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Designing a locomotive device driven by a shape memory alloy composite

a mimicry of the caterpillar movement

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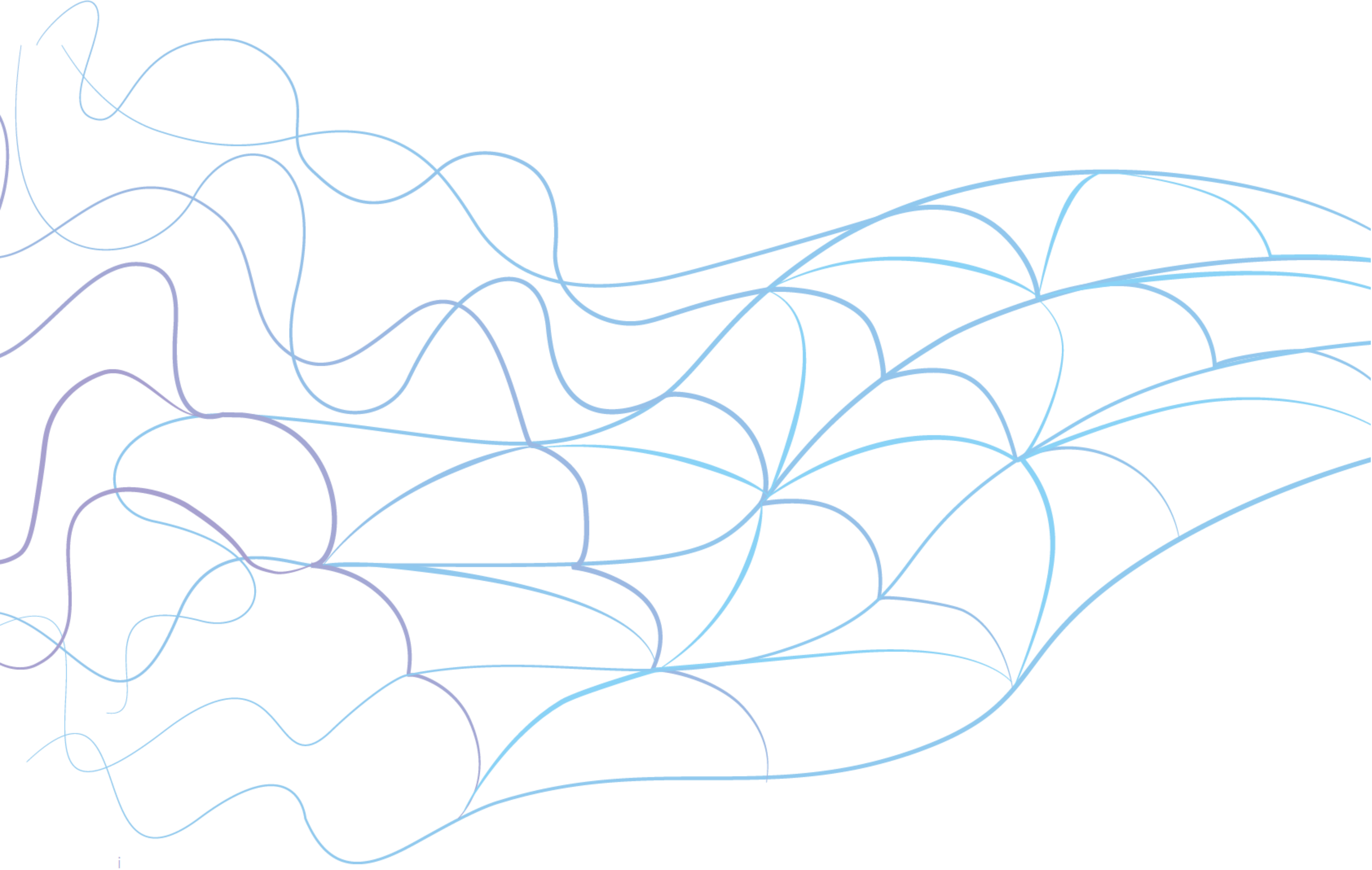

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Executive Summary

The materials we encounter in our every day lives already extend beyond the traditional materials of wood, metal, ceramics and glass. The characteristics and behavior of materials and material composites are continuously being tweaked. The introduction of new materials that can respond to inputs from the environment has brought about a new movement for material development and interaction design: computational composites. A computational composite is capable of sensing inputs from the environment, processing and controlling the consequent expression or formation of the material.

The aim of the thesis was two-fold: to design and develop a soft bodied mechanism inspired by the movement of a caterpillar, using a Shape Memory Alloy-based (SMAs) composite, and to design material concepts based on the qualities of the composite.

This was an explorative project, investigating the application of a bio-inspired approach and the Material Driven Design (MDD) approach to the development of a moving material.

The first phase of the project focused on uncovering the technical aspects of a SMA-based composites and its relation to a computational composite. To understand caterpillar locomotion, a thorough study on its anatomy and locomotion strategies was performed. A qualitative study on how designers interpret caterpillar-like motion lead to four interesting movements, which were further developed in moving SMA-based composites from silicone and 4D printed textile.

One SMA-based composite was selected for further improvement of the mechanism to be capable of translational caterpillar-like motion.

The mechanism can also be interpreted and applied in other ways, and thus the experiential characteristics of the material were uncovered to define a material experience vision for further applications. Through a creative session and ideation phase three material concepts were proposed, suited for three types of user input on the computational composite: none, indirect and direct.

The ultimate purpose for the material would be to sensitize people to the idea of a world where materials move from passive objects to active elements in our daily lives. It is recommended to do more research on the composite and to apply the materials experience vision to applications beyond every day objects and into the more innovative field of computer interface design and human-material interaction.

List of Abbreviations

CPS	Creative Problem Solving Process
FSMA	Ferromagnetic Shape Memory Alloys
MDD	Material Driven Design
OWSME	One-way shape memory effect
PE	Pseudoelasticity
SE	Superelasticity
SMA	Shape Memory Alloys
SMC	Shape Memory Composites
SME	Shape Memory Effect
SMH	Shape Memory Hybrids
SMM	Shape Memory Material
SMP	Shape Memory Polymers
MEMS	micro-electro-mechanical systems
MSMA	Magnetic Shape Memory Alloys
TWSME	Two-way shape memory effect
TZP	CeO2-tetragonal zirconia poly- crystal

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References

APPENDICES

Chapter 1

Introduction

An introduction to the graduation project is first given in Section 1.1. The approach to the project is further described in Section 1.2.

Section 1.1 Project Overview

This report represents a documentation of the graduation project executed at the Industrial Design Engineering Faculty of Delft University of Technology, as part of the master Integrated Product Design.

The aim of the project is to design and prototype a soft-bodied mechanism driven by a novel shape memory alloy (SMA) based composite. Overall, the project is mainly technology driven and first and foremost the material and mechanism is developed to demonstrate the possibilities with SMA. With the development of the computational composite an identity and meaning can be given to the material by adopting a Material Driven Design (MDD) approach. This project will embark on combining MDD with a bio-inspired design approach and apply it to the development of a shape changing material. The compatibility of both approaches will become apparent as the project advances. As a starting point for this project, inspiration is taken from caterpillars, which are a well studied organism.

Computational composites and smart materials both exhibit temporality, meaning that they can change their form depending on the inputs from their environment. Smart materials are capable of sensing changes in their surroundings and responding consequently (Bergstrom et al., 2010). Computational composites on the other hand process the inputs by means of computation and formulate a consequent response. In this project, Shape Memory Materials are adopted to facilitate actuation of the material. To manage the complexity of the project, the key elements are mapped as can be seen in Figure 1.1. Overlapping characteristics are highlighted and show how the material components contribute to actuation, movement and expressive qualities.

The aim of this project is:

> “To develop SMA-based composite, capable of a soft-bodied mechanism, taking inspiration from the caterpillar locomotion.”

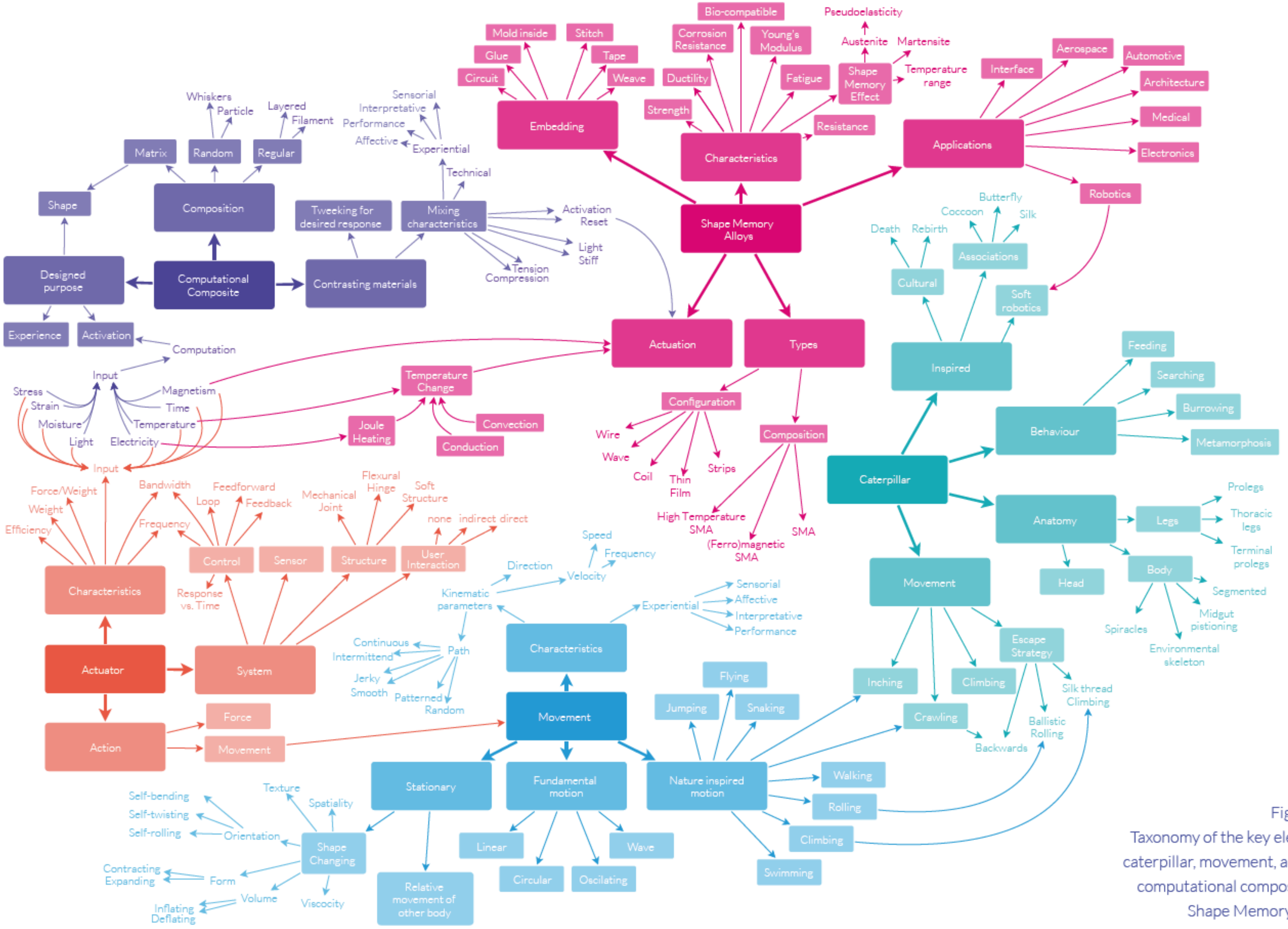


Figure 1.1
Taxonomy of the key elements: caterpillar, movement, actuator, computational composite and Shape Memory Alloys.

Section 1.2 Approach

This project will embark on combining MDD with a bio-inspired design approach and apply it to the development of a shape changing material. The combination op approaches has not been documented yet, and poses the question how MDD should be adapted to incorporate a bio-inspired vision. At the end of the project, a reflection on the effectiveness of the combination of approaches is made. Both MDD and bio-inspired design approaches are described below.

Material Driven Design

The materials we encounter in our every day lives already extend beyond the traditional materials of wood, metal, ceramics and glass. New materials are continuously being invented to fulfill specific functions. For instance, by changing the lattice structure of ceramics on a nanoscale, this traditionally brittle material can be designed to be compressive and ductile (Meza, Das, & Greer, 2014). However, not only material characteristics are being tweaked. New behaviors are also being developed from the combination of two or more materials, resulting in composites. 'Smart' or 'computational' composites have the ability to continuously respond to inputs from their environment based on their internal programming (Bergstrom et al., 2010).

As material scientists continue to develop novel materials, with extraordinary capabilities beyond the current framework of material understanding, designers are faced with the challenge of designing with these new materials. The opportunities for the designer are to create new materials as well as adapting the behavior and performance of these materials. However, the capabilities of a designer should move beyond understanding the utilitarian and functional aspects material characteristics contribute to products. To aid in the adoption of a new material, designers must also find a way to make the material socially and culturally acceptable (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015).

A new design approach was developed by Delft University of Technology and Politecnico di Milano, Material Driven Design, which facilitates the design for material experiences. The method emphasizes that material experiences should be qualified just as technical characteristics are (Karana et al., 2015).

MDD follows four main action steps:

1. **Understanding The Material: Technical and Experiential Characterisation**

   A thorough understanding of the material is formed through tinkering with the material, benchmarking and user studies.

2. **Creating Materials Experience Vision**

   By reflecting on the overall material characterisation, a vision is created on the material's role in a unique user experience where the functional aspects of the material are used to its full potential. The purpose of the material is defined in relation to other products, people and a broader context.

3. **Manifesting Materials Experience Patterns**

   Other examples of the envisioned user experience are sought and a link is made between the created vision to formal qualities of new materials and products.

4. **Designing Material/Product Concepts**

   All the main findings are integrated into a design phase. A product idea may have already be found, and is worked out with the material. Alternatively, material concepts are made from the insights found in step 1 and 3.

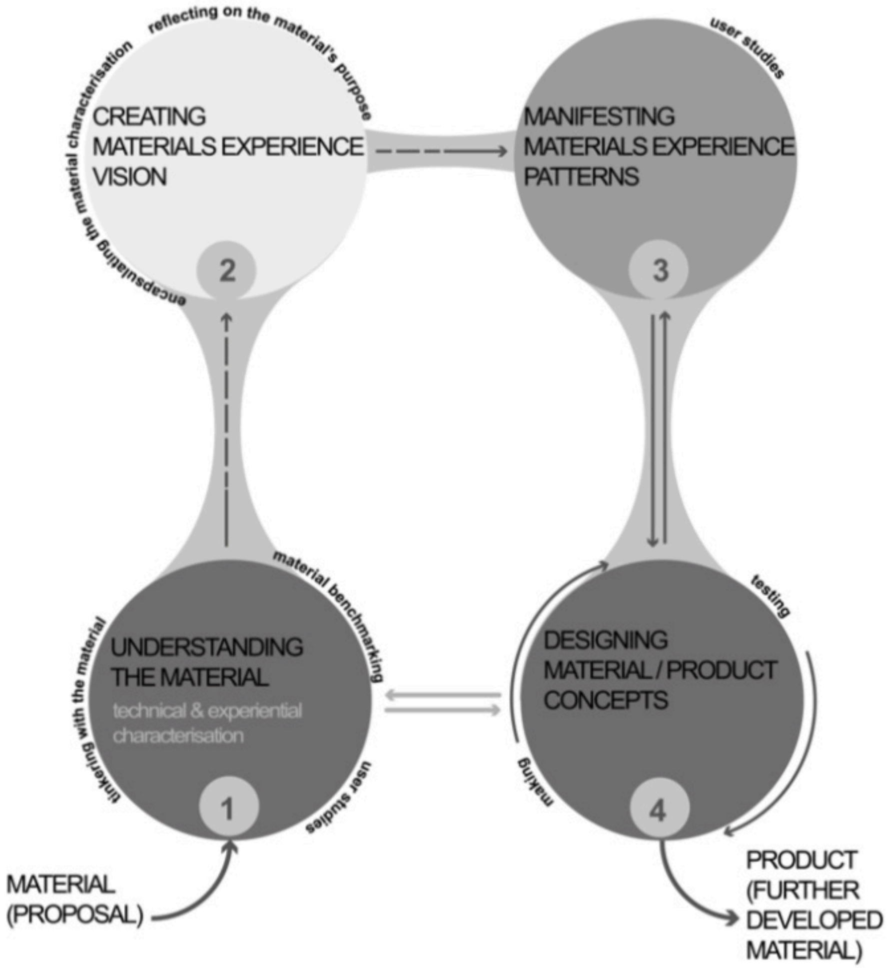


Figure 1.2
Framework for material driven design (MDD) method (adapted from Karana et al.(2015)).

Challenge to biology

Challenge to nature

Figure 1.3
Biomimicry thinking from challenge to nature (top) and From Biology to Design (bottom) (adapted from Baumeister et al., (2014)).

Taking inspiration from nature

The act of taking inspiration from nature to find new ideas in science and technology or to solve problems rests on the assumption that these natural phenomenons have been refined and perfected over the course of the last millions of years. Two main directions have surfaced: biomimicry and bio-inspired design.

Biomimicry Design

Biomimicry differs from bio-inspired design in that it aims to precisely imitate the designs of biological systems. Biomimicry as defined by Biomimicry 3.8 takes inspiration from Life's Principles and employ two design approaches for Biomimicry Thinking: Challenge to biology and Biology to design, as can be seen in Figure 1.3 (Baumeister, Tocke, Dwyer, Ritter, & Benyus, 2014).

For this project, using the Biology to Design approach would be applicable, with the caterpillar taken as starting point. However, for this project it is not necessary to mimic the caterpillar one on one, instead it will be used as inspiration for it behavior, movement and associations. Therefore a more suitable approach would be bio-inspired design.

Bio-Inspired Design

To make a case for how biomimicry and bio-inspired design is different, take for example an airplane wing. Following the bio-inspired design approach, the principle of flying was inspired by birds, but the anatomy and mechanisms of a bird were not copied in the design of an airplane wing. The wing tips however, are an example of biomimicry of the curved wing tips of an eagle.

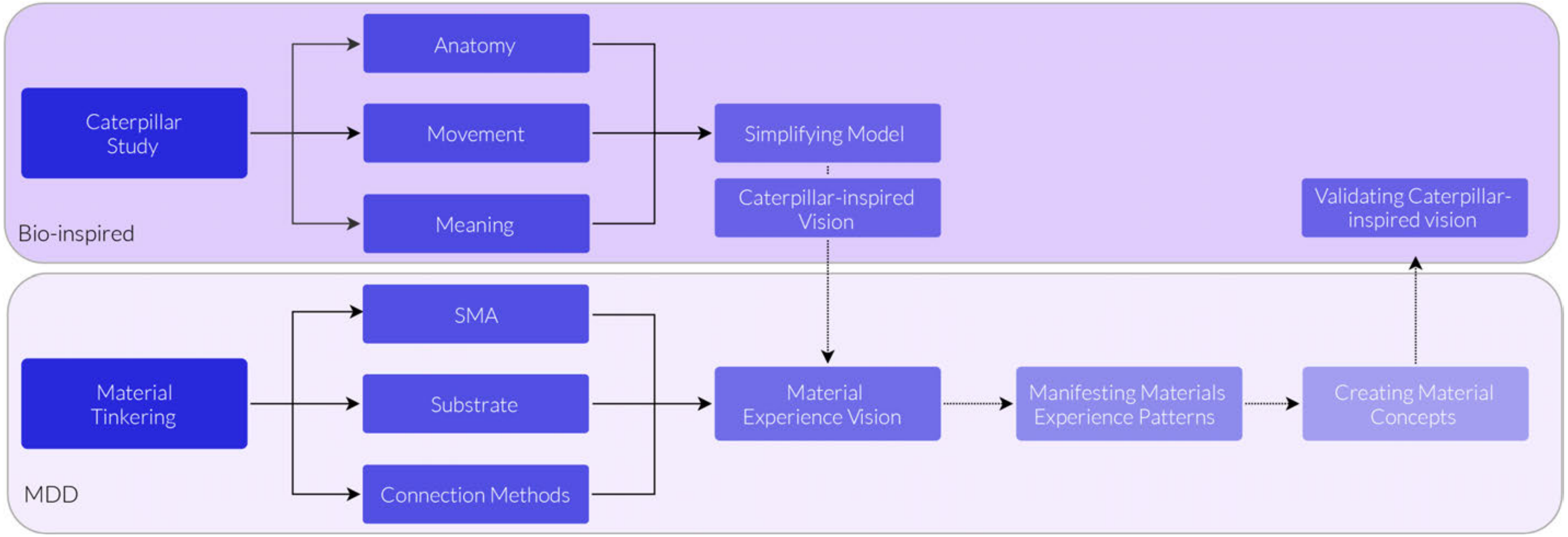
The core principle of bio-inspired design can be defined as learning from nature, while creating a model that is simpler and more effective than that observed in nature. Bio-inspired design has been applied in many fields, such as chemistry, material science and the medical field.

An interesting development is bio-inspired robotics, which translate the principles found in nature to the rigid components currently employed in robotics. Contrastingly, when looking into nature it is found that most animals are predominantly composed out of soft materials (Kate et al., 2008). To bridge the gap between conventional robots and organisms, the bio-inspired soft robotics movement emerged. Key aspects to the design of these robots are the integration of sensing of the environment and passive or active mechanisms as a response. This can be done by creating multi-functional material architectures and by replacing the hard exterior with soft bodies (Coyle, Majidi, LeDuc, & Hsia, 2018). In relation to the computational material designed in this project, this perspective might provide the connection between MDD and bio-inspired design. Challenges for this project will be the simplification of the caterpillar aspects and its adaptation to a composite. Secondly, a suitable material architecture must be selected to simulate the behavior and qualities of a caterpillar.

Combining Approaches

The combination of both approaches is visualized in Figure 1.4. The combination of the vision for the caterpillar and the material experience is combined in the second step of MDD. At the end of the project a v reflection on the combination of methods will be made.

Figure 1.4
Combining Bio inspired & MDD Approach.



Section I:

Literature Review

Chapter 2

Caterpillar Analysis

The behavior of insect larvae and in particular caterpillars has been studied extensively. The anatomical structure of the manduca sexta, or tobacco hornworm is described in Section 2.1. The strategies for locomotion can be categorized in forward movement and escape techniques. Forward movement is typically: crawling, inching or a combination of the two, further elaborated on in Section 2.2. Finally, a representative model for caterpillar locomotion is presented in Section 2.3.

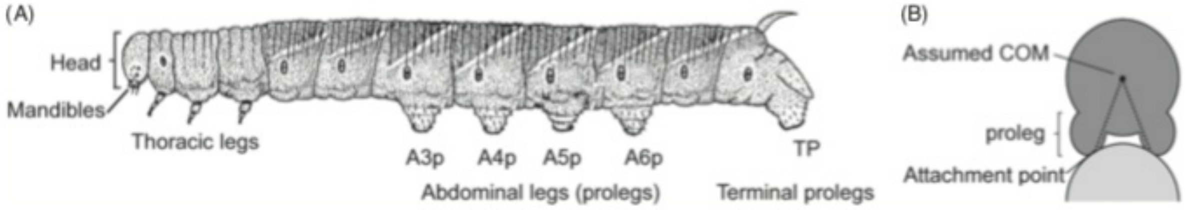


Figure 2.1
The anatomy of larval Manduca sexta (fifth instar) (Trimmer and Lin 2014).

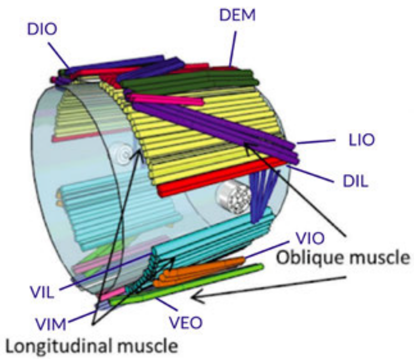


Figure 2.2
Muscle location and denomination (Trimmer and Lin 2014).

Section 2.1 Caterpillar Anatomy

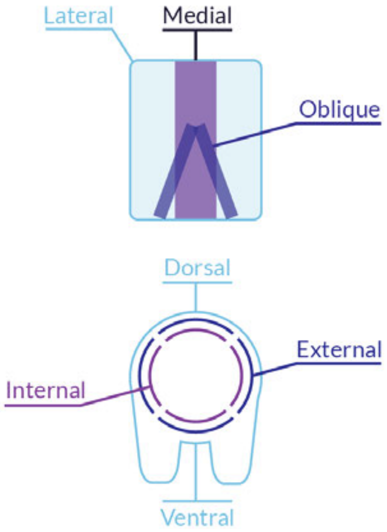
Caterpillar Body

Caterpillars have a typical cylindrical body shape with pairs of prolegs, soft leg like structures, located from the posterior end of the body to the abdominal part. The body wall of a caterpillar is made of thin and flexible cuticle, which allows unlimited freedom of body movement. Intersegmental folds, which have longitudinal muscles attached to it, separate the body segments.

At the head, the thoracic stiff-jointed legs can be found. The haemocoel, located at the centre of the body, is a fluid-filled cavity in which the muscles, fat body, gut and trachea are found. The body is made up of several segments, with spiracular openings on either side. Through the spiracles the gas exchange can be regulated by opening and closing them (van Griethuijsen & Trimmer, 2014). Therefor, the body does not have a fixed volume (Trimmer & Lin, 2014). The caterpillar does not rely on the hydrostatic pressure to control the body and limb movement, but instead uses it as internal pressure to produce baseline turgor. By doing so, the caterpillar remains relatively soft. Locomotion is accomplished by using an environmental skeleton, where compressive forces are transmitted on the substrate. The turgor can also be increased to bridge large gaps. It is presumed that the caterpillar can not accurately control their body due to their large, compressible air-filled tracheal system (Prescott, Lepora, & Verschure, 2018).

