silicone between them (see figure 65-B). Furthermore, I used rigid, 3D-printed panels with interlocking grids as inextensible layers.

Inflation resulted in an angular deflection without 'balloon-blowing effect' (see figure 65-C). However, the achieved deflection was only slight and insufficient for the realization of an appearance change. The material should therefore be able to expand much further.

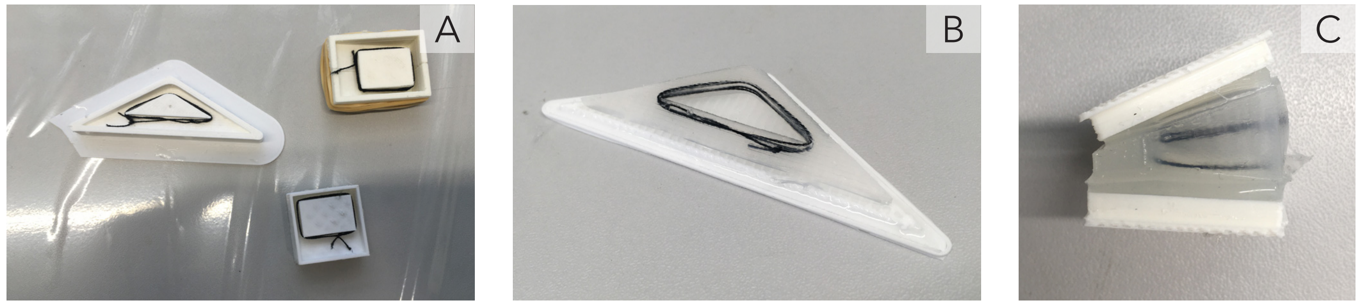
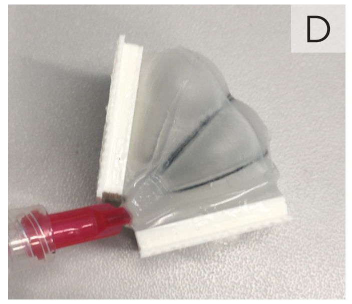


Figure 64: Iteration 3: Prototyping process - **A:** Molds with threads placed within. **B:** Casted shape with integrated reinforcement placed on inextensible layer before bonding. **C:** Casted shape bonded together with inextensible layers. **D:** Prototype after inflation, resulting in an increased angular displacement and decreased balloon-blowing effect.



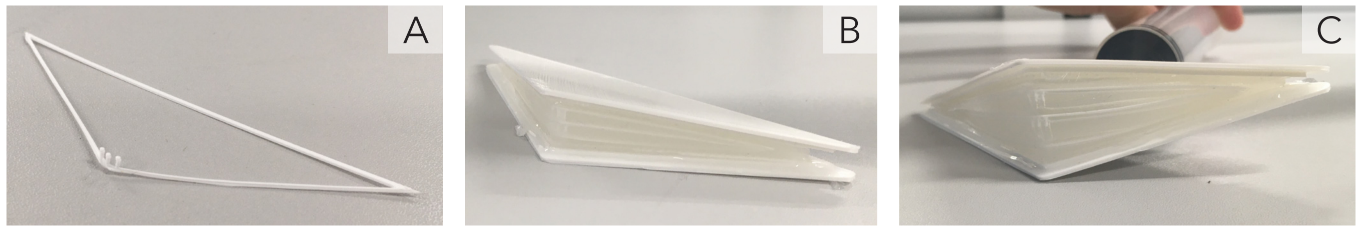
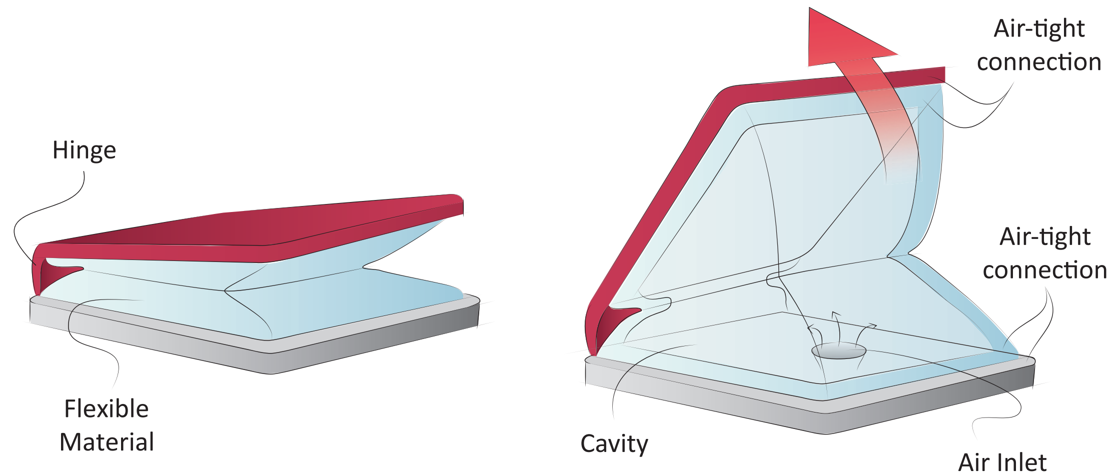


Figure 65: Iteration 4: Prototyping process - **A:** Rigid reinforcement structure **B:** Prototype with integrated reinforcement structure **C:** Prototype after inflation, resulting in rotation without balloon-blowing effect

CONCEPT 2.1
THE 'BELLOW SHAPE' - SILICONE CASTING



The goal of this first prototype was to test the working principle of a bellow shaped part fabricated with casted silicone. The bellows should assure that the material has more room to expand, allowing an increased angular displacement after inflation. I used a three-part mold, including two halves and a central block responsible for the air chamber within the shape (see figure 66-A). I used fabric, laminated with silicone, as inextensible layers on the top and bottom of the casted part (see figure 66-B).

Inflation resulted in an angular displacement of the top layer and a decreased 'balloon-blowing effect' on the front of the shape (see figure 66-C). However, since the bellows were only used at the front of the shape, a large 'balloon-blowing effect' still occurred at the sides (see figure 66-D). Therefore, I found that it is required to use the bellows on all sides of the shape. Finally, inflation ensured that the inextensible layers were bloated, which is unintended. Therefore, the inextensible layers on the top and bottom of the model should be made from a more rigid material.

ITERATION 1

For this prototype, I used bellows on all sides of the shape. I modelled a triangular shape with one deep crease instead of multiple bellows (see figure 67-B&D). This, to keep the part as flat as possible, while allowing a large expansion. I used a three-part mold with two halves and an inner triangle responsible for the air chamber (see figure 67-A). Furthermore, I used rigid, inextensible layers with interlocking grids in order to bond them to the casted shape (see figure 67-B&C).

Although inflation resulted in a rotational movement of the top layer, it also caused the top layer to ascend entirely (see figure 67-E). Therefore, the back wall should be made thicker or an additional inextensible structure should be included. Also, I concluded that the air chamber was too small. Therefore, the material expansion only occurred in the middle of the shape, which resulted in an unintended 'balloon-blowing effect'. Thus, a wider air chamber is required.

ITERATION 2

To avoid ascendance of the top layer after inflation, the aim for this iteration was to ensure an inextensible back wall, operating as hinge for rotation. This was done by binding the top and bottom layer together with threads (see figure 68-A). Also, I included a wider central block to ensure a wider air chamber (see figure 68-B), and I added an air inlet and tube to enable more secure inflation (see figure 68-A&C). Inflation resulted in a significant angular deflection of the top layer of the shape, without lifting up entirely (see figure 68-D). Furthermore, the wider air chamber assured an enhanced spread of expansion. However, in order to use this principle for creating an appearance change, the angular deflection should be far greater than currently achieved. Possibly, this could be achieved with multiple bellows. However, this would require a much thicker shape.

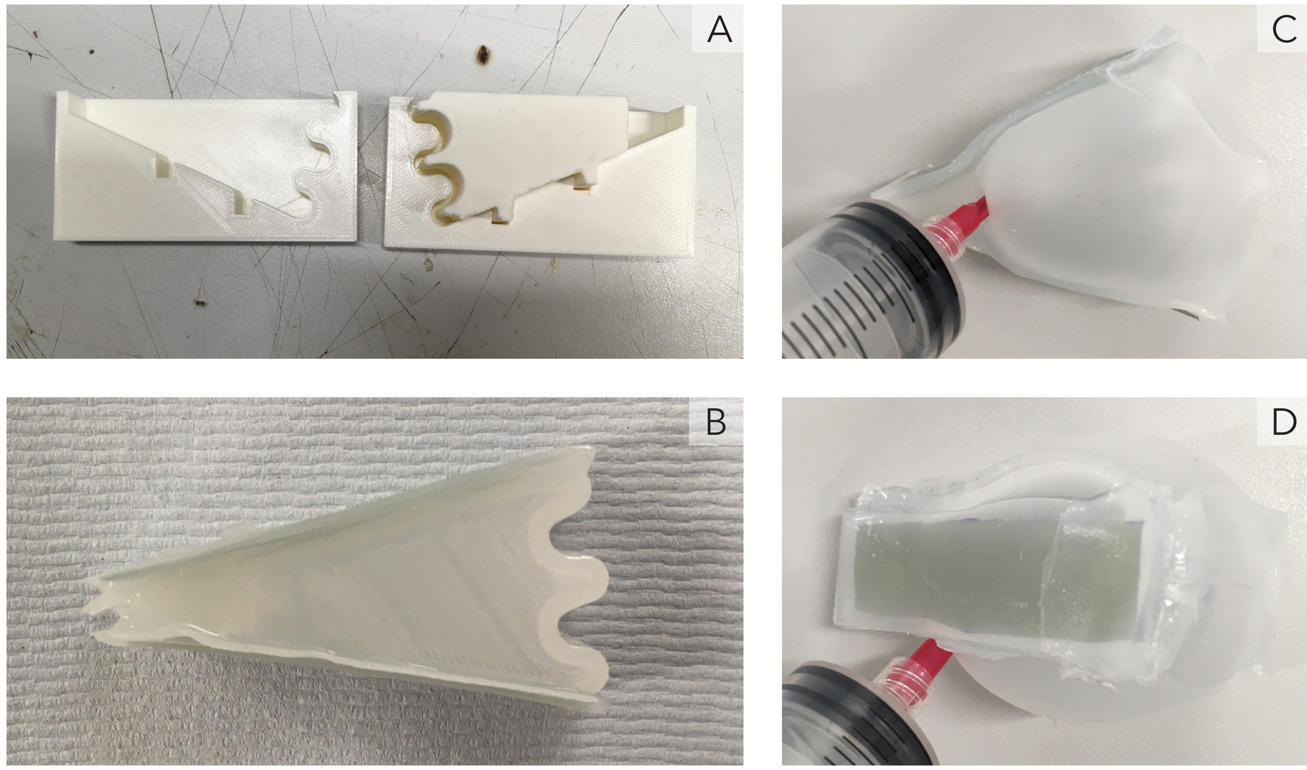


Figure 66: Casted 'Bellow-Shape': Prototyping process - **A:** Three-part mold. **B:** Casted shape with inextensible layer on top and bottom. **C:** Prototype after inflation, resulting in angular displacement. **D:** Balloon-blowing effect on the sides

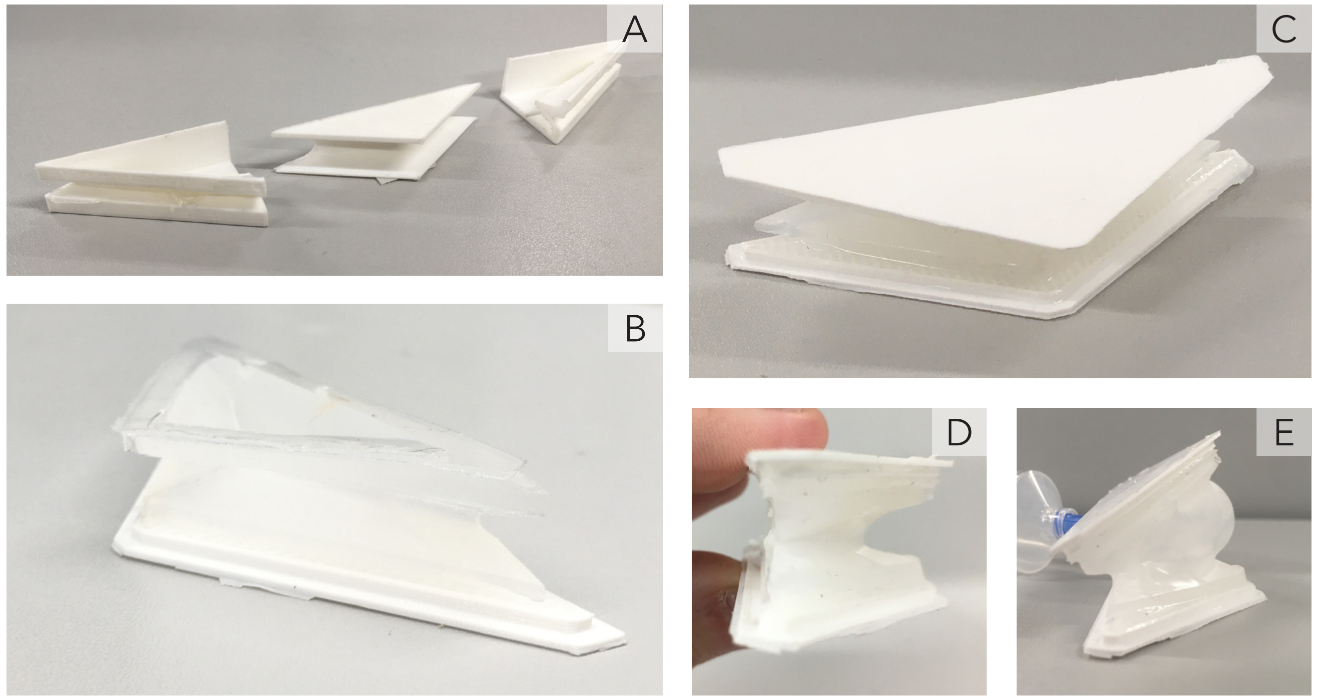


Figure 67: Iteration 1: Prototyping process - **A:** Three-part mold. **B:** Casted shape on inextensible layer before bonding. **C:** Casted shape with inextensible layer on top and bottom. **D:** Casted shape with one crease. **E:** Prototype after inflation, resulting in angular displacement but also ascendance of the top layer.

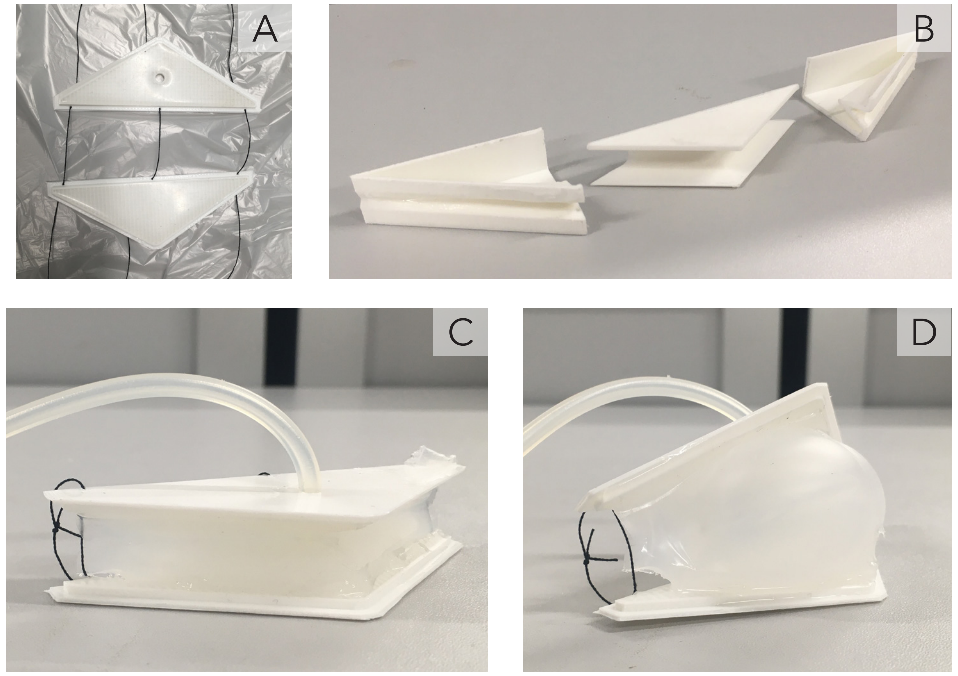
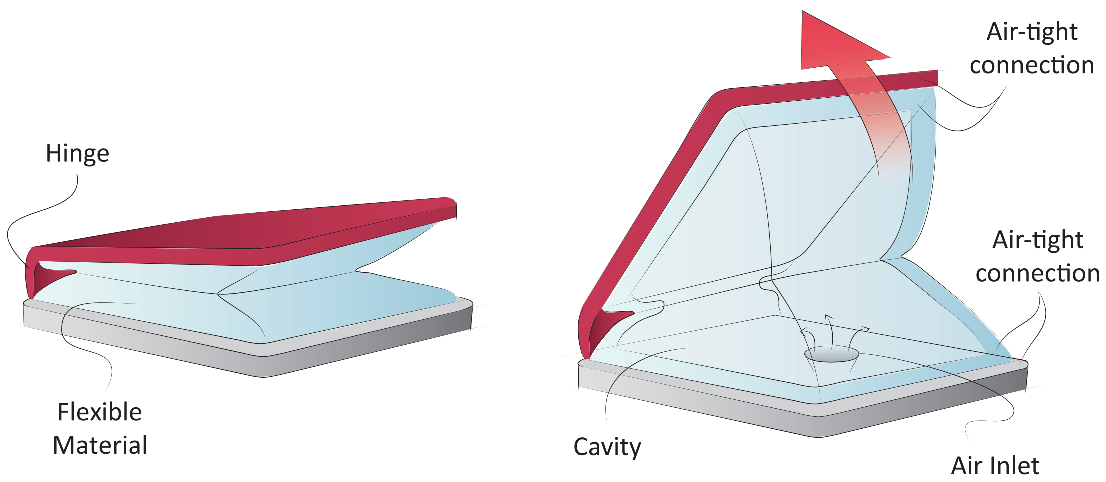


Figure 68: Iteration 2: Prototyping process - **A:** Three-part mold. **B:** Inextensible layers binded together with threads **C:** Casted shape with inextensible layer on top and bottom. **D:** Prototype after inflation, resulting in angular displacement without ascendance of the top layer.

CONCEPT 2.2

THE ‘BELLOW SHAPE’ - FABRIC SEALING



For the first fabric prototype, I reproduced the rotary actuator from Khin et al. (2017), described in the previous part. The goal of this prototype was to explore the heat-sealing process and to achieve an angular displacement after inflation. I used a transparent TPU film for the inner part of the actuator and a grey TPU-coated nylon for the outside. The material for the inside can be sealed from both sides of the sheet, while the material for the outside can only be sealed from one side. I chose to model a triangular shape, as patterning triangles allows to fill a surface entirely. I laser-cut the sheets into the desired shapes, as this is more accurate than cutting with a knife or scissors (see figure 69-A). Finally, I used a flat iron to seal the sheets together and create an air-tight pouch (see figure 69-B).

Inflation of the pouch resulted in a significant angular displacement of the fabric (see figure 69-C). Here, the actuator folds open and the inner part bloats out. However, when observing from above, the achieved angular displacement did not result in a clear appearance transformation (see figure 69-D). First of all, this is due to the isometric expansion of the shape rather than the top layer folding open exclusively. Furthermore, due to the sealed edge, the inner material is embedded into folded shape and thereby covered by the outer material. To solve this, I found that when the model is rearranged to an upright position, the rotational movement is used more efficiently, and the inner material becomes more visible. Thereby, a more significant appearance change can be achieved.

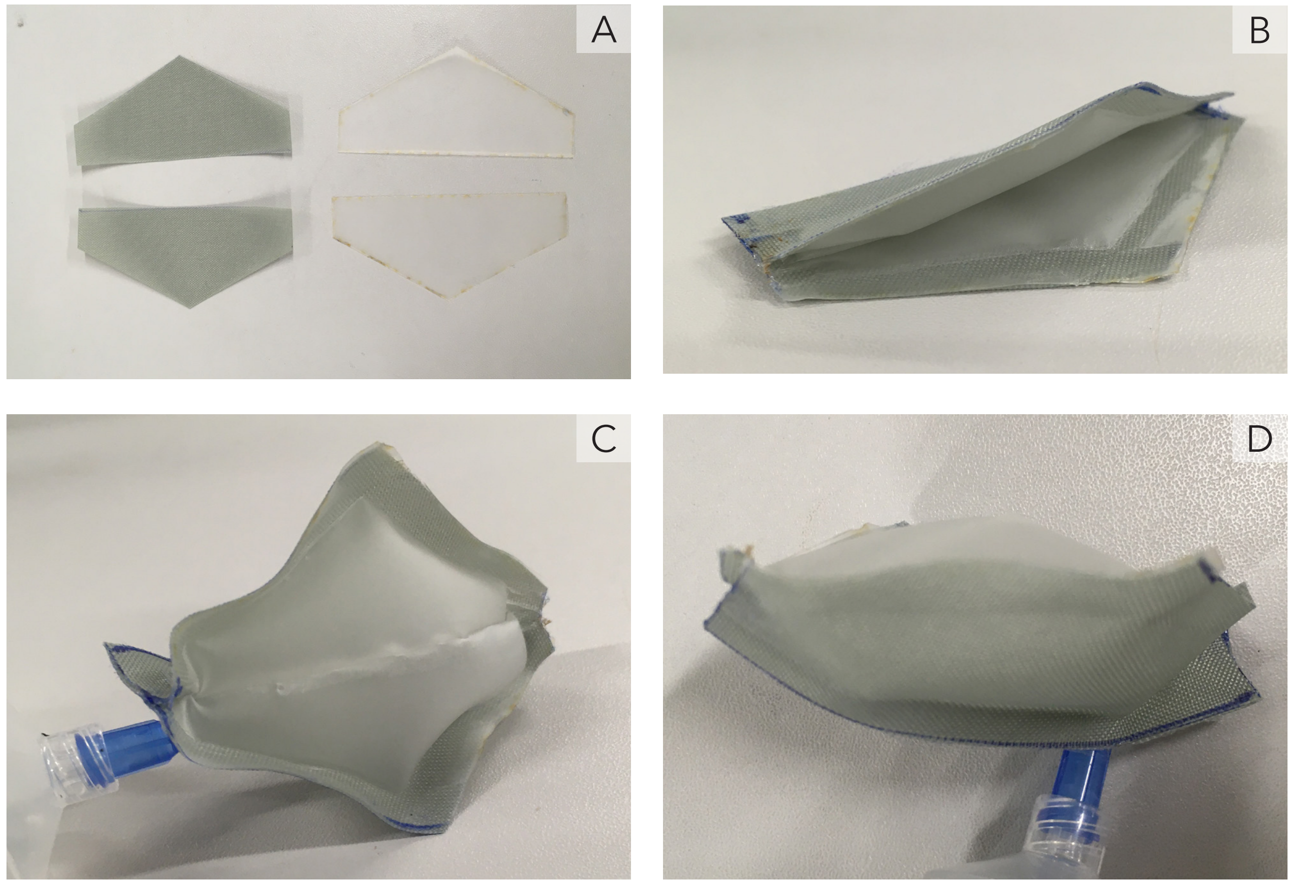


Figure 69: Sealed ‘Bellow-Shape’: Prototyping process - **A:** Laser-cut material. **B:** Sealed pouch **C:** Prototype after inflation, resulting in angular displacement (sideview). **D:** Prototype after inflation, resulting in angular displacement (topview).

ITERATION 1

For this iteration, the prototype was placed upright instead of flat and sealed onto a flat sheet of fabric to keep it fixed in place. I used a lighter, more flexible material with a darker, more contrasting color. Also, I added a 3D-printed air-inlet which I sealed onto the material with an additional piece of fabric (see figure 70-A&B&C). This, to simplify the inflation process. Inflation of the prototype resulted in a significant angular displacement, revealing the differently colored inner material (see figure 70-D&E&F&G). Therefore, a clear appearance change was achieved.