In each body segment there are about 70 muscles, oriented longitudinally and obliquely, all consisting of 2-14 fibres of 4-6 mm long (Woods, Fusillo, & Trimmer, 2008). The muscles are either longitudinally or obliquely oriented, not circularly. The small angle between the oblique and longitudinal muscles is expected to develop low flexural stiffness and resistance to dorsoventral movement, while still assisting in keeping turgor (Woods et al., 2008). The main muscles can be divided in two layers and are denoted in Table 2.1 and Figure 2.2 and 2.3.
The central pathways controlling crawling are still unknown. Anatomical studies show that the muscles in each segment are controlled by a local ganglia. However, to coordinate a crawl, intersegmental communication is necessary. Sensorial feedback

Figure 2.3
Diagram of the position and orientation of the muscles divided over the internal and external layer.



is essential in the coordination of normal crawling (Hughes & Thomas, 2007; Song, Onishi, Jan, & Jan, 2007). The brain is most likely the central complex which inhibits or excites the initiation of a crawl. By exciting isolated nervous cords, so called 'fictive crawling' can be observed, where an anterograde wave of nerve activity is seen throughout the body segments. A resemblance is found between the sequence of activation of the fictive crawl and the EMG recordings of a crawling caterpillar, though the patterns are more unstable.

It has also been argued that this phenomenon is a product of the dominant connections between neurones. Consequently, the activation of isolated neural cords may not necessarily reflect the actual mechanisms of crawling.

Thoracic legs

The thoracic legs can be divided into six posits: the coxa, trochanter, femur, tibia, tarsus and pretarsus as indicated in Figure 2.4 (Gillott, 2005).

For an adult, the body wall of each segment is covered with cuticle, which gradually becomes tanned and forms the exocuticle. In between segments this exocuticle is missing, which keeps the membrane flexible and often folded. In the case of intersegmental membranes there is complete separation of the harder parts (sclerites), leading to unrestricted movement. These area's are also denoted joints. Movement in the thoracic legs is restricted by dicondylic joints between the coxa and trochanter, similar to a hinge, meaning there are two articulations for the legs. (Gillott, 2005)

During sequence the thoracic legs may take extra or out-of-sequence steps to re-grip the substrate (Johnston, Consoulas, Pflüger, & Levine, 1999).

Abdominal prolegs

A caterpillar will have from 2 to 5 pairs of abdominal prolegs, depending on the family it belongs to. Prolegs consists of three segments: the planta, coxa and subcoxa, illustrated in Figure 2.5 (van Griethuijsen & Trimmer, 2014). Two rows of crochets, hook-like structures, are located at the plant and can be drawn in by the principle plants retractor muscle (PPRM). Accessory plants retractor muscles (APRM) are located along the coxa. Both muscles originate in the lateral body wall near the spiracle and attach to the plants and coxa. Proleg extension is achieved by muscle relaxation, where the default state is extended with the crochets rotated towards the midline.

During stepping sequence it was found that the distance between the origin (at the spiracle) and the proleg tip remains approximately the same and

Table 2.1
Categorization of caterpillar muscles

Outer Layer	Internal	External	Lateral	Medial
Dorsal	DIO			DEM
Ventral	VIO	VEO		VEM
Lateral			LIO	
Inner Layer				
Dorsal	DIL			DIM
Ventral	VIL			VIM

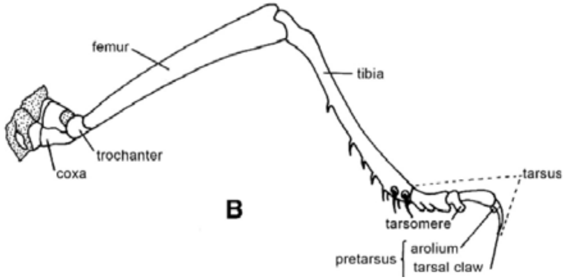


Figure 2.4
Ground plan of the typical leg of a modern insect (Gillott, 2005).

the points stay parallel to one another over time, as illustrated in Figure 2.6. It can thus be assumed that the prolegs act as support struts (Trimmer & Lin, 2014).

Terminal Proleg

The terminal prolegs (TP) behaves different from the abdominal prolegs, as can be seen in Figure 2.6. During swing phase the TP shortens and rotates significantly around the origin. During stance phase the TP is forward phasing and gradually pivots to a posterior facing orientation (Trimmer & Issberner, 2007).

Figure 2.5
Ground plan of the proleg of the manduca sexta larva (van Griethuijsen & Trimmer, 2014).

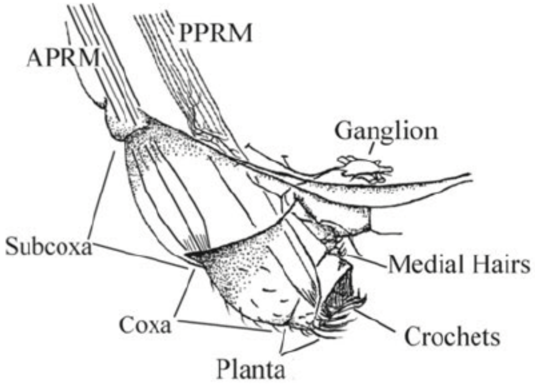


Figure 2.6
Depiction of the location of 2 Pointers on the Tp And A4 Proleg, in intervals of 1/7 Second (Trimmer & Issberner, 2007).

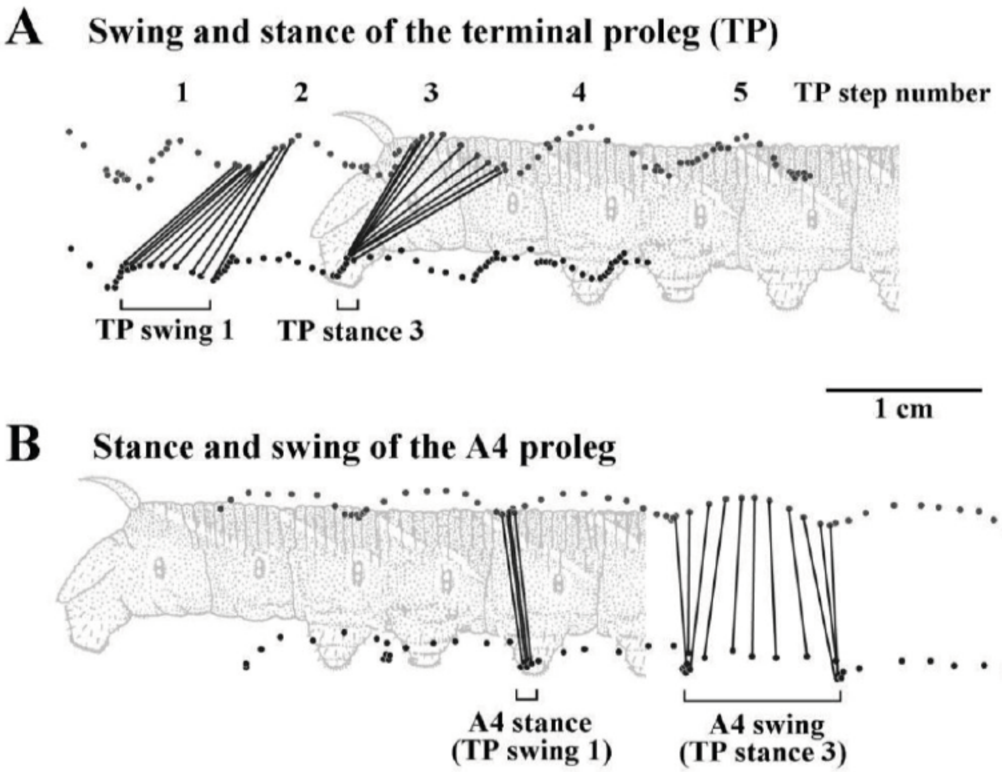
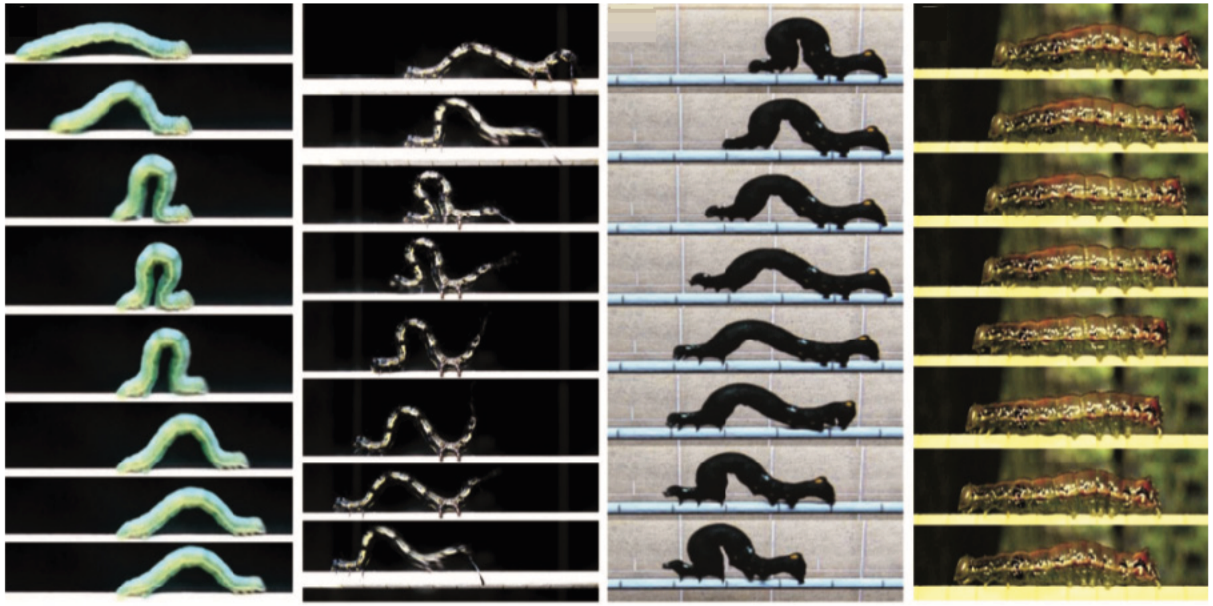


Figure 2.7
Examples of a complete movement cycle of a caterpillar forward locomotion strategies: (A) Inching pattern of Sphacelodes sp., (B) Selenisa sp. and (C) Gonodonta sp. show a combination of crawling and inching, (D) an unknown species using a crawl pattern similar to that of Manduca (Trimmer and Lin 2014).



Section 2.2 Forward Movement Patterns

Within the Lepidoptera group of moth and butterflies, the larvae can be distinctly described as having maximum 5 pairs of abdominal prolegs. Caterpillars belonging to the sub-group Geometridae only have 2 to 3 pairs of abdominal prolegs. Depending on the anatomical structure, the caterpillar will adopt different moving techniques, as can be seen in Figure 2.7. (Trimmer & Lin, 2014).

Crawling pattern

The Lepidoptera caterpillar Manduca Sexta, also know as the Tobacco Hornworm is known to use a crawl pattern to move forward. Anterograde stepping or crawling is a behaviour generally adopted by larger and thicker caterpillars. The crawl pattern is initiated by moving the terminal proleg (TP) at the posterior end of the body to right before the first set of prolegs at the abdomen. This movement, also referred to as swing phase, is then followed by a stance phase, when the TP is in contact with the ground. Both the TP and the thoracic legs at the front push into the ground, thereby tensioning the body of the caterpillar. Starting from the posterior most proleg, the proleg is lifted and swung to the front. Using the same strategy the rest of the prolegs move forward in an anterior wave. Different swing-phases can overlap, and consequently multiple pairs of legs can be lifted simultaneously. At this point the TP and thoracic legs release and the cycle starts over again.

The activation of the longitudinal muscles can be categorised in three main phases (Hughes and Mill, 1974; Brackenbury, 1999). As the dorsal longitudinal muscles and transverse muscles are shortened, the body segment shortens dorsally causing the posterior end of the body segment is raised. The segment behind is then lifted from the substrate. In the second phase the prolegs and segment are lifted from the substrate by contracting the dorsoventral muscles and leg retractor muscles. Finally, with the contraction of the longitudinal muscles and relaxation of the dorsoventral and leg retractor muscles the segment is moves forward and down to the substrate again (Gillott, 2005).

An interesting finding is that the prolegs do not shorten during the swing phase and instead are lifted by the body that has curved upwards, as can be seen in Figure 2.6. (Trimmer & Issberner, 2007). The contraction of the leg retractor muscles releases the gripping hooks on the prolegs from the substrate, allowing the proleg to be lifted up. It can be seen that the angle of the TP continuously changes during swing, while during stance it pivots significantly. Contrastingly, the proleg located at a4 remains close to vertical during step and stationary during stance (Trimmer & Issberner, 2007).
When obstacles are found, the anterior body segments communicate this towards the posterior. The prolegs are then increased in size or the body segment is lifted faster so that the prolegs land on top of the obstacle (van Griethuijsen & Trimmer, 2010). The crawling pattern is also exhibited by climbing caterpillars.

Inching pattern
In inching or looping locomotion the TP is essentially pulled forward towards the thoracic segment. While the thoracic legs grip the substrate, the body forms a dorsal body loop, hence the locomotion is referred to as looping. The TP is then able to place itself right behind the thoracic legs, after which the thoracic legs are lifted and the body is extended forward. This behaviour is also displayed by Noctuidae caterpillars (van Griethuijsen & Trimmer, 2014)

Escape Strategies
Escape strategies are usually short term, as they are used only in dangerous situations. The mother-of-pearl moth (Cacoecimorpha pronubana) and the carnation tortrix (Tortricidae) can reverse crawl and at a faster pace even reverse gallop (Brackenbury, 1999).
Some species also curl themselves into a wheel shape and are propelled of the substrate consequently (Brackenbury, 1997, 1999).
Another escape strategy is deploying silk life-lines when dropping from a leaf. The silk thread acts as a way for the caterpillar to climb up again, after the thread has passed. Although one species has been found to use an anterograde wave to climb upwards, most species only use the thoracic leg (Brackenbury, 1999).

Section 2.3 A Representative Model of Caterpillar Locomotion

Based on the analysis done on the anatomy, nervous system and locomotion strategies a simplified model for caterpillar movement is proposed. A general representation of the segments of the caterpillar body is depicted in Figure 2.8.

The two most representative forms of locomotion for caterpillars are crawling and inching, illustrated in Figure 2.9.
Crawling motion can be simplified by having multi segmental movement, i.e. A6 is lifted from the substrate and moves relative to the rest of the body. Movement of segments may overlap.

During locomotion the environmental skeleton of the caterpillar is important to keep the body in tension. This is done by applying frictional forces to the substrate, effectively aching both ends of the body to the surface. A representation of the free body diagram of the environmental skeleton is illustrated in Figure 2.10. During stance, the prolegs also act as friction points.

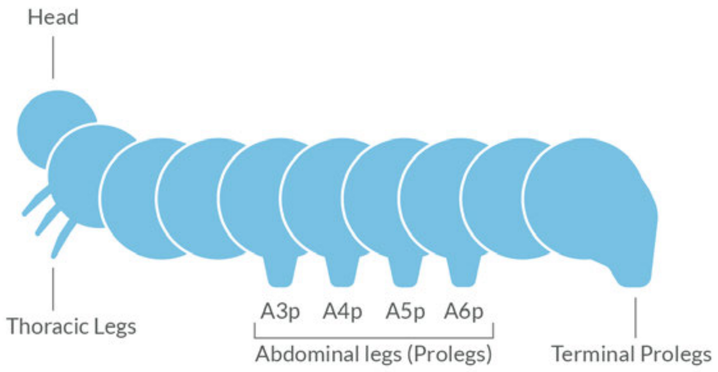


Figure 2.8
Representation of caterpillar anatomy.

Figure 2.9
Simplified model of crawling and inching.

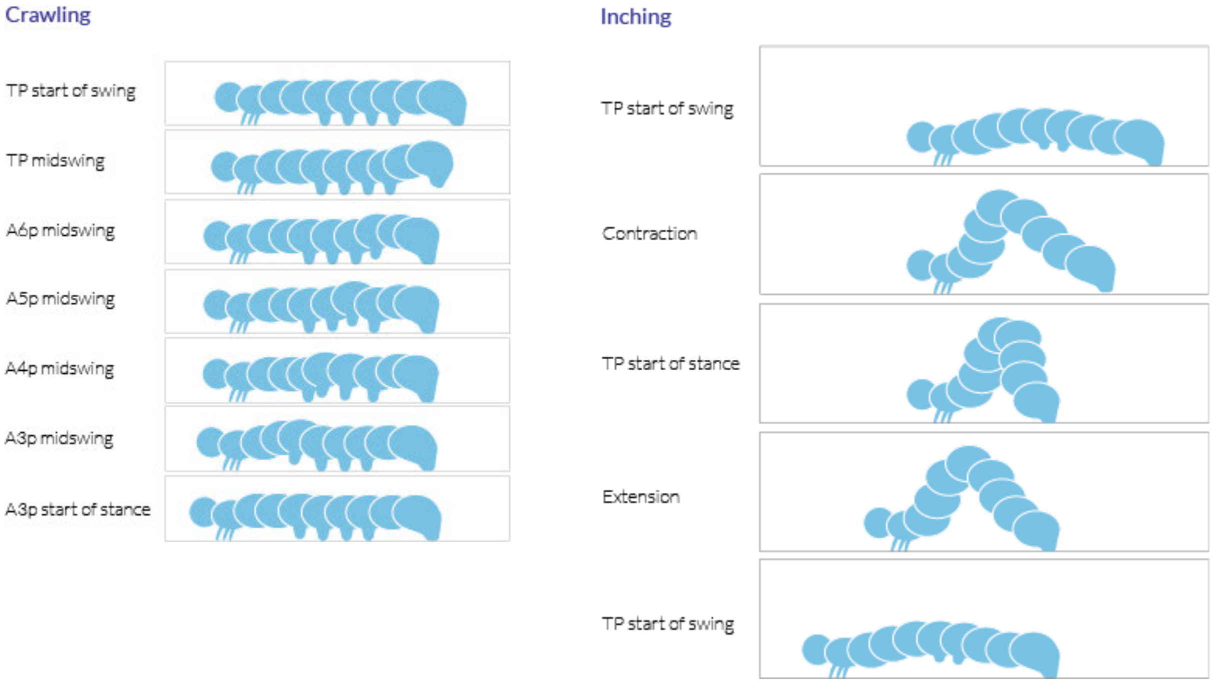


Figure 2.10
Simplified FBD of environmental skeleton, frictional forces (blue) and reaction forces on the body (purple).

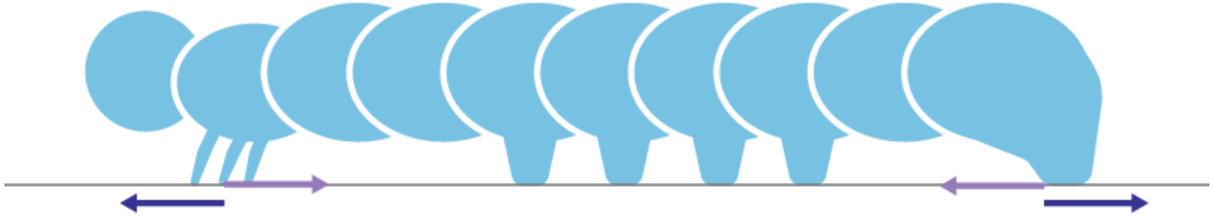


Figure 2.11
Locomotion simplified in 4 fundamental movements.

Lifting

Retraction

Bending

Contraction

An ideation was done on the several types of movement that are discernible for the anterior, abdominal and posterior body segments and can be found in Appendix A. Four different movements are identified, illustrated in Figure 2.11. In the anterior/posterior parts: lifting of the body segments, and orientation changing by bending of the body segment. For the abdominal parts, since these segments are attached on both sides the lifting of the prolegs can be simplified by extending and retracting these extremities. All body segments are extended and contracted axially.

Chapter 3

Shape Memory Materials

The history of SMA is discussed in Section 3.1. The types of shape memory alloys are listed in Section 3.2. The SME is described in Section 3.3, together with other characteristics of SMAs. The applications of SMAs are discussed in Section 3.4. Design considerations for SMA actuators are given in Section 3.5.

The technical characterisation of SMA wire and springs are presented in Section 3.6 and Section 3.7, respectively.

Section 3.1 History

Shape Memory Materials (SMMs) are materials that exhibit smart behaviour of being able to return to a certain shape they were “trained” to adopt (Bengisu & Ferrara, 2018). SMMs can be classified in metals, polymers, ceramics and composites.

Though the application SMM in our day to day lives is not widespread nor apparent, the first material, a gold-cadmium alloy, was already discovered in 1932 by Arne Ölander. This discovery was followed by the development of other metal alloys capable of exhibiting the same behaviour, including Cu-Zn, Cu-Sn, Ni-Ti, Fe-Mn-Si, Cu-Zn,Al and Cu-Al-Ni alloys also referred to as SMAs. Their behaviour to remember or retain their previous form called the Shape Memory Effect (SME) was described by Buehler and Wang in 1962. As nickel-titanium, also referred to as Nitinol, was further developed and investigated, the engineering world gradually started adopting SMAs in a wide range of applications, as discussed in Section 3.4 (Leary, Jani, Gibson, & Subic, 2014). The current fields of application are in (soft)robotics, automotive or aerospace actuators and medical tools.

Section 3.2 Types of Shape Memory Materials

SMMs can be classified in metals, polymers, ceramics and composites. For each material group a small overview is given. The SMM composites based on SMAs will be discussed in more detail in Chapter 4.

Shape Memory Alloys

SMAs are typically activated by an increase in temperature, which shifts its phase from martensite to austenite. This activation is actually the SME, which is further elaborated on in Section 3.3. The material can be heated by air convection or joule heating.

Ni-Ti alloys are most employed in commercial applications due to their affordability and reliability compared to iron- and coper- based SMAs which are also low-cost yet unstable and impractical due to brittleness (Bengisu & Ferrara, 2018) (Leary et al., 2014).

Co-Ni-Ga and Ni-Mn-Ga alloys can be categorized as High Temperature Shape Memory Alloys (HTSMA), developed in response to the recent demand for high temperature applications. Its operating temperatures start at 100 °C with martensitic phases ranging in 100-400 °C, 400-700 °C and above 700 °C (Leary et al., 2014).

(Ferro)Magnetic Shape Memory Alloys (FSMAs/MSMAs) can be actuated using magnetic fields. Compared to SMAs the actuation frequency is higher while the output power is the same. However, MSMAs are very stiff and brittle. In addition, the manufacturing and shaping of the material at present is still difficult and a better understanding of the material is necessary for further development.

Ni-Ti can also be produced into thin films, widely applied in the micro-electro-mechanical systems (MEMSs) field. In this configuration the materials have a high actuation force and displacement while its activation can occur at a lower frequency and efficiency.

Shape Memory Polymers

The stimuli that trigger shape change in Shape Memory Polymers (SMPs) are typically heat and light, or indirectly: IR-light, electricity, magnetism). A pH-induced SMP has also been developed (Han et al., 2012). Important SMPs are amorphous poly-norbornene and shape memory polyurethanes.

SMPs are capable of much larger strains, 400% compared to SMAs, with a maximum recoverable strain of 8%. Its manufacturing temperatures are lower and the shape programming is easier. They also have the potential of being less costly than SMAs. However, SMPs have lower application temperatures, lower strength and stiffness. The actuation force is also lower (Bengisu & Ferrara, 2018).

Shape Memory Ceramics

Although ceramics are commonly known to be brittle, in 1988 Reyes-Morel et al. were able to demonstrate shape memory in CeO2-tetragonal zirconia poly-crystal (TZP), though the recoverable strains were relatively small: in the range of 1%. A mixture of the super-elastic and shape memory ZrO2 and CeO2 and/or Y2O3 resulted in a material capable of 50 transformation cycles and a recoverable strain of over 7% without microcracking. The scale of the samples are however very small, in the range of 1 μm.

Shape Memory Composites

Shape Memory Composites (SMCs) are comprised of two or more materials, with the aim of adding reinforcement or additional properties to the host material. The usual composition is layered or composed of a host material combined with particles, fibres or whiskers of another material. The most commonly studied type of SMCs is SMP composites which are typically reinforced with high modulus materials to improve stiffness. Another type of composites capable of SME are Shape Memory Hybrids (SMHs), which are made from two materials that individually do not posses the SME (Bengisu & Ferrara, 2018).

The shape memory effect (SME) is the ability of a material to change to a predetermined form upon a change of temperature, stress or magnetic field.

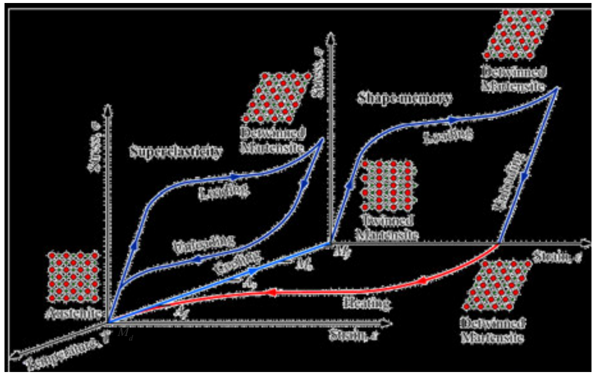


Figure 3.1
Three axis graphs of the temperature strain and stress depicting the crystal structures of SMA and SE.

Section 3.3 Shape Memory Effect

SMAs have the ability to return to their original shape after a considerable amount deformation, activated by applying an external stimulus. This characteristic is known as SME.

SMAs can have two phases and crystal structures, martensite and austenite. Because the SMA is stable at low temperatures in martensite phase and at high temperatures at austenite phase the SMA will go through a phase transformation when it is heated. This transformation starts at austenite-start-temperatue, A_S, and finishes at autenite-finish-temperature, A_F. When the temperature of the SMA is higher than A_S the material contracts back to its original shape. Beyond A_S, there is M_d, the temperature at which the martensite can no longer be stress induced.
By cooling the SMA down the material will revert back to the martensite phase starting at martensite-start-temperature, M_S, and finishing at martensite-finish-temperature, M_F.
Four shape memory characteristics can be found for SME:

Hysteresis

Hysteresis is defined as a value between the temperatures at which the material is 50% transfomed to martensite upon cooling and austenite upon heating. It measures the difference in transition temperatures by: A_F - M_S. This value is especially important to consider for targeted application: for fast actuation in for instance robotics a small hysteresis is most suitable, whereas applications where the predefined shape should be retained for a large temperature range the hysteresis should be large.

One-way shape memory effect (OWSME)

A one-way SMA (OWSMA) can be deformed and remains deformed after removal of the external force. Upon heating, the SMA can recover to its original shape.

Two-way shape memory effect (TWSME)

A two-way SMA (TWSMA) behaves the same way as a OWSMA, as in it can show the OWSME. In addition, to this a TWSMA can remember a shape at low and high temperature.

Pseudoelasticity (PE) / Superelasticity (SE)

When the SMA is loaded at a temperature between A_F and M_d, the SMA can revert back to its original shape without any thermal activation.

Section 3.4 Application of Shape Memory Alloys

One of the first applications of SMA in consumer products was in eyeglass frames, where it showcased its SE properties as a material with memory in the bendable eyeglasses, in 1981. Due to the low reliability, poor durability and high costs of the material further applications in consumer products were not found until 1986, when it was applied in bras and in 1992, in mobile phone antenna's.

For its excellent bio-compatibility, flexibility and large elastic deformation, the medical industry soon grew interested in the possible applications. SMAs are now used for instance in catheter guide wires and stent implants (Leary et al., 2014).

Opportunities for the application of SMA in the automotive industries have been growing due to the increased customer demand for safer and more comfortable vehicles. Though the research in applications have been going on for far longer, as General Motors stated they started their work on SMA since the mid 1990s. Mercedez-Benz already implemented a SMA control valve based on thermal response in 1989.

In the Aerospace sector, SMA has been used in several different applications, from Flexsys shape morphing wings to SE SMA wheels by NASA.

Since the 1980s, SMAs have been applied in several robot designs in micro-actuators and sensory systems. Applications of SMA robots are nowadays more biologically inspired since many robotics researches are more interested in developing humanoid and biomimetic robots. Interests have also shifted from conventionally stiff jointed robots to soft bodied robots with multi-functional material architectures (Coyle et al., 2018).

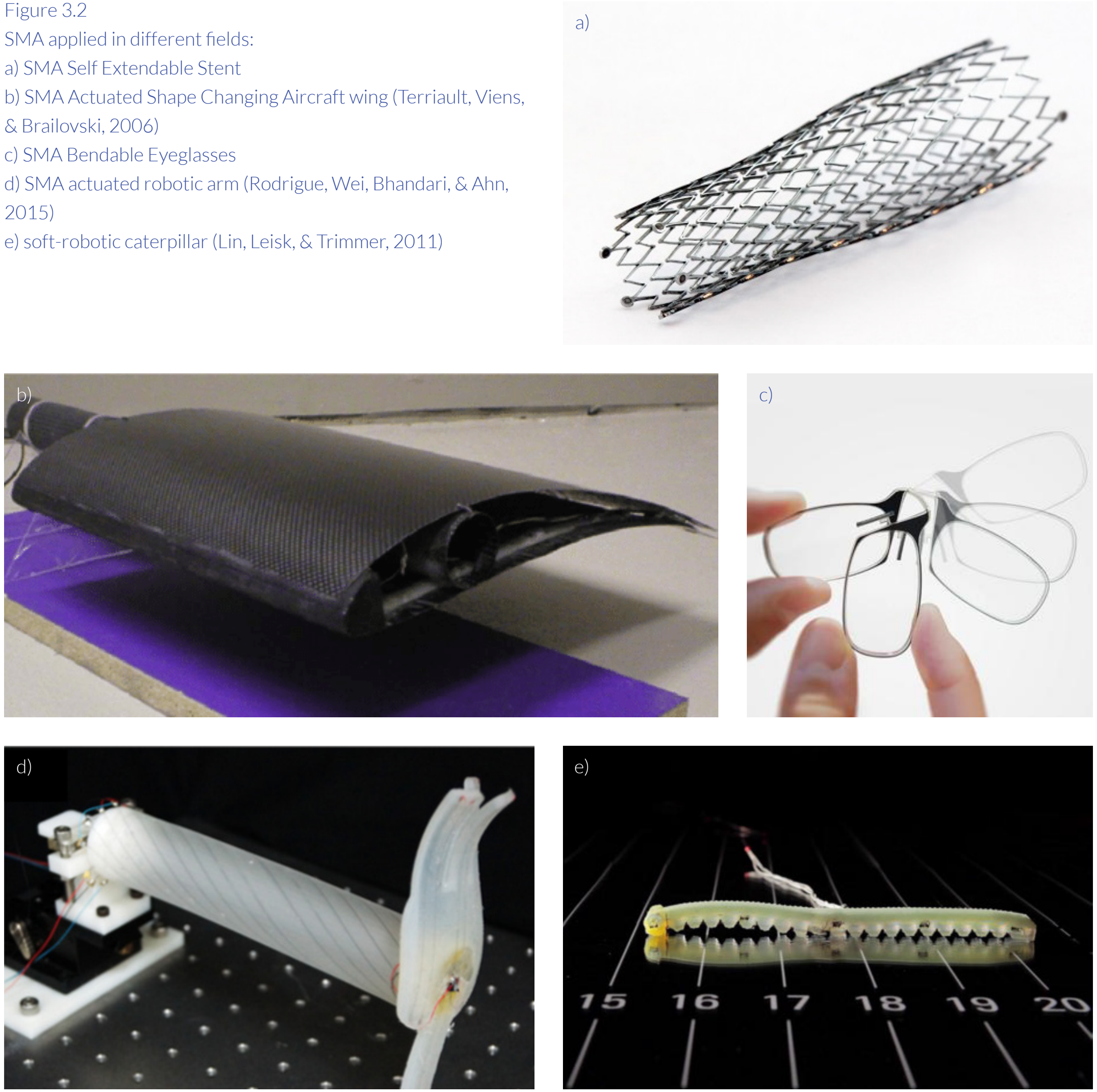


Figure 3.2
SMA applied in different fields:
a) SMA Self Extendable Stent
b) SMA Actuated Shape Changing Aircraft wing (Terriault, Viens, & Brailovski, 2006)
c) SMA Bendable Eyeglasses
d) SMA actuated robotic arm (Rodrigue, Wei, Bhandari, & Ahn, 2015)
e) soft-robotic caterpillar (Lin, Leisk, & Trimmer, 2011)

Figure 3.3
Shape memory Alloy manufactured to different configurations:
a) plate
b) rod
c) wire
d) flat wire
e) welded loop
f) springs with different wire diameter and mean diameter.

Section 3.5 Design Considerations

Actuator types

Shape memory alloys can be manufactured as wires, flat wires, plates and rods. From wires, helical, springs, micro-springs, flat springs, torsional springs and welded loops can be made. The type of configuration contributes to the behavior of the SMA and determines the motion. For instance, torsional springs produce rotational motion, while wires contract.

Cycle time

The time the SMA wire requires to contract and relax is dependent on the wire's composition, the power applied and on the local cooling conditions. For the contraction phase, the time required to reach the transition temperature does not influence the force exerted by the SMA since the phase change only occurs at the transition temperature (Gilbertson, 2005).

The main factor in the cycle time is the cooling time. Thin wires will cool faster than thicker wires, since the smaller volume means less heat must be dissipated. It is therefor advised to use several smaller wires in parallel, when strength must be increased (Gilbertson, 2005).

Lifetime

The amount of cycles the SMA wire can be activated is limited by the force it should exert. For wires operating at the maximum recovery ratio (about 8% deformation) only a few dozen cycles can be expected. The recommended recovery ratio is around 3-5%, at which the wire can function for millions of cycles. The wire should also be kept from overheating, since this damages the wire.

Reset
After activation, the SMA will not return to its original position on its own when the shape recovery is not 100%. To ensure the actuator can be activated again, the SMA must be moved back. A bias force can be used near the recommended deformation force of the SMA. This bias will provide just enough force to return the wire to its initial position. Another method is the use of antagonistic SMA components, where two components are working against each other to create two-way motion control.

SMA Heating
The SMA wire is activated by temperature change. To heat up a single wire, multiple methods can be used.
By convection, the wire is heated by the fluid or gas surrounding it, which could be by using a water bath or by blowing hot air out of a heat gun on the wire. In general, these methods heat the entire environment and cannot target their heat to a single wire.
Another method is by conduction. Where heating elements are positioned in direct connection to the wire. The heat then travels through the materials itself.
Finally, the lattice structure of the SMA allows current to pass through it. Due to the resistance of the material, the electrical energy is converted to heat, this is called Joule heating. Using this method, multiple wires can be activated individually. In addition, the method of using electrical input also allows for easy integration into a control system.
By using a larger current on a wire, the heating rate of the SMA wire can be increased. However, applying a current higher than the safe value over a certain amount of time also involves the risk of overheating and damaging the SMA (Teh & Featherstone, 2004).

The maximum current and voltage can be calculated in the following way (Kellogg's Research Labs, 2019).

The energy required to heat up the material and to bring about the phase transition is determined by the following relation:

$$E = c\Delta T m + L m$$

Where c is the specific heat, m the mass of the wire and L the specific latent heat. The temperature difference is based on the ambient and transition temperature.

Determine the amount of power based on the activation time, t. The resistance can be calculated with the resistivity, length and cross-sectional area of the wire.

$$P = \frac{E}{t}$$

$$R = \frac{\rho L}{A}$$

Finally, the current can be determined based on the following equation:

$$P = I^2 R$$

While performing initial tests on the SMA wires, a tabletop electrical box was used. The desired values for current and voltage were manually set. The SMA wire was gripped between two alligator claws. The drawbacks of using this system are the inability of controlling two SMA wires separately and the bulkiness of the heating element and the electrical cables.
When applying power to the wire the amount of time the current is supplied to the wire is crucial, as well as the reached temperature of the wire. Overheating of the wires occurs at around 100 °C, a strong odor can be detected and in some instances the SMA wire can glow red.

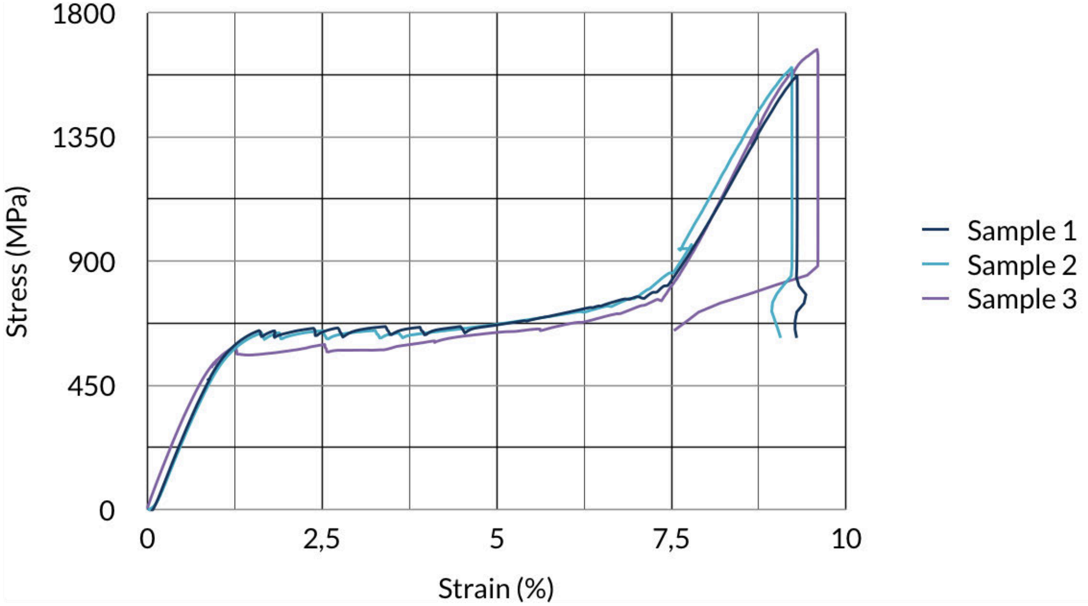


Figure 3.4
Tensile stress-strain curve of three 1mm diameter SMA samples.

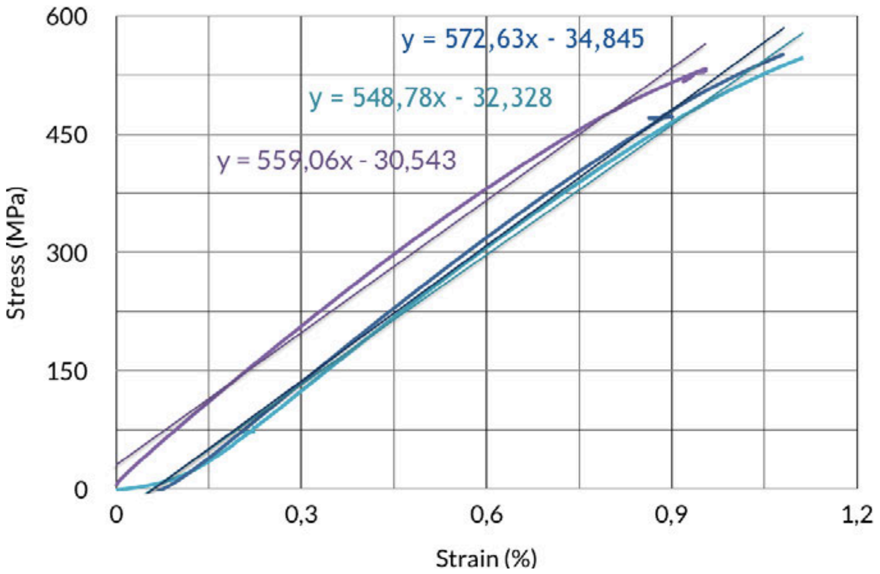


Figure 3.5
Linear part of tensile stress-strain curve with trend line to determine austenite Young's modulus

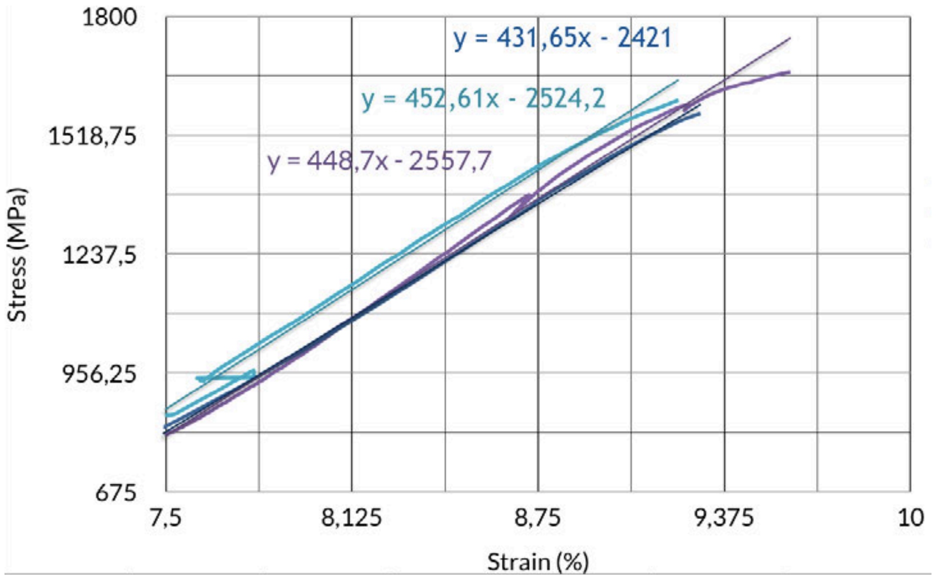


Figure 3.6
Second linear part of tensile stress-strain curve with trend line to determine martensite Young's modulus

Section 3.6 Technical Characterisation of SMA wire

The Young's modulus of Nitinol is dependent on the crystallographic phase of the SMA. In austenite phase it is approximately 83 GPa and in phase martensite 28 to 41 GPa (Johnson Matthey, 2019). According to Suresh, Lahiri, Agarwal, and Suwas (2015) have found that the range for austenite and martensite phase is even 30-80 GPa and 20-50 GPa, respectively.

As stated by Johnson Matthey (2019) the Young's modulus can vary nonlinearly with temperature. The exact composition of the NiTi Alloy will influence the material properties, for this reason the SMA ordered from Muscle Wires was tested again.

In total three samples of SE SMA wire were tested, with a diameter of 1 mm at room temperature. Tensile tests on SMA wires has resulted in the following stress-strain curve, depicted in Figure 3.4. The Young's modulus was determined for the austenite and martensite linear parts of the curve and can be seen in Figure 3.5 and 3.6.

The average Young's modulus in both phases, Yield and Tensile strength were determined from the graph and are shown in Table 3.1. The resulting graph matches the findings of Šittner et al. (2014), depicted in Figure 3.7. The Young's modulus of the material found from the test falls in the range Johnson Matthey proposed for the martensite phase, but is much lower in the austenite phase than expected. The austenite Young's modulus does approach the values indicated in Figure 3.7 by Šittner et al.

Table 3.1
Young's modulus, Yield stress, Tensile stress and max strain of the SMA.

	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
Young's Modulus Austenite [GPa]	57.3	54.9	55.9	56.0	1.2
Yield Stress [MPa]	649	636	577	621	38
Young's Modulus Martensite [GPa]	43.2	45.3	44.9	44.4	1.1
Tensile Stress [MPa]	1570	1600	1666	1612	49
Max Strain [%]	9.3	9.2	9.6	9.4	0.2

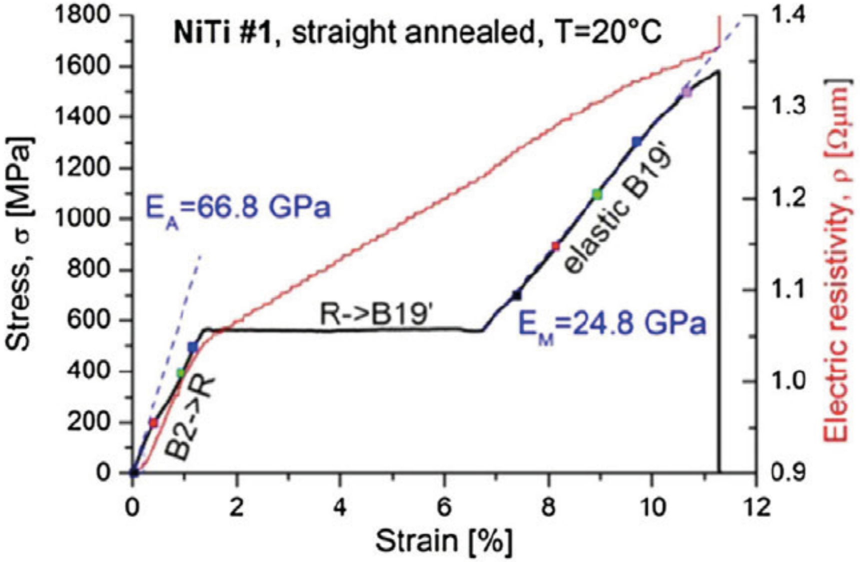


Figure 3.7
Tensile stress-strain curve of SE NiTi wire of 0.1mm diameter at room temperature (Šittner et al., 2014).

The maximum stress for which full strain recovery is possible is 600 MPa, with the recommended stress is of the order 200 MPa. (Gilbertson, 2005). This is in line with the results from the graph where it can be seen that the loading plateau starts to from around 675 MPa, at which the amount of force required levels off substantially. Limiting the stress on the SMA to 600 MPa ensures that the wire can be used for multiple cycles. The amount of cycles is dependent on the strain that is put on the wire. Most wires can only perform for a few cycles at maximum deformation.

To verify this a multiple cycle test was performed on SMA wire with a diameter of 0.5 mm. A strain interval was set to the cyclic test of 2%, 5% and 8%, for the duration of 10 cycles. The resulting graphs can be found in Figure 3.9, 3.10 and 3.11, respectively. The same linear-elastic region and loading plateau can be distinguished as in the tensile test. However, this time the sample was not loaded until failure. Upon unloading the Nitinol contracted until it reached the second, lower plateau and at the end behaves like a linear- elastic material again. In the following cycles, this response is repeated again.

It can be seen that the after 8% loading the wire follows a different path, where it goes out of the plateau region and does not go back to 0% strain anymore. An offset percentage of strain is around 0.05%. After 10 cycles the offset strain is 0.28%. It can be expected with more cycles this offset deformation will continue to grow. Eventually this will accumulate and may influence the effectiveness of the actuator.

Figure 3.8
Tensile stress-strain curve of cyclic test with 2% intervals.

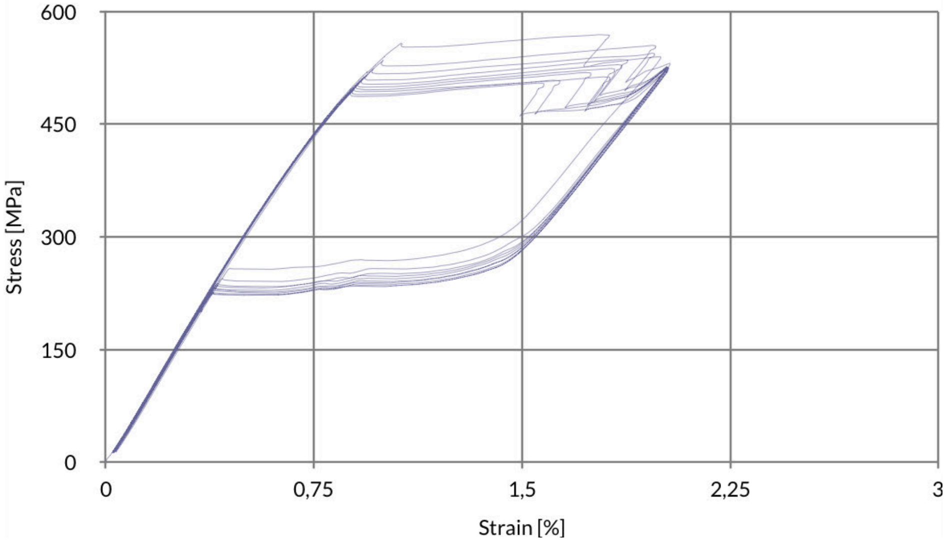
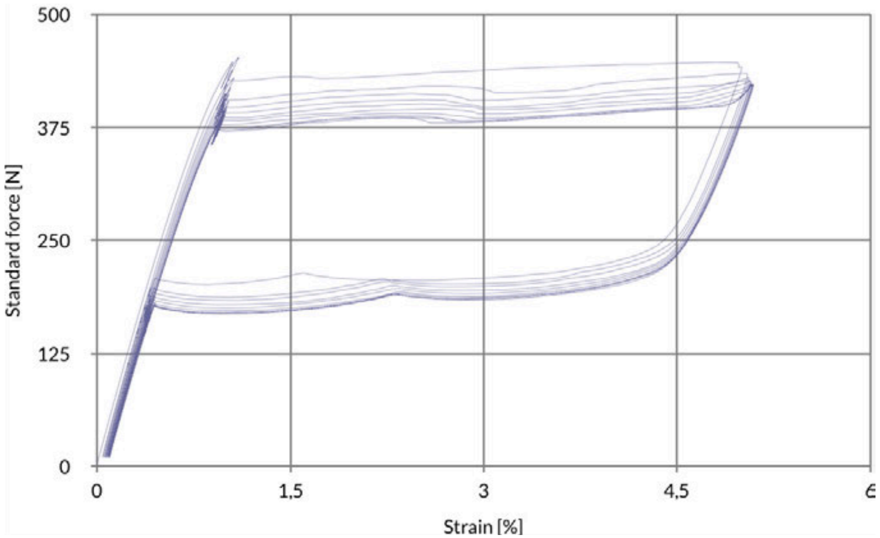


Figure 3.9
Tensile stress-strain curve of cyclic test with 5% intervals.