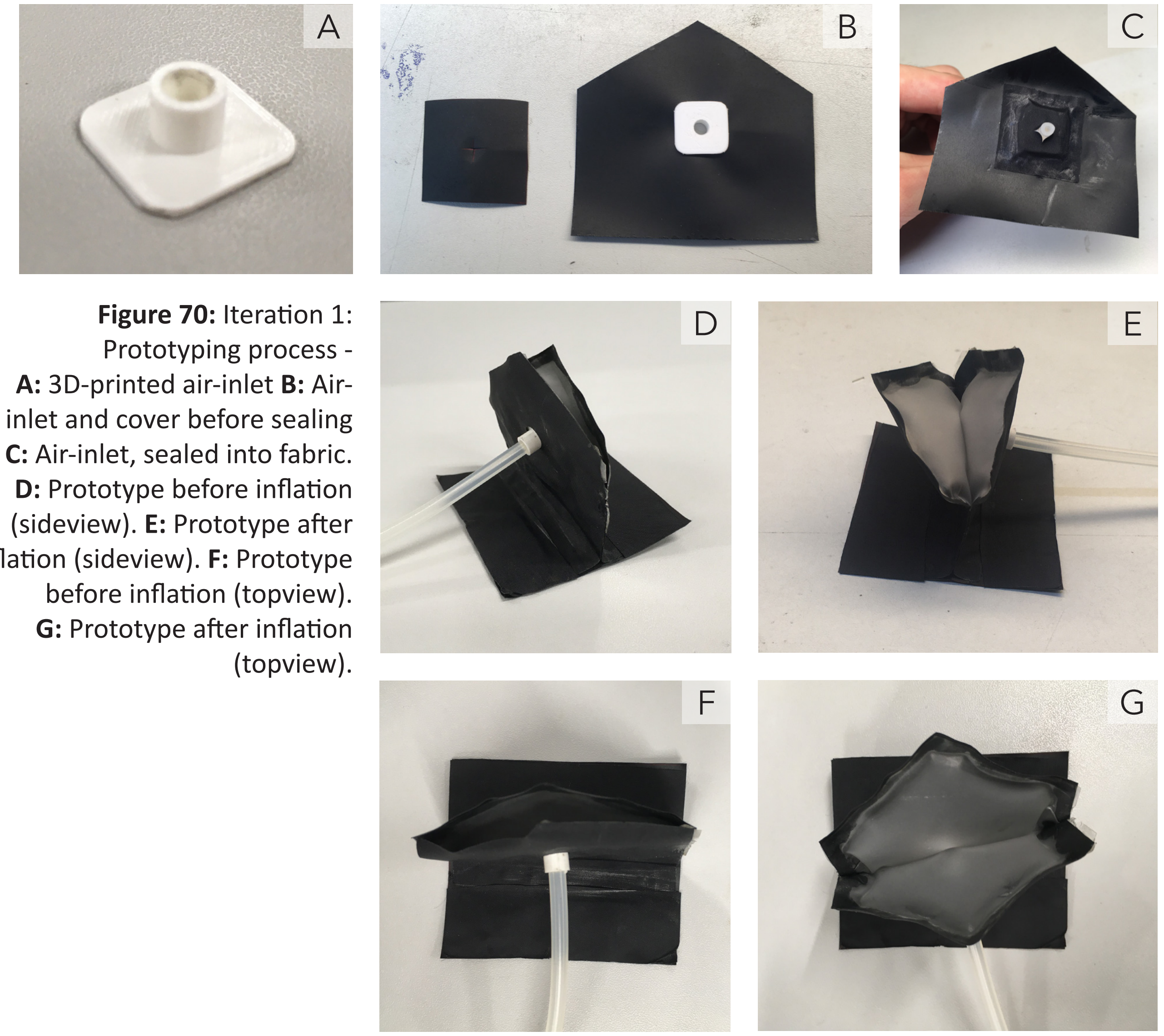
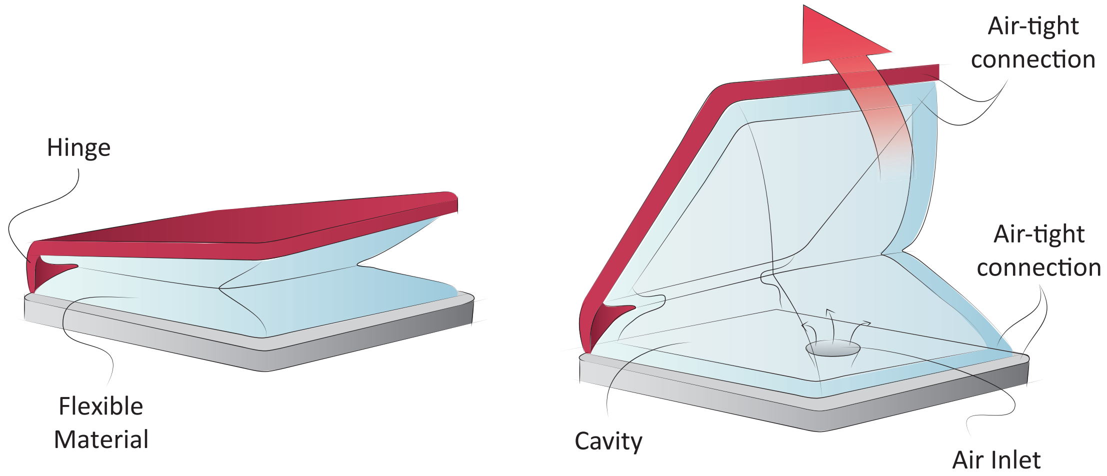


Figure 70: Iteration 1: Prototyping process - **A:** 3D-printed air-inlet **B:** Air-inlet and cover before sealing **C:** Air-inlet, sealed into fabric. **D:** Prototype before inflation (sideview). **E:** Prototype after inflation (sideview). **F:** Prototype before inflation (topview). **G:** Prototype after inflation (topview).

CONCEPT 2.3
THE 'BELLOW SHAPE' - 3D-PRINTING



The goal of this prototype was to explore the possibilities of 3D-printing with flexible material and to achieve an angular displacement due to inflation. I used SolidWorks to model a separate part for each material. Since the intended model consists of both rigid and flexible material, I modelled two parts in an assembly. I used a similar shape as the previously described silicone 'Bellow' prototype, as this model ensured a significant angular displacement. Furthermore, I modelled a rigid beam, placed unattached on the inside the shape. Since this beam is easy to remove by hand, it allows to remove the support material inside the pouch. I modelled an additional lid for closing off the cavity created by this beam (see figure 71-A&B).

After modelling was done, the prototype was 3D-printed with a 'Stratasys 735' PolyJet printer. Finally, I removed the support material by hand and with a water jet.

The intended shape was printed successfully (see figure 71-B&C), and a strong bond was created between the two separate materials. However, I found that the folding crease did not allow enough room for rotation (see figure 71-D). Also, tears emerged in the flexible material while removing the support material (see figure 71-E). Therefore, I found that the folding crease should be made deeper and the wall thickness of the flexible material should be made thicker.

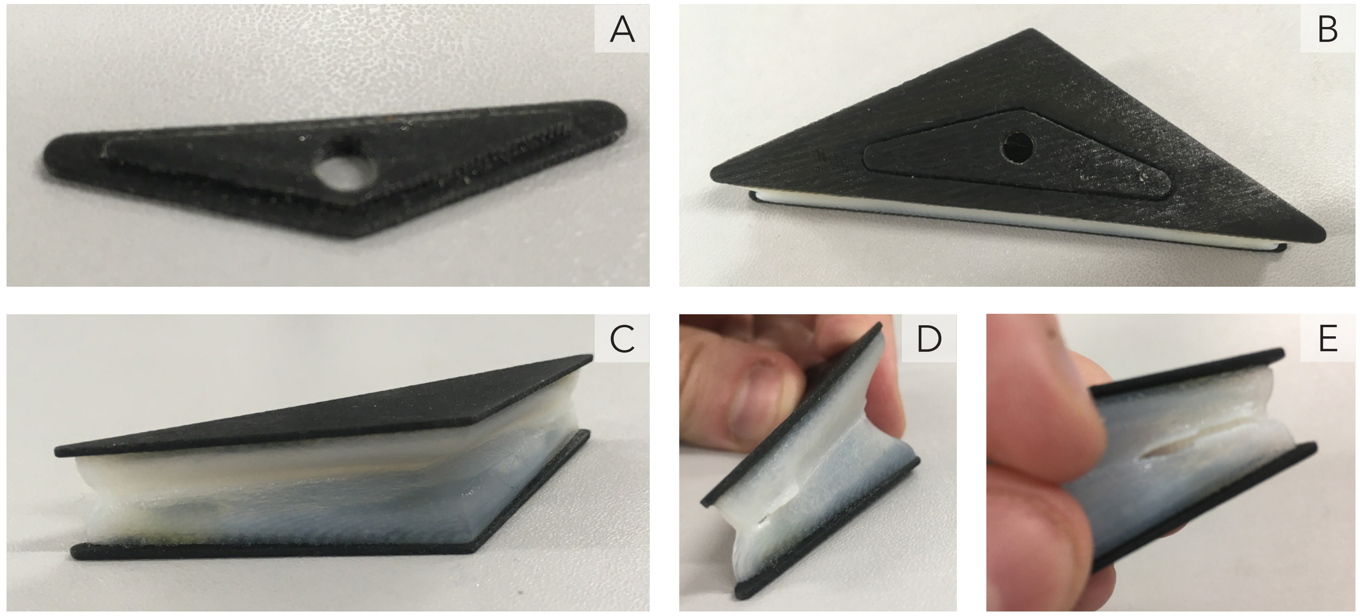


Figure 71: Printed 'Bellow-Shape': Prototyping process - **A:** Lid to cover cavity. **B:** 3D-printed part (topview). **C:** 3D-printed part (sideview). **D:** Prototype's maximum rotation. **E:** Tears in flexible material.

ITERATION 1

The goal for this iteration was to improve the flaws of the previous prototype. Therefore, I modelled a deeper folding crease and doubled the wall thickness. For this prototype again, I modelled a rigid beam which can be removed to create space for the removal of support material on the inside of the prototype (see figure 72-B&C).

Also, I printed lids to close off the cavities, created by this beam (see figure 72-A&D). Inflation of the prototype resulted in a significant angular displacement of the top layer of the prototype (see figure 72-E&F&G&H). Hereby, the differently colored inner material was revealed, and an appearance change was achieved.

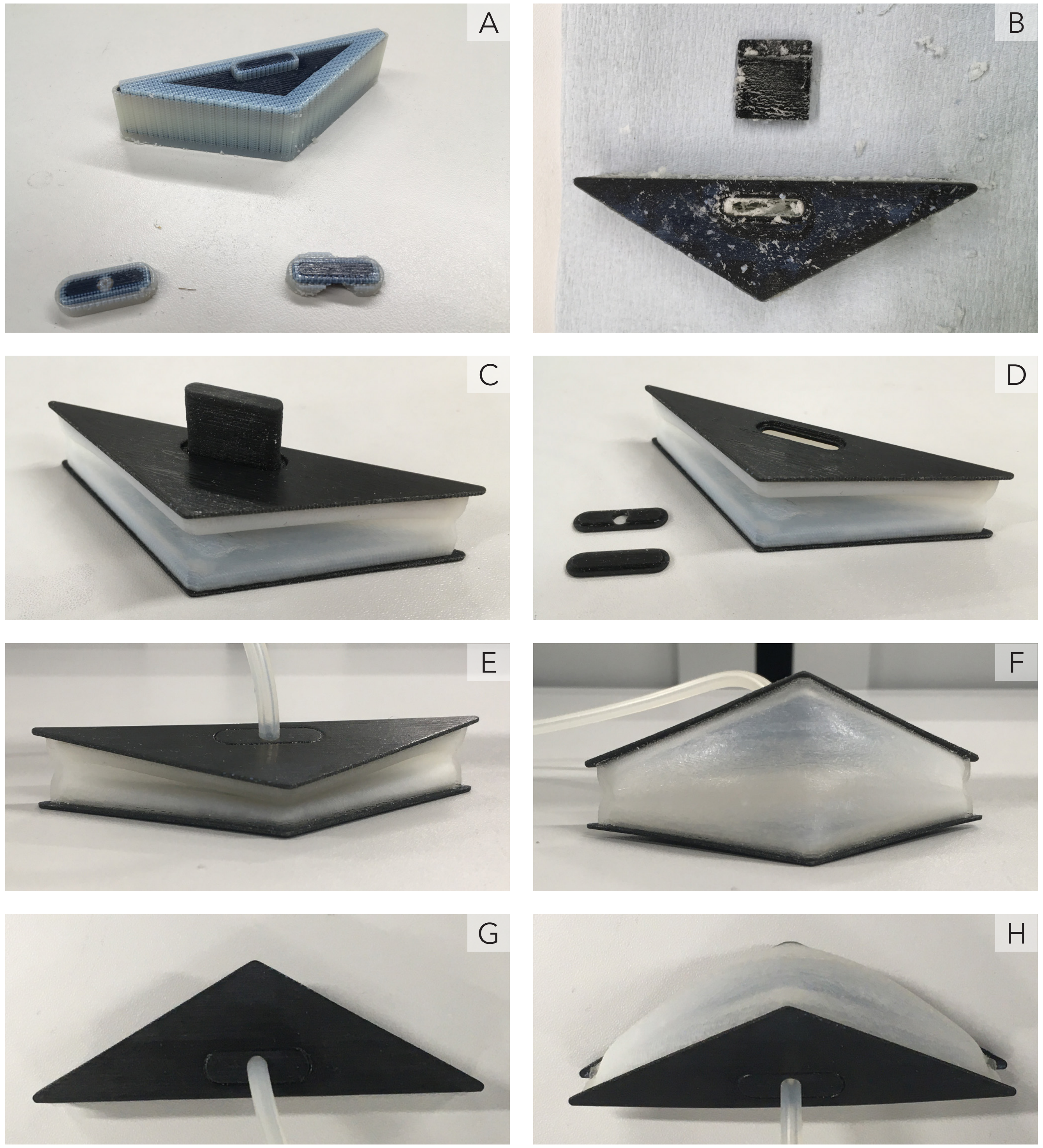
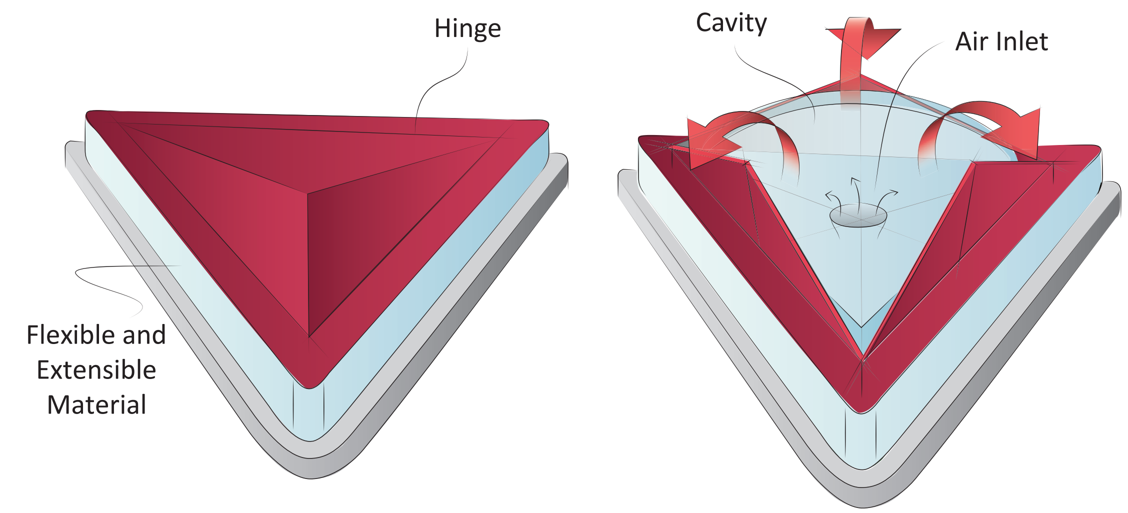


Figure 72: Iteration 1: Prototyping process - **A:** Prototype with support material. **B:** Removal of rigid beam **C:** Prototype and rigid beam after removing support material. **D:** Prototype and closing lids after removing support material. **E:** Prototype before inflation (sideview). **F:** Prototype after inflation (sideview). **G:** Prototype before inflation (topview). **H:** Prototype after inflation (topview)

CONCEPT 3

THE ‘CENTRAL BALLOON’



This prototype consists of three layers: a plastic bottom layer, a silicone middle layer and a cardboard top layer (see figure 73-A&B). For the production of the silicone layer, I used a 3D-printed mold. This mold assured a cavity in the casted shape, acting as air-chamber for inflation. I chose a triangular shape, as patterning triangles allows filling a surface entirely. The bottom layer was 3D-printed and included a previously described ‘interlocking grid’, which is used to create an air-tight bond between the bottom and middle layer. Moreover, the top layer was cut in shape with a laser-cutting machine (see figure 73-B). Here, three triangular lids and a triangular outer ring were created. Finally, I used tape to connect the lids to the outer ring and to create a hinge for the rotation of the lid after inflation (see figure 73-C).

Inflation of the prototype ensured that the silicone bloated upwards. This resulted in an angular rotation of the three lids, revealing the silicone layer underneath the cardboard layer and a clear appearance change was achieved (see figure 73-D). However, at some point, the lids rotated more than 90 degrees, which reduces the achieved appearance transformation. I assumed that this was due to the triangular shape and the triangular shaped air-chamber. As the material expands isometrically, a spherical balloon arises. I suspected that a shape that encloses a circular shape better, as for instance a square or diamond shape, would solve this problem.

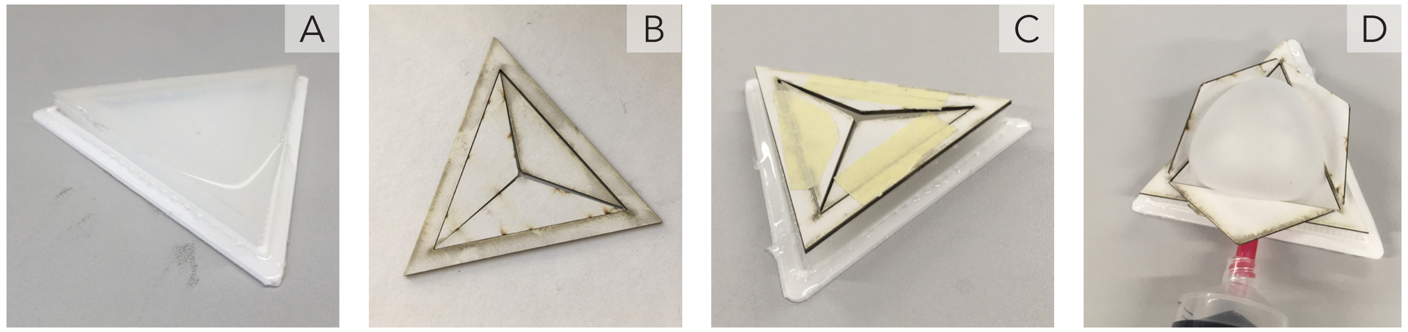


Figure 73: The ‘Central Balloon’ concept: Prototyping process - **A:** Casted shape on top of inextensible layer. **B:** Laser-cut cardboard **C:** Prototype with tape as hinges before inflation. **D:** Prototype after inflation

ITERATION 1

For this iteration, I used a diamond-shaped mold with a circular air-chamber (see figure 74-A). Furthermore, I performed the same steps as the previous prototype. However, in this case, four lids were created. Inflation resulted in angular rotation of these four lids, revealing the silicone shape and thereby achieving a clear appearance change (see figure 74-B). Also, as intended, the lids did not rotate further than a 90-degree angle. Therefore, I concluded that the working principle was successful.

ITERATION 2

In the previous prototypes, tape was used as hinge for rotation. This was done for a quick proof-of-concept prototype but was not intended as definite solution. Therefore, I created several alternatives and evaluated their performance in terms of ease of rotation and achieved deflection. I used the following materials and techniques for creating potential hinge solutions: 3D-printed lids with rotation axles (see figure 75-A&B), cardboard with a laser-cut 'living hinge-pattern' (see figure 75-C&D), fabric with four laser-cut 'flaps' (see figure 75-E&F), and this same fabric, reinforced with cardboard panels (see figure 75-G&H). Here, I found that the living-hinge and the reinforced fabric gave the best result, as the lids are stiff while the hinge allows a smooth rotation.

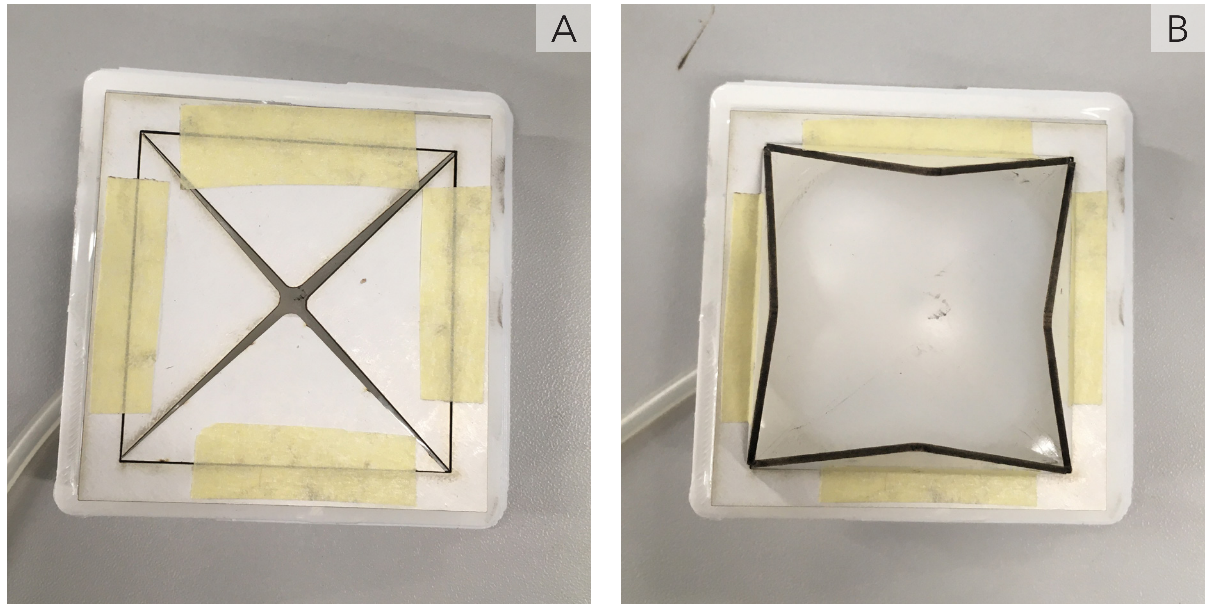


Figure 74: Iteration 1: Prototyping process - **A:** Diamond-shaped prototype. **B:** Prototype after inflation

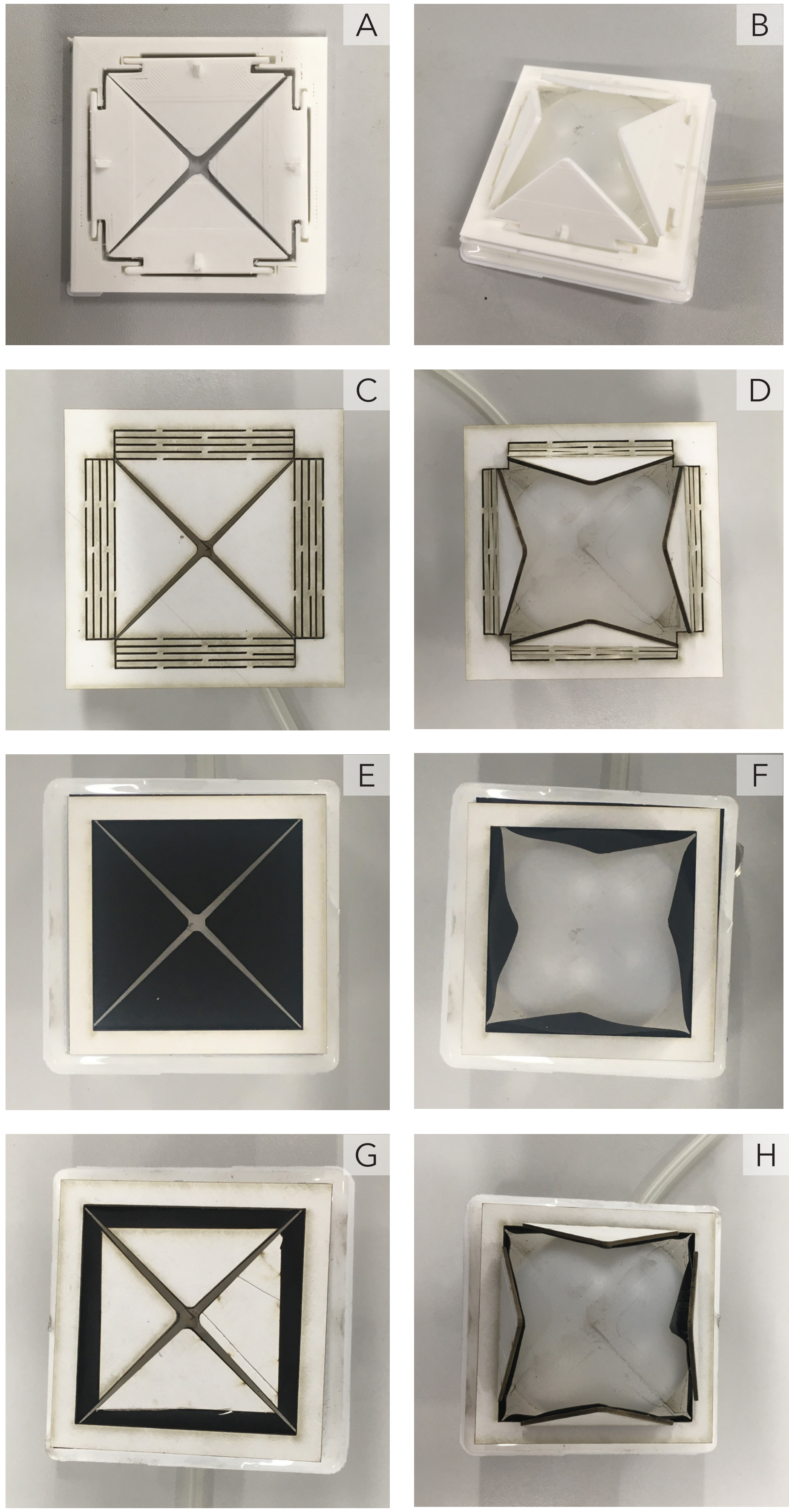
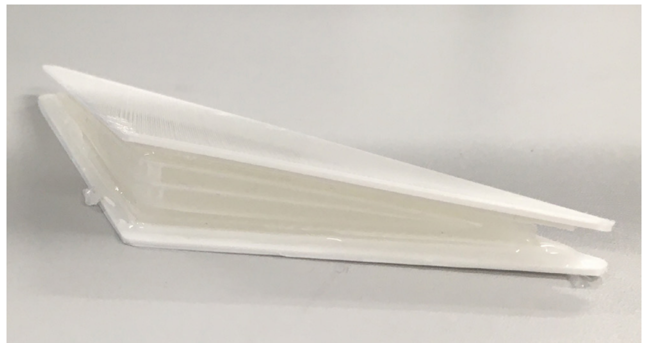
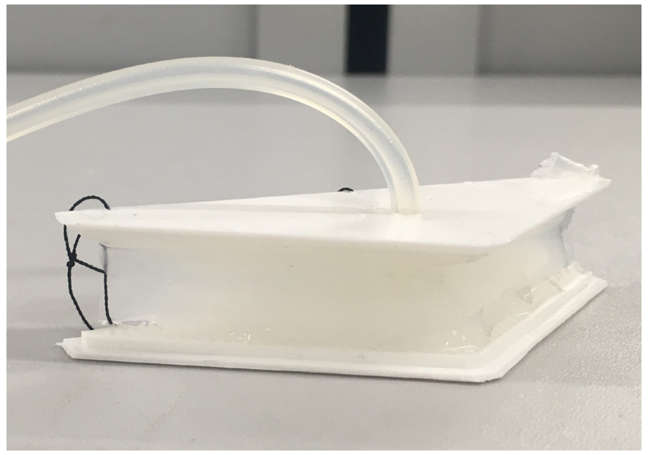