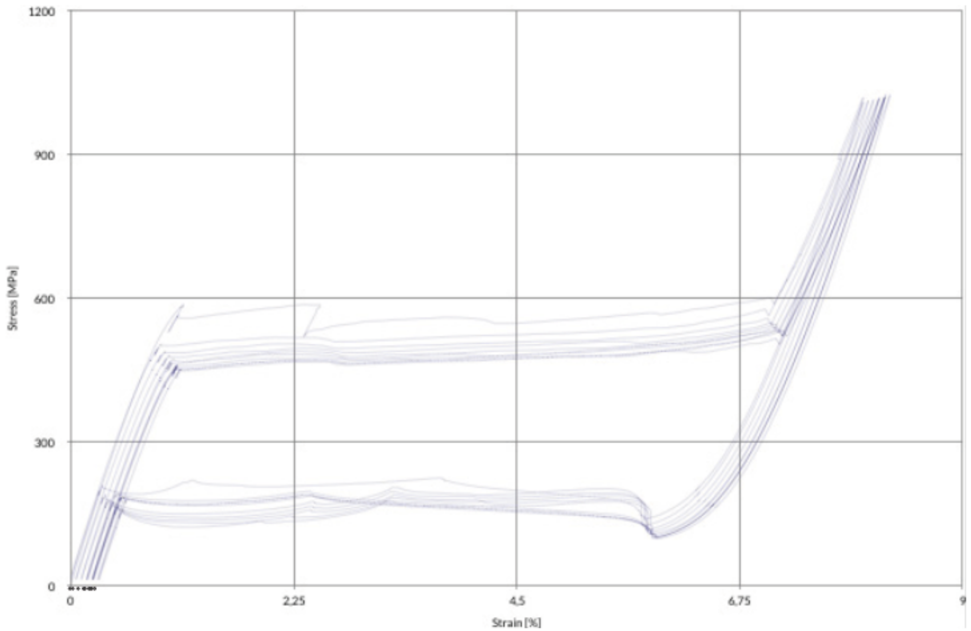
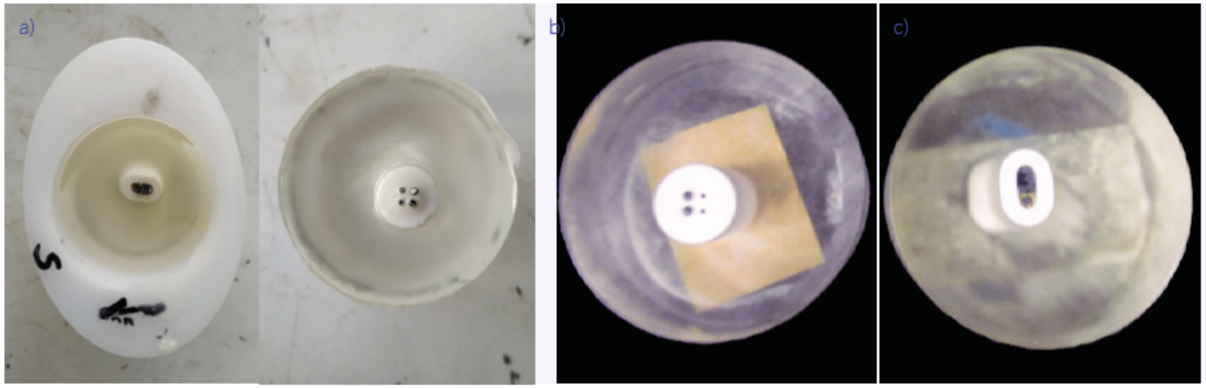


Figure 3.10
Tensile stress-strain curve of cyclic test with 8% intervals.

Figure 3.11 Samples prepared for etching to investigate the micro-structure:
a) Samples cured inside resin before the surface is grinded and polished.
b) SMA with high (70 °C) and low (35-45 °C) transition temperatures of 1 and 0.5 mm diameter
c) Super-elastic SMA of 1mm diameter 10 °C transition temperature



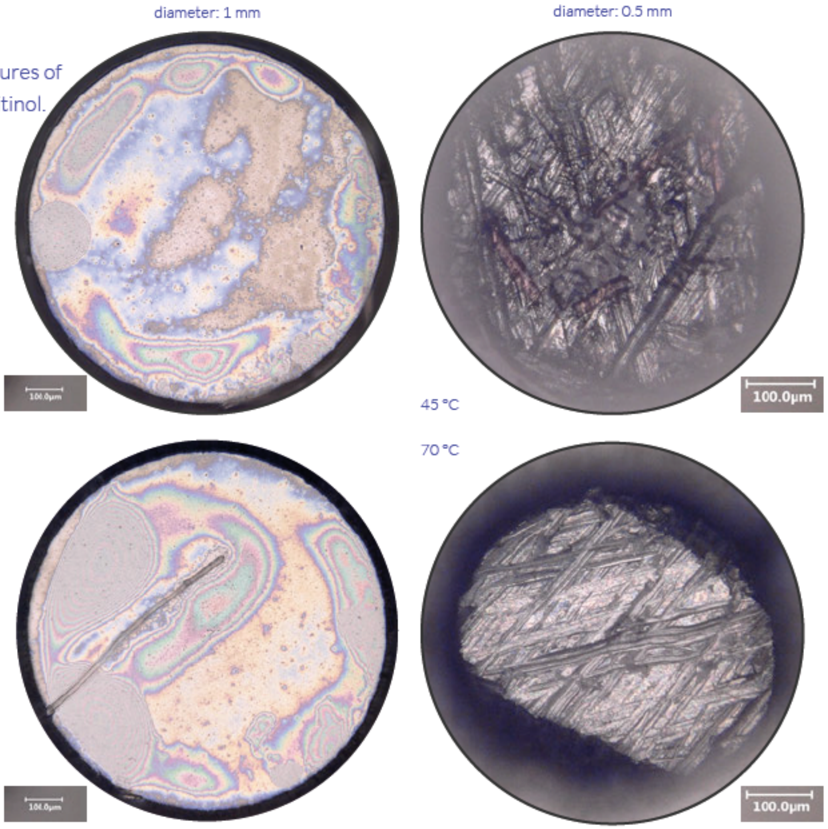
Section 3.7 SMA Micro-structures

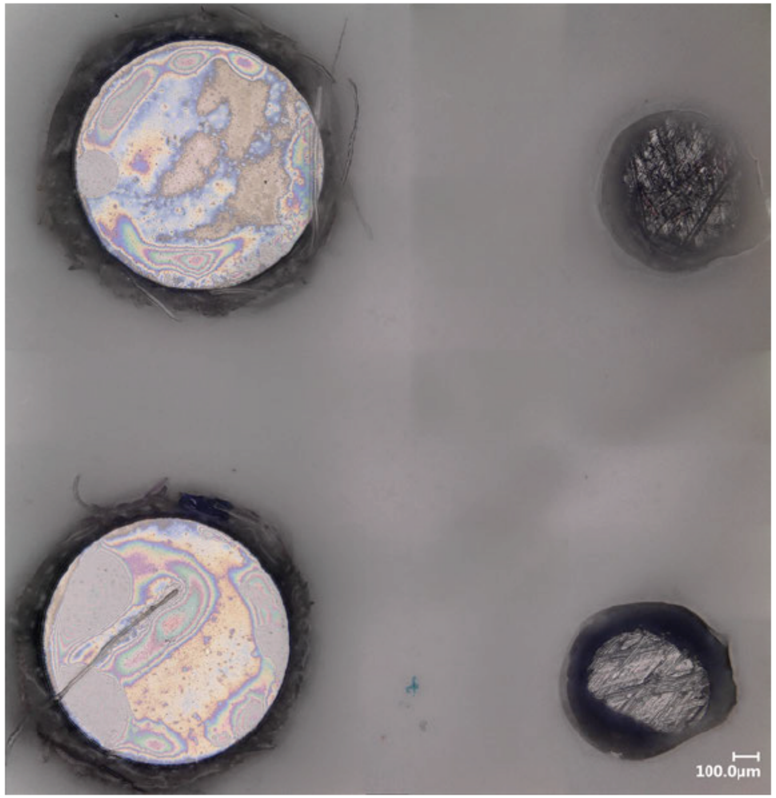
To manufacture an ingot of Nitinol, with equal parts nickel and titanium to the desired shape it first goes through a series of manufacturing processes: the ingot is heated, rolled and formed, then drawn through a series of dies. At this stage the material may be heat treated to set the shape of the material, or left untreated. An additional heat treatment at a lower temperature can be applied, called aging, which causes the transition temperature to rise without resetting the memory shape.

In the case of SE nitinol, the austenite-finish-temperature is kept below a reference temperature. For instance, if A_F is 10 °C and no stress is applied to the material, the microstructure shoud be austenite at room temperature. Wheras, a SME SMA that is below austenite-start-temperature exhibits the martensite phase. As aging of the material and further heat treatments affect the transition temperature, it would be interesting to investigate the difference in micro-structures between SE and SMA with different transition temperatures.

To study the micro-structure, samples were prepared for etching. A 3D printed structure was used to hold the SE and SMA wires in place. 5 SE wires of 1 mm diameter were placed in the oval structure. As can be seen in Figure 3.11, two 1 mm wires were placed, with a transition temperature of 70 and 35 °C and two 0.5 mm wires with a transition temperature of 70 and 45 °C, respectively. To handle the specimen better and to secure the wires, the structures were placed in a mold and a mounting material was poured into it, in this case a cold-curing resin. The samples were then ground on rotating disks using a finer paper for each successive stage. The final step is to

Figure 3.12
Micro-structures of SME SMA Nitinol.





polish the surface with soft cloth that is impregnated with fine abrasive particle and lubricant, in this case 3 microns and afterwards 1 microns in diameter. Finally, an etchant is used to reveal the micro-structure of the material by selectively attacking high energy sites, such as boundaries and defects. Two types of etchant were used: a mixture of nitric and acetic acid and a mixture of hydrofluoric acid, nitric acid and water.

Results

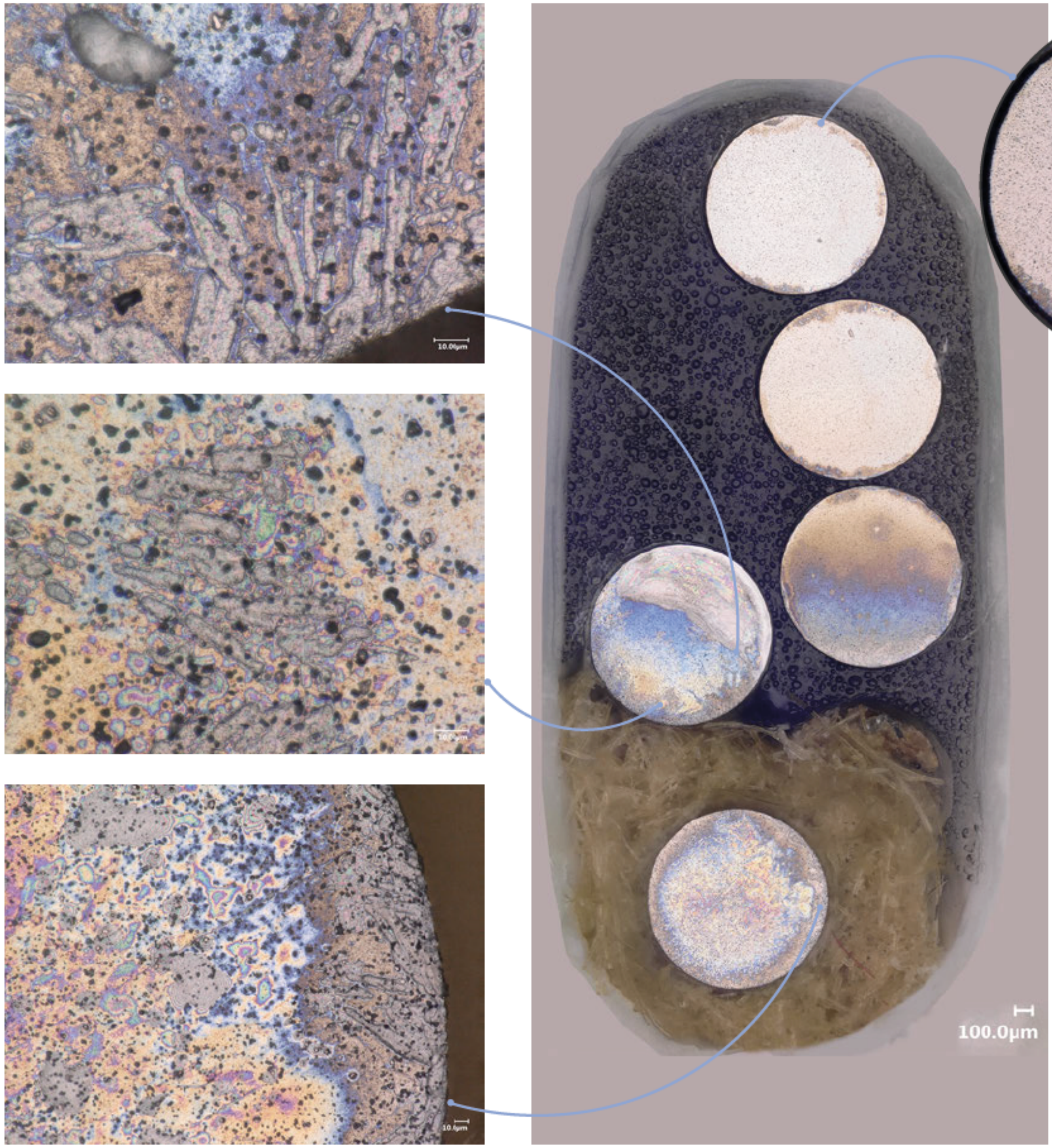
As can be seen in Figure 3.12, the surface of the 1mm SME Nitinol samples were unfortunately not etched enough to determine the phase composition of the material. In addition, the 0.5 mm samples shows a fracture pattern, which leads to the conclusion that these wires were broken off during the preparation process. Because of this the phase can again not be determined.

Noticing the gradient in etching from top to bottom in Figure 3.13 it can be concluded that the etchant was unevenly distributed over the surface which may be due to a pocket in the mounting material where the etchant pooled together.

For the top wires, hardly any phase can be made up, the black dots are most likely voids in the wire.

The bottom wires do show a distinct pattern, which is similar to the Nitninol micro-structure found by (Losertova et al., 2017) depicted in Figure 3.14, which represents a course martensitic micro-structure.

Although this is not the phase that what was expected of a SE material, the heat treatments applied to the sample of Losertova are similar to the heat treatments the SE material has gone through during manufacturing. On the other hand, the micro-structure may also be the result of over-etching.



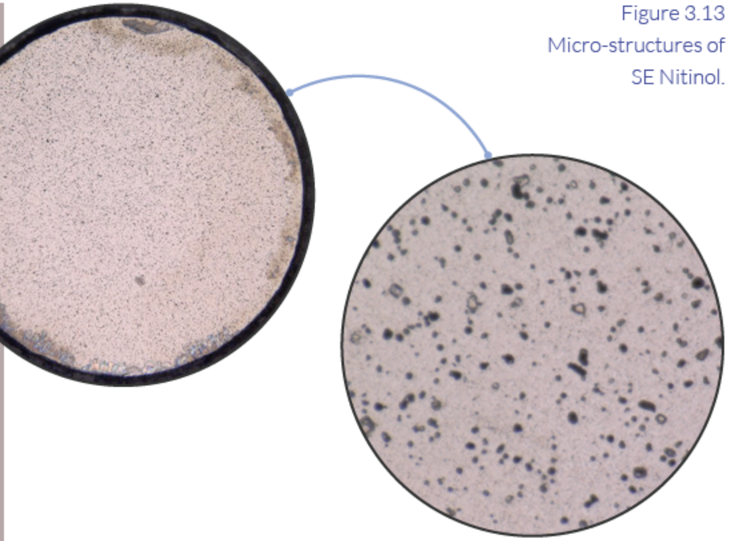
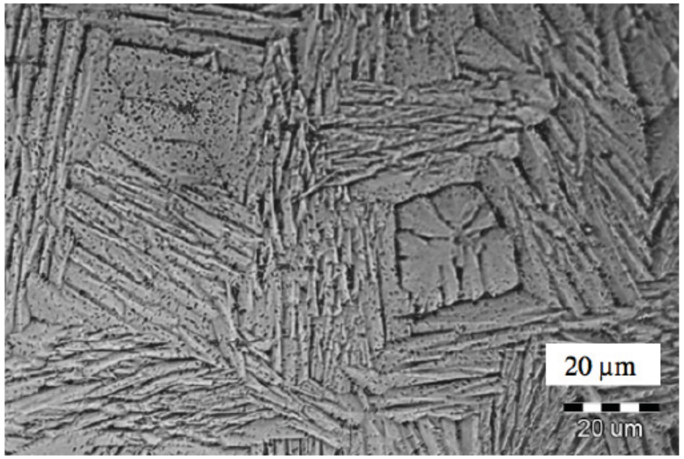


Figure 3.13
Micro-structures of
SE Nitinol.

Figure 3.14
Microstructure of NiTi
annealed at 600 °C for 1 h,
water quenched and
aged for 30 minutes at 450 °C
(Losertova et al., 2017).



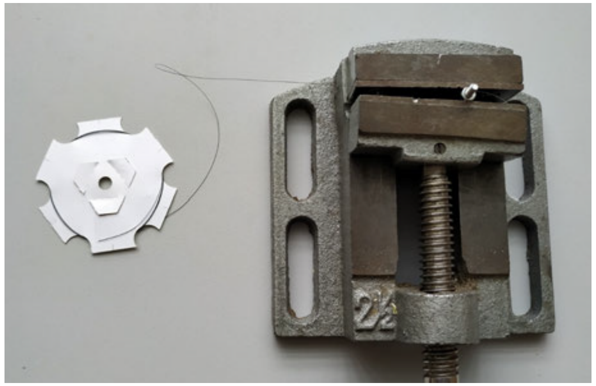


Figure 3.15
Method of holding the bolt, while looping the wire around it.

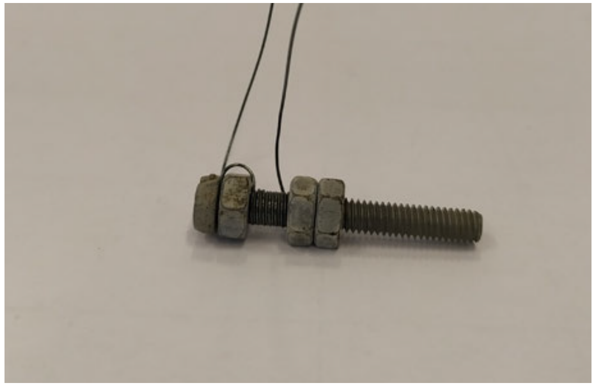


Figure 3.16
Clamped wires between two nuts.

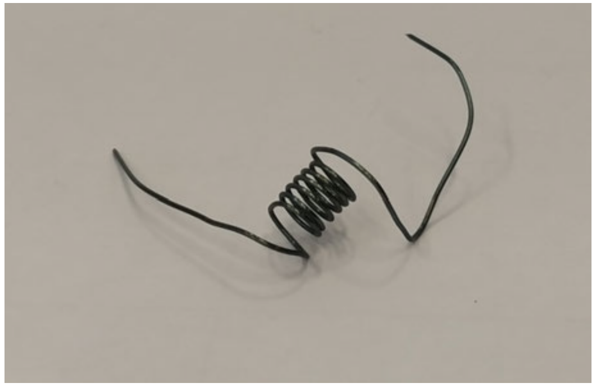


Figure 3.17
Trained wire removed from bolt after being cured inside the oven for 30 minutes at 450 °C.

Section 3.8 Technical Characterization of SMA springs

The wire can be trained to be in the shape of a spring so that the wire can have more deformation, however this is compromised by the wire being able to exert less force.

Production

The wires are trained to take the shape of a spring by winding it over a bolt. The end of the wire are secured using a two nuts, depicted in Figure 3.16. The wires were then cured at 450 °C for 30 minutes.

The force and stroke that the SMA spring can exert upon deformation are dependent on the following relations (Follador, Cianchetti, Arienti, & Laschi, 2012). The shear modulus can be calculated as follows, with martensite Young's modulus taken as 34.5 GPa and a possions ratio of 0.33:

$$G_a = \frac{E}{2(1+\nu)}$$

The spring rate (K) is derived from this as:

$$K = \frac{G_a d^4}{8nD^3}$$

The maximum force the SMA spring can exert is dependent on the maximum shear stress, taken as 450 MPa recommended by Follador et al. (2012) for design purposes and the mean spring diameter, D, and wire diameter, d:

$$F = \frac{\tau_a \pi d^3}{8D}$$

The maximum spring deflection can be calculated from:

$$F = Kx$$

The equations described in the model have already been validated by the Folladar et al. (2012) and according to the very low errors and good repeatability should result in successful SMA spring design.

The model was hence validated again, to see if similar results could be found for the trained spring of 0.2 mm. The spring was loaded for 10 cycles with 10 and 20 grams, respectively.

From table 3.2 it can be seen that the calculated stroke is comparable to the measured stroke. The expansion of the wire overall stayed the same as can be seen from the standard deviation.

Table 3.2
Calculated and Measured stroke comparison for 0.1 N and 0.2 N loads.

		Applied Force [N]	Calculated Stroke [mm]	Measured Average Stroke [mm]	Standard Deviation [mm]
Wire diameter	0.25	0.1	4.5	5.89	0.44
Mean Spring diameter	2.9	0.2	9	9.12	0.25
Number of Coils	12				
Spring Rate	0.02				

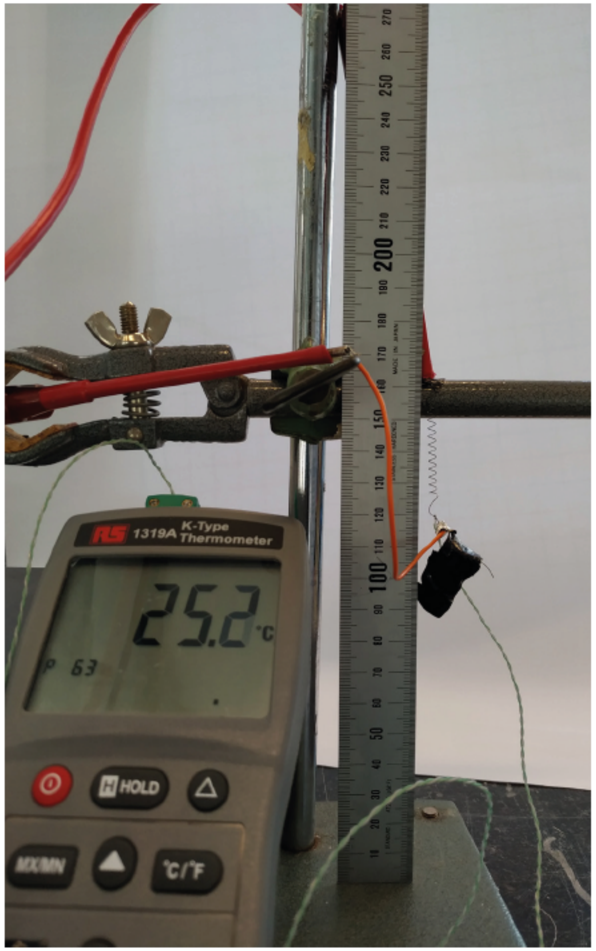


Figure 3.18
Test set-up to determine the elongation of the spring by the weight attached and the amount contraction when activated.

Chapter 4

SMA Composites

SMAs have been applied in many composite configurations of different materials, types of SMAs and connection methods. An overview of these composites has been made in Section 4.1.
The insights from the SMA composite benchmark are presented in Section 4.2.
Two material directions for the development of the SMA composite are proposed in Section 4.3.

Section 4.1

SMA Composite Overview

The SME of SMAs shows their capability of functioning as an actuator, but an SMA on its own will not have a meaningful effect, and should be incorporated in a structure to demonstrate a movement. These structures can be categorized in three constructions: a mechanical joint, flexural hinge and soft structure, see Figure 4.1 (Rodrigue, Wang, Bhandari, Han, & Ahn, 2015). The kinematic characteristics of movement are dependent on the structure of the actuator, for instance a mechanical joint can only produce intermittent movement in steps, whereas a soft structure will continuously deform with the SMA.

On its own, SMAs can already be considered a smart material, capable of sensing changes in the environment and responding accordingly. In the case of SMAs this change in the environment is temperature and results in shape change if it was trained to do so. Combining SMAs with other materials forms a shape changing structure or smart material, capable of sensing changes in the environment and responding accordingly. Taking this simple actuator and defining a set of input and respective outputs evolves the smart material into a computational composite (Bergstrom et al., 2010). Especially in a system of multiple actuators, the computational stage between input and output is desirable. Computational Composites are further described in Chapter 5.

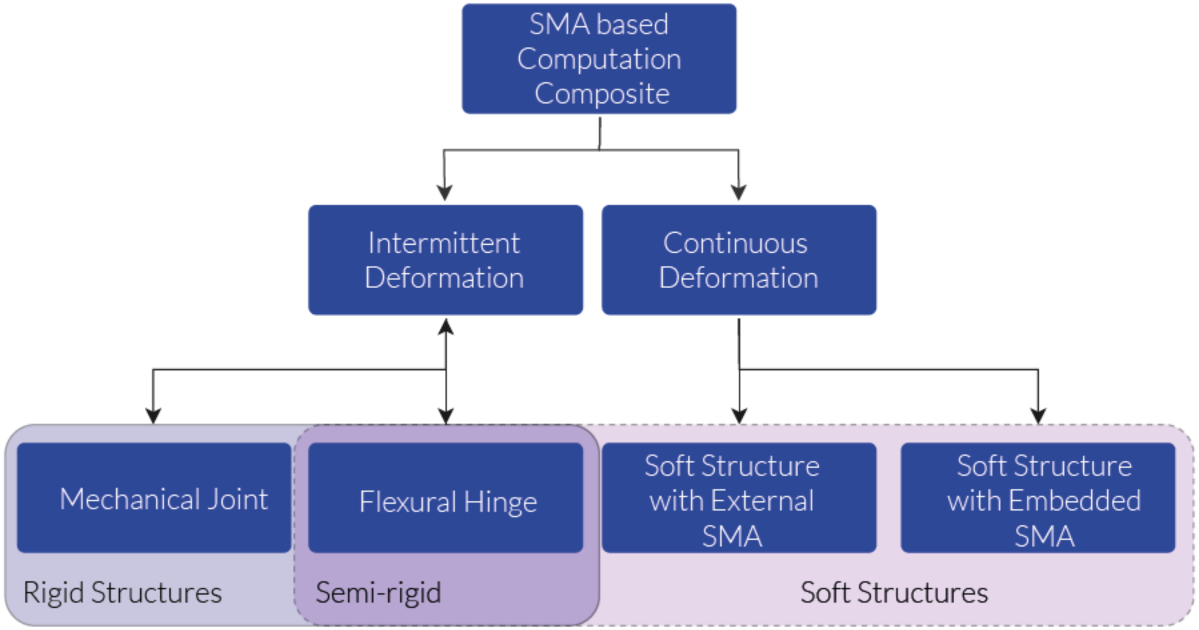


Figure 4.1
Overview of the types of SMA-based composite structures and the resulting type of deformation.