Figure 75: Alternative hinges - **A:** 3D-printed hinge. **B:** 3D-printed hinge after inflation **C:** Laser-cut hinge. **D:** Laser-cut hinge after inflation. **E:** Fabric hinge. **F:** Fabric hinge after inflation. **G:** Fabric hinge, reinforced with cardboard **H:** Fabric hinge, reinforced with cardboard after inflation

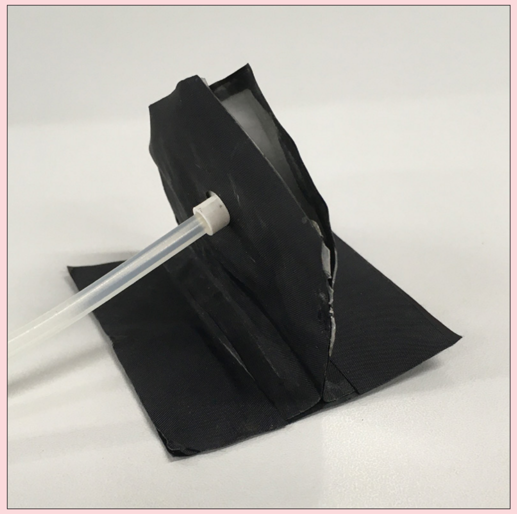
4.3 FINAL CONCEPTS

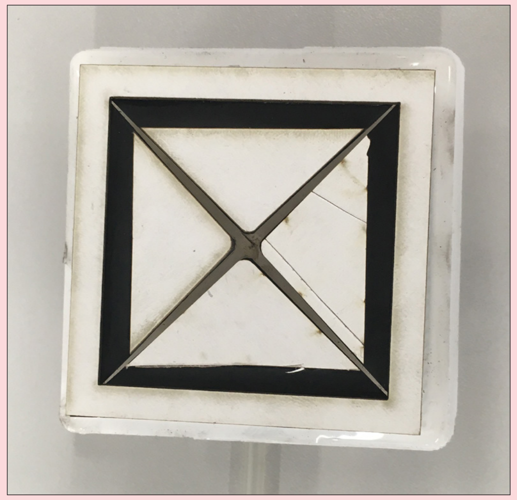
After comparing the final prototypes of the five iteration processes, three were selected in terms of performance: the sealed and 3D-printed bellow-shape concepts and the central balloon concept. Not only did these prototypes gave the most promising results in terms of achieving an appearance change, selecting these three concepts also allows to compare the three different fabrication methods.



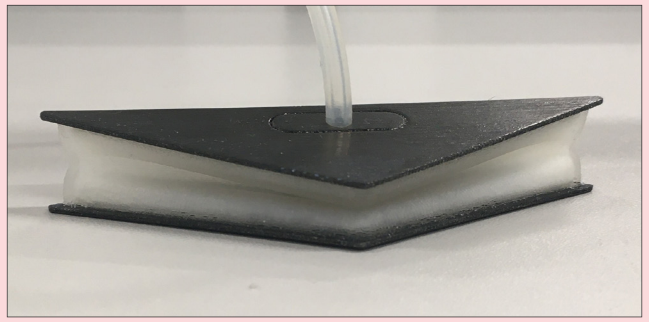


CHOSEN CONCEPT





CHOSEN CONCEPT



CHOSEN CONCEPT

APPROACH

In order to test and compare the visual effect of the three selected prototypes, I constructed three more fabric actuators and two more 3D-printed actuators and placed them together on wooden panels. This, because these specific actuators were intended to be part of a mechanism unit of multiple actuators, folding open simultaneously. For the selected silicone 'Central Balloon' concept, this was unnecessary, as this is already a complete mechanism unit, with multiple included rotating lids. In order to actuate all actuators in a mechanism unit simultaneously, I 3D-printed air-dividing parts (see figure 76). Here, for the fabric and 3D-printed concepts, one tube is divided to respectively four and three tubes. Again, for the silicone concept this was unnecessary, as one inflatable air-chamber actuates four rotating lids together.

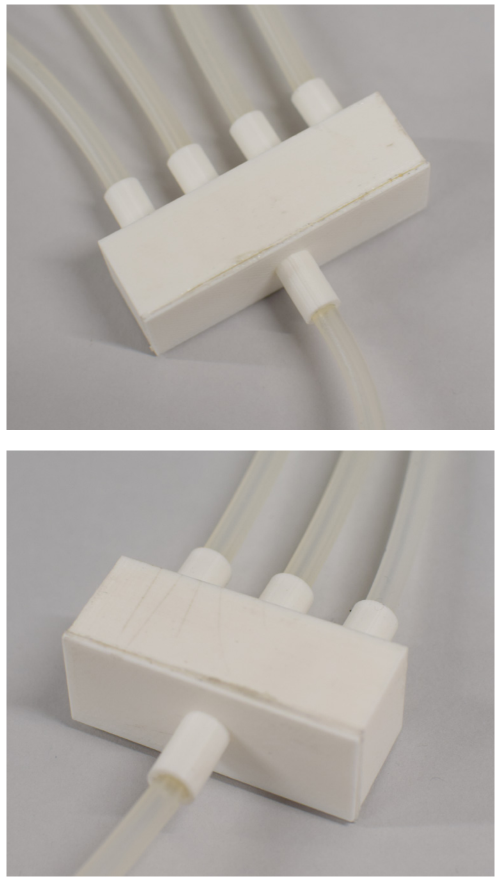


Figure 76: Air-diving parts

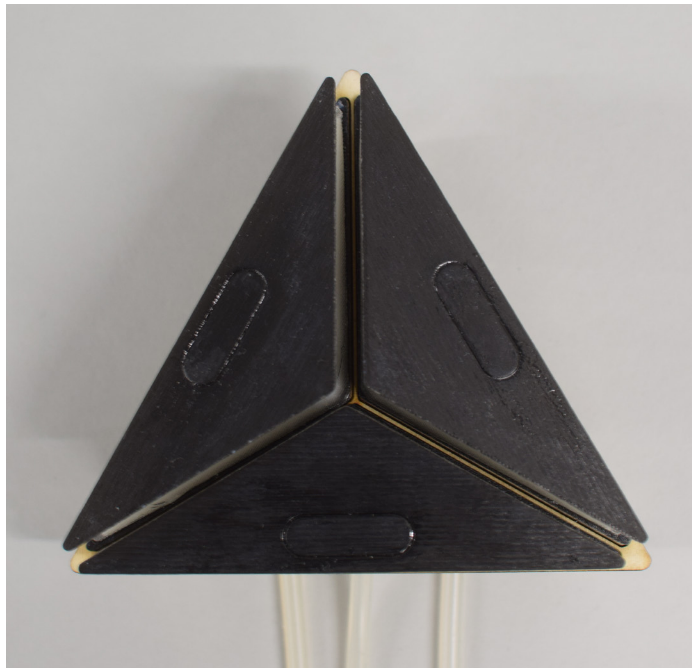
FINAL CONCEPT 1
THE 'BELLOW-SHAPE' - FABRIC SEALING

BEFORE INFLATION

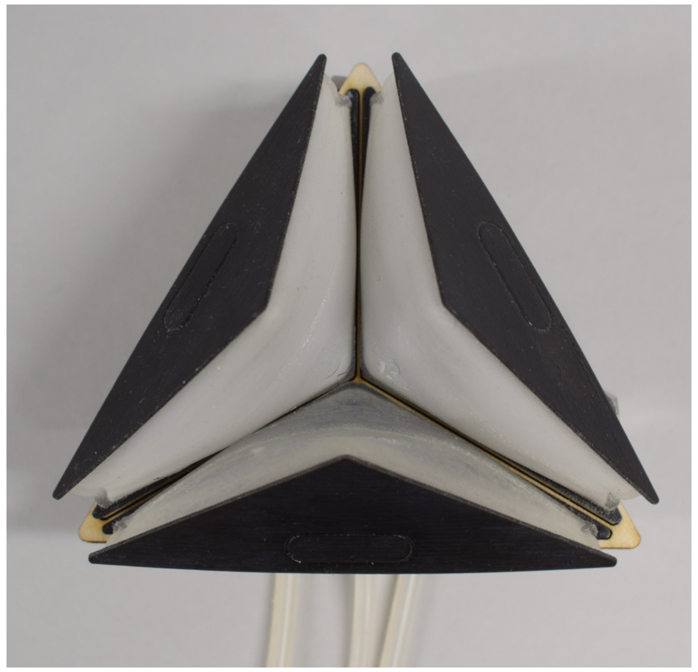
AFTER INFLATION

FINAL CONCEPT 2

THE ‘BELLOW-SHAPE’ - 3D-PRINTING



BEFORE INFLATION



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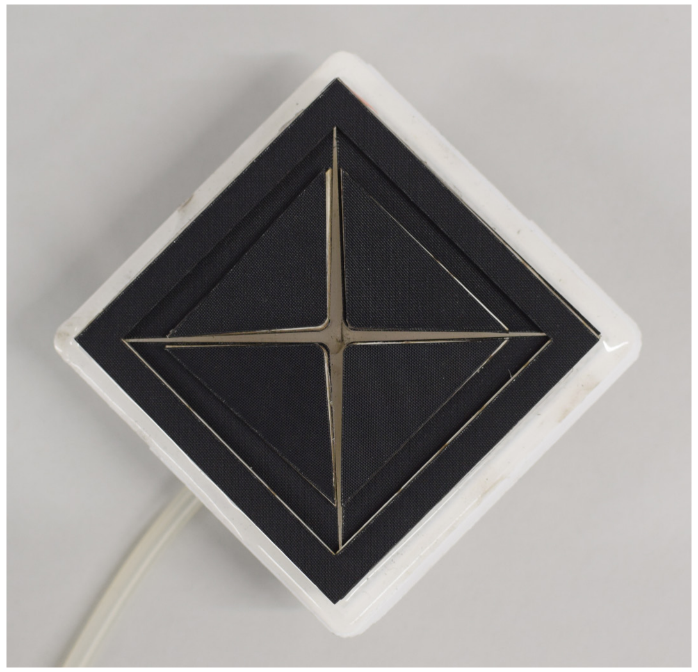
FINAL CONCEPT 3

THE ‘CENTRAL BALLOON’ - SILICONE CASTING



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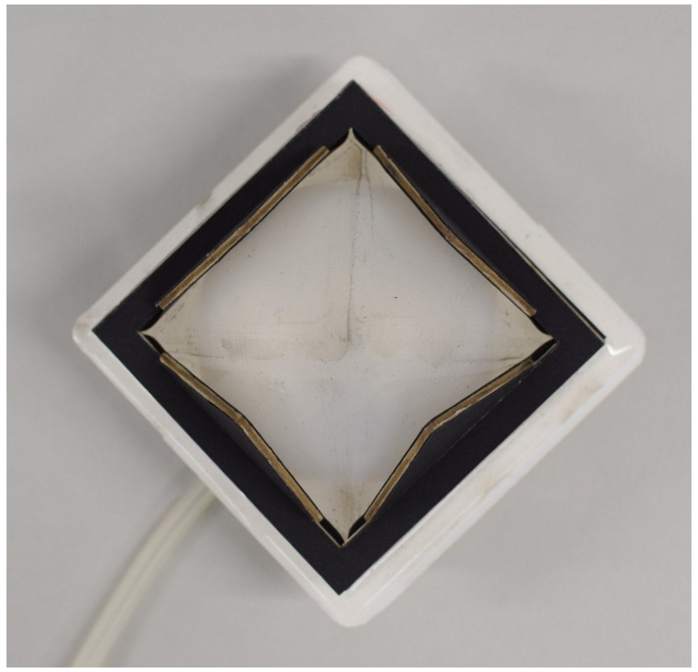


AFTER INFLATION

4.4 CONCEPT EVALUATION

The final concepts were evaluated by means of nine points of criteria and one concept was chosen for the final design.

APPROACH

In order to choose the most promising mechanism among the three proposed concepts, I evaluated the concepts in terms of performance, feasibility and applicability. Here, I used the same nine requirements as previously stated in Part 2, where I used them for evaluating the five formerly proposed mechanism concepts. Again, I used Harris Profiles to evaluate and compare the concepts. Also, in this case again, I mainly rated the requirements as comparison to each other, and in some cases the rating could only be assumed. However, the Harris Profiles assisted in choosing one concept for the final design.

CRITERIA

PERFORMANCE:

How well does the mechanism succeed in the goal of active appearance change?

1: The mechanism provides a clear change of appearance by changing from one color to another or from opaque to transparent, *to ensure that the effect is noticeable and that it can therefore be used for the purpose of interactivity, expression, communication or response*

2: The mechanism enables a spectrum of appearances instead of only a few states, *which broadens the possibilities for using the mechanism for the purpose of interactivity, expression, communication or response*

3. The mechanism enables the possibility of local appearance change, *which broadens the possibilities for using the mechanism for the purpose of interactivity, expression, communication or response*

FEASIBILITY:

Is it possible to build the mechanism within the given time with the available resources?

4. The mechanism can be actuated with simple mechanical or pneumatic actuators, *in order to fulfill the goal of keeping the solutions simple and ‘low-tech’*

5. The mechanism can be fabricated, assembled and actuated with many at the same time or together as one part, allowing quick and effortless production on a larger scale.

6. The mechanism can in total, or to a large extent, be fabricated with digital fabrication technology, assuring high precision and consistency while minimizing manual labor.

APPLICABILITY:

How suitable is the mechanism for the application to a product?

7. The mechanism is applicable to any surface or shape, *and can therefore be applied to products of any shape*

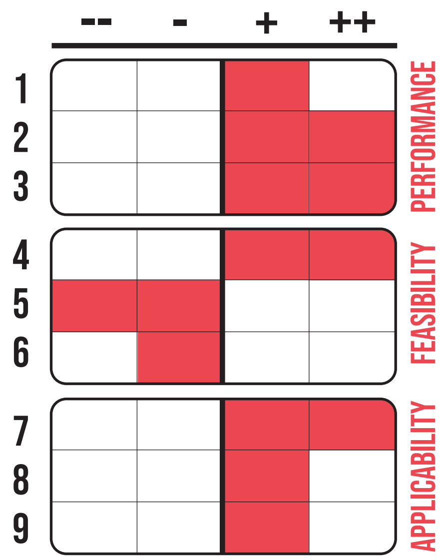
8. The mechanism keeps the overall contour or shape of the surface intact during the transformation, *and thereby keeps the product’s functionality intact*

9. The mechanism keeps the product’s surface rigid without loose or fragile parts, *and is thereby suitable for contact and interaction*

HARRIS PROFILES

PERFORMANCE
1: The mechanism provides a clear change in appearance
2: The mechanism enables a spectrum of appearances instead of only a few states
3: The mechanism enables the possibility of local appearance change
FEASIBILITY
4: The mechanism can be actuated with simple mechanical or pneumatic actuators
5: The mechanism can be fabricated, assembled and actuated with many at the same time or together as one part
6: The mechanism can in total, or to a large extent, be fabricated with digital fabrication technology
APPLICABILITY
7: The mechanism is applicable to any surface or shape
8: The mechanism keeps the overal controur or shape of the surface intact
9: The mechanism keeps the product’s surface rigid without loose or fragile parts

FABRIC SEALING

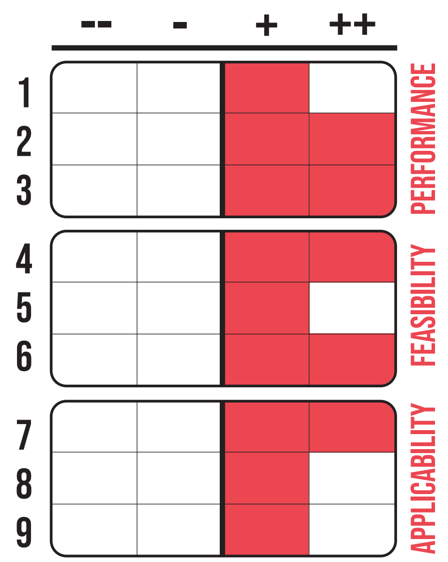


Although the actuators fold open well, they do not close entirely
Color visibility can be regulated by controlling inflation
Actuators can be actuated seperately

Mechanism is actuated by simple inflation
Actuators are fabricated per unit and require much manual labour
Only cutting is done by laser-cut, further fabrication is done by hand

Actuators can be attached to any surface
Inflation changes the surface morphology
No loose parts but the material is fragile

3D-PRINTING

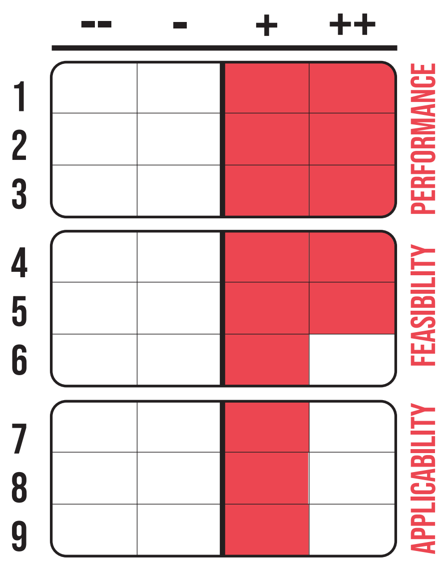


Actuators do not fold open entirely
Color visibility can be regulated by controlling inflation
Actuators can be actuated seperately

Mechanism is actuated by simple inflation
Printer has a maximum working area, can not print many together
Whole fabrication process is done with 3D-printing

Triangular shape suits well for patterning on any shape
Inflation changes the surface morphology
No loose parts but the material is fragile

SILICONE CASTING



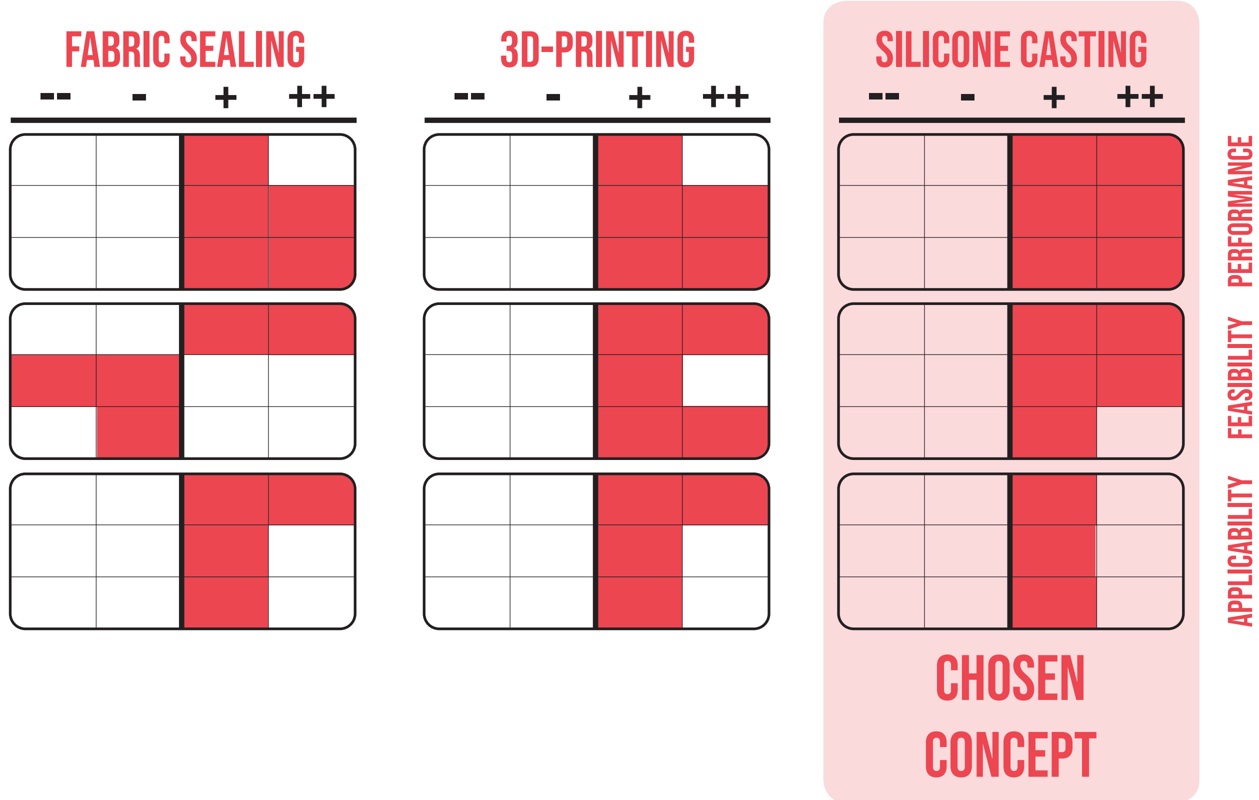
Lids open and close entirely, creating a clear color change
Color visibility can be regulated by controlling inflation
Actuators can be actuated seperately

Mechanism is actuated by simple inflation
Units can be casted and laser-cut at the same time or as one part
Casting and assembling requires manual labour

Diamond shape is not as suitable for patterning as triangles
Inflation changes the surface morphology
No loose parts but the material is fragile

CHOOSING DIRECTION

When placing the Harris Profiles next to each other, they can be compared. This shows that in terms of performance, Concept 3 exceeds Concept 1 and 2. This, because the mechanism shows the clearest color change effect after inflation. In terms of feasibility, Concept 1 and 2 both score roughly equal, as they can both (partly) be fabricated with digital fabrication and with multiple mechanisms at the same time. This, while Concept 1 was found to be very complicated and time consuming to fabricate. Finally, in terms of applicability, Concept 1 and 2 outscore Concept 3, as they are both more suitable for the application to curved surfaces. All in all, it can be concluded that Concept 3 has the best overall score, as it exceeds in terms of performance and feasibility, which are prioritized over applicability.



PART 5

APPLICATION & DESIGN

INTRODUCTION

After choosing the mechanism in the previous part, the goal for this part was to find a suitable application for the mechanism, and to create a final design and demonstrating prototype. In order to accomplish these aims, the mindmap of application ideas, created in Part 1, was evaluated in terms of how well the ideas suit the chosen mechanism. Here, five ideas were selected and elaborated as application proposals and one was chosen as most desirable and suitable application. Finally, a final design and demonstrating prototype were created.

CONTENT

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5.2	APPLICATION PROPOSALS	**78**
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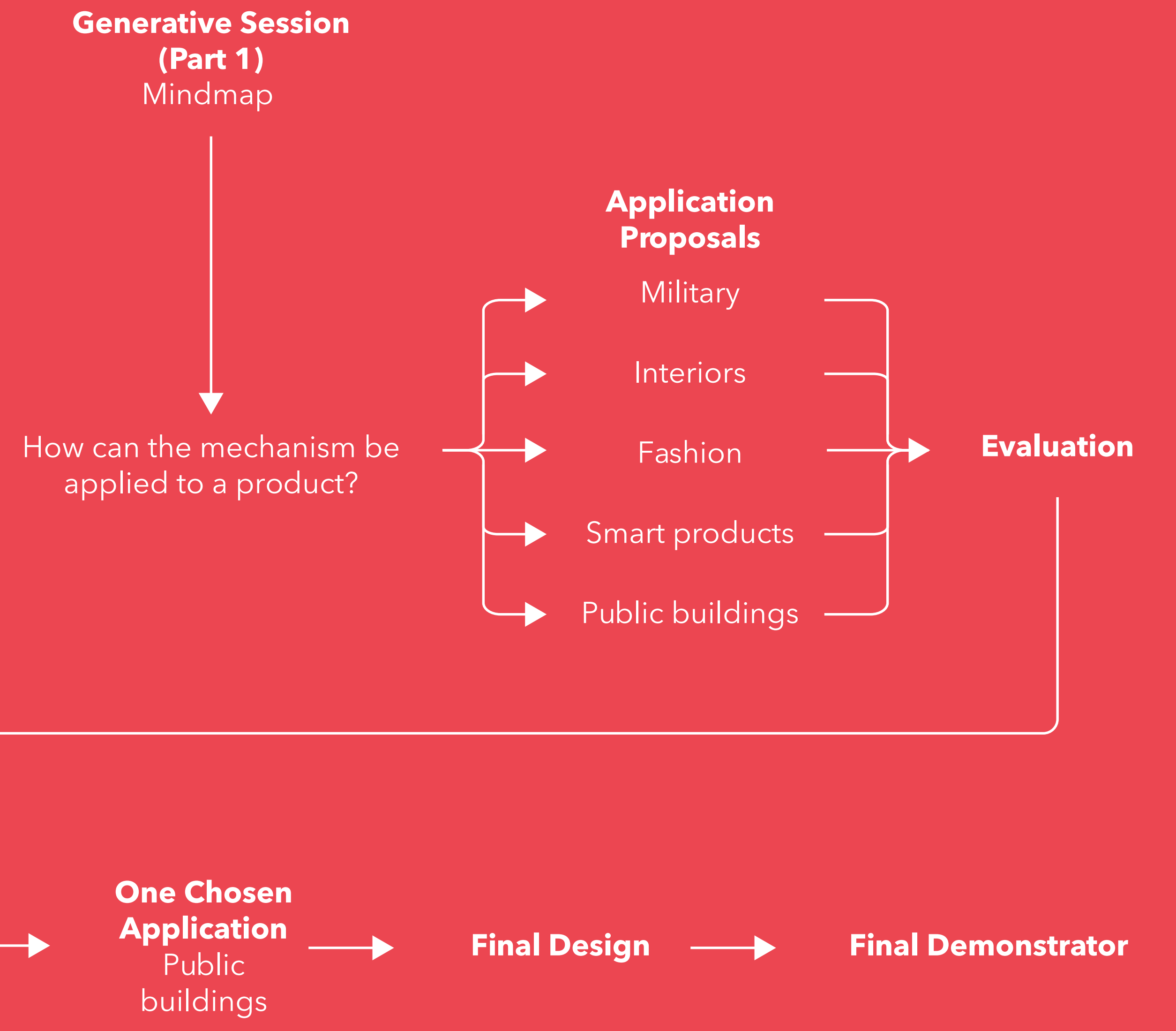


5.1 SELECTING SUITABLE APPLICATIONS

The chosen mechanism was evaluated, after which properties were listed. These were used to evaluate the earlier generated application ideas and select ideas that matched the mechanism properties.

APPROACH

In order to find a suitable application for the chosen mechanism concept, I started with listing properties of the mechanism's working principle, materialization and visual effect. Afterwards, I evaluated the generated ideas of the generative session executed in Part 1 (see figure 79). Here, I selected (combinations of) potential applications for further consideration (see next chapter). This selection was based on how well the ideas suited to the mechanism's properties and on their level of originality, novelty and functionality.

MECHANISM PROPERTIES

The mechanism can be bescribed according to the following properties, of which some are illusrated in figure 77 or demonstrated in figure 78.

MATERIALIZATION:

- The mechanism is built up of a silicone pouch with a rigid top and bottom

STRENGTHS:

- The mechanism provides a clear color change from one color to another

- The mechanism enables the possibility of creating a gradual transformation between two colors, allowing to create a gradient between these colors

- The mechanism can be actuated per unit, allowing to create patterns or messages with multiple mechanisms together

- Multiple mechanisms can be actuated and controlled together from a separately located, central energy source and controller, allowing a 'low-tech' application with few electrical components

- The mechanism's size can vary while the mechanism can be patterned with many mechanisms together, thereby filling a surface of any size

WEAKNESSES:

- Although both the pouch and the rigid panels are from a strong material, tearing of the silicone material would ensure that the pouch is no longer air-tight and damaging the hinging lids would separate them from the panels or constrain rotation. Both would make the mechanism inoperable.

- The mechanism does not fold open when the lids are obstructed and is therefore less suitable for hand-held products or products that require extensive contact

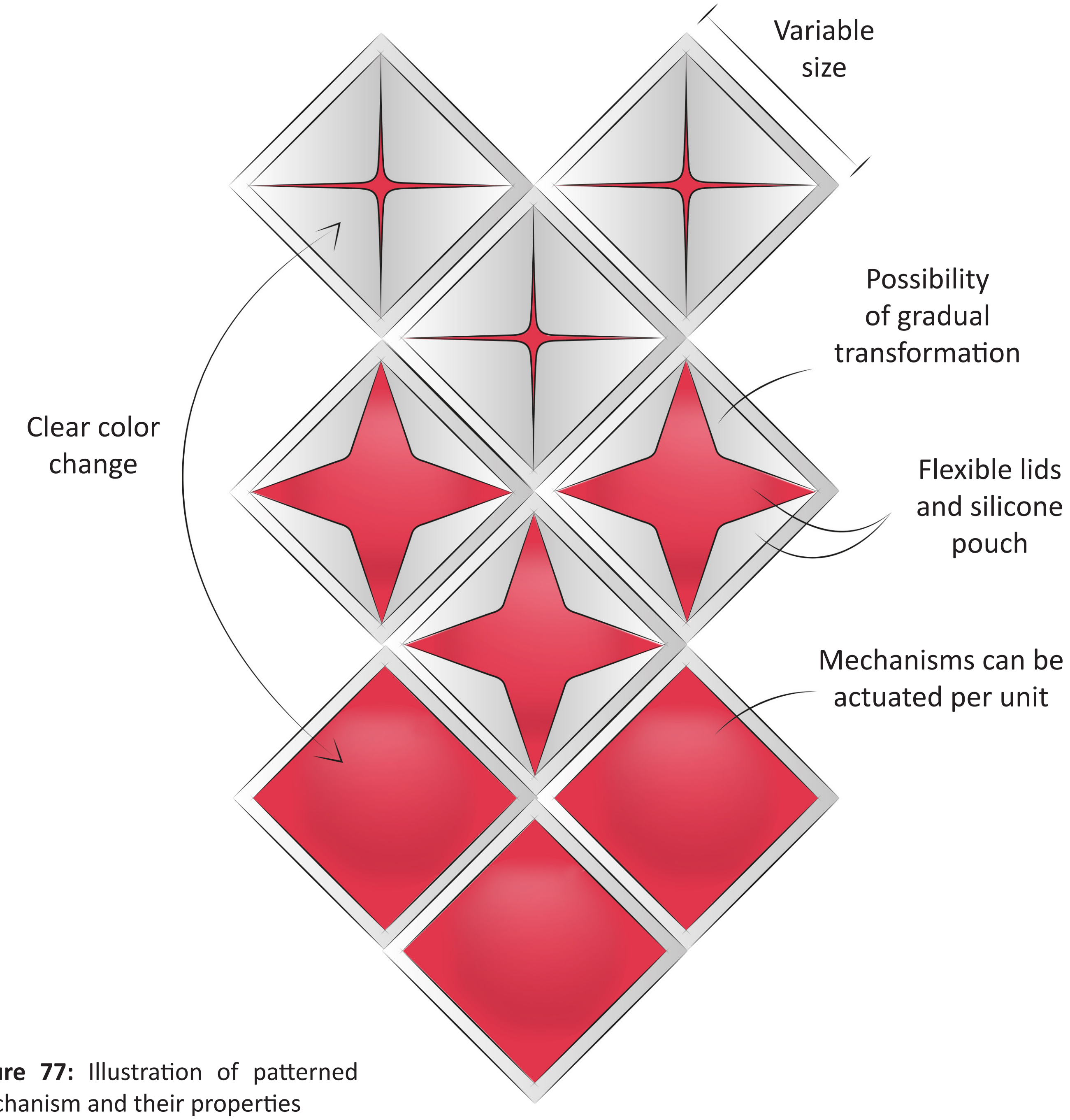


Figure 77: Illustration of patterned mechanism and their properties

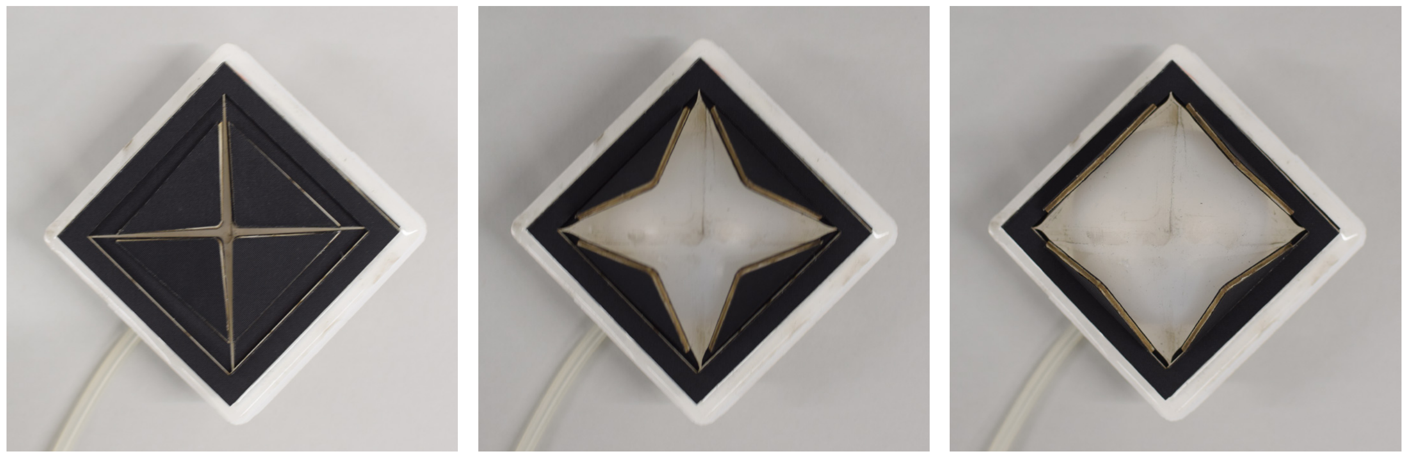


Figure 78: Prototype demonstrating color change after actuation

APPLICATION SELECTION

The following (combinations of) ideas were selected as most suitable for application, based on how well they suit to the mechanism's working principle, materialization and visual effect and on their level of originality, novelty and functionality.

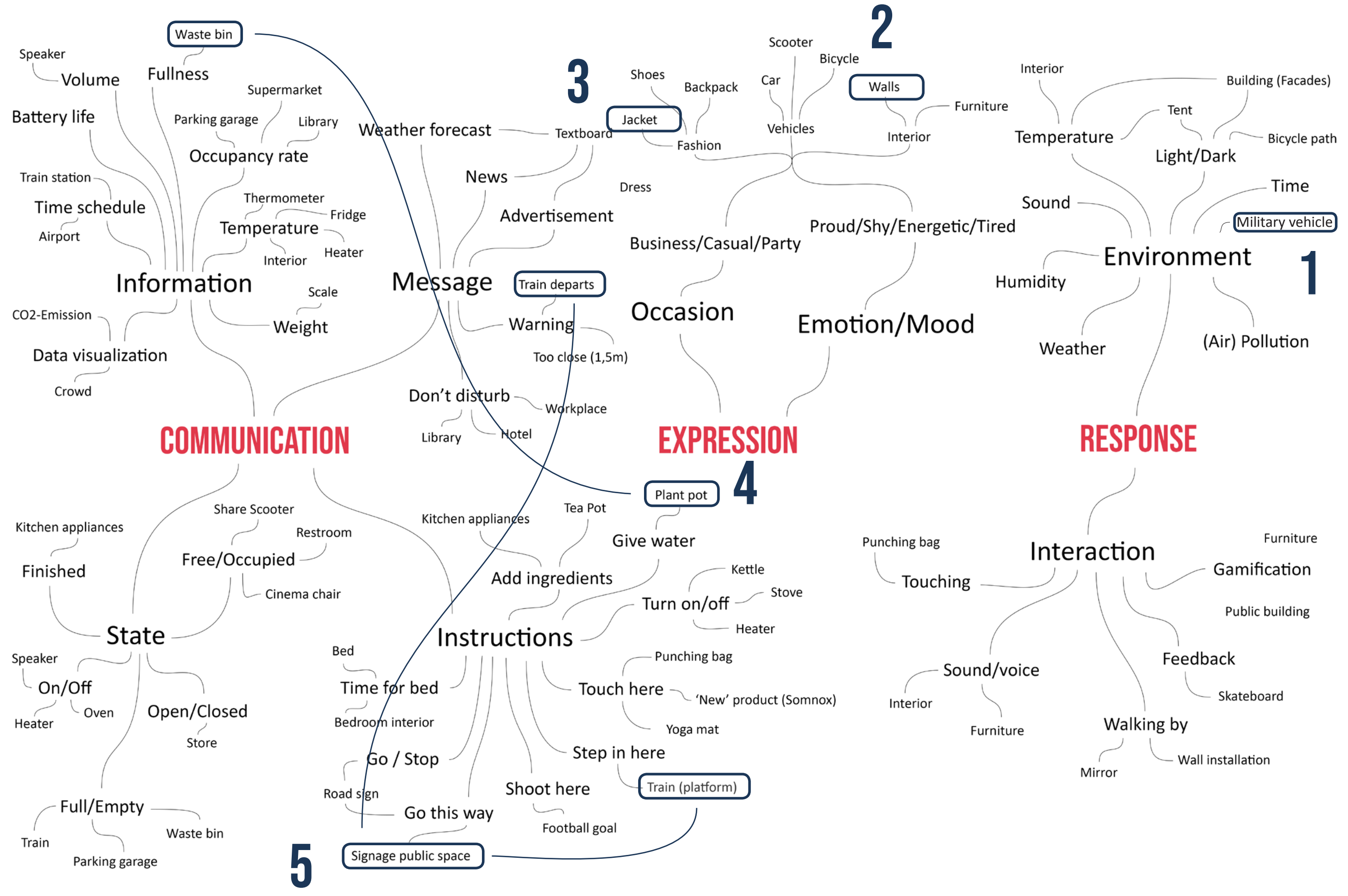


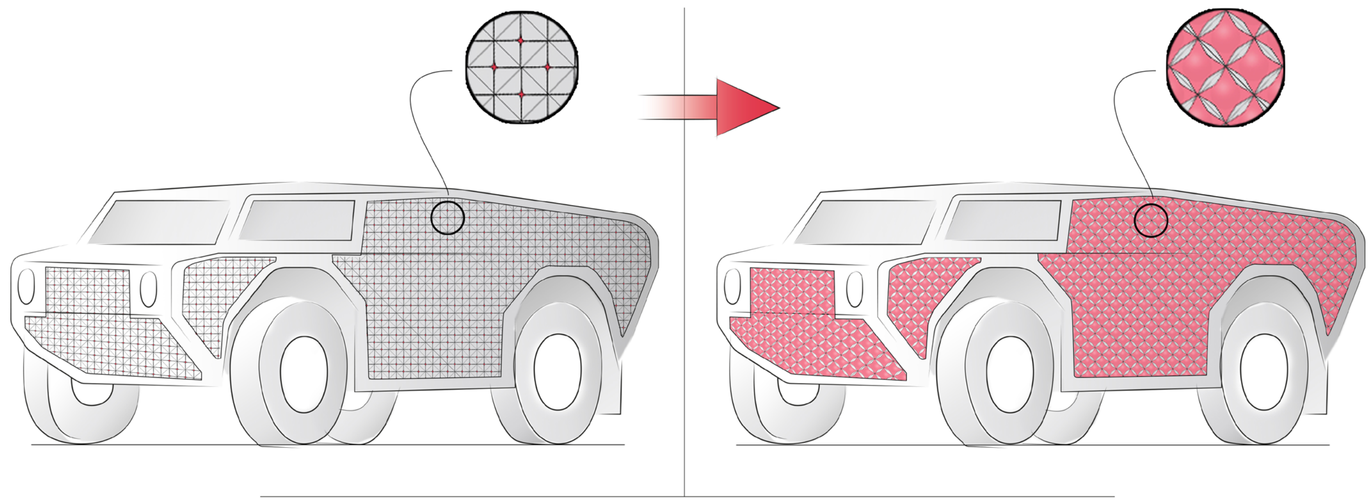
Figure 79: Mindmap of generated ideas and a selection of five (combinations of) most suitable ideas for application of the mechanism

5.2 APPLICATION PROPOSALS

Five (combinations of) application ideas from the mindmap, created in Part 1, were selected according to how well they suited with the mechanism's Strengths and Weaknesses and illustrated to get an impression of the visual effect that the mechanism would create.

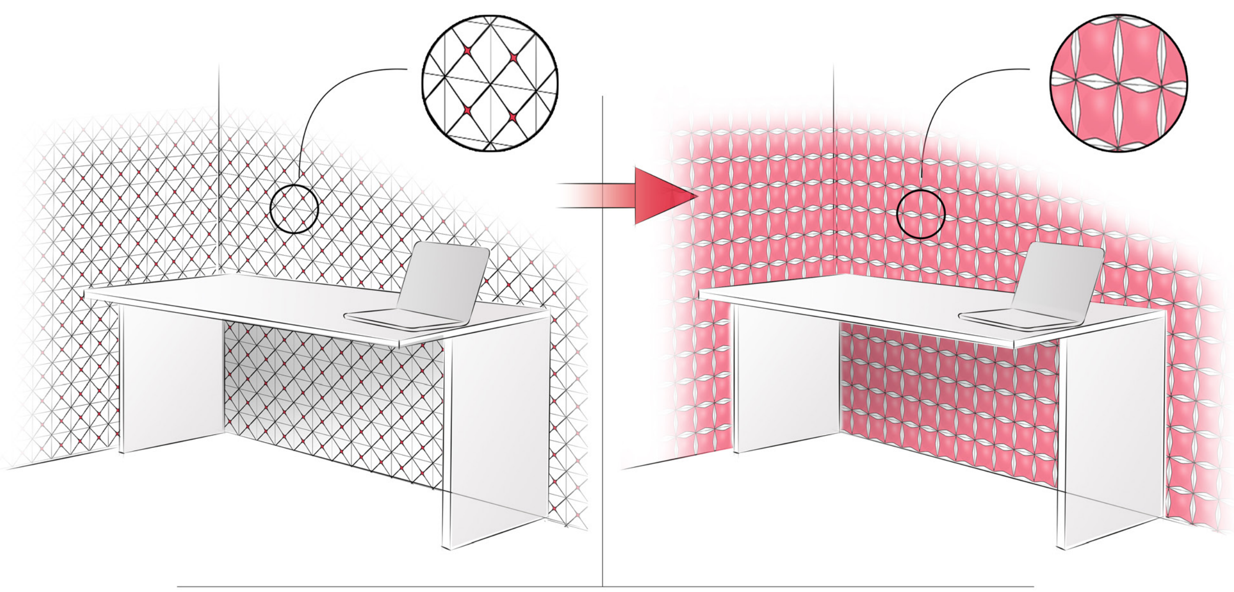
APPLICATION PROPOSAL 1
ACTIVE CAMOUFLAGE FOR MILITARY VEHICLES

Patterned mechanisms, placed on military or reconnaissance vehicles, shifting in color in order to resemble the background and thereby assuring active camouflage in order to stay out of sight of the enemy. Here, a camera would detect the environment after which a resembling two-colored pattern is created.



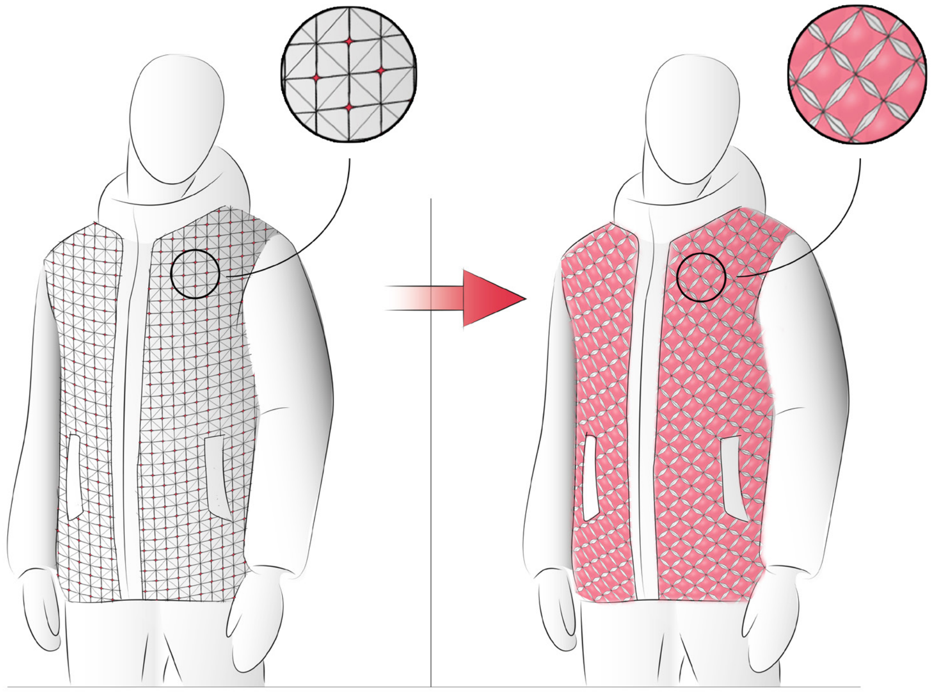
APPLICATION PROPOSAL 2
MOOD AND OCCASION ADAPTIVE INTERIOR

Patterned mechanisms, placed on the walls of office buildings or residential houses, shifting in color according to moods or occasions. Also, this could be used to control the acoustics of the room.



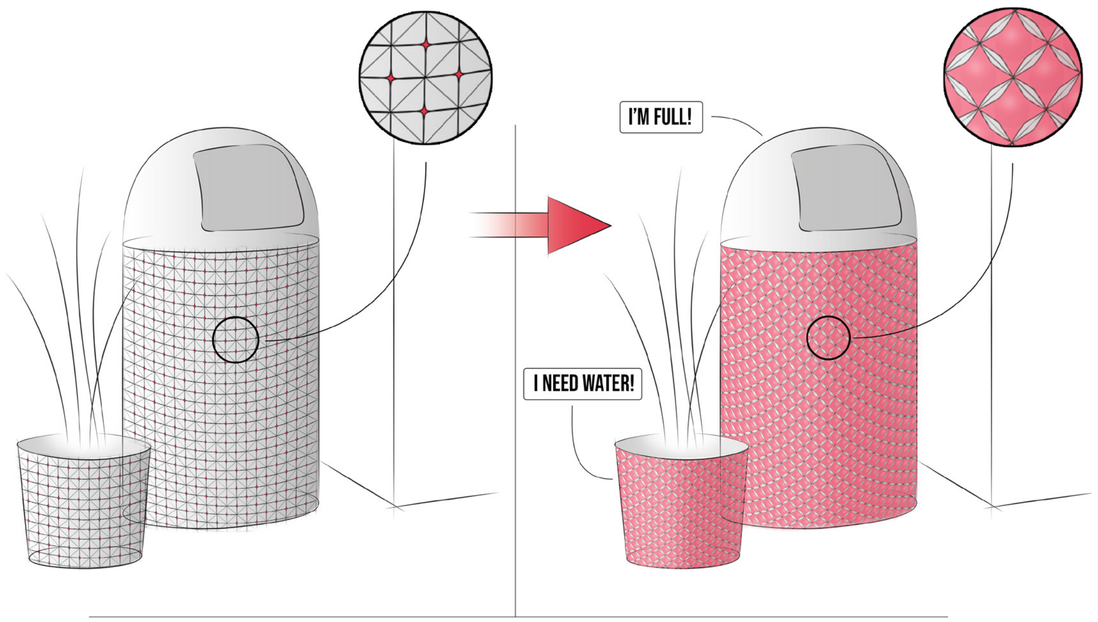
APPLICATION PROPOSAL 3
MOOD AND OCCASION ADAPTIVE CLOTHING

Patterned mechanisms, integrated within clothing, shifting in color according to moods or occasions. Also, this could be used to increase visuality during nighttime.