Section 4.2 SMA Composite Benchmark

Before the configuration and combination of materials for the SMA composite can be chosen, a benchmark is performed on the currently developed composites. The combination of SMA with different materials has already been researched in many different fields, a complete overview of the literature review can be found in Appendix B.

All developed composites were designed for a specific purpose or movement. To design a specific movement the materials are selected based on their individual strengths, for instance silicone is flexible but lacks the stiffness to make the initial shape straight. The configuration of the materials is tweaked until a desired response is achieved, this could involve changing the location of the SMA or embedding stiff plates to influence the stiffness.

Based on the overview it became apparent that there are many ways of influencing the response of the structure on the activation of an SMA. But also the deactivation of SMA should be taken into account when designing a computational composite. An counterforce element is necessary to return the shape to its original state. This could be the structure surrounding the SMA or even a second SMA element.

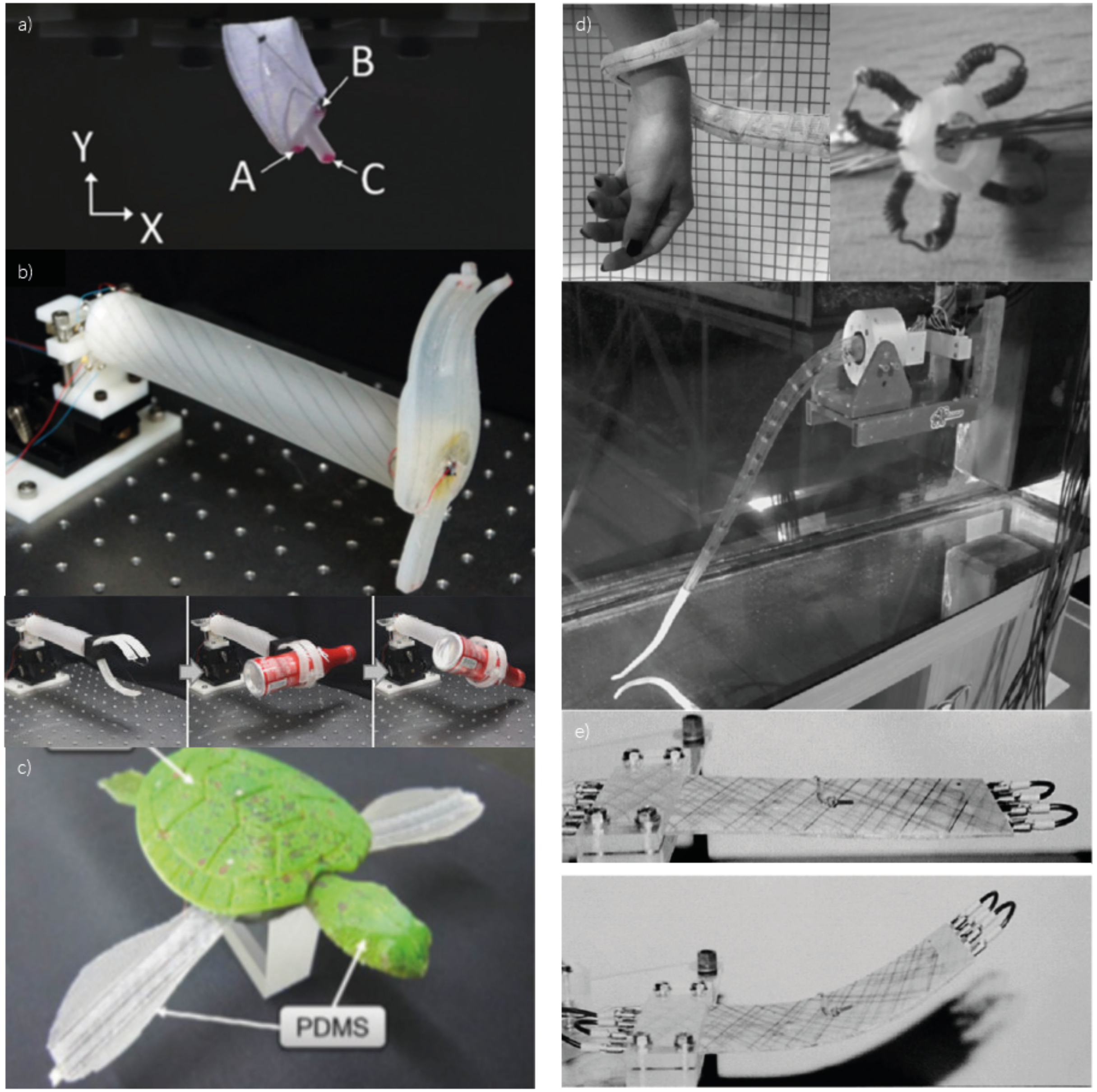


Figure 4.2
SMA based composite benchmark
a) curved SMA based soft gripper (Rodrigue, Wang, Kim, & Ahn, 2017)
b) Wrist-like SMA-based actuator (Rodrigue, Wei, Bhandari, & Ahn, 2015)
c) A turtle-like swimming robot using a smart soft composite (Kim, Song, & Ahn, 2012)
d) Soft Robotic Arm Octopus-Inspired (Laschi et al., 2012)
e) SMA reinforced composite beams (Baz, Chen, & Ro, 2000).

Section 4.3 Material Selection

Two flexible and stretchable materials are chosen as separate structures for the SMA wire. Especially the stretchable nature of materials has not yet been investigated in combination with SMAs. It elicits the question, why has this not been done? What might be the undesirable effects of stretchable materials. Are these effect controllable? And how can they instead contribute to a meaningful experience?

4D printed Fabric

Another interesting material that has not been applied to SMA composites is 4d printed textile. In essence, the textile is stretched before a thin shape is printed on its surface. After the tension is removed from the fabric, the material will jump into a shape due to the restriction to return to a normal position for the parts where the filament is attached. The resulting shape can be seen in Figure 4.3.

The deformation can be approximated by using Kirchhoff-Love assumptions (van Manen, Janbaz, & Zadpoor, 2018). The effect of time on the printed structure, adds the fourth dimension to 3D printing. How the stretching of the fabric and the printed shape influences the final form should be investigated. Based on the current research it seems that the shape of the material remains the same unless an external input is added, such as stretching the material in a single direction or crumpling it up again. It has not been documented how the material would respond and if this is controllable or not. The movements that can be facilitated by the shapes have many degrees of freedom, due to the flexible nature of the fabric and filament, however this also depends on the thickness of the print.

Figure 4.3
4D printed textile
(Tessa Petrusa, 2017).

Figure 4.4
Dragon Skin Silicone dress
by Iris van Herpen (2016)

Silicone

Based on the benchmark it was found that silicones (PDMS or Dragon Skin) are a frequently used material for SMA composites. This may be because of its flexible characteristics, meaning it acts as a soft structure capable of continuous deformation. The main advantage of using soft materials is their elastic deformability and in turn adaptability to the environment. Loads can be distributed over a larger area due to their compliance and lowers the maximum impact stress. The typical moduli of materials found in nature is in the range of biological materials, 102–109 Pa (Majidi, 2014). To mimic these natural materials, a wide range of soft materials can be applied: including silicone, urethanes, hydrogels, braided fabrics, hydraulic fluids and gasses (Nassar, Rojas, Hussain, & Hussain, 2016).

The production techniques for silicones also do not need special tools or equipment. In most example projects it is cast into a 3d printed mold, as seen in Figure 4.4. Embedding SMA wires or stiff materials inside the silicone is also not difficult and lends itself to many configurations.

Finally, Dragon skin also allows for significant stretch (763%) after which it returns to its original shape. The stretchy nature of the silicone has not been applied in such actuators to its fullest extend yet.

Shape Memory Alloy Types

In combination with the structures, multiple types of SMA will be incorporated, depending on the need for either large displacements or force. In addition, the attachment of the wire, spring or hinge will be changed to see how the structure responds.

Chapter 5

Computational Composites

Section 5.1 explains the definition of a computational composite. The role of SMA in a computational composite is discussed in Section 5.2. Finally, the types of user interaction that can be envisioned with a computational composites are described in Section 5.3.

Section 5.1 Computational Composites

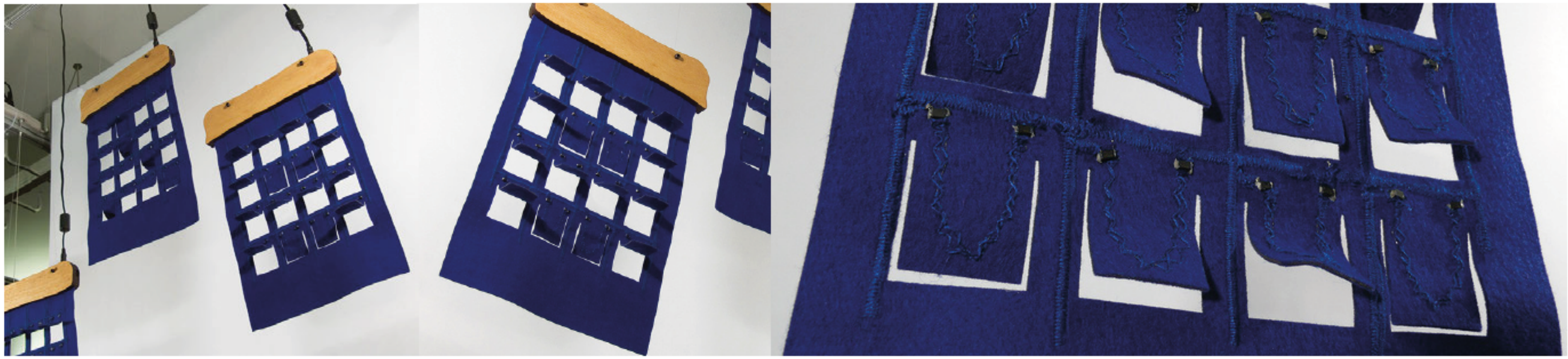
The introduction of new materials that can respond to inputs from the environment has brought about a new movement for material development and interaction design: computational composites. As described in Chapter 4, a computational composite is a material that incorporates a computational step from an input to an output of the material. A computational composite is capable of sensing inputs from the environment, processing and controlling the consequent expression or formation of the material.

Section 5.2 SMA-based Computational Composite

Referring back to the taxonomy, depicted in Figure 1.1, the movement that the SMA composite is designed to have can be categorised as shape changing. Shape changing can be defined as changes in orientation, form, volume, texture, viscosity or speciality (Rasmussen, Pedersen, Petersen, & Hornb, 2012). Naturally, these movement can have kinematic and experiential characteristics. 'Life-like' expressions can be communicated by using continuous and small movements, taking inspiration from nature.

The composite should take advantage of the continuous movement that the soft structured SMA composite can provide and focus it on creating a caterpillar inspired motion. This movement can be regarded as the output of the composite. A direct input to the composite is the temperature of the environment, since the material characteristic of SMA is being temperature sensitive. However, this does not need to be the only input that the composite might be responsive too. The activation of the SMA can be programmed to respond to numerous inputs by having a computation and actuation system. For example, Shutters is a shape-changing fabric curtain for environmental and lighting control, each square is individually controlled to regulate the daylight intake and ventilation. It can also be used as information display. Shutters combines smart materials with textile and computation and so creates living environments that are considerate to inhabitants' activities, depicted in Figure 5.1.
The several types of approaches to user interaction with the computational composite are defined in Section 5.3.

Figure 5.1
Shutters by
Marcello Coelho (2009).



Section 5.3 User Interaction

Computational composites are bringing about a new movement from material development and interaction design. In this vision, smart materials are used to respond to inputs from the environment and use a computational step to determine the resulting output.

The user can interact with the entire computational composite system, which is defined as the environment, the composite and the additional elements. Three approaches to interaction, adapted from Rasmussen et al. (2012), can be defined as: none, indirect and direct, as illustrated in Figure 5.2.

No user interaction

Inputs are not related to the user interaction and may be influenced by the environment of the material which can be detected using sensors. SMA are already influenced by the temperature of the environment which relates to the activation of the shape memory effect. However, other inputs can be used to influence the output, such as sound and light.

Indirect user interaction

Indirect user interaction is based on implicit interaction, as described by Rasmussen et al. (2012): when users may not realize their actions are being used as input. Several shape changing installations exemplify this approach. The Pinwheels installation, illustrated in Figure 5.3, monitors human behavior and responds to specific actions: sending an email or using the elevator (Ishii, Ren, & Frei, 2001). Sound input from the surroundings is used for a Murmur, a sonic sculpture (Rydarowski, Samanci, & Mazalek, 2008). This demonstrates the several realms the user can influence: data streams, the environment and connected elements.

Other online data can be taken as an input, such as number of tweets using a single hashtag. Similarly connected elements may be buttons, switches and even elevators.

Direct user interaction

The user interacts intentionally with the system through directed manipulation, such as creating a specific sound, manipulating light and direct touch. The shape of the material may even be deformed as part of the input of the user. In this way shape change is taken as input and as output and can be applied in different ways Rasmussen et al. (2012).

One approach to use shape change as an input is *action and reaction*, where the shape change input has an specific output related to it or where the input shape change is recorded and played back as an output of the material.

Figure 5.2
Illustration of elements of input in none indirect and direct user interaction.

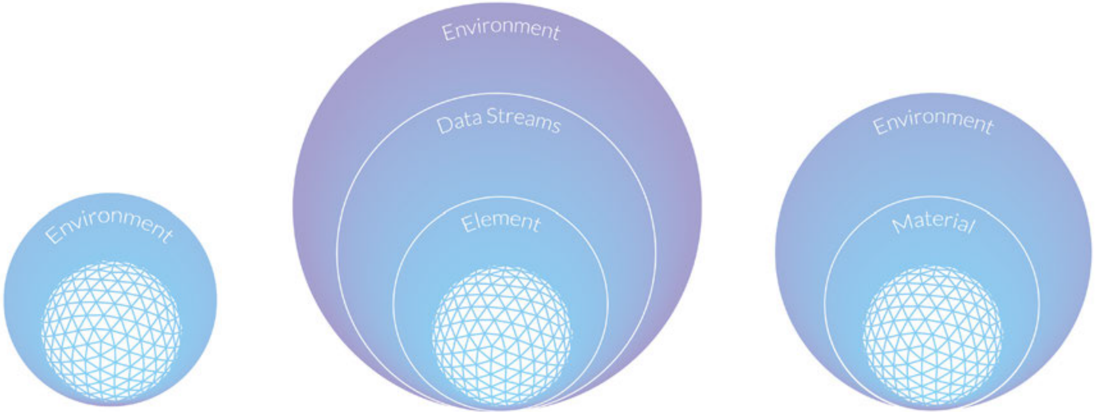
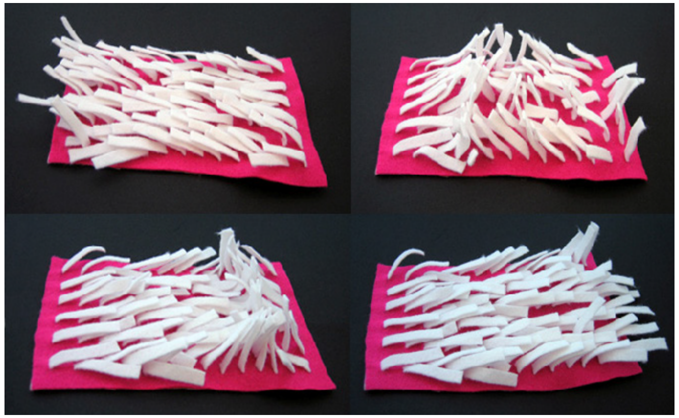


Figure 5.4
Sprout I/O
(Coelho & Maes, 2008).



An *input and output* approach sees these as not directly related. An example is Sprout I/O, depicted in Figure 5.4, where SMA is used to sense touch and also to move the kinetic textile strands (Coelho & Maes, 2008), using it both as a sensor and actuator.

Multiple approaches to interaction can be adopted at the same time, for instance the sound from the environment may influence one characteristic in the output and direct contact with the material may influence another characteristic. The effect of having multiple inputs on the user perception and understanding of the system should be investigated.

Figure 5.3
Pinwheel Installation
(Ishii, Ren, & Frei, 2001)

Chapter 6

List of Requirements

The list of requirements, derived from the project brief and literature review are stated in this chapter.

The following list of requirements was established based on the project brief and the literature review.

It was established in the project brief that forward locomotion should be driven by SMA in a segmented and controllable manner. The locomotion should be inspired by the caterpillar. In Chapter 2 this movement was simplified and categorized as: bending, lifting contracting/expansion of the body and retraction within the body.

Needs

- The material structure should be activated using SMA
- The material structure should be segmented/modular
- The actuation should be controllable
- The actuation should be reset after activation
- The material structure and movement should be caterpillar-like
- The material structure should move forward

Wishes

- The complexity of the material structure should be as low as possible
- The cycle time of the actuation should be as low as possible
- The material and movement should be inspirational
- The material and movement should be meaningful

Section II:

SMA Composite Development

Chapter 7

4D Printed Textile

First an overview of past projects on 4D printed structures is given in Section 7.1. The experimentation with 4D printing is explained in Section 7.2. Finally, the resulting structures and its most influential parameters are defined in Section 7.3.

Section 7.1 Material Overview

There have already been several design projects which required 3D printing on stretched textile. The resulting shapes and the interplay between textile and filament have been listed. In particular the research on deformation of the textile and the production methods has been examined.

3D Printing on stretched Fabric

An overarching production sequence can be found in all projects: stretching the fabric over a frame, printing the pattern on top, letting the filament cool down and releasing the textile. The shape sample can then be cut out of the textile, so it can completely take shape.

Inspiration was taken from the work of Tessa Petrusa, Responsive Tactility: 4D Printed Skins, illustrated in Figure 7.1. The scale of the work she does is large, which is why she printed it in collaboration with 3D Robot Printing in Rotterdam. The resulting structures are organism-like pieces, with the shapes hinting to muscles and skeletons.

Next to artworks, 4D Printed textiles have also already been explored by different research labs. The Self Assembly lab of MIT did a preliminary research on the progammability of materials, Figure 7.2. Their aim being to take existing material structures like fibers and sheets and program them to take properties and shape on demand (Guberan, N.D.). This project also served as an inpsiration for the Fabricflation project by Papakonstantinou (2015) for the Institute for Advanced Architecture of Catalonia. A thorough exploration of different filament materials, printing patterns and


Figure 7.1
Responsive Tactility
(Tessa Petrusa, 2017)

The video of the production process of The Self Assembly lab of MIT can be viewed in the following QR code:

Figure 7.2
Programmable Materials.
QR: Production Video
(Guberan, N.D.)

Figure 7.3 Sample curvature change by incremental change (0.5mm) of height (left) and width (right) of the pattern print (Papakonstantinou, 2015).

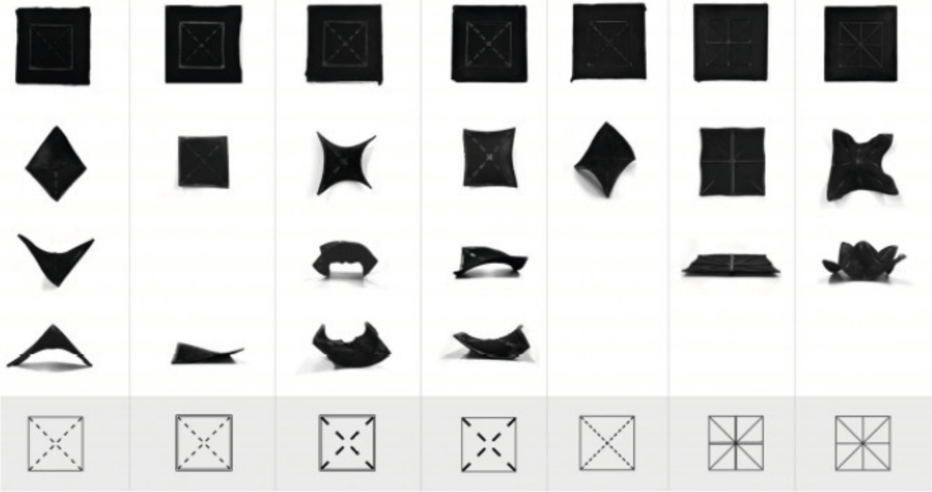


Figure 7.4
4D printed sample exploration from Fabricflation project (Papakonstantinou, 2015).

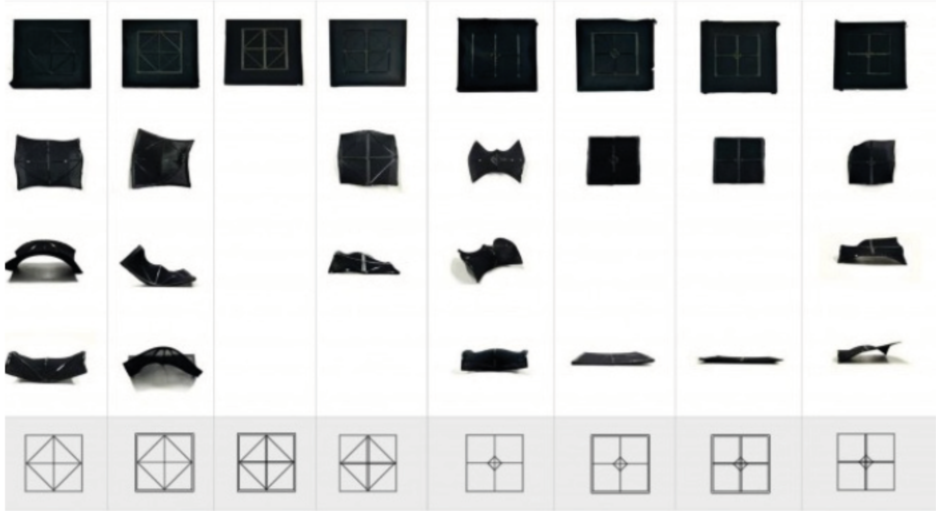


Figure 7.5
Second batch of 4D printed samples from Fabricflation project (Papakonstantinou, 2015).

dimensions was performed. Initially, Lycra fabric with PLA filament was chosen and further explored in the height of the print. It was found that the curvature and flexibility of the sample decreases with an increasing amount of height and width of the print, as illustrated in Figure 7.3.

Regarding the pattern of the print, the possibilities are endless. As can be seen in Figure 7.4, the shape of the 4D material is bound by the perimeter of the printed pattern. Increasing this perimeter in width makes the shape more curved, while making inner pattern wider leads to a flatter shape. A careful balance needs to be found between the width of the inner and outer filament. In Figure 7.5, the effect of changing the inner pattern can be observed in the resulting shapes. For instance the first sample from Figure 7.5 has a flat though curved shape while the last a sample from Figure 7.4 features a large curve in the center.

The patterns used to create the 4D printed samples developed by Papakonstantinou (2015) were taken as a starting point for the development of 4D printed textile samples for the SMA composite.

Section 7.2 Production and Experimentation

Method 1

The main steps of method 1 are illustrated in Figure 7.6. An Ultimaker 2 is used to print on the textile, mainly because this still has the manual calibration feature. The Ultimaker 3 features an automated calibration program using a sensor. Unfortunately, using this feature with a textile surface the system gives an error and it is not able to continue printing afterwards.

Steps

1. 3D Printing the pattern until 1 mm high (Figure 7.6a)
2. Outlining the 3D print with paper tape
3. Removing the 3D print
4. Stretching the textile over the area
5. Attaching the textile with tape (Figure 7.6b)
6. Resume 3D print (Figure 7.6c)
7. Wait for built plate to cool down

Securing the textile

The fabric was stretched on the glass build plate of the 3D Printer and secured using tape. Several types of tape were used: double sided tape, paper tape and duct tape were used to secure the edges of the stretched fabric. Overall, this method did secure the fabric but it was observed that when the printer was turned on and the build plate would heat up, the connection would deteriorate since the adhesive would let go of the textile.

Printing on textile

An initial offset of the print head was needed to the thickness of the textile. To achieve this, the pattern was printed up to a height of 1 mm and then paused, after the 3D print was removed and the textile was stretched over the area, the print was resumed again. Downsides to this method were the additional steps necessary and the unreliability of the print. A certain amount of friction is necessary between the surface and the print head to create a smooth extrusion of the material, though the print head should not be pushing into the textile, since it will then just drag it along. In some instances when the print head is positioned too low, the textile is slightly melted by the heat of the print head, leaving a coarse texture, depiced in Figure 7.7a. On the other hand, without adequate resistance between the textile and print head, the connection between the first pattern layer and the textile is poor and the filament structure easily lets go of the textile, illustrated in Figure 7.7b.