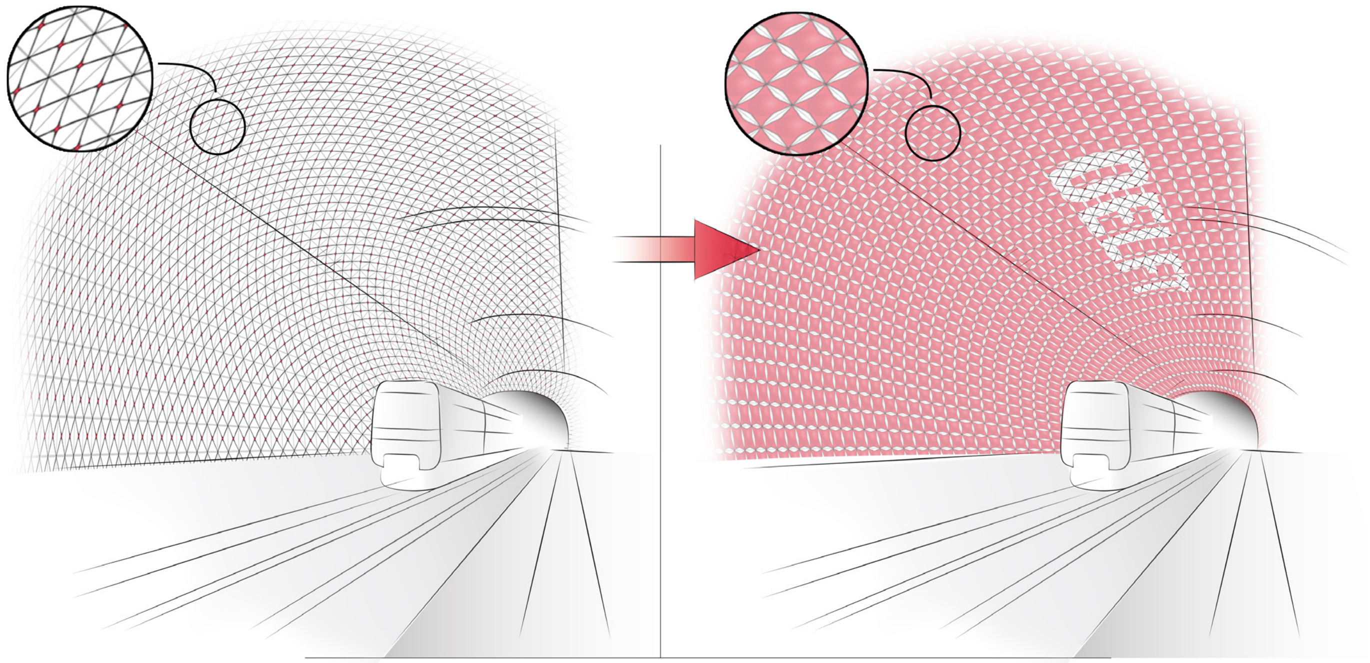
APPLICATION PROPOSAL 4
COMMUNICATING SMART PRODUCTS

Patterned mechanisms, integrated in household products, shifting in color and thereby communicating information, instructions or other messages to the user.



APPLICATION PROPOSAL 5
INFORMING WALL INSTALLATIONS

Patterned mechanisms, placed on the walls of public buildings, shifting in color and thereby communicate information, instructions or other messages to the user.



5.3 APPLICATION EVALUATION

The application proposals were evaluated by means of desirability of the application and on how well the application suits the mechanism's properties. Afterwards, one proposal was chosen as application for the mechanism.

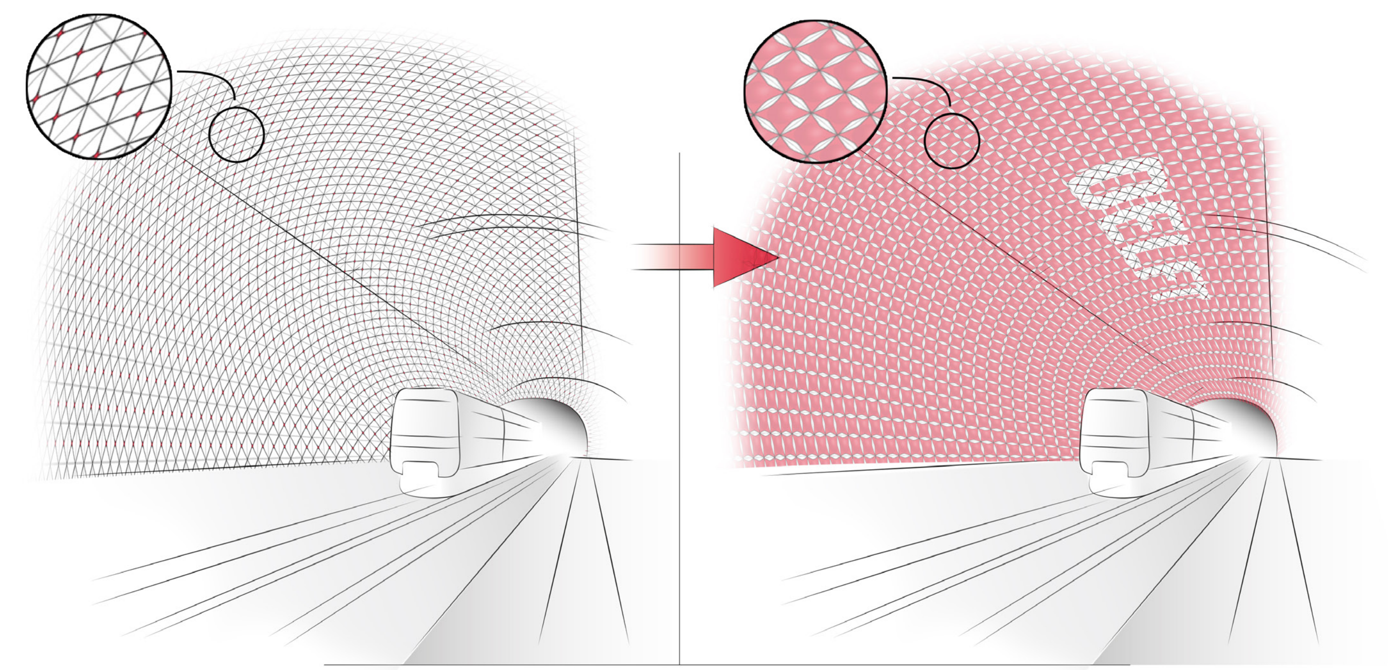
CHOOSING DIRECTION

I compared and evaluated the proposals in terms of desirability. Here, I assessed each proposal's attractiveness, originality and functionality. Also, I evaluated how well the proposals suit the mechanism's properties.

Afterwards, I concluded that the 'Military vehicle' suits well to some of the mechanism properties and is a functional application. However, the application is not very attractive and original and does not make use of the aesthetic and artistic effect that the mechanism provides. This, in contrary to the proposals 'Adaptive interior' and 'Adaptive fashion' where these values can be used to ensure an attractive and original product. However, these proposals are not as functional and do not match all the mechanism properties. For example, the mechanism's ability to change color locally and gradually, thereby creating patterns, messages or gradients, does not come into its own.

Furthermore, I concluded that the proposal's 'Communicating products' and 'Informing wall installation' both are desirable and suit well to the mechanism properties. This, because the applications are attractive and original, and the ability to change color is used in a functional way. Also, the ability to change color locally and gradually can be used to communicate messages. Finally, when comparing the latter two proposals to each other, I decided to choose the 'Informing wall installation' proposal as application for the mechanism. This, because I found this proposal slightly more attractive and functional and suitable to the mechanism properties.

CHOSEN PROPOSAL
INFORMING WALL INSTALLATIONS



5.4 FINAL DESIGN

In the previous chapter, the decision was made to apply the developed technology to the inner or outer walls of public buildings, for the purpose of communication. For this application, large areas ought to be covered with the color changing mechanisms. Therefore, the final design includes a panel with numerous integrated mechanisms (see figure 80). In order to make it possible to cover curved surfaces, it was decided to make use of triangular-shaped mechanisms instead of the currently proposed diamond-shaped mechanism. This, because using triangles allows more form freedom (see figure 81). Furthermore, the mechanisms can be actuated individually in order to create patterns and messages (see figure 82&83).

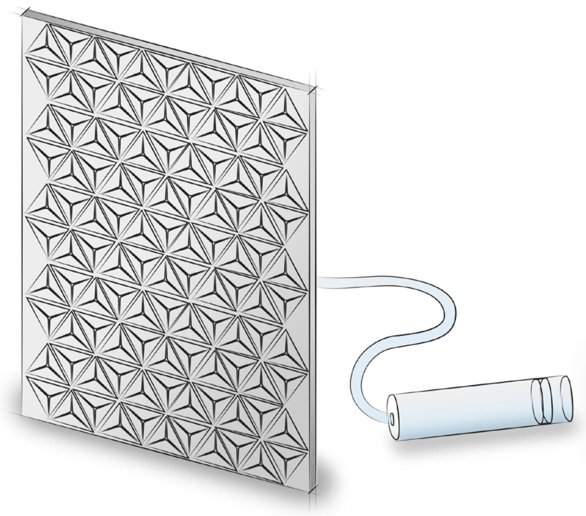


Figure 80: Panel and air pump

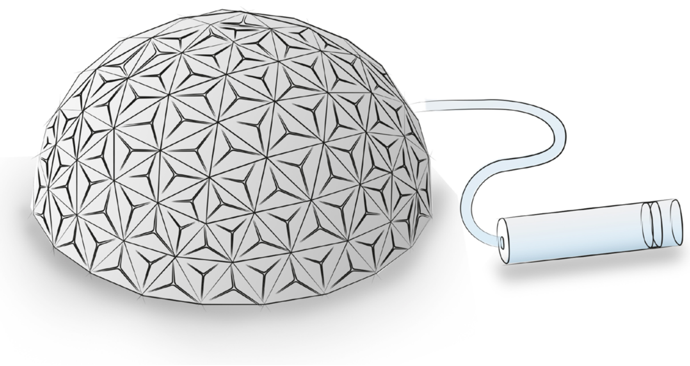


Figure 81: Curved panel

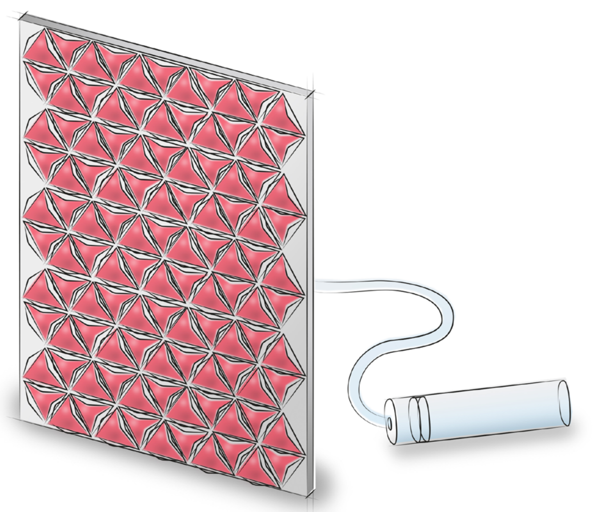


Figure 82: Panel after actuation

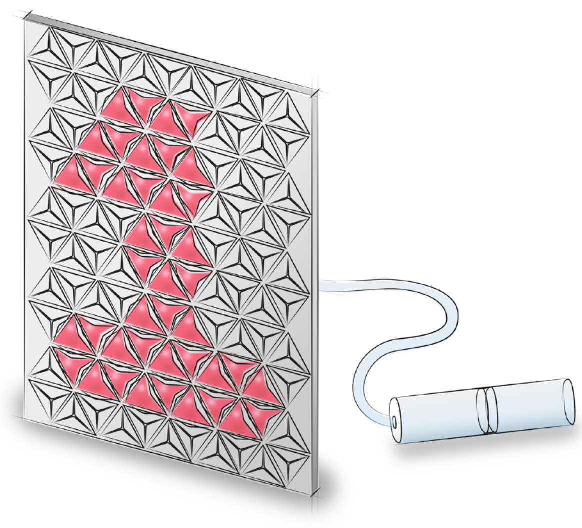


Figure 83: Panel with individually actuated mechanisms

EMBODIMENT & MATERIALIZATION

The proposed panel of color changing mechanisms will consist of five layers (see figure 84&85).

The front layer includes a steel sheet with a cut-out pattern of triangles. This sheet ensures reinforcement and protection and enhances the rotational movement of the lids.

The second layer includes a rubber sheet with a cut-out pattern of lids which can fold open after actuation. Here, rubber was chosen as material, as its flexibility allows the lids to fold open, but the materials is stiff enough to stay closed when placed upside down.

The third and fourth layer include two sides of the silicone pouches. As the pouches require cavities for air-chambers, these two layers cannot be casted as one layer but require to be connected after demolding with additional silicone mixture. However, multiple pouches can be molded together in one mold, creating one sheet for many mechanisms.

The fifth and final layer includes a constructive steel plate on which all other layers are fixed. This plate involves cut-out holes through which air tubes are inserted. These air tubes lead to a central point where multiple air pumps are actuated and controlled.

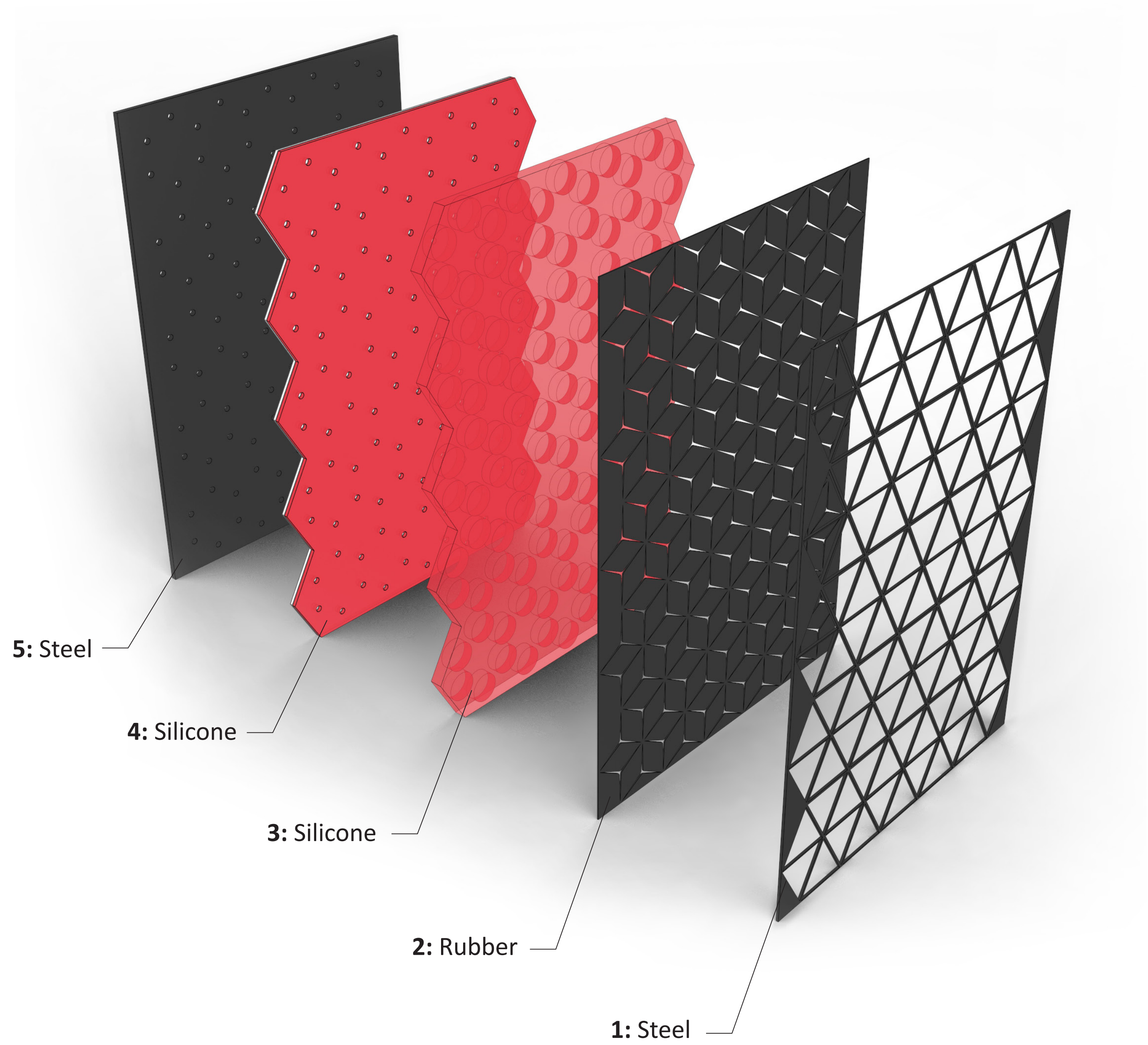


Figure 84: Exploded view of final design

Figure 85: Final design assembled and (partly) actuated

POTENTIAL FUNCTIONALITES

By controlling the color change and individually actuating mechanism units, patterns and messages can be created (see figure 86). This could be used for communication and therefore offers endless possibilities.

The panels can for example be applied to the inner walls of a train station. As the mechanism units can be controlled and actuated individually, these walls can act as canvas for patterns and messages. For example, a change of color of specific mechanism units could inform travelers when a train arrives and in what direction its going (see figure 87). Furthermore, it could be used to indicate where the doors of the arriving train will be located in order to accelerate the boarding process (see figure 88). Finally, the entire interior of the station could change color to warn travelers that a train is about to depart (see figure 89).

Figure 86: Patterns created by actuating mechanisms individually

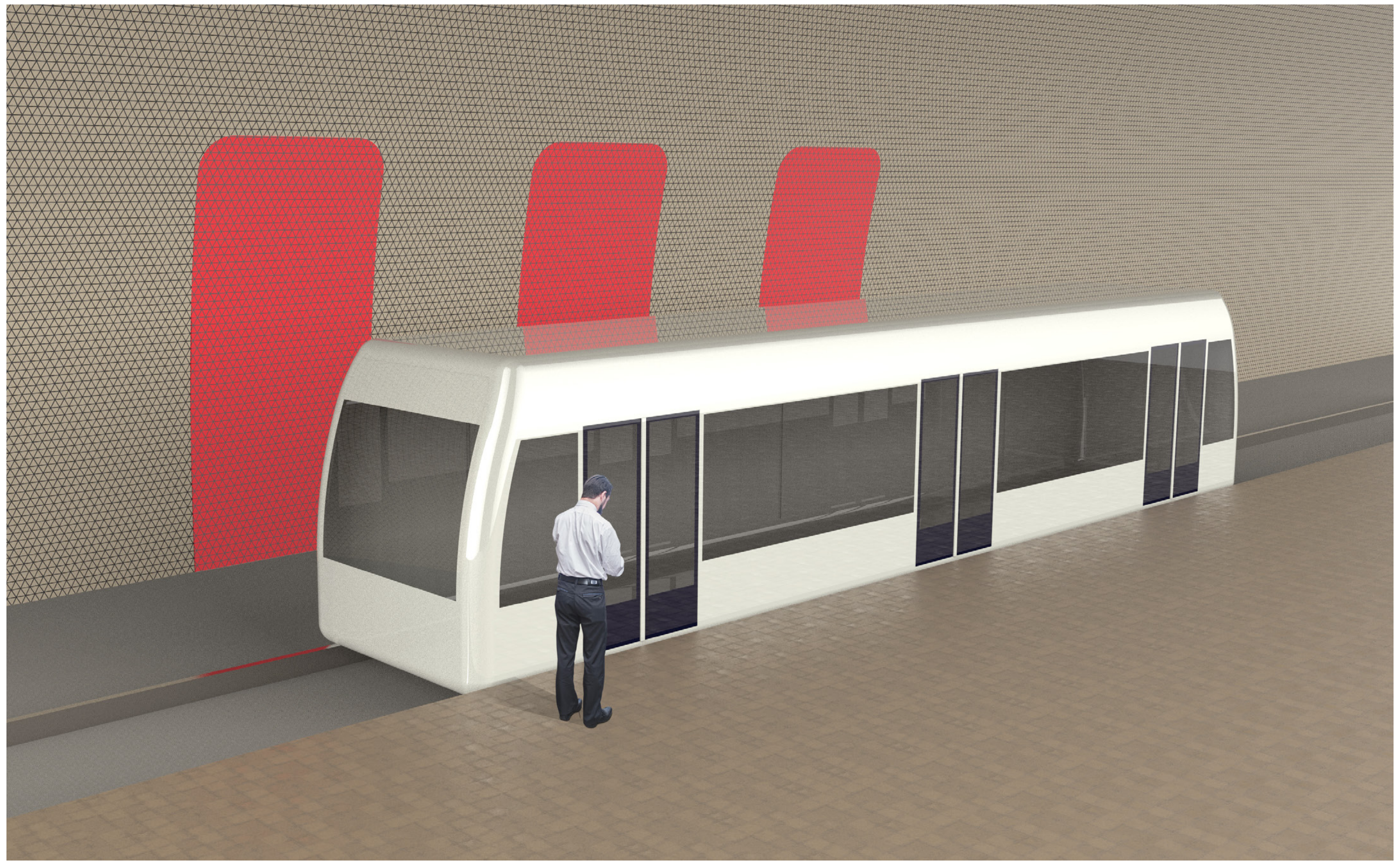


Figure 88: Mechanisms used to inform passengers about the locations of the doors of a train

Figure 87: Mechanisms used to inform passengers about the direction and departure time of a train

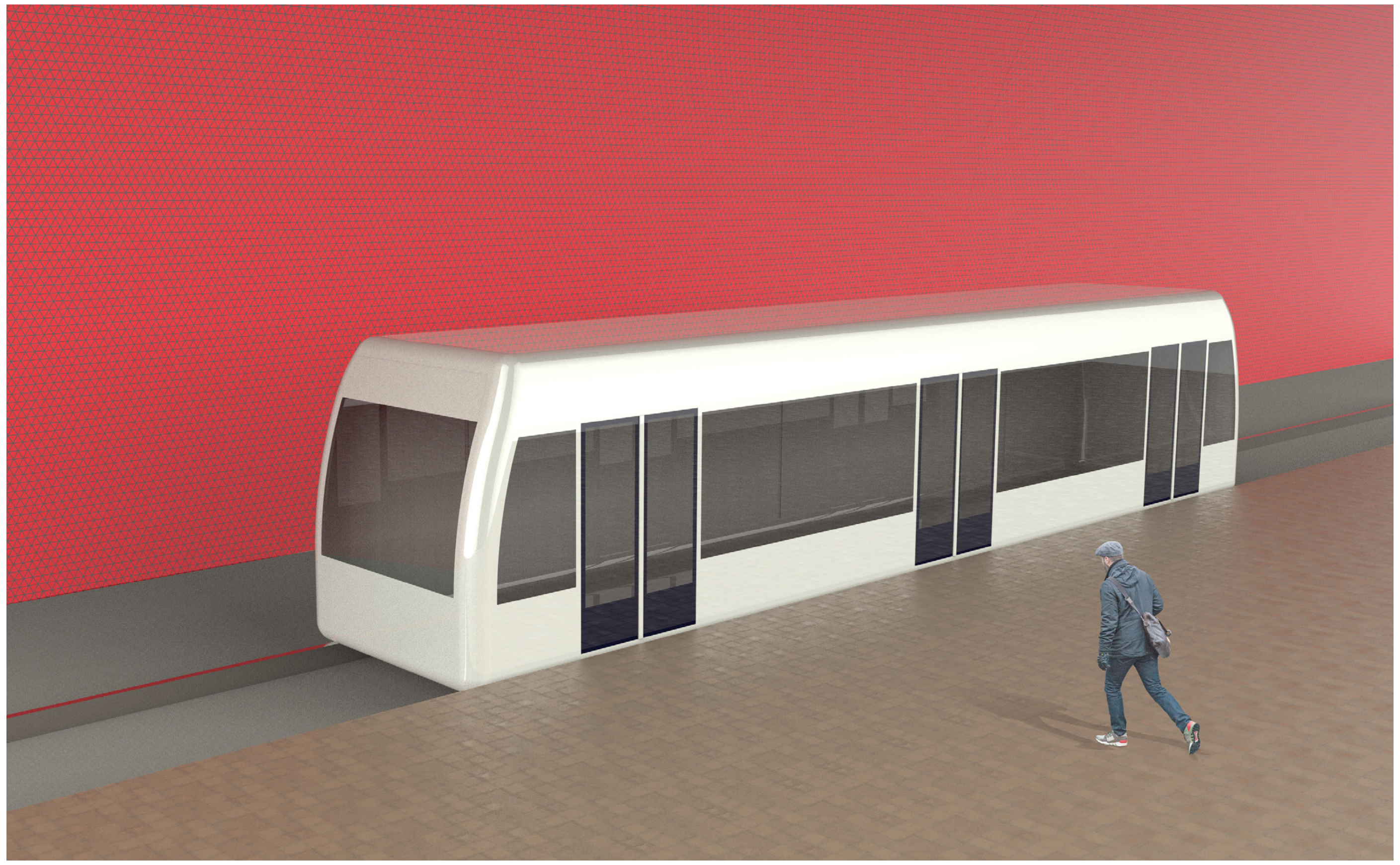


Figure 89: Mechanisms used to warn passengers about a train departing

5.5 FINAL DEMONSTRATOR

A final prototype was made in order to demonstrate the functionality and performance of the technology and the final design.

APPROACH

The prototyping process of the final demonstrator was derived from the previously executed prototyping process of the 'Central Balloon' concept, explained in the previous part. However, for the final prototype, I made a panel of numerous integrated mechanisms, as proposed in the previous chapter. Again, I molded Ecoflex® 00-30, Smooth-On Inc silicone in 3D-printed molds. In each mold, I casted six pouches together as one part (see figure 90-A). In order to clearly demonstrate the prototype's ability to change color, a bright red colorant was added to the silicone mixture before casting. This colorant was purchased from www.siliconesandmore.com. In order to close off the air chambers of the casted silicone, a hard plastic layer, laminated with silicone, was included. This part fits six pouches and was 3D-printed with an integrated 'interlocking grid' (explained in Part 3 & 4) which enables an air-tight connection to the casted silicone (see figure 90-B).

I connected both layers with additional silicone mixture and patterned them onto a wooden backplate. This plate was laser-cut into shape and includes holes for air supply and fastening bolts (see figure 91-A). Furthermore, a rubber sheet with a thickness of 1mm, purchased from www.rubberwinkel.nl, was cut into shape with a laser-cutting machine. Here, for each pouch, three foldable lids were created (see figure 91-B).

Then, a 1mm steel sheet was laser-cut with a metal laser-cutting machine (see figure 91-C). and bended with a manual bending tool (see figure 91-D). This layer ensures reinforcement and protection and enhances the rotational movement of the lids. The steel part was spray-painted with black paint to avoid oxidation of the steel and to enhance the aesthetics (see figure 91-D).

I fastened all layers together with bolts and nuts and I inserted 2x4mm air tubes, purchased from www.greendalerubber.nl to each pouch (see figure 92-A & B). These tubes were led to two 3D-printed air dividers (see figure 92-C). Both air dividers are actuated by 350ml manual pumps (see figure 92-D). Finally, I made a wooden stand to keep the panel upright and to make it presentable (see figure 92-E)

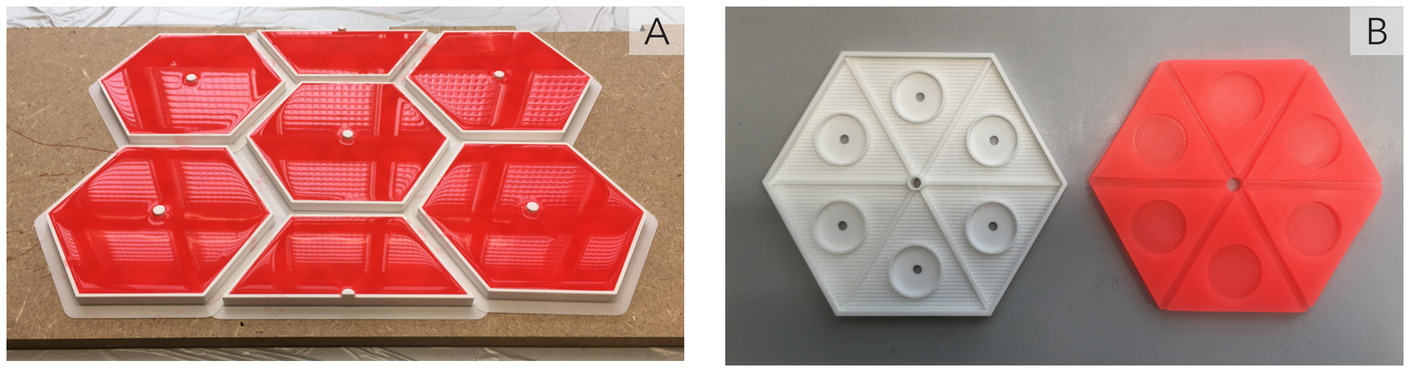


Figure 90: Prototyping process - **A:** Molds casted with colored silicone mixture. **B:** Silicone pouhces after curing and plastic layer **C:** All casted pouches and plastic layers before connecitng together

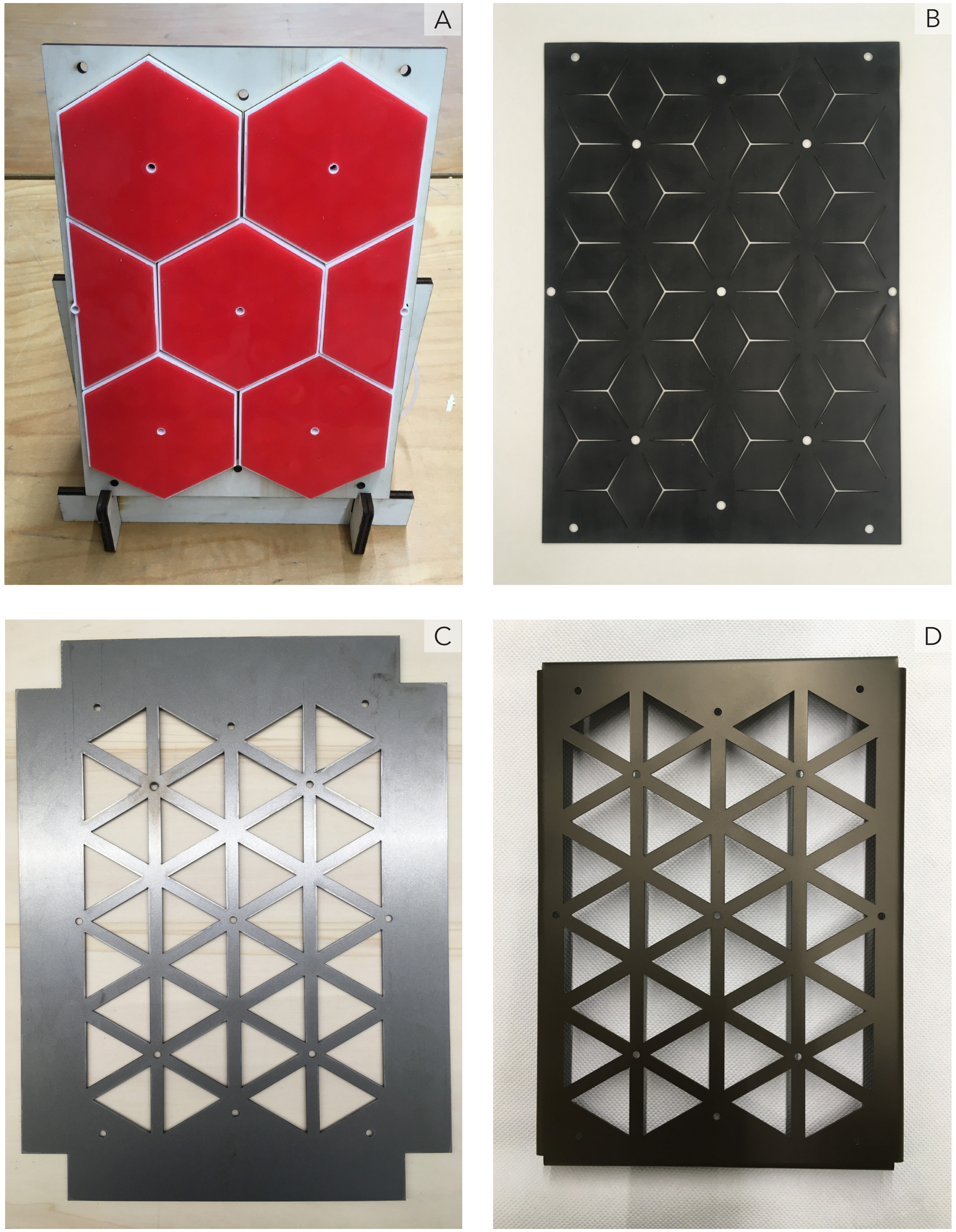


Figure 91: Prototyping process - **A:** Patterned pouches on wooden backlayer. **B:** Laser-cut rubber sheet **C:** Laser-cut steel plate . **D:** Steel plate after bending and spray painting

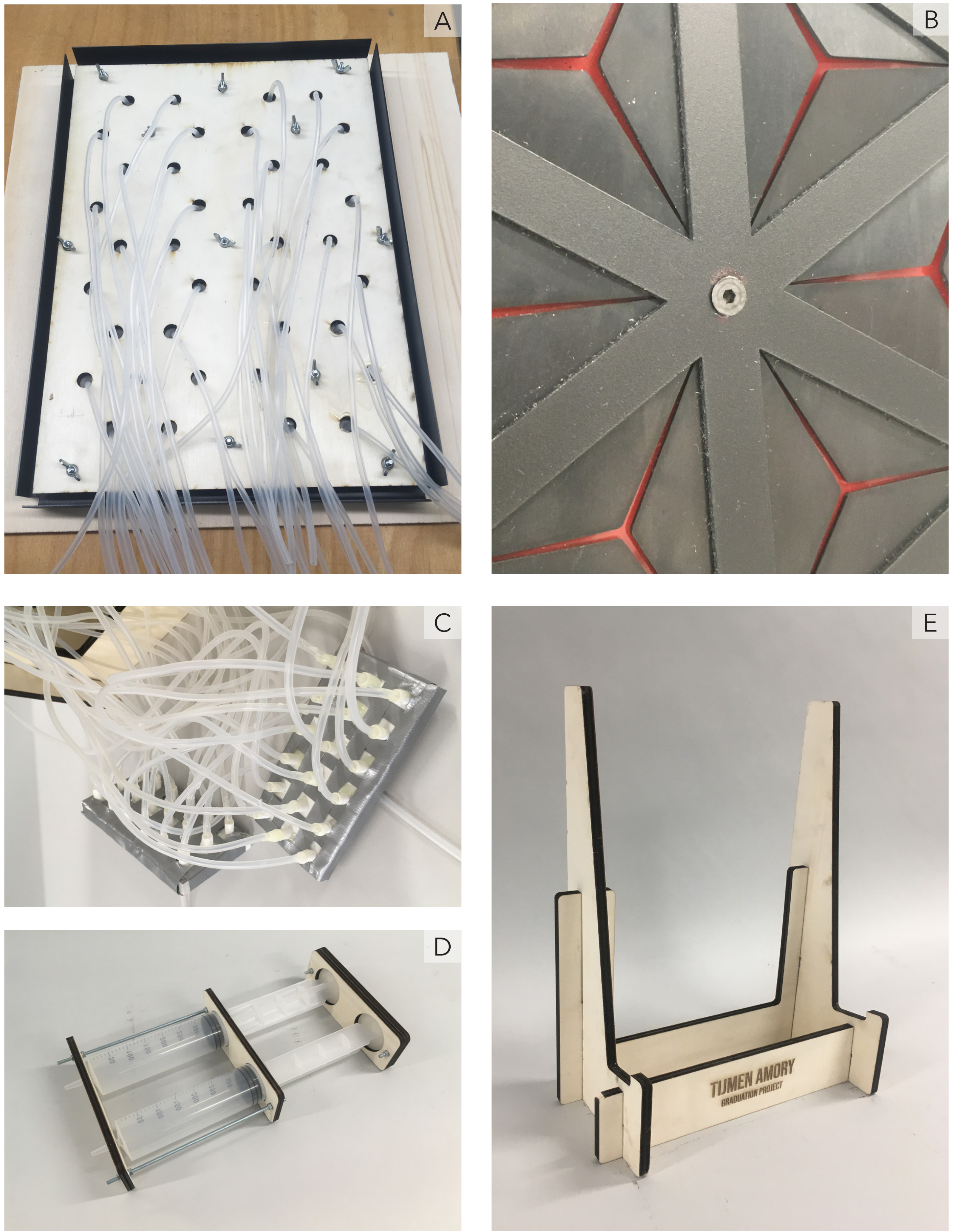
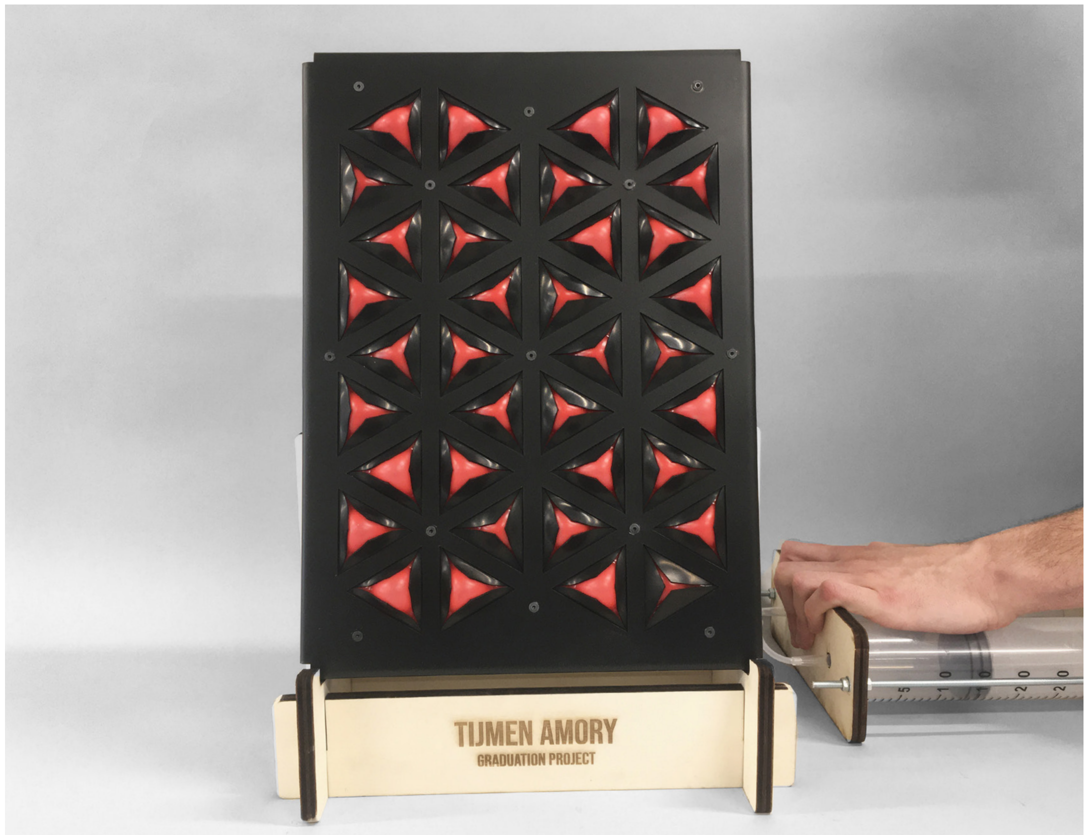


Figure 92: Prototyping process - **A:** Backside with all tubes and nuts for fastening. **B:** Bolts for fastening **C:** Air dividers with tubes. **D:** Two pumps **E:** Stand for presentation

RESULTS

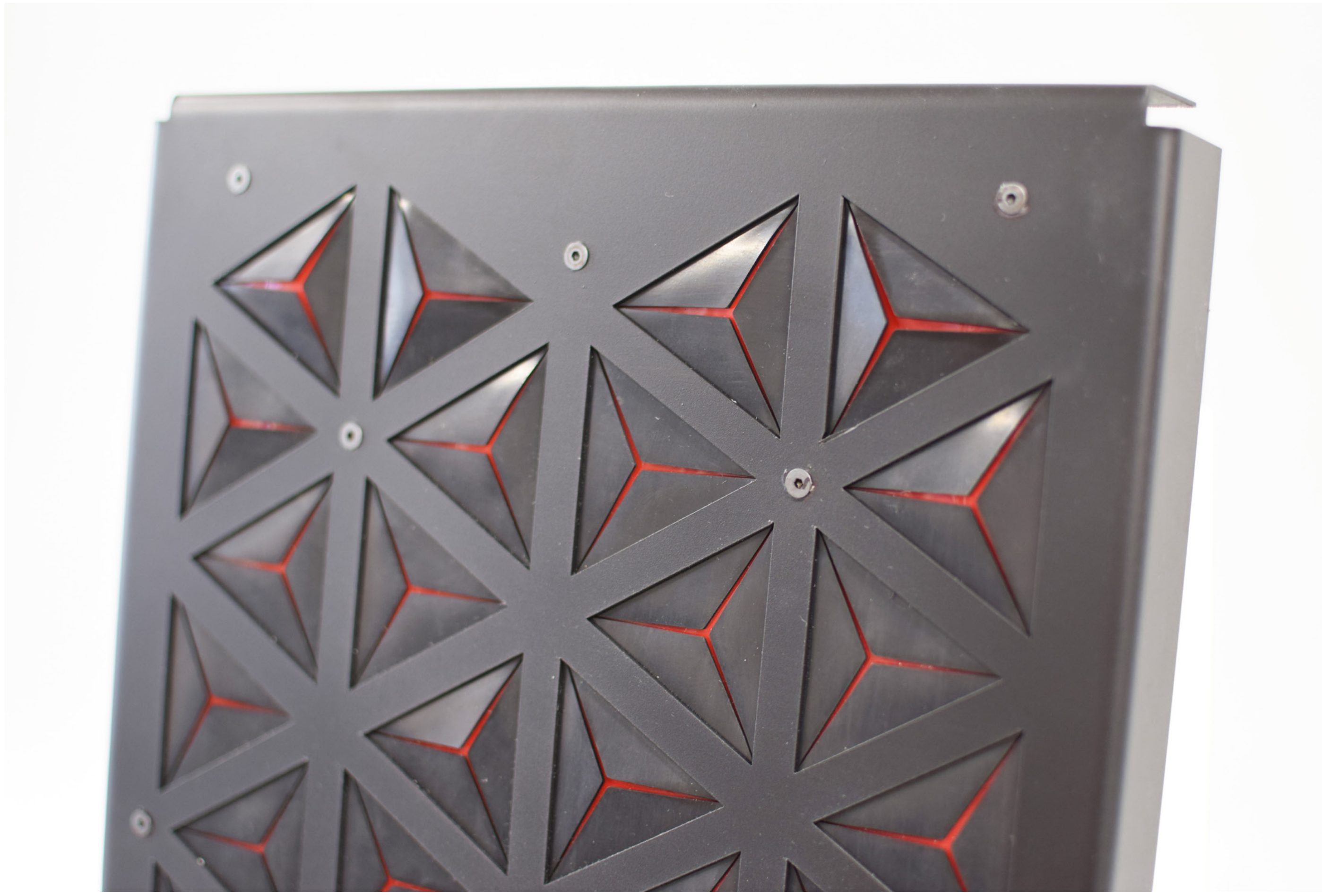
BEFORE INFLATION



AFTER INFLATION


TIJMEN AMORY
GRADUATION PROJECT


TIJMEN AMORY
GRADUATION PROJECT



CONCLUSION

VALIDATION

After finishing the project, the design goal and scope can be evaluated and compared to the achieved results. Hereby, a judgment can be done on whether the project was successful.

DESIGN GOAL EVALUATION

The following design goal was stated prior to the project:

The goal of this project is to design and create a solution, applied to a product or environment, which enables an appearance transformation. Thereby creating an added value to this product or environment, by facilitating communication opportunities, enhancing interactions or enriching the user experience.

First of all, the goal was to create a solution for an appearance transformation in terms of color, texture or transparency. As the created technology ensures a change of color, it can be concluded that this part of the design goal was succeeded. Also, by applying the developed technology to panels that can be attached to the inner or outer walls of buildings, the developed technology is applicable to an environment. Thereby, this part of the design goal was succeeded as well. Furthermore, the developed technology facilitates communication opportunities by allowing to actuate mechanism units individually and thereby creating informing messages. Finally, the technology can provide aesthetic and artistic value to a building and could therefore ensure an enriched user experience for users of the building or for people passing by. However, this is an assumption which should be verified with a user test or questionnaire. Nonetheless, it can overall be concluded that the design goal was succeeded.

SCOPE EVALUATION

Also, prior to the project, a scope was defined. Here, the decision was made to focus on a 'simple and low-tech' and mechanical solution to achieve the design goal and to focus on digital fabrication technology for the production of the product and prototype.

First of all, the production processes of the both the proposed final design and the final demonstrating prototype consist mainly of digital fabrication processes. The back plate, the rubber sheet with rotatable lids and the reinforcing front layer, are all cut into shape with laser-cut technology, which is a form of digital fabrication. At the same time, the silicone pouches are fabricated by casting silicone in 3D-printed molds which are fabricated with 3D-printing technology, which is a form of digital fabrication as well. Only the casting itself is a manual process, but this process could be automized with an injection-molder. Therefore, this part of the scope definition was succeeded.

The technology behind digital fabrication processes can be considered complex. However, utilizing the technologies is rather simple and accessible and ensures high precision while minimizing manual labor. Thus, using these technologies fits with the focus point of keeping the product 'simple and low-tech'

Additionally, the working principle of the developed color-changing mechanism is fully mechanical, whereby an appearance change is achieved without involving more complex technologies such as light emitters, thermo- or photochromic materials, light refractors or adjustable light transmitters. Therefore, the developed solution is mechanical and can be considered 'simple and low-tech'.

Nonetheless, the proposed application of the developed technology, where mechanisms on panels are actuated individually and thereby patterns and messages are created, requires advanced control and actuation systems. These systems should convert the desired patterns and messages to pixels, represented by the mechanisms, which are individually actuated by controllable valves. This system is rather complex and requires valves for each mechanism, resulting in many components. Therefore, the chosen application does not match well with the goal and focus points.

CONCLUSION

The developed technology and its production process fulfill the priorly defined design goal and scope. However, the proposed application makes the product rather complex and therefore does not fit entirely with the goal and focus points.

RECOMMENDATIONS FOR FURTHER DEVELOPMENT

In this chapter, several recommendations are given for the further research and development of the design, production process, application and validation of the developed solution.

DESIGN

The current design, where numerous triangles are patterned geometrically, could be reconsidered in a potential redesign. This, as digital fabrication technology offers the opportunity to create customized and complex shapes with high precision. Therefore, the separate mechanisms do not require to be equal in shape and size but can be designed in a way that artistic patterns are created. Also, one can experiment with various color combination and could even give separate mechanisms different colors to create multiple-colored patterns. Furthermore, additional research is required concerning the currently proposed materials. Here, an optimization analysis should be done in terms of material specific properties such as stiffness, elasticity, costs and ecological footprint. A similar optimization analysis should be done in terms of the shape and size of the parts. Here, factors such as the shape, size and wall thickness of the silicone pouches and the thickness of the steel and rubber layers should be optimized to maximize the performance while minimizing energy consumption, costs and ecological footprint.

PRODUCTION PROCESS

The production process which was used to create the demonstrating prototype leaves room for improvement, especially when production on a larger scale would be contemplated. First of all, the production of the molds for casting the silicone pouches should be reconsidered. These molds are currently produced with 3D-printing technology, which is too time consuming and limited in available space. A more suitable fabrication process would be CNC-milling. Also, the casting of silicone, which was currently done manually, should be automized to reduce manual labor and to optimize material usage. Finally, the current prototype makes use of separate air-tubes for each mechanism. As the proposed panel includes many mechanisms, the many required tubes are now inserted by hand which requires a lot of manual labour. Also, the tubes become tangled easily and form a large mass. A more convenient solution would be to produce an additional panel with integrated air-channels towards each mechanism.

APPLICATION AND FUNCTIONALITY

In order to carry out the proposed application of the panel and thereby realize the proposed functionalities of communicating information and instructions towards users, an integrated actuation and control system should be produced and programmed. Here, each mechanism should contain a valve with which the amount of passing air is controlled. A central controller then controls the actuation of all valves individually and thereby realizes the display of messages and signals. Here, each mechanism is considered as a pixel which can vary between two colors.

VALIDATION

The validation description, given in the previous chapter, where the design goal and scope are compared to the achieved results in order to evaluate the success of the project, is not entirely complete. Therefore, it cannot yet be concluded whether the currently proposed design has fulfilled the priorly set-up goals and requirements. First of all, the proposed design and demonstrating prototype should be demonstrated to potential users. These people should then be given a questionnaire in which they are questioned about the performance and desirability of the design. Thereby, an assessment can be made on whether the proposed design provides added value and enriches the user experience of the environment in which it is applied.

Also, a calculation should be given concerning the costs, energy consumption and ecological footprint of the design. The outcoming values of these calculations, together with the outcomes of the questionnaire, should be compared to equivalent assessments of existing technologies (described in Part 1). Afterwards, a judgment should be made on the feasibility, viability and desirability of the proposed design, compared to its competitors.

REFLECTION

In this final chapter, a reflection of the project is given. Here, I evaluate whether specific parts of the project went well or not. Also, I describe what I learned during the project.

LITERATURE STUDY

The project started with a literature study about the topic 'appearance change', with the purpose to orientate on existing technologies and to get inspiration for a new solution. I found this to be very complicated for various reasons. First of all, literature research is not my strong point. I still find it hard to concentrate on reading and understanding a complex paper, to determine whether papers are useful for my project and to pick out the relevant information and translate it to new insights and conclusions. Furthermore, as the assignment was very broad, it was challenging to determine what I wanted to accomplish with the research. Therefore, it was difficult to come up with the right keywords while searching for papers. Finally, the topic 'appearance change' is quite abstract and not a frequently recurring research topic. It was therefore quite difficult to find research papers that were useful for the project.