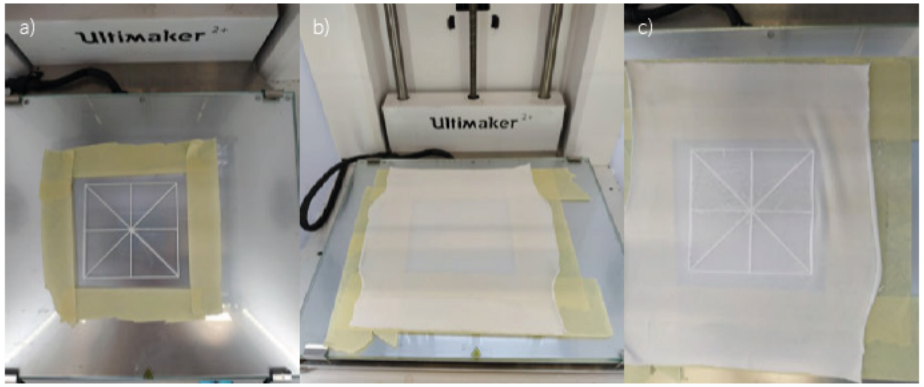
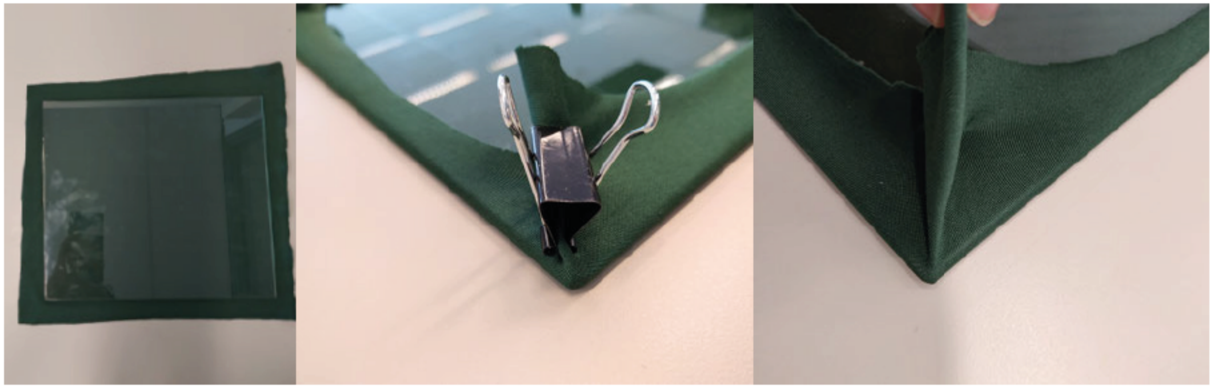


Figure 7.6
Main steps of Method 1:
a) printing the pattern, pausing and removing print,
b) stretching and attaching the textile,
c) printing on the textile.

Figure 7.7
Printing failures encountered in the development of Method 1:
a) damaged textile due to the hot print head and
b) a 3D printed pattern that separated from the textile.



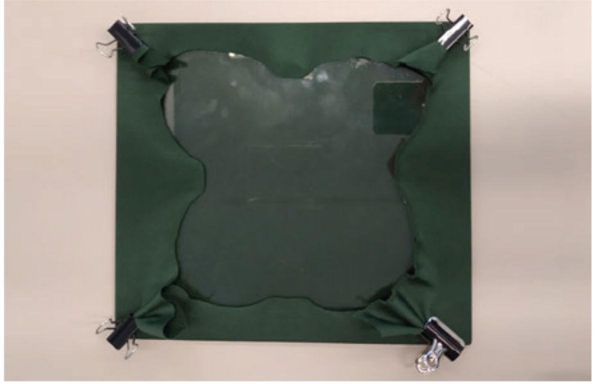


Figure 7.8
Main steps of Method 1:
a) Cutting textile to the built plate size
b) Stretching over the corners and securing corners with clamps
c) folding corners down and attaching to double sided tape
d) stretching sides and securing with double sided tape.

It is important to use clips to secure the textile on the sides of the built plate to the printer, otherwise the sides will move due to the force of the print head

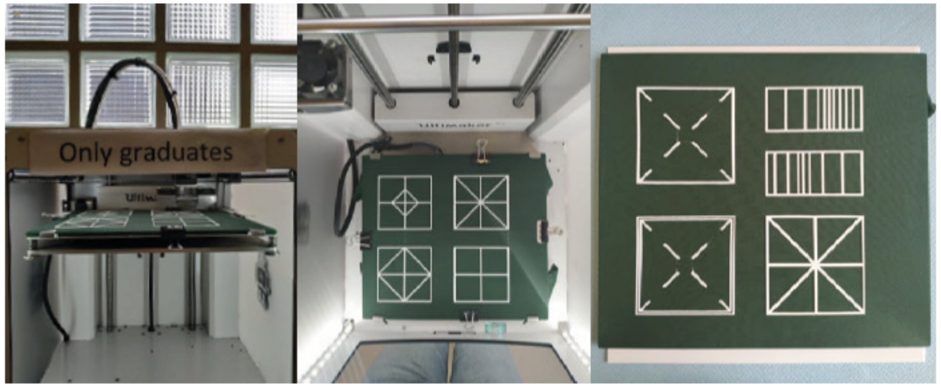


Figure 7.9
3D printing on a stretched textile surface

Method 2
Steps

1. Stretching the textile over the build plate (Figure 7.8b)
2. Attaching the textile with tape (Figure 7.8c)
3. Attaching the build plate to the 3D printer with clips
4. Recalibrating the built plate
5. 3D printing on textile (Figure 7.9)
6. Wait for the built plate to cool down

Securing the textile

The textile is initially cut slightly larger than the built plate since the textile will be stretched around it. The corners diagonal from each other are first stretched and secured with clips. Afterwards, double sided tape is attached to the corners of the built plate. One by one the corners are secured to the tape by folding the sides down. To secure the sides of the textile, double sided tape is first attached to it. Each element is stretched and then sticked to the build plate.

Printing on textile

Another method to change the offset of the print head from the built plate is used. With the textile stretched over the surface, the printer is re-calibrated to the surface of the textile. During calibration special attention is paid to the amount of resistance between the print head and the textile, which should be medium to high.

Using Method 2 a wide range of samples were printed. Most patterns were adapted from the research of Papakonstantinou (2015), with some additional patterns tried out to see the result. Three different stretchy textiles were used to see the difference in the response to the pattern: Polyester Viscose, Polyester Lycra and Lycra. The difference in shape can be seen in Figure 7.9. An overview of these shapes can be found in Appendix C.

Section 7.3 Insights

It was found that all samples are flexible to a certain degree. The thicker the pattern was printed, the less curvature the sample would attain and the stiffer it would be. After deforming the thinner samples, they would always spring back to its original shape. A large difference is seen based on the different materials. The effect of the 3D print on Polyester Viscose was the smallest, which is also the least stretchy material. The sample printed on Lycra shows the most the most distinctly curved shape, which can be due to the highly elastic nature of the material.

Finally, an unexpected outcome for some of the samples was bi-stable behavior, which meant the sample was able to retain another shape when the sample was deformed over a certain threshold. It would resort back to its original shape when the material was again deformed back over a threshold.

Figure 7.10
Resulting shapes of the same 3D printed pattern with different height and textile.

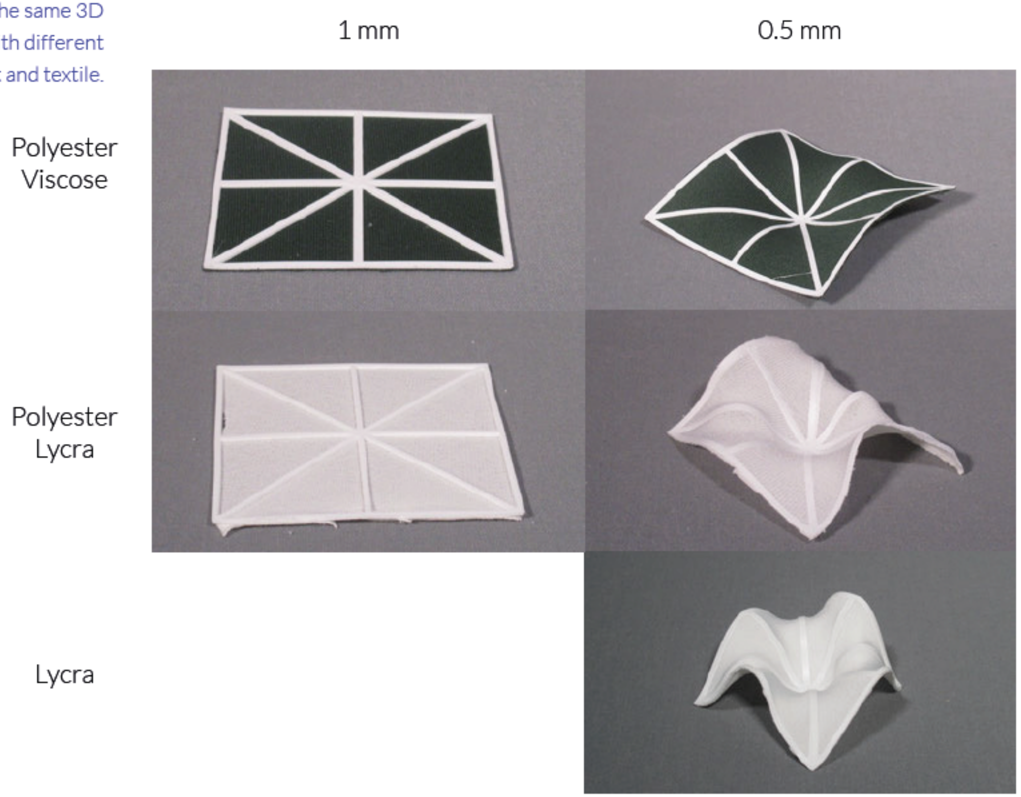
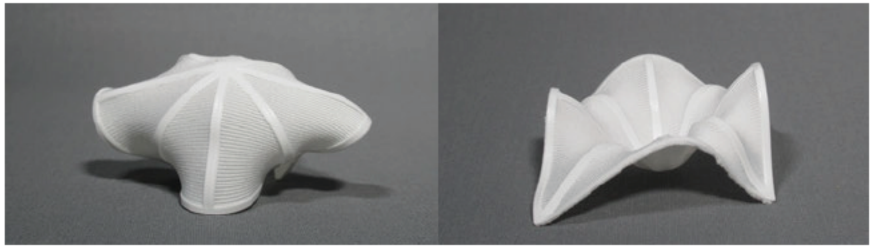
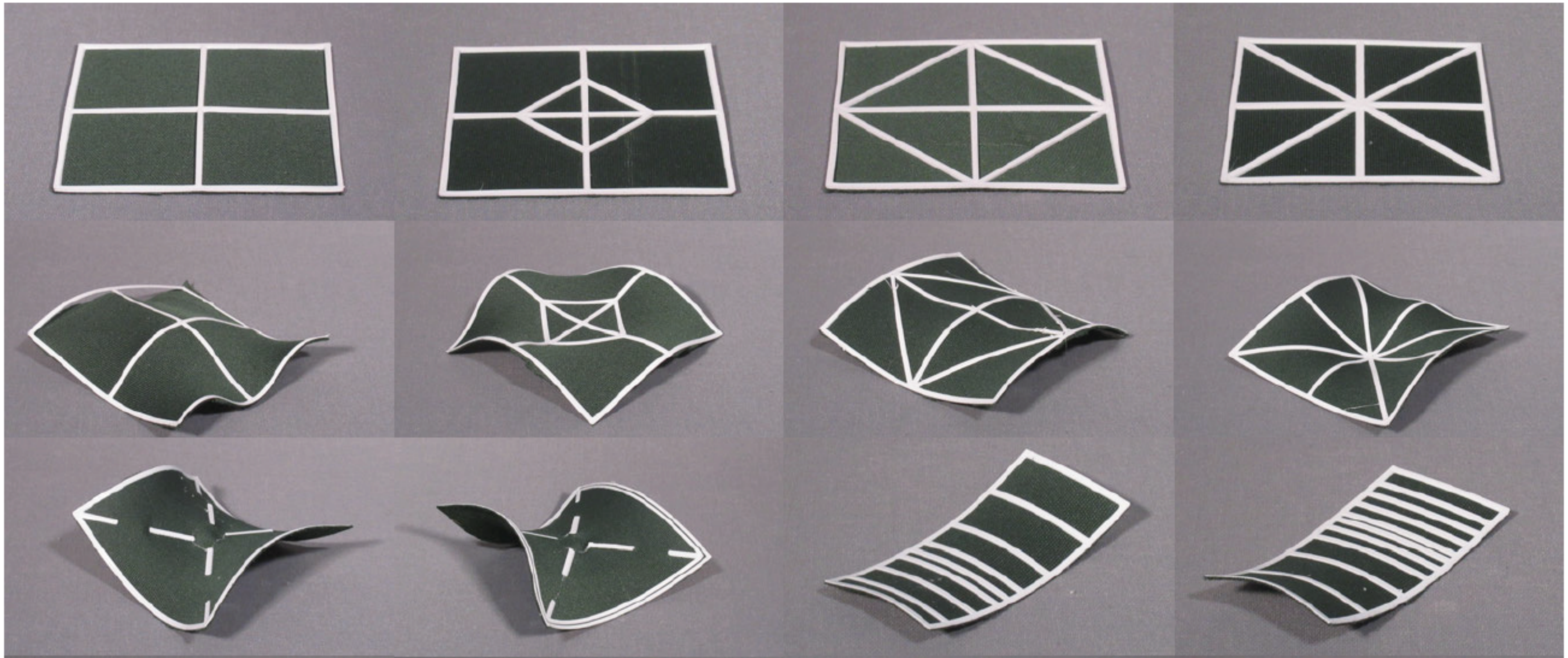
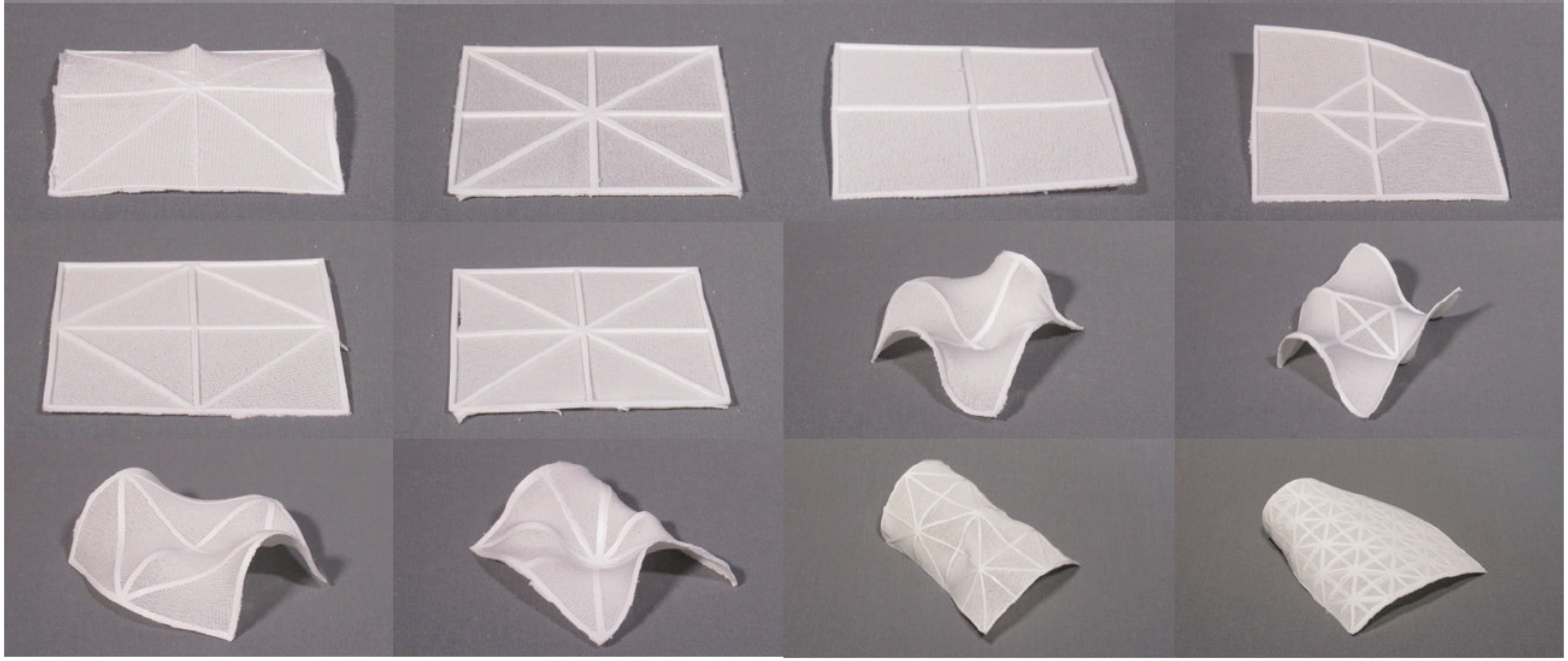


Figure 7.11
0.5 mm pattern printed on Lycra is bistable: has 2 different shapes which can be changed by 'plopping' the shape.

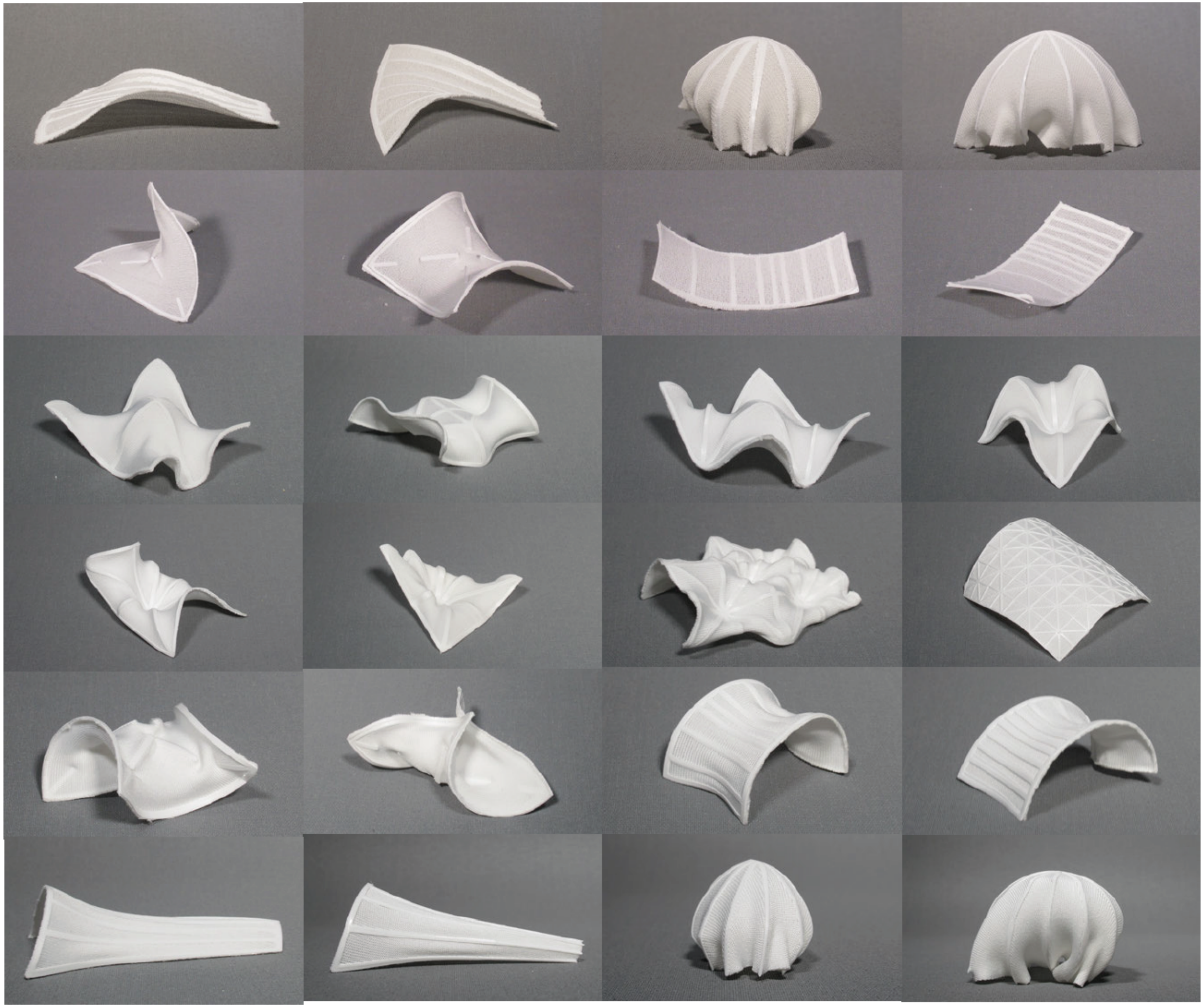




Polyester
Viscose



Polyester
Lycra



Lycra

Chapter 8

Silicone

First an overview of the material properties is given in Section 8.1. The production steps are discussed in Section 8.2. Finally, the insights from the resulting structures are given in Section 8.3.

Section 8.1 Material Overview

As discussed in Chapter FIXME, silicone and in particular Dragonskin FX-Pro has been used in several SMA based composite projects. The material characteristics were supplied by the material producer Smooth-on, and have been further investigated by Atieh (2012) (Smooth-On, 2019).
(Atieh, 2012; Smooth-On, 2019). A summary of relevant material characteristics can be found in Table 8.1.

An important material characteristic for safety is the flammability, when the silicone will be in contact with the SMA wire. For full austenite phase, the SMA wire must reach 70 degrees, but may be overheated. The flammability of the silicone starts at 93 degrees. It should also be noted that the silicone will most likely only be heated in the small contact area with the wire.

Table 8.1
Material Properties of Silicone Dragon Skin FX-Pro
(Atieh, 2012; Smooth-On, 2019).

Young's Modulus [MPa]	Tensile Strength [MPa]	Maximum strain [-]	Flammability Start Temperature [C]
0.56	1.99	763%	93

Section 8.2 Production and Experimentation

The equipment used to cast the silicone is depicted in Figure 8.1a. A 3D printed mold is used to cast samples of silicone of Dragon Skin FX-Pro, depicted in Figure 8.1b. To change the texture of the silicone 3d printed plates with a with different surface pattern can be placed at the bottom of the mold.

Steps

1. Preparing mold by placing the extraction tab inside and spraying release agent
2. Mixing equal parts of component A & B
3. Pouring mixture into the mold (Pot Life 12 minutes) (Figure 8.1b)
4. Curing silicone for 40 minutes at room temperature (inside a vacuum machine to extract air bubbles)
5. Using the extraction tab to pull the silicone out of the mold.

Figure 8.1
a) The necessary equipment to produce dragon skin material samples
b) 3D printed mold with texture on the bottom surface

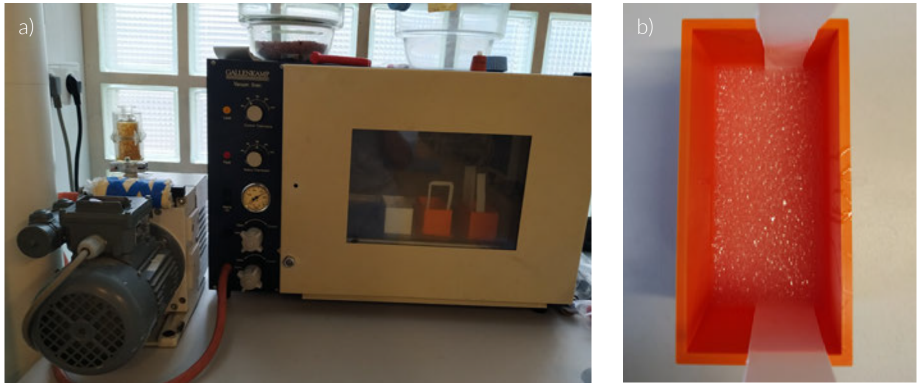


Figure 8.2
a) Molds are put into the vacuum machine to draw out the air bubbles
b) the effect of the vacuum machine on a thick sample: bubbly texture due to air bubbles that escaped the bottom of the sample and left a mark

Several texture patterns were tried out on the silicone, with a range in the aspect ratio and density of the pattern. The aspect ratio was either geometric or random. The resulting samples can be seen in Figure 8.3.

Section 8.3 Insights

An couple of unexpected surface patterns were found after producing the silicone material. Due to the print strokes in the 3D printed mold, a very fine linear surface finish could be seen in the sample without a textural pattern. This effect is highlighted when the sample is stretched.

During production air bubbles may get trapped inside the material when the material is poured into the mold. To extract the air bubbles the molds can be put in the vacuum machine. It has been observed on the thicker samples that the air bubbles leave a marking on the surface as they escape the material, also visible in Figure 8.3a and 8.3e.

An overview of these Dragon Skin samples can be found in Appendix C.

The thinner samples show the least resistance to stretch and are also easy to deform. The thicker the sample their have more resistance to stretching. It was also observed that the samples with a texture the frictional resistance to movement was lower than that of the flat surface.

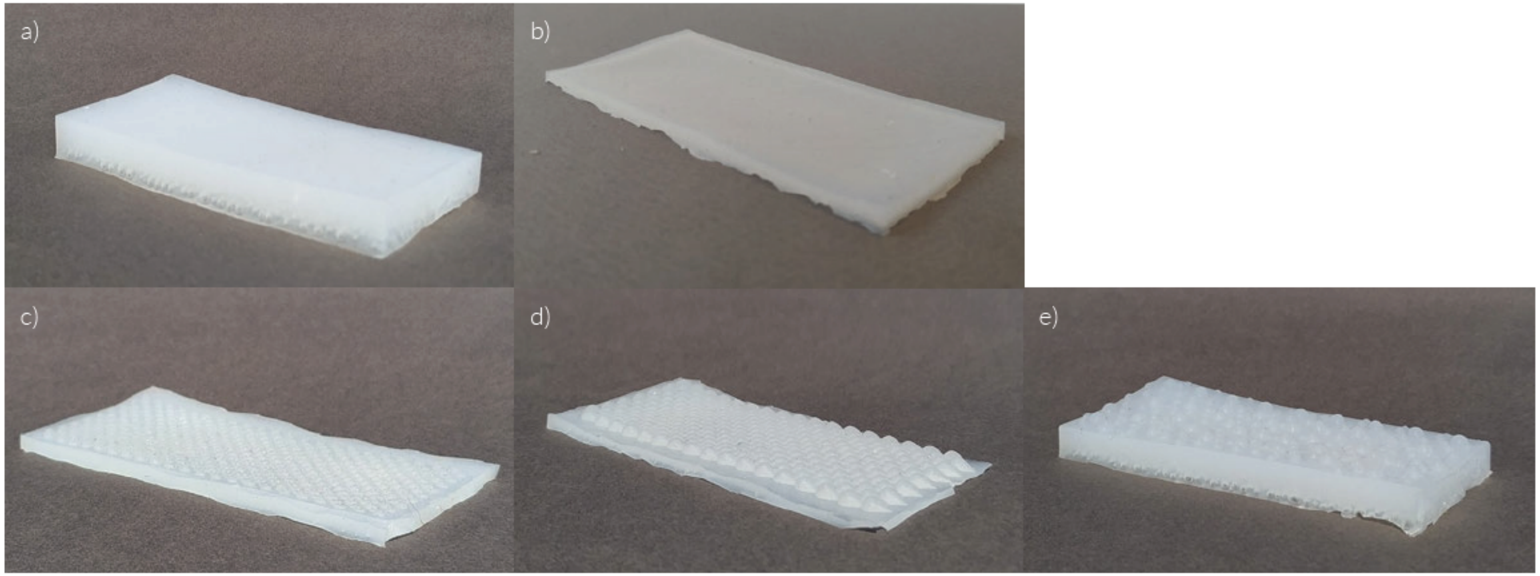


Figure 8.3
Developed silicone samples:
a) thick sample with no textural pattern on one side and air bubble texture on the other side
b) thin sample with no textural pattern on both sides
c) thin sample with small diamond pattern on one side
d) thin sample with unsymmetrical overlapping drop pattern on one side
e) thick sample with random semi-sphere pattern on one side and air bubble texture on the other side.

Chapter 9

SMA + Material Connection

The connection methods between the material structures and the SMA types are first categorized in Section 9.1. For each material structure the connection method is then described and evaluated in Section 9.2 and 9.3, respectively.

Section 9.1 Connection Types

The connection of the SMA to the materials can be approached in two ways, firstly layering the SMA on the material structure or by embedding it within the structure. To layer the SMA on top of another surface, an adhesive or fixation method is necessary. A study is performed on the effectiveness of different connection methods to attach the SMA wire to the 4D printed textile and silicone substrates, depicted in Figure 9.1a.

Glue

A straightforward solution would be the use of adhesives to connect SMAs with the substrate. However, in previous research on the connection methods it was found that adhesives such as glue are ineffective in fixating the SMA in place and have been shown to melt (van Spijker, 2016).

Tape

Two types of tape are considered: Tesa Extra Power tape and Aluminium Heat Resistant Tape, depicted in Figure 9.1b and 9.1c. Overall, tapes should remain flexible over the entirety of the bond, which is preferable for the type of substrate. Tesa Extra Power tape has already been show to have a better performance over regular duct tapes (van Spijker, 2016). However, the tape has yet to be applied to silicone and 4D printed Lycra substrates.

Aluminium tape should maintain its performance up to 120 degrees Celsius, though this may only be true for more regular surfaces and has not been documented yet for silicone and Lycra substrates. In addition, the tape is thermally conductive, which may have an affect on the distribution of heat to the substrate.

Sewing

Another method for connecting two materials to each other is by sewing it together. This method may be most suitable for the 4D printed fabric. The main advantage to sewing is the relative indifference towards the substrate, as long as the material is tear resistant. In comparison to tapes and adhesive, the material finish determines the quality of the bond.

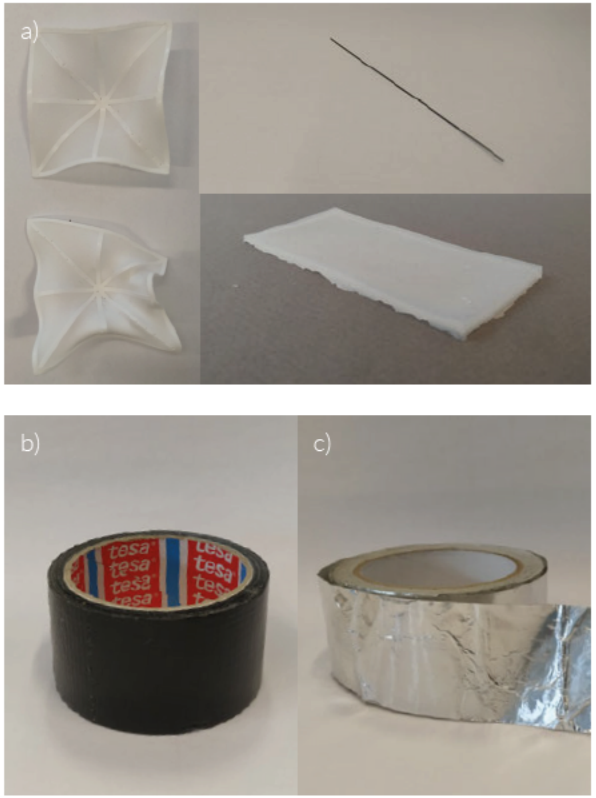
Weaving

The main difference between sewing and weaving is that in the case of weaving the SMA material is used to connect itself to the substrate instead of a thread. SMA wires can be woven inside the material by punching a series of holes inside the substrate and threading the SMA through them.

Casting

In the case of silicone, the SMA can effectively be embedded within the material structure by positioning it within the mold before casting the silicone inside. The location and orientation of the SMA within the structure can be of great influence to the actuation as has been seen in the material benchmark.

Figure 9.1
a) The SMA wire that is to be attached to the 4D printed textile and silicone substrates
b) Tesa Extra Power tape
c) Aluminium tape



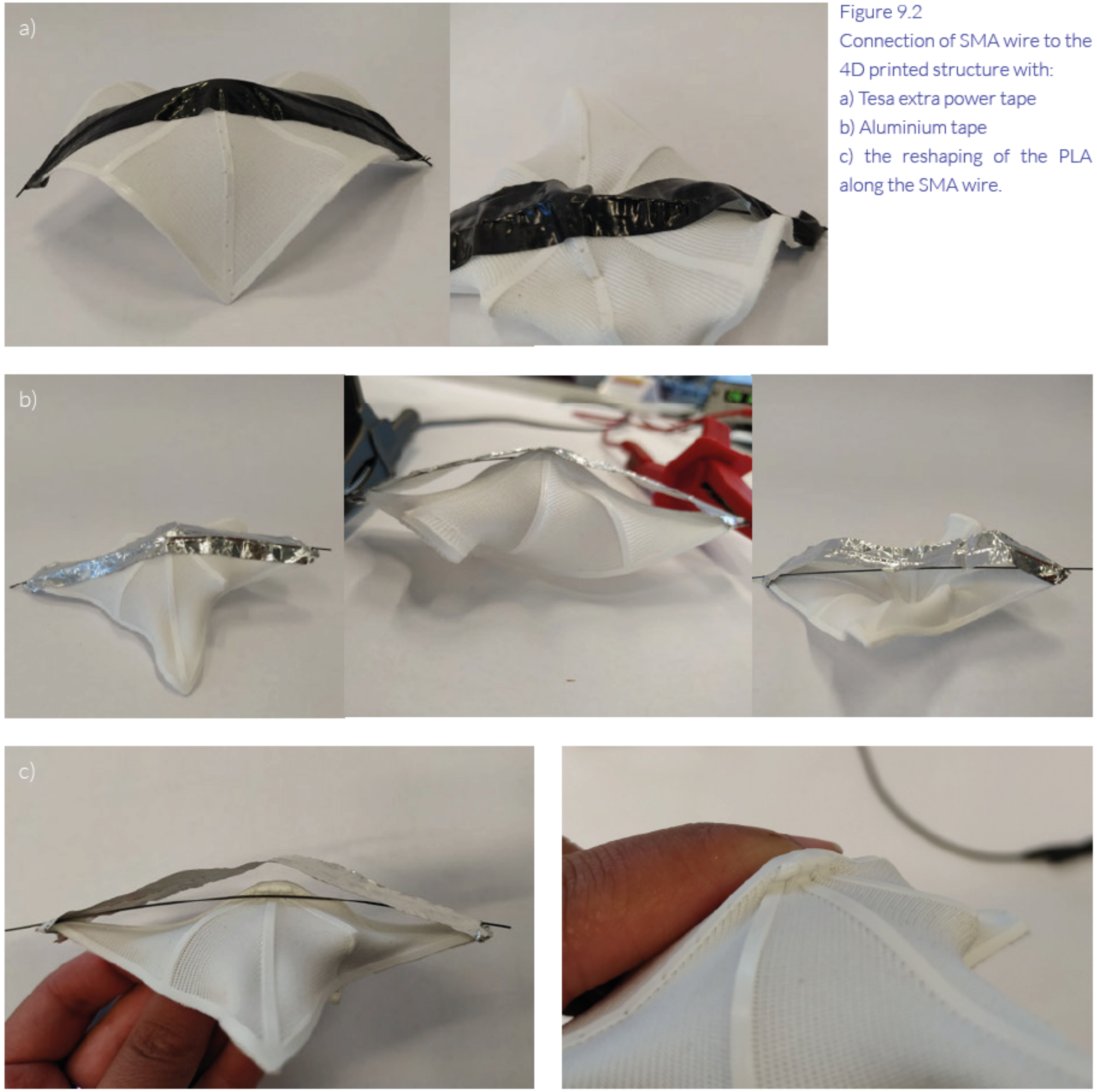


Figure 9.2
Connection of SMA wire to the 4D printed structure with:
a) Tesa extra power tape
b) Aluminium tape
c) the reshaping of the PLA along the SMA wire.

Section 9.2 SMA Connection with 4D Printed Structures

Both 4D printed structures based on Lycra and Viscose Lycra were investigated on the optimal SMA connection method. The results were generalized for both materials because a distinct difference in the material behavior was not found.

Tape

Initially, the bond between tape and the textile was relatively strong compared to the silicone. When the SMA was activated, the structure deformed and the tape was wrinkled due to the movement and the heat of the wire. Although the tape did keep the SMA wire in its place, the durability of the connection was low, depicted in Figure 9.2a.
When the SMA wire was activated, the Aluminium tape behaved differently. The tape had a strong hold on the SMA wire but released from the 4D printed substrate quite easily, as can be seen in Figure 9.2b. It is also noted that the starting position for the 4D printed structure is an important factor in the bond of the connection. When the starting position is not straight the tape does not hold on to the movement of the SMA wire, it remains in an arched position.
It should also be noted that the filament tends to deform under temperatures over 60 degrees since the PLA filament has a glass temperature of 60-65°C. When activated, the wire occasionally moved to the side, where the filament started to form according to the shape of the wire after about 30 seconds of heating, as can be seen in Figure 9.2c.

Weaving

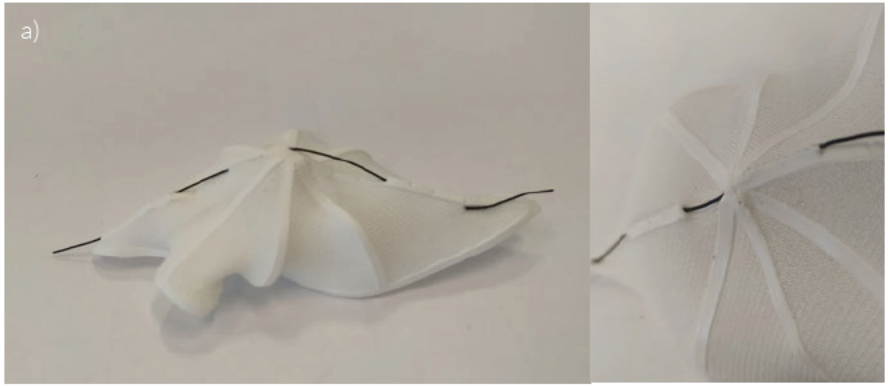
The wire can be woven into the textile itself and this serves as a good and durable connection. The usefulness of the connection in a 4d printed structure should be considered, since the filament should act as a guide for shape and movements. Embedding it into the fabric leaves an offset between the wire and the 4D printed filament structure and reduces the effectiveness of the structure to return the material to its original shape. Another option for weaving the wire into the structure would be inside of the filament by first punching holes into the strip using a sewing machine. A downside to this method was the structural weakening of the filament strip as well as the close contact to the filament, leading to warping of the filament due to the heat of the SMA wire, depicted in Figure 9.3a.

Sewing

Different factors of the zig-zag pattern were changed to find a regular and smooth pattern, capable of securing the SMA wire. Although the filament facing side of the stitch seems to draw out the bottom thread too much, the alternate side has a nice finish, as can be seen in Figure 9.3b. The overall shape of the 4d printed material seems unencumbered by the added stitching, however the stiffness of the wire does inhibit some of the curves of the wire in the ends. The connection is durable, irrespective of the side the wire is connected to. The wire does seem to indent the filament it is attached to after a longer time of activation. For this reason an initial dense pattern was stitched as a base for the wire to be attached to, serving as an isolation layer between the wire and filament.

Conclusion

The most suitable connection method for SMA and 4D printed structures is (hand) sewing.



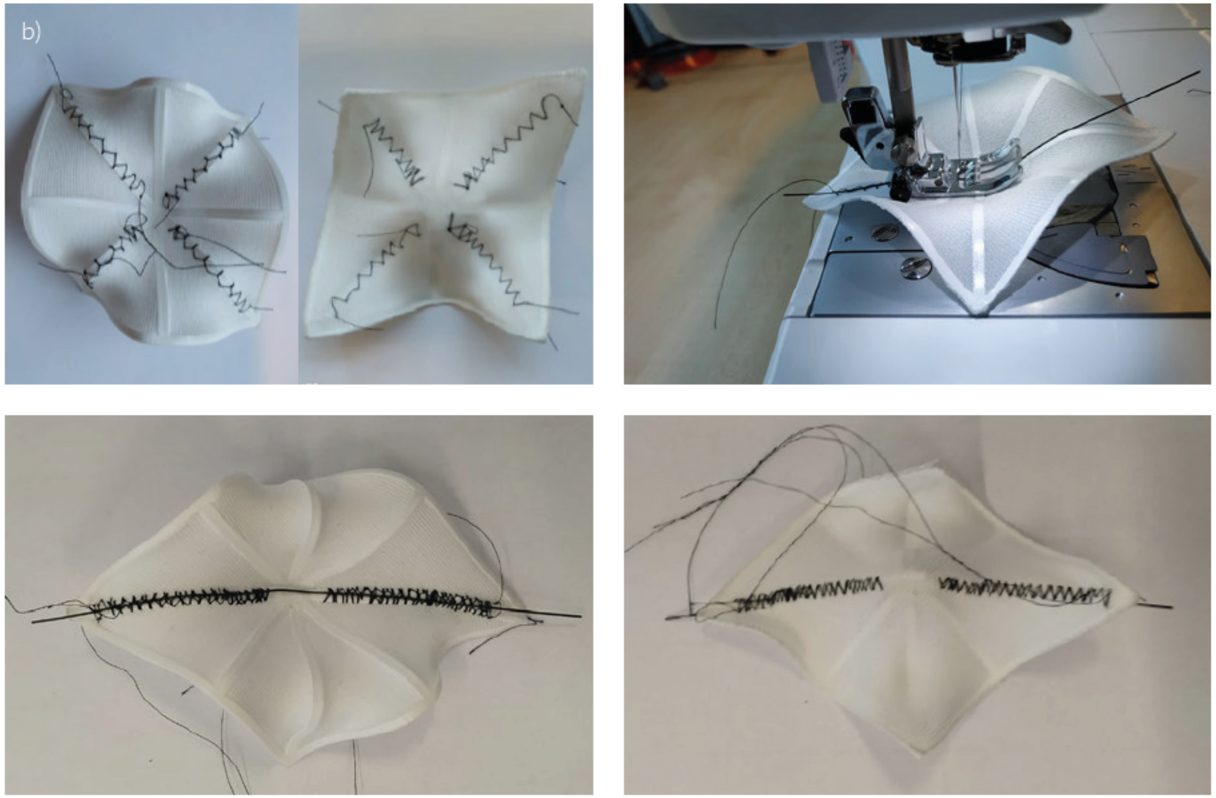


Figure 9.3
Connection of SMA wire to 4D printed structure by a) weaving it inside the filament strip and
b) sewing the SMA wire down using a sewing machine

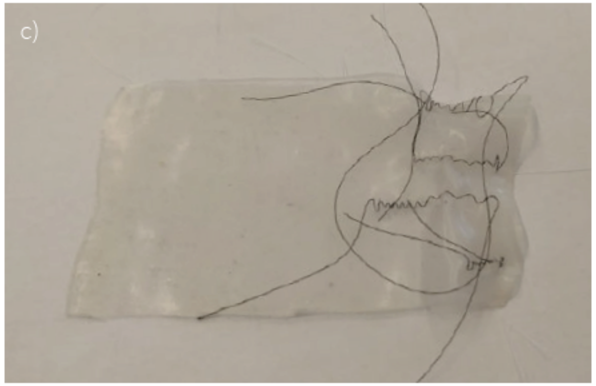


Figure 9.4
Connection of SMA wire to Dragon Skin silicone with:
a) Tesa extra power tape
b) Aluminium tape and
c) machine stitching.

Section 9.3 SMA Connection with Silicone Structures

Tape

At a first glance the Tesa extra power tape already did not prove to make a good bond with the surface of the silicone. The tape was easy to remove from the surface and gave no resistance. When the wire was activated, warping was also observed, where presumably the adhesive let go of the silicone due to the heat, depicted in Figure 9.4a. After pressing down on the tape again, the tape reconnects with the surface.

The Aluminium tape adheres to the silicone surface in the same way as the Tesa tape, however, after activating the SMA wire, it is severely bent, as can be seen in Figure 9.4b. After pushing the tap back onto the surface, it becomes clear that the tape will not reattach anymore. The bond was not durable.

Sewing

A sewing machine was used to create a zig-zagging pattern using thread. The following parameters were changed to find the most suitable combination: the width and spacing of the pattern and the tightness between the upper and lower thread. While sewing the silicone was resisting to move forward due to friction, making the spacing of the zig-zag uneven. It became clear that machine sewing is unsuitable to the material, since the silicone gathers together and wrinkles, illustrated in Figure 9.4c.

Hand sewing showed that the sewing pattern can be embedded into the silicone without tearing the material. The connection can be tight and flexible enough to provide a durable connection method for SMA wires.

Weaving

Weaving the SMA within the silicone requires no external materials while securing the SMA in place, as can be seen in Figure 9.5a. During activation no changes were noted along the penetration points, the silicone did not seem to be affected by the direct connection with the hot SMA wire. The connection method was durable and effective.

Casting

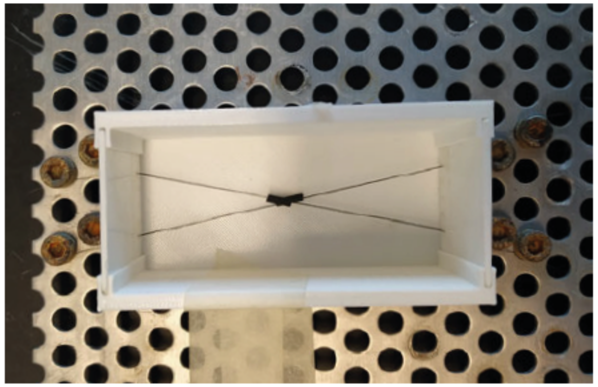
The SMA wire was embedded within the silicone by inserting it inside the mold before the silicone is cast. To ensure the wire will contract inside when it is activated the material is prestrained with weights and secured inside a frame using bolts, illustrated in Figure 9.5b. Afterwards, the silicone was cast inside the material. To prevent both SMA wires from creating a short circuit, an isolation material was placed at the crosspoint of the two wires.

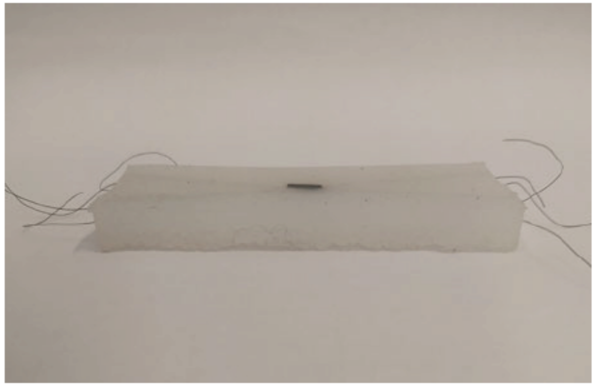
The embedded SMA wires created a durable connection to the silicone substrate, the sample is depicted in Figure 9.5c. The SMA does not release from the rest of the material. A benefit to this connection was that the SMA wire does not move around in the material, and after activation was returned to the starting position by the weight of the silicone substrate.

Conclusion

The most suitable connection methods for SMA and Dragon Skin is hand sewing, weaving and embedding.

Figure 9.5
Connection of SMA wire to Dragon Skin Silicone by:
a) weaving the SMA inside the material and
b)by first attaching the SMA wire inside the mold before the silicone is casted which results in an
c) embedded sample





Chapter 10

User Test: Caterpillar Inspired Movement

Considering the changing structures of the materials, its performative qualities are important when developing a computational composite that moves. For each material sample a wide range of movements can be imagined, but within the scope of this project what is most important is if this expresses the movement of a caterpillar. For this reason an in depth study is performed on the user interaction with the different samples, to uncover what caterpillar like movement can be performed with the material. The goal and method are discussed in Section 10.1 and 10.2, respectively. The results are described in Section 10.3.

Section 10.1 Goal

The goal of the test is to see whether specific shapes of the samples remind people of a specific body part or movement of the caterpillar. Participants are asked to demonstrate a caterpillar inspired movement using the samples. It is hypothesized that by initially asking people to identify and demonstrate caterpillar-like shapes and movements, incorporating them in a future concept will allow users to recognize a caterpillar-inspired design.

Section 10.2 Method

Four participants took part in the study, ranging in age from 24 to 26 with little experience or knowledge about the material or project. All participants have a background in product design.

Before conducting the test, participants were asked to sign a consent form and a release form of the recorded audio and video footage during the test.

First, the purpose of the study was explained to the participant: to identify caterpillar inspired shapes and movement. To sensitize the users to what a caterpillar looks and moves like an introductory explanation was given. The descriptive images can be found in Figure 10.1.

The samples were categorized based on the material: silicone, lycra, polyester lycra and polyester viscose. For each category, all samples were laid out on a sheet of paper in front of the participant, depicted in Figure 10.2. The participant was asked to play with the samples they find most interesting and to 'think out loud' and verbally express their thoughts and actions. Participants were also asked to express other associations to the materials, even if they are unrelated to a caterpillar

Watch the caterpillar crawling and inching locomotion examples using the QR codes

Figure 10.1
Descriptive pictures of caterpillar types and video's of the crawling and inching locomotion.

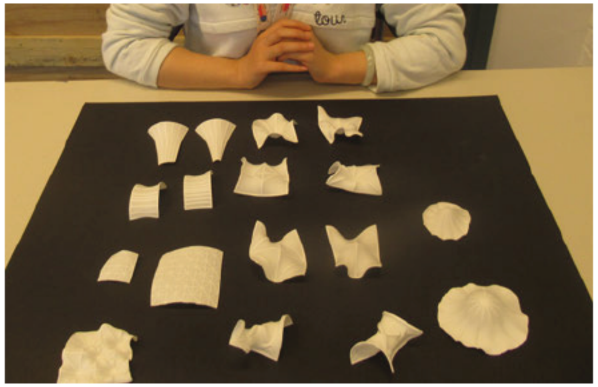


Figure 10.2
Sheet with Lycra material samples laid out in front of the participant.

Section 10.3 Results

When the participants were asked to imagine caterpillar-like movements with the material samples in front of them, most participants would first grab a sample by two sides and try to move it in a crawling or inching way. Afterwards they would move the sample in other ways, exploring the degrees of freedom the material had and the possible new ways of moving the material.

The recorded expressions of associations and thoughts were collected for each material sample and can be found in Appendix D. All observed actions were also recorded, to see how often a single movement is associated with a material sample.

Polyester Viscose

Participants found the relation between a caterpillar for this material mainly through the color of the material: green. The material does not have a very accentuated curvature due to the type of textile, for this reason one participant thought it was more soft and endearing and wanted to squeeze and caress the material.

The main movement the participants performed with the samples was putting two edges of the material on the paper and using both hands to move the sample in an inching way.

Polyester Lycra

Participants found this material more delicate in comparison with the Lycra since the material is thinner than Lycra and the samples were less curved. Two interesting movements performed with this material were inching and bending related. By pushing the top of the sample shown in Figure 10.3a, the material was deformed and released, in this process the samples moved forward. Secondly, the downward facing edges of the square sample depicted in Figure 10.3b were first folded together and then its other ends were bend together. This created a new tubular shape.

The bi-stable samples, such as the one depicted in Figure 10.5 sparked wonder and were exciting to interact with according to all participants.

Lycra

The material was regarded as more active and alive by all participants. The textile gave the samples more character because the shapes were more curved and reactive. The thickness of the material also made one participant feel more secure to touch and play with the samples.

Due to the structural similarity between the three 4D printed samples, the same movements were performed by the participants.