However, the literature study helped me to get an overview of existing solutions, which enabled me to set up the 'Knowledge Gap' and thereby determine what I wanted to do more specifically. Also, during the literature study, I found plenty of research on potential technologies which I could use as inspiration for the development of a new technology. When looking back, I found that for this project, doing practical research with physical mock-ups and prototypes was more suitable and useful than reading research papers. However, I did find that I developed myself in collecting useful research and understanding complex papers and I learned that it is not necessary to understand a paper completely to use it as inspiration.

METHODOLOGY AND PROCESS

In the Design Brief, I mentioned that I hoped to make use of some of the many design tools and methods which I learned during my studies and to make use of new methodology which I am unfamiliar with. When looking back, I can say that the performed design process of this project was very much based on the typical processes that I was taught during my studies. This, as it involved multiple diverging and converging phases, following up on each other. In the diverging phases, I did research and created sketches and prototypes to get a broad overview of potential solutions. In the converging phases, I evaluated the many possibilities and narrowed them down to only several concepts by clustering ideas and evaluating them based on criteria. When looking at specific design methods and tools that I used to generate ideas or evaluate concepts, I can conclude that I mainly made use of methods and tools that I was familiar with and did not explore new ones. However, after finishing the project, I feel that it was not required to include more methods and tools than was currently done.

Priorly to the project, the goal was to apply a 'bio-inspired' design approach. Here, the idea was to analyze occurrences of 'appearance change' in the natural environment and use these as inspiration for the design of the technical solution. When looking back, I can conclude that although I did do research about appearance changing animals, I did not use the outcomes in my design. However, it was interesting to learn about biological phenomena and to see how other designers used them as inspiration for new technologies.

As mentioned before, the executed design process was mainly based on a conventional design process which I was taught during my studies. However, this project was still very different than what I was used to. This, as the project involved a 'technology-driven design process' where the focus lay on the development of a technology, after which the outcomes of the research were used as inspiration for the search of a suitable application for this technology. This meant that, in contrary to previously conducted projects, both the working principle and the application were unclear for a large part of the project. The combination of these two uncertainties and the fact that the development of the technology did for a long time not give the intended results, led to a long period of frustrations and discouragements. At the peak of these times, I even considered quitting and choosing a different project that was more specific and concrete. However, I decided to continue and finish the project regardless of what the final results would be. At this point, the development of the technology started to give more promising results and thereby I gained new energy and motivation for completing the project. When looking back, I can conclude that this was a very instructive period in which I learned to deal with uncertainties, setbacks and frustrations. I learned that persistence can be very rewarding, and I am happy that I decided to finish the project. Finally, I learned that, despite my initially difficult experiences, a 'technology-driven design process' is a very interesting way of developing new product ideas. This, as it offers the opportunity to come up with unexplored solutions based on cutting-edge technologies.

TECHNOLOGY DEVELOPMENT

For this project, I did a lot of practical research by creating and testing physical mock-ups. I iterated these mock-ups towards a final prototype with which the intended technology can be demonstrated. I often started with replicating a technology from research papers, and then altered the technology to achieve the intended result. Here, I generally made use of a 'trial and error' approach, where I would analyze the performance of the prototype and make iterations towards a working technology. Although this approach seemed most suitable for this project and also led to the intended results, I found that the approach was also very time consuming and lacked efficiency. Partly due to the many setbacks during the phase, the project was delayed six weeks. I found that it would be more efficient to try out many different variations at the same time instead of creating one model and improving it step by step. Also, I found that I should try to do more research, calculations and simulations beforehand, to avoid wasting time on making small improvements to a dysfunctional mock-up.

Nonetheless, I really enjoyed doing practical research and during this phase, I developed myself in technical aspects. For example, I became experienced with digital fabrication processes such as laser-cutting and 3D-printing and I gained experience with materials and fabrication processes that were unfamiliar to me. Also, when looking back, I can conclude that the process of creating tangible designs is what I enjoy most about Industrial Design.

END RESULT

When comparing the final design and demonstrating prototype to the priorly set-up design goals, I can conclude that I am generally pleased with the results. As the design goal was quite abstract and broad, it was beforehand very unclear how the technology and design would turn out. Therefore, I am happy that I came to a clear result with which the design goal was achieved. Also, in my opinion, the final prototype turned out to be very slick and neat and the final design and application turned out to be a feasible solution which could ensure a very attractive and desirable effect. However, I also acknowledge that the final prototype did not give the effect I hoped for, as the color change was not as clear as I hoped. This, because the system was not entirely air-tight which ensured that not all pouches bloated completely. Also, the hinging lids were not flexible enough to open up entirely.

WORKFLOW AND PLANNING

The graduation project is one of the few design projects during the curriculum which is executed individually. This fact has both its advantages and disadvantages. I found that during some phases of the project, I really missed to have someone around that observes the project from a different perspective. This, to have someone to brainstorm with, in order to come up with a larger number of potential solutions or to have discussions concerning the best way to overcome obstacles and accomplish goals. Also, I sometimes found it hard to take important decisions on my own and therefore avoided and postponed these situations. However, when the intended direction of the project became clear, I found that working alone was very effective and comfortable.

The project was delayed for approximately six weeks and therefore it can be concluded that I did not keep a tight planning. However, the delay was mainly due to setback during the development of the technology. All other parts of the project proceeded roughly according to the priorly set-up planning.

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APPENDICES

A: INITIAL PROJECT BRIEF

INTRODUCTION

Through evolutionary development, animals such as cephalopods (e.g. squids, octopuses, cuttlefish) or chameleons have developed the ability to blend into the surroundings by adapting their appearance in terms of color and/or shape. Some have evolved this ability to hide for predators while other animals have evolved the same ability to outwit their preys. Humans have tried to imitate this ability for similar purposes. For instance in the military, where soldiers wear uniforms in various earth tones, to blend in with the environment and therefore stay out of sight of the enemy. A limitation of this type of camouflage is that it is static, and not dynamically adapting to its environment. Moreover, the ability to shift in appearance can also be interesting for other purposes. For example for communicating a message through the appearance of a product, to match a product to a dynamically changing environment or for artistic purposes, such as fashion or architecture.

There are various research papers which explore this topic. In these papers, the researchers present different principles to imitate cephalopod's color changing abilities: sensitive film (Phan et al., 2016), 3D-printing (Jiang & Li, 2017), flexible electronics (Yu et al., 2014) or other advanced technologies. These papers explore the fundamental principles that can be used. However, they require complex technologies in order to function and only show proof-of-principle results, which are still (far) removed from the application of these technologies in actual products or industries.

This graduation project aims to explore this topic further, by on the one hand, analyzing the visual appearance changing effects in cephalopods' skins such as color, texture and/or translucency. This will be used as inspiration, or even attempting to mimic these effects (partially) in order to create a similar effect. For fabrication the focus will lie specifically on digitally fabrication, i.e. by creating mechanically or pneumatically driven mechanisms, constructed from highly compliant materials. Such mechanisms are for instance found in the domain of soft robotics. This technology is still largely unexplored for this type of application, and therefore offers the opportunity to come up with cutting-edge solutions. For example, (multi material) 3D-print technology (or a hybrid manufacturing technique involving 3D printing) can enable the creation of customized, and complex geometries, which could be used for creating appearance changing surfaces. Different additive manufacturing techniques will be explored as production method to model prototypes, as well as the final concept/demonstrator. In the process of analyzing new working principles, the findings will be used as guideline to explore the possibilities of implementing this technology to product applications.

This project was initiated by Willemijn Elkhuizen, who is specialized in material appearance reproduction, 3D-scanning and 3D-printing and Zjenja Doubrovski, who is specialized in additive manufacturing. It is in their interest to explore new technologies and findings in their field of expertise.

PROBLEM DEFINITION

The ability to be camouflaged - passively or actively - or other ways of dynamically changing appearances of products and/or surfaces has been of interest in product and material development. Apart from static solutions such as camouflage clothing, more dynamic solutions of appearance change exist as well. For example chemical processes such as photochromic sunglasses which change in color after being exposed to sunlight, or LED screens which can emit an endless combination of colors and thereby show any desired image. However, these technologies are limited in terms of shape and application possibilities.

Here the complex abilities of animals such as cephalopods can serve as an inspiration, in their ability to not only change color, but also shape, texture and even translucency. These types of visual effects might be mimicked in surfaces and products using state-of-the-art digital fabrication techniques.

A dynamic appearance change realized with mechanically or pneumatically driven mechanisms is a new and unexplored field and therefore offers the opportunity to analyze state-of-the-art technologies, explore solution space for new working principles and to come up with interesting implementation solutions which solve present-day problems, such as improving the product experiences or simply enhancing aesthetic or artistic value.

The project will focus on (multi-material) 3D-printing or a hybrid technique involving 3D-printing. Other solutions to dynamic appearance change, such as bio-design, electromagnetic fields, flexible electronics or sensitive film lie outside the scope of this project. Phenomena of appearance adaption occurring in nature will be used as inspiration for this project. However, the possibilities of digital fabrication and materials suitable for this technology will be leading factors in the process of exploration and conceptualization. The Material Driven Design method (Karana et al., 2015) will be used as framework to support the exploration process.

ASSIGNMENT

In this graduation project, I will analyze the ability of cephalopods and other animals to adapt their appearance and explore the possibilities for imitating this ability using digital fabrication techniques. To activate the appearance change, I intend to apply mechanically or pneumatically driven mechanisms. Subsequently, I will explore possible applications for these types of appearance changing solutions, which will be communicated via one (or several) demonstrator(s).

The project will include:

- A literature research overview concerning:
o Available techniques, methods and mechanisms for appearance change.
o Occurrences of appearance adaption in nature, which can act as inspiration for the exploration process.
o The possibilities of digital fabrication and suitable materials for this fabrication method.

- Design guidelines for designing and producing mechanisms or products that can adapt in appearance, realized with digital fabrication.

- Physical prototypes to test the intended result, developed in an iterative process towards (a) final demonstrator prototype(s) which shows the most promising working principle(s).

- One or several suggestions related to product applications for the most promising working principle, in the form of (a) demonstrator prototype(s) showing the possibilities of appearance change in a concrete or conceptual product idea.

- A report including all the research, solutions and results and video demonstrating the working principle.

MOTIVATION & AMBITIONS

I chose to do this project because it involves a cutting-edge field of research which is yet to be explored and therefore it is very original and innovative. It involves state-of-the-art technology and manufacturing processes which interest me a lot and which I'm eager to explore.

The aim of the project is to transform the appearance of a material or product. Therefore, the outcome of the project will in the first place be guided by visual and aesthetic aspects, rather than functional aspects. This attracts me, since I am very interested in combining technology with aesthetics or arts. I think it is interesting to start with the exploration of a technology and use the outcome of the research as base for the conceptualizing of product solutions. This, instead of a conventional design process where one would begin with a problem, leading to the implementation of an applicable technology for solving the problem.
Also, this project attracts me because it involves a 'bio-inspired' design approach where organic occurrences or processes act as inspiration for new technologies. This way of product development has always fascinated me, but I have never undertaken such a process.
Furthermore, I assume that this project involves plenty of prototyping and practical research. During my master I found that this always gives me the most satisfaction and I always enjoy this a lot.

During this project, I hope to develop my knowledge in some technical aspects, as for instance the behavior of various plastics and state-of-the-art manufacturing processes such as digital fabrication. This, because this field interests me a lot and I would like to develop my current basic knowledge towards a more expert level. Also, I hope to make use of some of the many design methods and tools which I have learnt during my studies or to make use of new methodology which I am yet unfamiliar with. This, because I feel that they can be very helpful in a creative process but often seems unnecessary or too time-consuming to dive in to. Furthermore, I hope to develop myself in doing scientific research by effectively using findings from scientific research papers to come to conclusions and present them in a scientifically appropriate manner. Finally, I want to evolve in working independently. During my studies I have mostly worked in groups and I found that when I work alone, I can improve myself in taking necessary decisions on the right time, keeping a strict planning and to make time for required aspects within in the project that are more out of my comfort zone.

PROJECT PLANNING

Date		KICKOFF: 14 SEPT	14-sep	21-sep	28-sep	05-okt	12-okt	19-okt	26-okt	02-nov	MIDTERM: 6 NOV	09-nov	16-nov	23-nov	30-nov	07-dec	14-dec	21-dec	28-dec	04-jan	11-jan	GREEN LIGHT: 18 JAN	18-jan	25-jan	01-feb	FINAL REPORT: 5 FEB	08-feb	15-feb	GRDUATION: 22 FEB
Calender week	<38		38	39	40	41	42	43	44	45		46	47	48	49	50	51	52	53	1	2		3	4	5		6	7	
Project week	0		1	2	3	4	5	6	7	8		BREAK	9	10	11	12	13	BREAK	BREAK	14	15		16	17	18		19	20	
0: Orientation																													
Exploring topic																													
Planning																													
Project Brief																													
1: Analyzation & Exploration																													
Literature research																													
Exploring materials & mechanisms																													
Scope/Design brief																													
2: Conceptualizing mechanisms																													
Ideation																													
Conceptualzing																													
Concept development																													
Testing																													
Choosing concept																													
3: Application																													
Research																													
Ideation																													
Conceptualzing																													
Choosing concept																													
Design																													
4: Demonstration																													
Final design																													
Final demanstrator prototype																													
Final testing																													
Documentation																													
Reporting																													
Presentation																													
Graphic work																													
Movie / Clip																													

B: APPEARANCE CHANGE OCCURING IN NATURE

CEPHALOPOD

Cephalopods can change their appearance in terms of color, transparency and texture (see figure 93). They use this ability to avoid being detected by both preys and predators and to communicate to other cephalopods, for the purpose of mating (Hanlon et al., 2011). Cephalopod's change in transparency and color is caused by organs and cell bodies within their skin. A typical cephalopod skin consists of three layers, each containing a different type of cell (see figure 94). These cells work in concert but fulfill different functions.

Figure 93: Cephalopod (Malkov, 2014)

PIGMENT DISTRIBUTION

In the upper layer of the skin, chromatophore cells are located (see figure 94). These cells can be best described as pigmentation sacs: balloons that contain black, yellow or brown pigment. They can expand due to radial muscles around the cell and thereby increase in area, spreading the pigment under the skin of the cephalopod. Expansion of the cells also makes the cell wall more transparent, making the pigment more visible. Because the chromatophores are controlled neurally, they can be opened and closed very quickly. Therefore, cephalopods can change color within milliseconds. Figure 95 shows microscopic images of chromatophore cells before and after expansion.

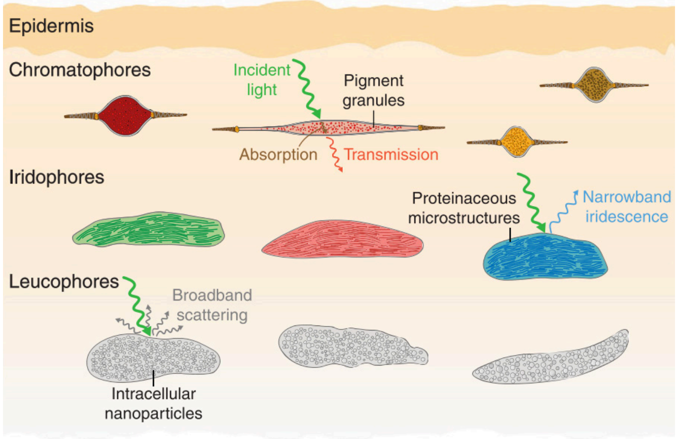

Figure 94: Cephalopod skin consisting of three layers (Xu et al., 2020)

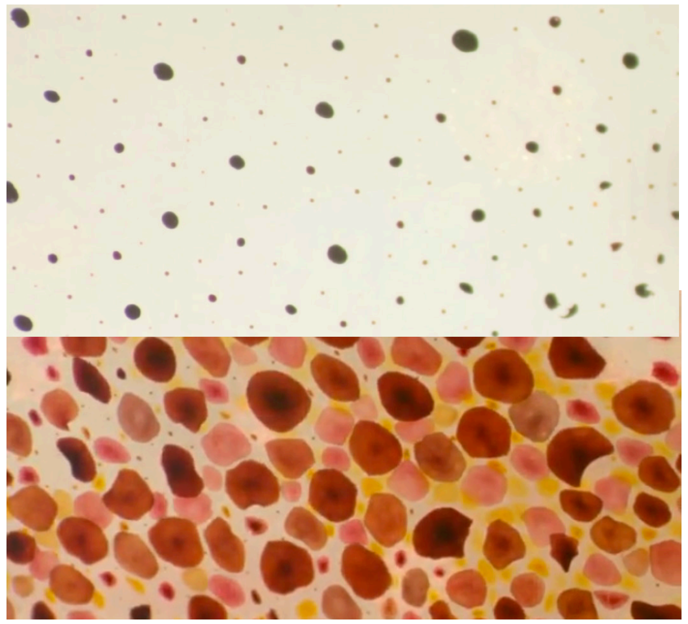

Figure 95: Chromatophore cells before and after expansion (Laughing Squid, n.d.)

LIGHT REFRACTION

Subjacent to chromatophores there are irodophores: crystallin cells which reflect light of different wave lengths dependent on the angle from which they are observed (see figure 96)(Mathger & Hanlon, 2007). For example, irodophores can appear blue from above but red from aside. In the bottom layer, leucophores reflect white and blue hues and together with irodophores act as base layer upon which the darker pigment of the chromatophores is layered (see figure 94) (Hanlon et al., 2011) (Phan et al., 2016).

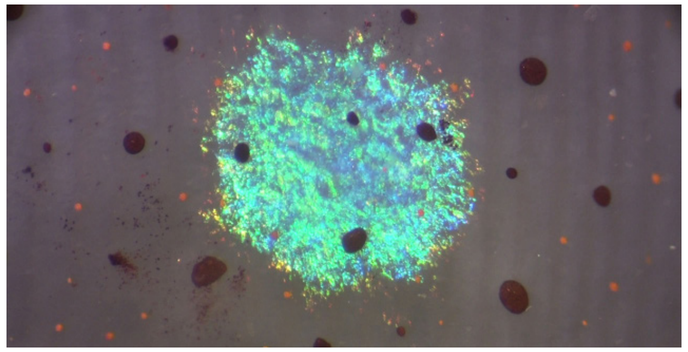

Figure 96: Irodophore cells scattering light below chromatophore cells (Staaf, 2012)

LIGHT EMISSION

Finally, cephalopods are able to emit light in order to disguise their shadows, entice their preys, seduce mates and communicate to other cephalopods. This is done through bioluminescence, produced by bacterial symbionts (see figure 97) (ClearlyExplained, n.d.)

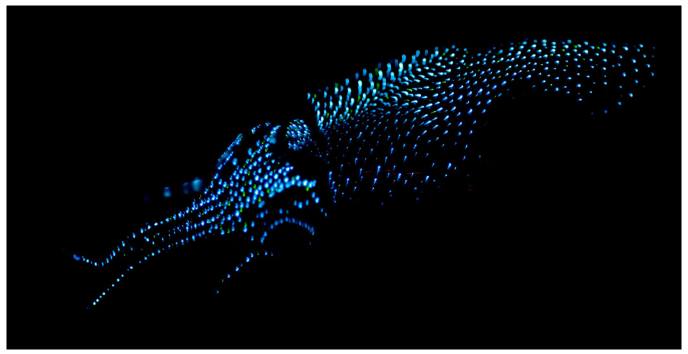

Figure 97: Cephalopod emitting light with bioluminescence (NY Times, 2016)

SKIN DEFORMATION

Apart from adapting their skin's color and transparency, cephalopods can also adapt their skin texture from planar and stretchable into a continuum of bumps, ridges or spikes (see figure 98) (Pikul et al., 2017). These protrusions or 'papillae' are created by three groups of muscle fibers within the skin. These muscles lift the skin upward, determine the shape and spread out the base, making them wider (Allen et al., 2014). The combination of the patterns created by the chromatophores, the reflected light caused by the irodophores and leucophores and the adaptive morphology of the skin, ensures that cephalopods can appear almost identical as their surroundings (Hanlon et al., 2011).

Figure 98: Cephalopod with textured skin (Create Digital, 2018)

CHAMELEON

Chameleons can change the color of their skin within the timespan of one to several minutes (see figure 99)(Kamrava et al., 2019). They mostly use this ability to communicate their mood and regulate their body temperature (Sciencing, 2018).

Chameleon skin consists of a superficial layer which contains pigment and a layer underneath which contains crystalline cells which reflect light of different wavelengths, depending on the space between the cells. These cells are comparable to the irodophores and leucophores in cephalopods skin. Chameleons change their skin color by changing the space between the crystals (see figure 100) (Teyssier et al., 2015).

Figure 99: Chameleon (Facts, 2020)

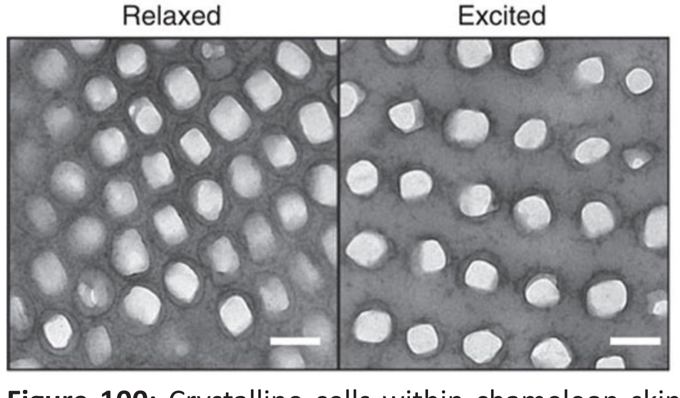

Figure 100: Crystalline cells within chameleon skin (Ask Nature, 2017)

TORTOISE BEETLE

The tortoise beetle can transform its appearance from reflective gold (see figure 101) to red and black (see figure 102) within in two to three minutes(Kamrava et al., 2019). This change in hue happens when the beetle is disturbed and is caused by the displacement of a reflective liquid within grooves underneath the beetle's armor, revealing a less reflective red-colored layer (Vigneron et al., 2007).

Figure 101: Tortoise beetle reflective gold (Wired, 2015)

Figure 102: Tortoise beetle red and black (Dyer, 2020)

PEACOCK FLOUNDER

Peacock flounders and other flatfish can change their appearance similarly as cephalopods. They can change color and create patterns on their skin within 8 seconds. This, to match their surroundings in order to stay out of sight of both predators and preys (see figure 103). The fish create these patterns by spreading pigment over cells within the surface of the skin while leaving others white by isolating the pigments (Brooke, 2013).

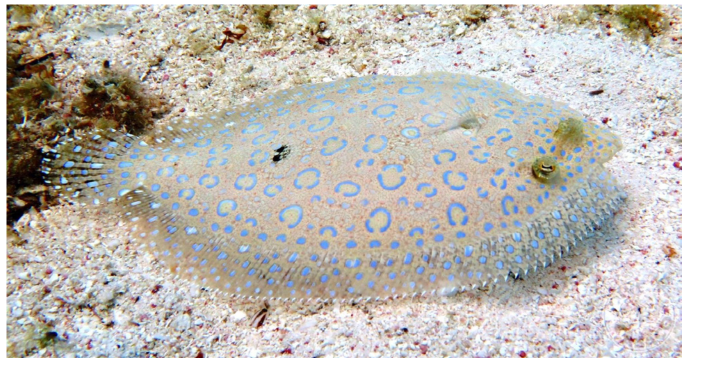

Figure 103: Peacock flounder (Rolling Harbour, 2019)

C: SHAPE CHANGING MECHANISMS

ELASTOMERS

Elastomers (or rubbers) can be stretched or compressed and thereby increase or decrease in area. Elastomers are polymers with a low elastic modulus (Young's modulus, a material's resistance to being stretched) which enables them to undergo large deformations without deforming permanently (Thill et al., 2008) (Qamar et al., 2018).

APPLICATIONS

As the elastomers are elastic and deformable, they are typically applied in sealing of storage boxes (see figure 104), dampers, insulation and, sport shoes (Global, n.d.)

Figure 104: Elastomers used for sealing of storage boxes (Speedtrendy, n.d.)

POTENTIAL USE

Elastomers can achieve a change in appearance by their ability to increase in area after being stretched. This could be used to relatively enlarge specific elements compared to others and thereby alter the proportions of the elements, which would result in a visual transformation. Furthermore, by transforming in shape, they can cover or expose an underlying surface.

AUXETIC STRUCTURES

Auxetics are structures or materials which have a negative Poisson's ratio. When stretched or compressed, these structures become respectively wider or narrower in perpendicular direction of the applied force. This is due to an internal 'honey-comb' structure of cells which can deform because of their hinge-like architecture (Kolken & Zadpoor, 2017).

Auxetic structures can be grouped in three main classes: re-entrant structures, chiral structures and rotating (semi-) rigid structures. Re-entrant structures consist of cells with inward directed ribs which re-align after stretching (see figure 105).

Chiral structures consist of asymmetric cells which rotate due to stretching or compression, and thereby respectively expand or contract (see figure 106).

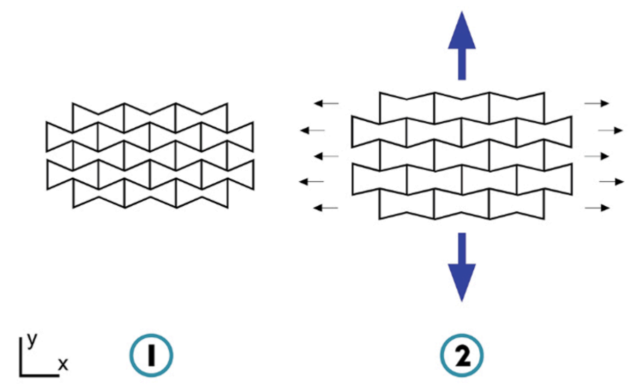

Figure 105: Re-entrant structures (Kolken & Zadpoor, 2017)

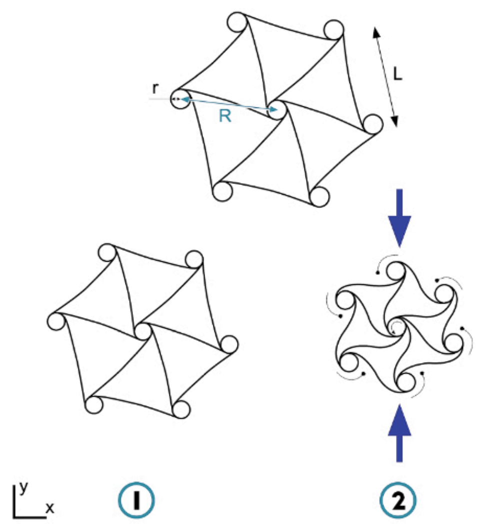

Figure 106: Chiral structures (Kolken & Zadpoor, 2017)

Rotating (semi-)rigid structures consists of rigid elements in various shapes such as squares, rectangles and triangles which are connected through hinges. After stretching or compressing the structure, the elements rotate at the vertices and thereby expand or contract (see figure 107) (Kolken & Zadpoor, 2017).

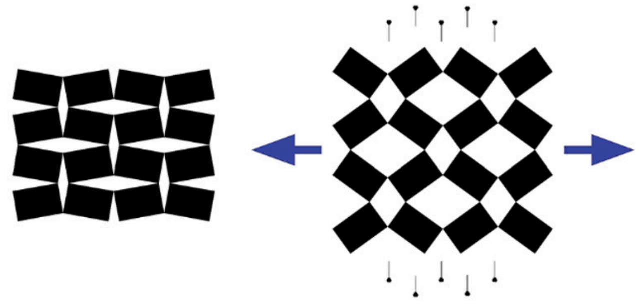

Figure 107: Rotating (semi-) rigid structures (Kolken & Zadpoor, 2017)

To build an auxetic structure, the Japanese art of paper cutting called 'Kirigami' can be used. This technique implies a cut-out pattern in a flat sheet, which changes the sheet's mechanical properties and enables the sheet to deform both two- and three-dimensionally after stretching or compressing (see figure 108) (Tang & Yin, 2017)(S. Chen et al., 2020).

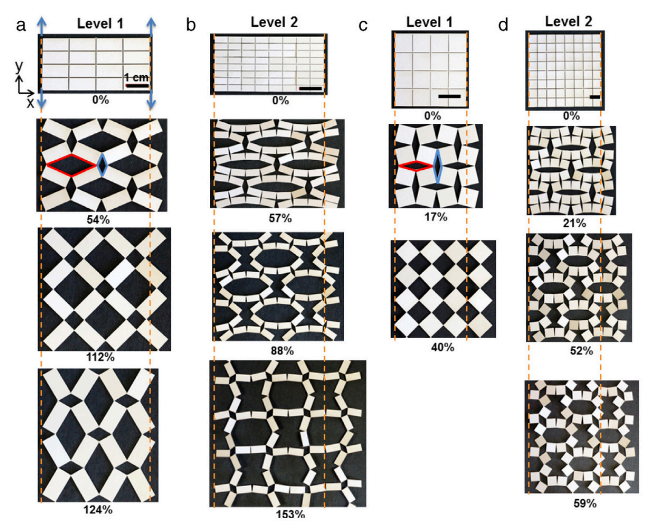

Figure 108: Auxetic structures created with kirigami (Tang & Yin, 2017)

APPLICATIONS

As auxetics are deformable and shock absorbent, they are typically applied in dampers, packaging, protective gear (see figure 109) and sport shoes (see figure 110) (Kolken & Zadpoor, 2017).

Figure 109: Auxetics used for protective gear (Grima, 2009)

Figure 110: Auxetics used for sport shoes (Nike, n.d.)

POTENTIAL USE

Auxetics can achieve a change in appearance by their ability to increase in area after being stretched and thereby relatively enlarge specific elements, creating a visual transformation. For example, Jiang & Li (2018) created an auxteix cell opening mechanism, fabricated with multi-material 3D-printing, where cells placed in a structure increase in area after being stretched and thereby achieve a transformation in color (see figure 111) (Jiang & Li, 2018). Furthermore, by increasing or decreasing in area, they can cover or expose an underlying surface.

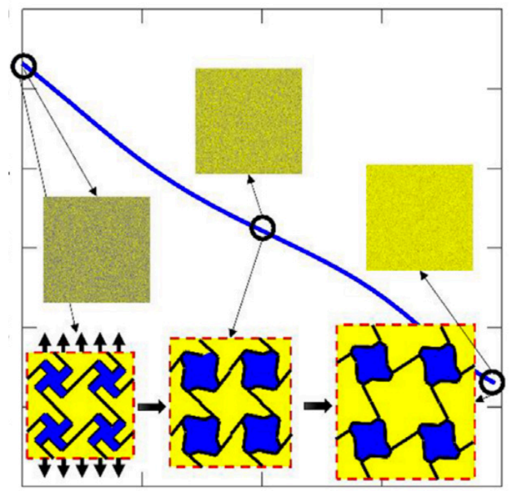

Figure 111: Auxetic structure used for a color transformation (Jiang & Li, 2018)

Auxetic structures can also be used to create dynamic surface morphologies which can perform a transition between two or three textures, creating a relief of brilliance and shading. As for instance performed in a study about 3D-printed cells which deform vertically after being compressed horizontally (see figure 112) (Ion et al., 2018). The study proposes several application possibilities such as a bicycle grip and a shoe sole which can transform from flat to treaded after being stretched or compressed.

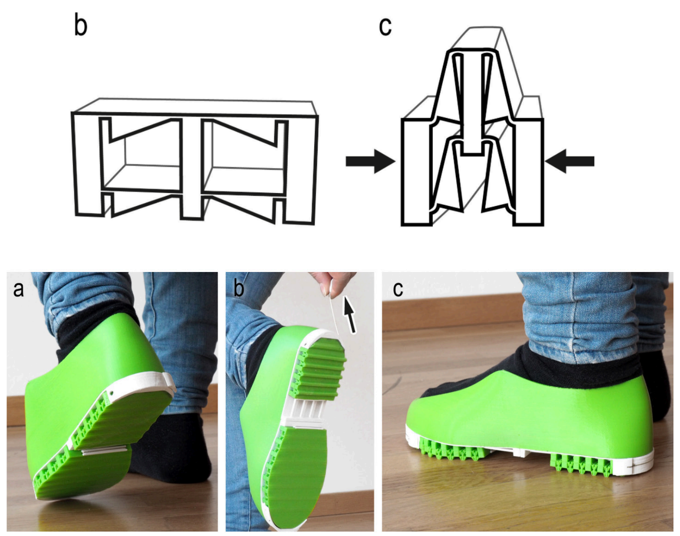

Figure 112: Auxetics used to create textured surfaces (Ion et al., 2018)

ROTATABLE STRUCTURES

Rotatable structures rotate around a central point or axis. Hereby, the shape itself stays the same but its position within a space changes (Khan Academy, n.d.). Thereby, a structure of rotating elements can transform in both shape and appearance.

APPLICATIONS

As rotatable structures can be used to put something in motion, they are widely used in numerous mechanisms and wheels for vehicles.

POTENTIAL USE

Rotatable structures can be used to achieve an alteration of the appearance of a surface, by rotating multiple sided elements with sides that have different appearances. Rotation would show a new side and thereby a new appearance (see figure 113). Furthermore, a rotatable structure can be used in the form of a hinged lid which exposes or covers an underlying surface.

Finally, rotatable structures can be used to expand or contract a surface. For example, with a diaphragm mechanism which rotates and thereby contracts and amplifies and opening within the mechanism and is used in cameras to regulate the light transmittance (see figure 114&115).

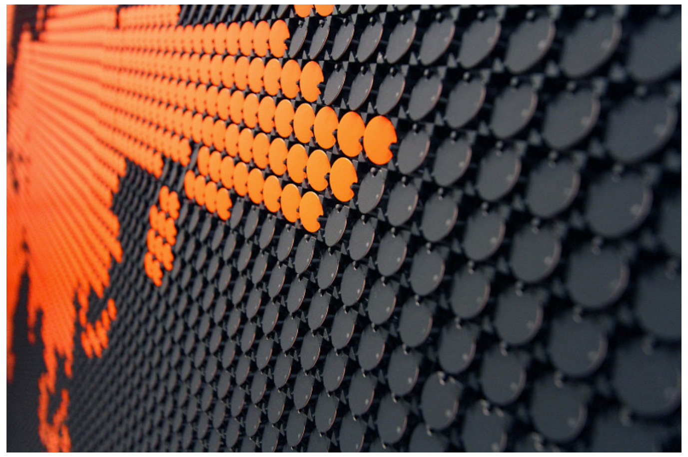

Figure 113: Rotating discs, creating a different appearance (Flipdots, n.d.)

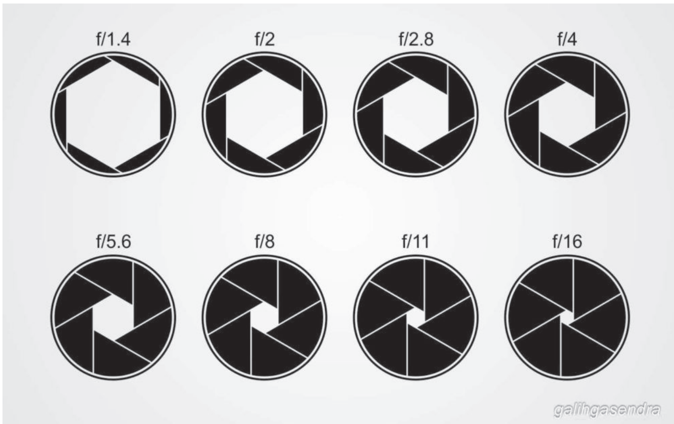

Figure 114: Diaphragm mechanism – Working principle (De Foto Blogger, 2019)

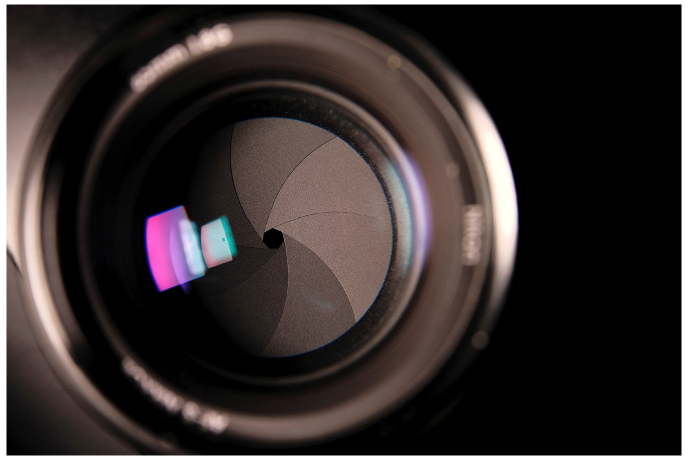

Figure 115: Diaphragm mechanism in camera (Vink Academy, n.d.)

ROLLABLE STRUCTURES

Rollable structures roll out by a combination of rotation and translation. Hereby, their area expands, and their shape transforms from a cylinder to a flat sheet.

APPLICATIONS

As rollable mechanisms can deploy and thereby increase in area, they are for example found in roller blinds (see figure 116), garage doors and storage of flexible materials as for example in spacecraft applications where solar sails have to be packed with a minimal volume during launch and deploy to a maximum area within space (Qamar et al., 2018).

Figure 116: Roller blinds (Ikea, n.d.)

POTENTIAL USE

Rollable structures can mainly achieve a change in appearance by their ability to increase in area. This could be used to relatively enlarge specific elements compared to others and thereby alter the proportions of the elements. Also, by transforming in shape, they can cover or expose an underlying surface.

FOLDABLE STRUCTURES

Foldable structures fold in or out and thereby, turn from a flat sheet into a three-dimensional structure or shape. By folding, they can increase or decrease in area (Qamar et al., 2018).

APPLICATIONS

Foldable structures are typically used in applications such as packaging, biomedical devices, spacecraft and architecture, because of their ability to deploy (Turner et al., 2016). For example, NASA uses folding techniques to deploy folded solar panels in space (see figure 117) (NASA, 2014) and architects used a folding structure for a deployable sunshade system to control indoor lighting in the Al Bahr Towers in Abu Dabi (see figure 118) (Reis et al., 2015).

Figure 117: Deployable solar panels (NASA, 2014)

Figure 118: Folding structure for sunshade system (Reis et al., 2015)

POTENTIAL USE
Foldable structures can achieve an appearance transformation by their ability to increase in area and thereby relatively enlarge specific elements compared to others, altering the proportions of the elements. Furthermore, by folding in or out, they can cover or expose an underlying surface. Finally, by folding, a flat surface can be transformed into a textured one, resulting in a pattern of brilliance and shading.

INFLATABLE STRUCTURES

Inflatables structures can be inflated with gas or air and thereby increase in size, strength and stiffness. Their advantages are their low weight and production costs, their ability to pack into small volumes and their ability to deploy into almost any shape (Qamar et al., 2018).

APPLICATIONS
As inflatables are typically shock absorbent and able to deploy , they are used in vehicle wheels, boats and airbags (see figure 119) (Qamar et al., 2018).

Figure 119: Airbags in car (Downling, 2018)

POTENTIAL USE
Inflatable structures can achieve an appearance transformation by their ability to increase in area and thereby relatively enlarge specific elements compared to others, altering the proportions of the elements. Furthermore, by inflation, a flat surface can be transformed into a textured one and thereby create a relief of brilliance and shading. For example, Pikul et al (2017) performed a study in which they imitated cephalopod's ability to shift its texture from flat into a texture of bumps, ridges and spikes. This is done by inflating stretchable membrane, on which a laser cut mesh pattern determines the shape (see figure 120) (Pikul et al., 2017).

Figure 120: Textured surface created by inflating stretchable membrane (Pikul et al., 2017)

MULTI-STABLE STRUCTURES

Multi-stable structures deform rapidly from one stable state to another. Typically, only low actuation forces are needed to generate large deformations and the mechanisms can hold their positions without power input. (Qamar et al., 2018). Multi-stable structures are often built-up of compliant mechanisms, which mobility is gained from the deflection of flexible members rather than from movable joints (Brigham Yung University, n.d.). Deformation of these mechanisms is based on buckling behavior of flexible beams (G. Chen et al., 2010). After being put in a first stable position, elastic strain energy is stored within the beams which 'snap-through' to another stable position after actuation (see figure 121) (Rafsanjani et al., 2015).

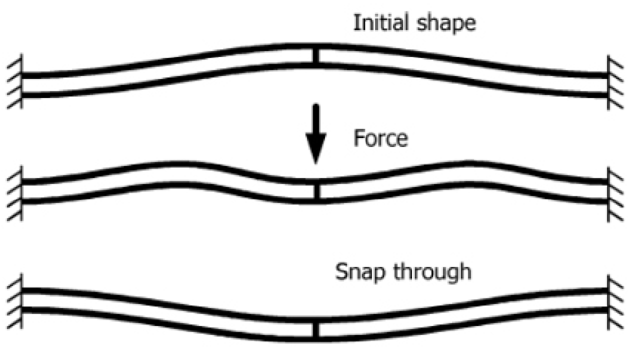

Figure 121: 'Snap-through' transition from one stable state to another (Rafsanjani et al., 2015)

APPLICATIONS
As multi-stable structures deform between stable states, they are often found in applications which require quick transitions between states such as switches (see figure 122), valves and relays (G. Chen et al., 2010).

Figure 122: Bi-stable compliant switch (Zirbal et al., 2016)

POTENTIAL USE
When combining multi-stable structures with foldable or rotatable structures, they can be used to unfold or open a structure and thereby revealing an underlying layer and keep its state without continuous actuation. Furthermore, they can be used to transform a surface from flat to textured and thereby create a relief of brilliance and shading. For example, Daynes et al. (2014) created a dynamic texture, inspired by cephalopod's papillae, constructed from silicone cells with locally reinforced regions (Daynes et al., 2014). The cells configure from flat into textured after pneumatic actuation (see figure 123). The reinforced regions assure that the cells maintain their shape in either a retraced or deployed state without sustained actuation, creating two stable states.

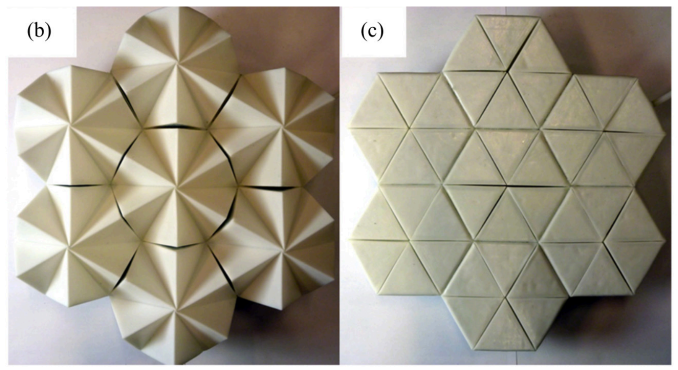

Figure 123: Dynamic bistable texture (Daynes et al., 2014)

D: ACTUATION

ELECTRICAL ACTUATION

With electrical actuation, movement is caused by a voltage or electric current. This movement is often the result of the attraction and repulsion of electromagnetism and electric charge. Several forms of this type of actuation exist, which could be used to create the required angular displacement.

ELECTROMOTOR

An electromotor converts a voltage into the rotation of a rotor. This rotation is caused by a combination of a constant magnetic field and a rotatable armature placed within that field. The armature consists of a coil, through which an electric current is directed. The combination of the electric current and the magnetic field results in a Lorentz Force which causes the armature to rotate (see figure 124) (Learn Engineering, 2014).

SERVO MOTOR

A servo is a combination of an electromotor and a sensor, detecting the rotor's position. Thereby, the motor's rotation speed and/or position can be controlled with high precision (Learnchannel, 2017).

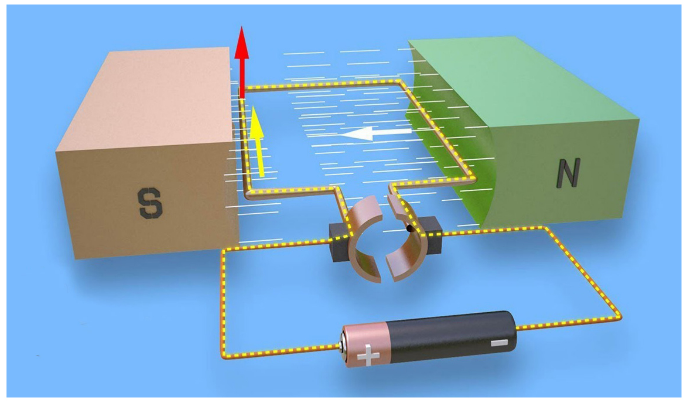

Figure 124: Working principle of an electromotor explained (Chrvoje Engineering, 2017)

STEPPER MOTOR

A stepper motor can control the angular position of a rotor with high precision, without the feedback from a sensor, by dividing a full rotation in a number of fixed steps. A basic stepper motor consist of a stator with inner teeth on which coils are attached, and a rotor with outer teeth (see figure 125). The stator has a different number of teeth than the rotor to ensure that only one pair of rotor teeth are in line with the stator teeth at the time.

When discharging the coils that are in line with the rotor teeth, and at the same time charging a different set of coils, the rotor will rotate until its teeth are in line with the teeth of the charged coils. Thus, the rotor rotates within fixed steps and thereby, the angular displacement can be a controlled with high precision (Learn Engineering, 2016).

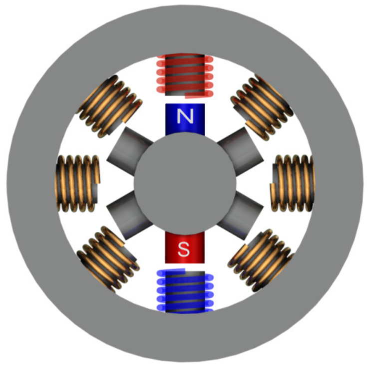

Figure 125: Working principle of a stepper motor explained (Satou, 2018)

ELECTROSTATIC ACTUATOR

Electrostatic actuators achieve displacement without the use of magnets or coils. Their working principle is based on the attraction and repulsion of electric charge. As these actuators typically require a high voltage supply, they are often used in microscopic devices where lower voltages are sufficient (Johnstone, 2004).

SOLENOID

A solenoid actuator consists of a hinging arm, a spring and a coil. When an electrical current is passed through the coil, an electromagnetic field pulls down the arm. When the electrical current is turned off, the spring pushes the arm back up (see figure 126) (Engineering Technology Simulation Learning Videos, 2015).

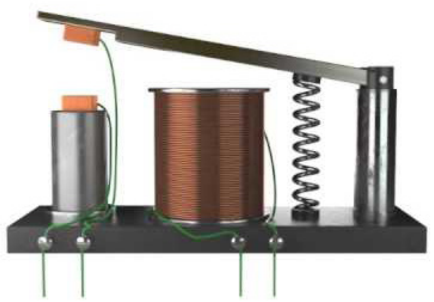

Figure 126: Solenoid actuator (Engineering Technology Simulation Learning Videos, 2015).

PIEZO-ELECTRIC ACTUATOR

A Piezo-electric actuator achieves angular displacement when a voltage is applied due to the Piezo effect where piezoelectric materials change dimensions when a force or voltage is applied (see figure 127) (American Piezo, n.d.).

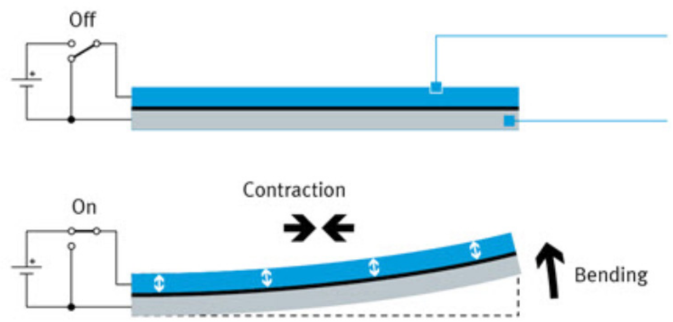

Figure 127: Working principle of a piezo-electric-actuator explained

PNEUMATIC ACTUATION

With pneumatic actuators, a cavity or pouch is filled with gas or pressurized air. After which the expansion of the fluid causes deformation or mechanical motion. There are various types of pneumatic actuators which can be used to achieve an angular displacement.

ROTARY VANE ACTUATOR

A typical pneumatic actuator used in industrial application is a rotary vane motor. This actuator consists of a closed cylinder with a vane inside, rotating around a shaft. When gas or pressurized air is pumped inside the cylinder, the vane is pushed away, creating rotational movement (see figure 128) (Rankin Automation, 2017).

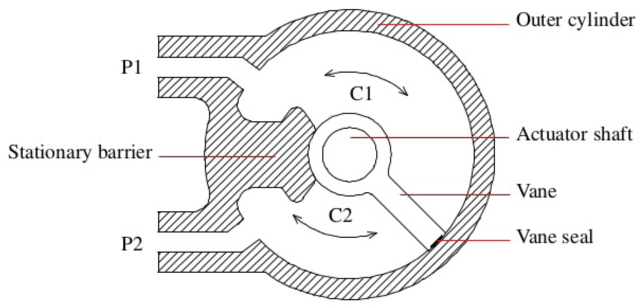

Figure 128: Working principle of a rotary vane motor explained (Murugan, 2016)

SOFT PNEUMATIC ACTUATOR

Soft pneumatic actuators (or soft robotics) are made of soft and flexible materials and consist of cavities, pouches or air channels, which deform after being inflated with gas or pressurized air. These actuators are shaped in a way, that their deformation caused by inflation, generates movement (see figure 129). They are mainly used to create soft actuators such as grippers, used to handle fragile products or interfaces which allow safe interactions with humans (Y. Sun et al., 2013).

Figure 129: Soft gripper (Wyss Institute, 2018)

THERMAL ACTUATION

With thermal actuation, an increased temperature is transferred to movement. This is due to certain materials which deform when they are heated.

SHAPE MEMORY ACTUATOR

Shape memory actuators make use of shape memory alloys or polymers. These materials are deformable when cold but return to their original shape after being heated. Therefore, they can achieve an angular displacement by applying heat. The advantages of these type of actuators are that they are low-cost, low-weight, reduced size and their ability to react directly to the environment (Qamar et al., 2018).