Figure 10.3
a) Rectangular 0.5mm
Polyester Lycra sample
b) Square 0.5mm
Polyester Lycra sample
c) Star 0.5mm
Polyester Lycra sample

Dragon Skin

Compared to the 4D printed structures, one participant thought this material looked passive, and did not have a clue to how it was supposed to move.

The feeling of silicone did remind two participants of an organic material, such as skin. The response to the texture samples were that it was overall not reminiscent of a caterpillar and boring since it was the same over the entire sample, such as the regular texture seen in Figure 10.4a. One participant did state that with their eyes closed the random semi-spherical pattern, depicted in Figure 10.4b felt like what they imagined a caterpillar skin would feel like. The air bubble texture, due to the vacuum machine was also regarded as organic.

To find a caterpillar like-movement the participants were again asked to freely explore the material. The material was also rolled up, stretched and catapulted. The thicker samples were regarded as caterpillar like but harder to deform. More exploration of movements was possible with the thinner samples, compared to the thicker ones.

Caterpillar-like

Bio-inspired shapes were seen as organic and curved. One participant mentioned that regular straight lines can not be associated with animals.

One set of visual queues that resemble the caterpillar are a rectangular body shape (long and narrow) and an omega shaped back while the material bends. One participant thought that 2 or 3 segments attached together would look even more like a caterpillar.

Another representation of a caterpillar was described as a shape with two low points that are touching the ground and a lifted belly. During movement the top part of the material is not important to resemble a caterpillar, but the belly has to compress. All participants defined a caterpillar-like movement as a material that is moved together in an inching manner.

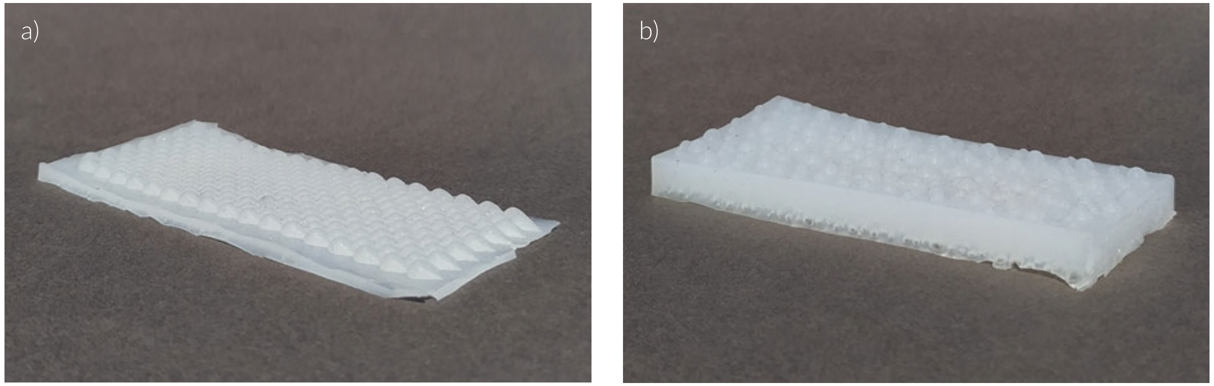


Figure 10.4
a) thin sample with unsymmetrical overlapping drop pattern on one side
b) thick sample with random semi-sphere pattern on one side and air bubble texture on the other side.

Section 10.3 Conclusion & Discussion

From the different movements demonstrated by the participants, 4 movements were chosen to continue developing. For both material types: 4D printed textile and Dragon Skin, 2 movements were selected. The samples and their movements are depicted in Figure 10.8.

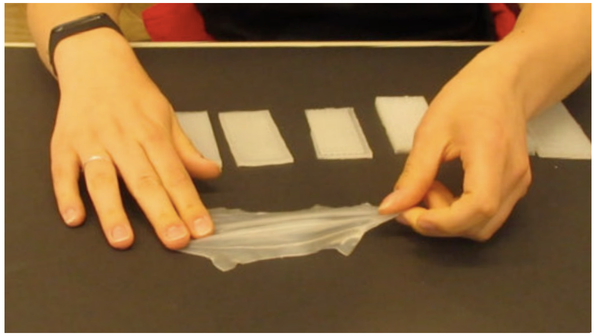
The sample is folded over to create a tubular shape. The free ends are moved together to represent an inching movement.

The sample is pushed from the top causing it to expand. As the force is reduced the ends contract together and the back is arched again, representing an inching movement.

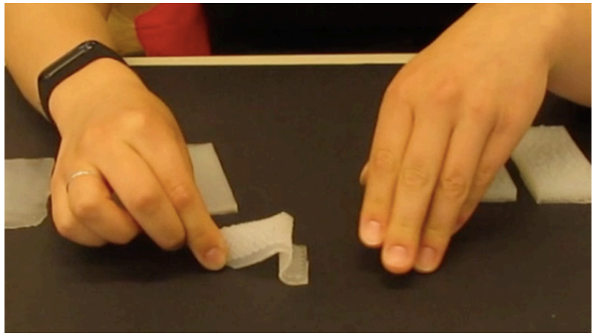
> “When I fold over the material, a new shape is revealed, which prompts me to deform it again.”
> - Participant 3

Scan the QR code to see the movements in a video

Figure 10.5
Selected movements for development into shape memory alloy composites.



The sample is stretched on both sides and released at the back. This movement is re-imagines the expansion and contraction of the body of a caterpillar as it moves.



The sample is pinched on one side and pushed forward. The movement is continued by the material in a rolling fashion over the free material. This movement can be seen as the continuation of a wave seen in a caterpillar while crawling.

"I like how the initial movement is translated by the material"
- Participant 3

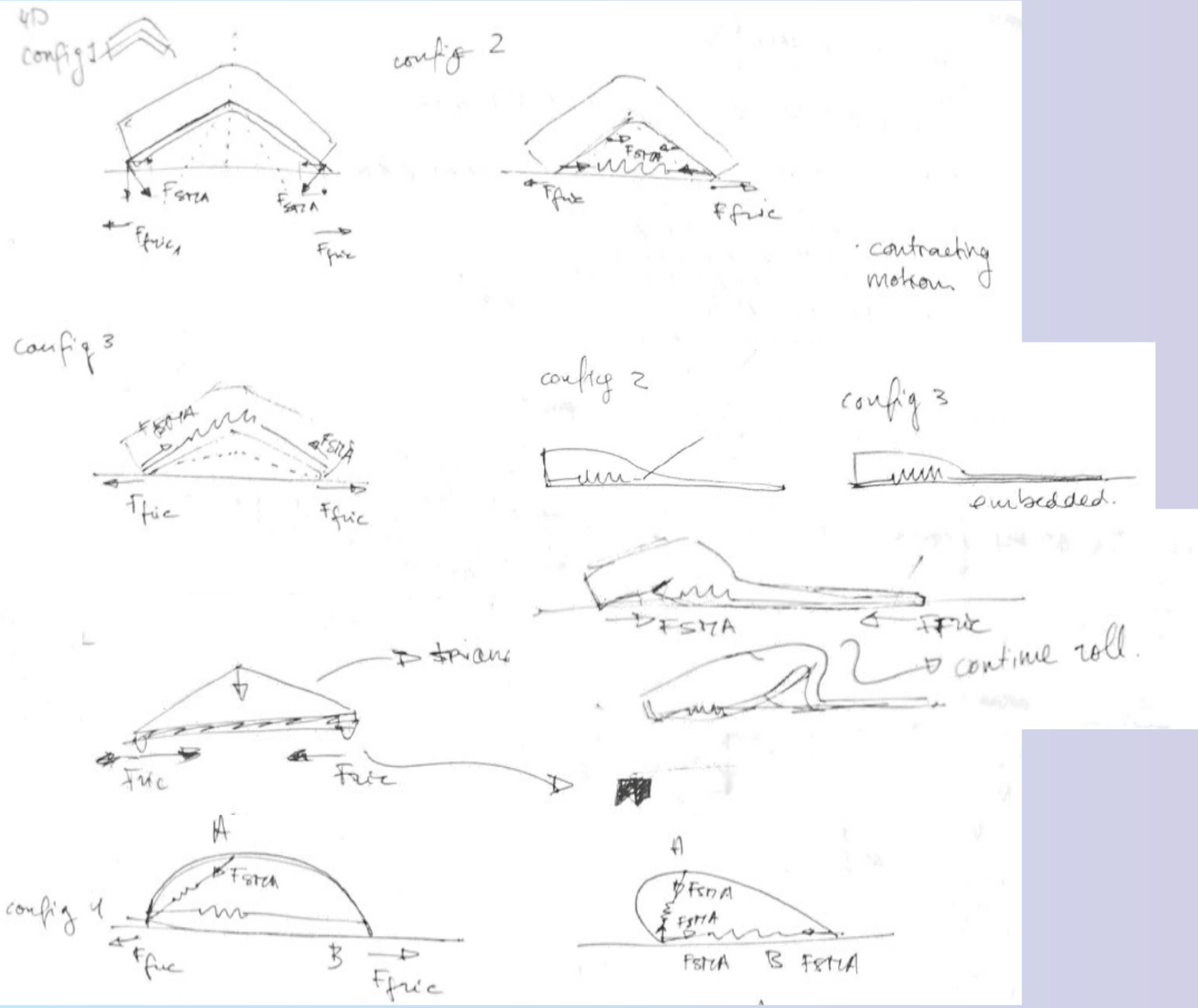
Chapter 11

Moving SMA Composites

SMA composites are developed to demonstrate the caterpillar-like movements found from the user test are can be realized in a moving material.

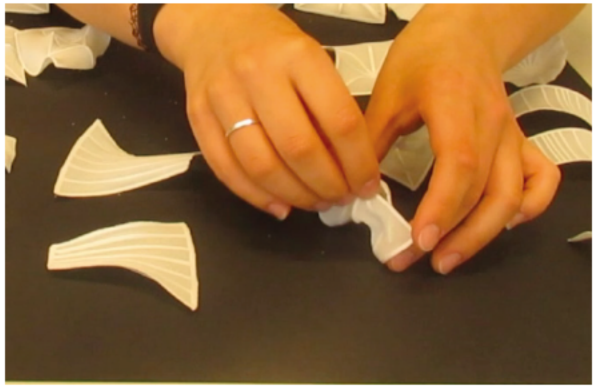
In the next development phase, translational movement will be further developed. In Section 11.1, starting from the caterpillar-like movements that were demonstrated by the participants of the user study, free body diagrams are developed to determine the location and magnitude of the force required from the SMA elements.

The development of the moving material composites is documented in Section 11.2 and 11.3, respectively. The final material samples and movements are listed in Section 11.4. The selection method for choosing one of these material samples for further development into a computational composite is described in Section 11.5.



Section 11.1 Simplified Model

To create the movements found in the user test a suitable SMA type should be connected to the material samples. The type and positioning are determined based on the required movement and the resulting forces from both the material and surface. The movement of the material is facilitated by the SMA, but after activation this SMA should be reset to its original position.



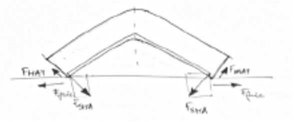
4D Printed Textile: Movement 1 - Crawling

Movement - The sample is folded over to create a tubular shape. The free ends are moved together to represent the inching movement of a caterpillar.

Simplified model - The required force to bend the material was measured using a pressure sensor and loading the material axially to be 0.2 N. Due to the low contact area with the ground on the bottom, the frictional force is assumed to be approximately zero.

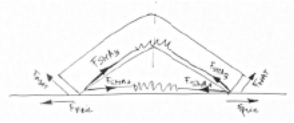
Configuration 1

2 Bending
SMA hinge



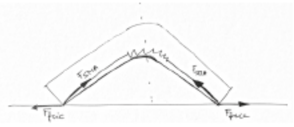
Configuration 2

External & Internal
SMA spring



Configuration 3

Internal
SMA spring



4D Printed Textile: Movement 2 - Inching

Movement - The sample is pushed from the top, causing it to expand. As the force is reduced the ends contract together and the back is arched again, representing an inching movement.

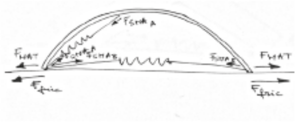
Simplified model - The required force to bend the material was measured using a pressure sensor. Due to the low contact area with the ground on the bottom, the frictional force is assumed to be approximately zero.

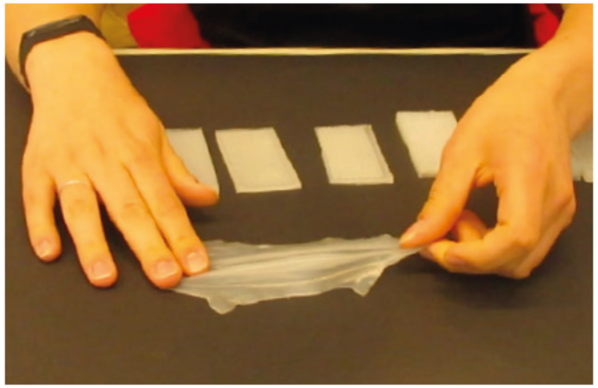
Configuration 1

1 External
SMA Springs

Configuration 2

2 External
SMA Springs





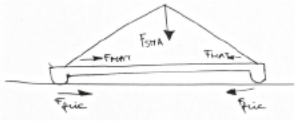
Silicone: Movement 1 - Stretching

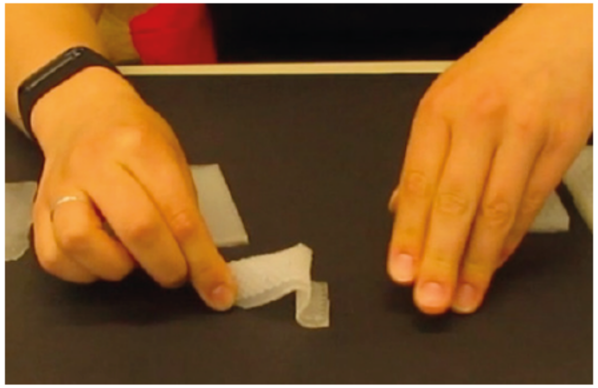
Movement - The sample is stretched on both sides and released at the back. This movement is re-imagines the expansion and contraction of the body of a caterpillar.

Simplified Model - The resulting force inside the material is estimated using the Young's modulus of the desired extension of the material while the SMA stretches it. Given an extension of 5% and a Young's modulus of 0.56 MPa, the material would have a normal stress of 2.8 MPa. With a material cross-section of 50x2mm the normal force necessary would be 0.028N. By lifting the silicone off the surface and attaching it to two feet the frictional force due to the silicone is minimized and dependent on the material used for the feet.

Configuration 1

Bending
SMA hinge





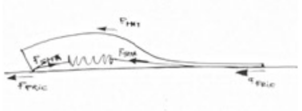
Silicone: Movement 2 - Rolling

Movement - The sample is pinched on one side and pushed forward. The movement is continued by the material in a rolling fashion over the free material. This movement can be seen as the wave rolling over the caterpillars back as it crawls.

Simplified Model - The friction force in the front and back parts are estimated using the static frictional coefficient. For a silicone rubber this coefficient can range between 0.25 to 0.75 and it has not been specified for Dragon Skin (Albright Technologies, 2019). Taking the maximum coefficient, the frictional force is calculated by: $F = \mu mg = 0.75 \cdot 0.014 \cdot 9.81 = 0.1$ N The required force to bend the material was measured using a pressure sensor to be 0.1 N.

Configuration 1

SMA spring



Section 11.2 Development of 4D Printed SMA Composites

Movement 1 - Crawling

Configuration 1

In the first configuration, a hinge was used that opens like a book, which was trained in the ceramic oven to have an initial shape where both sides are parallel to each other. The hinge was sewn in to the material structure and has an initial open angle of 130°. As the hinge closes when it is activated it should deliver a force of 0.1 N.

It was observed in Chapter 9 that the SMA wire can melt and deform the filament structure by heating the filament over a longer amount of time, since the glass temperature of PLA lies at 60 - 65 °C, and the wire's activation temperature is at 70 °C. A barrier was made between the SMA wire and the filament by sewing a thick thread pattern over the filament.

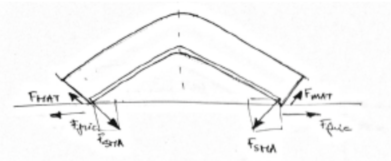
After this the first SMA hinge was attached a layer of electric tape was sewn in before the next SMA hinge was added. This was to prevent a short circuit between the wires.

The configuration of SMA hinges does result in a bending motion of the two ends. However, since the material lost most of the flexible properties due to the many layers of SMA wires. The balance between SMA and Material has not been reached in this composite.

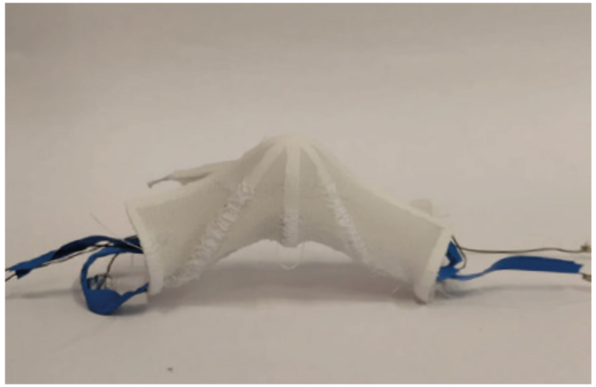
Configuration 1

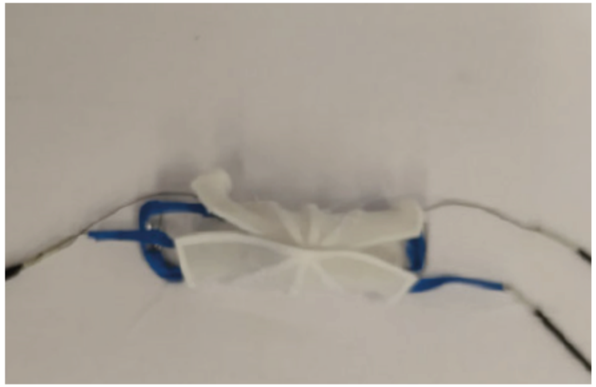
2 Bending
SMA hinge

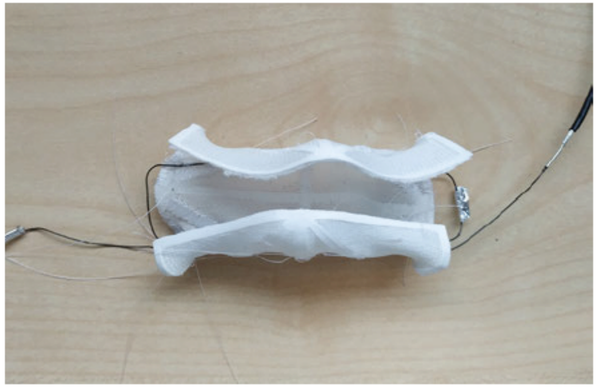
$F_{SMA} = 0.1 \cdot 2\ \mathrm{N}$
$F_{FR\,C} = 0$
$F_{MAT} = 0.2\ \mathrm{N}$



The resulting structure is stiff due to the amount of SMA wires and tape, the 3D printed textile has lost its flexibility and curved shape







Movement 1 - Crawling
Configuration 2

Two antagonistic springs are used in the second configuration, one is attached within the 4D printed textile structure, the other is located between the two ends. Paper feet were added to the structure for stability. The Antagonistic lay-out means that when one spring is activated and contracts the other one will be expanded, so that the system can be reset. By contracting the upper spring, the two ends should be pulled together, and in this way the bottom spring is expanded again. Using this method, the resulting force of the material is not really used to reset the spring.

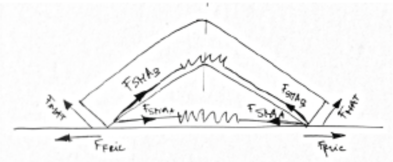
In practice the upper spring would slide to the side, thereby contracting the material even more because the coils would squeeze together the textile caught in between coils. Several methods for keeping the spring in the middle were tried: using a more rigid spring that was sown in place on one and both sides, putting paper below the spring to keep the textile from coming between the coils.

The external springs do not hide the mechanism adopted and leave little to the imagination of the user.

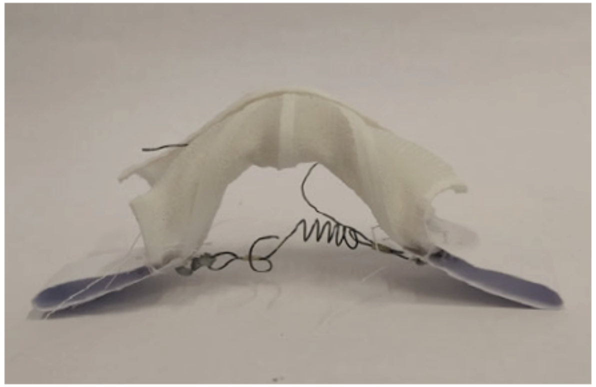
Configuration 2

2x 0.375 mm
SMA spring

$F_{SMA} = 0.2$ N
$F_{FR\,C} = 0$ N
$F_{MAT} = 0.2$ N



The final movement of Configuration 2 is similar to the inching and crawling locomotion of a caterpillar, but the external springs do not hide the mechanism adopted and leave little to the imagination of the user.



Movement 2 - Crawling
Configuration 3

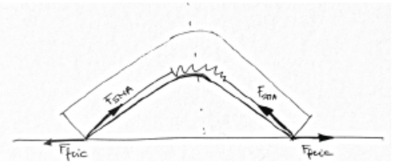
From configuration 1 and 2 it was observed that when the upper spring would slide to the sides, the spring would actually compress the material structure. The folding of the textile within the coils was also making the structure compress.

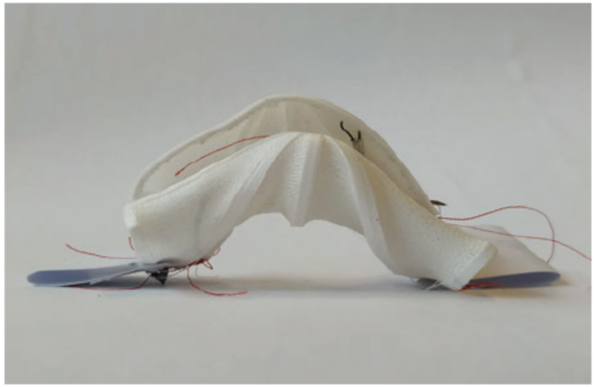
Two SMA springs were attached inside the material structure, both located on the side of the material structure. This way also both sides will contract, leading to a more symmetric movement. The force either spring should apply decreased.

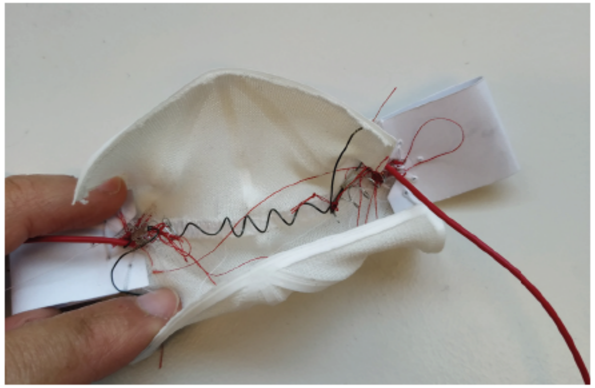
Configuration 3

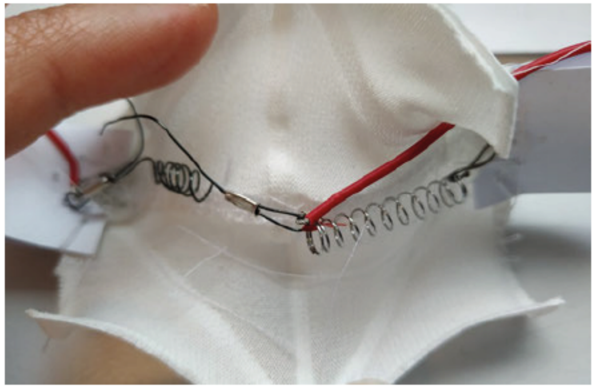
2x 0.375 mm
Internal
SMA spring

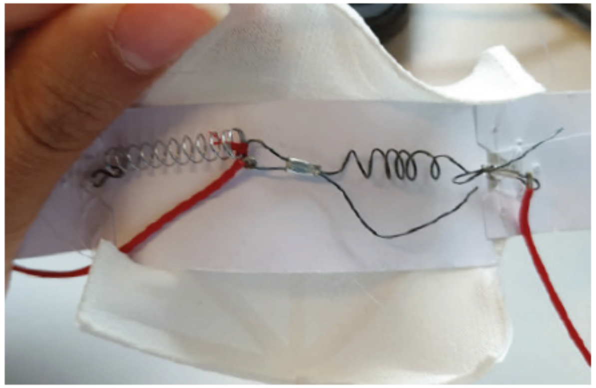
$F_{SMA} = 0.1$ N
$F_{FR\,C} = 0$ N
$F_{MAT} = 0.2$ N

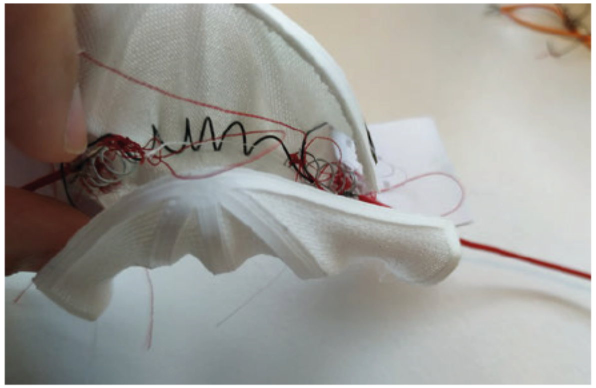


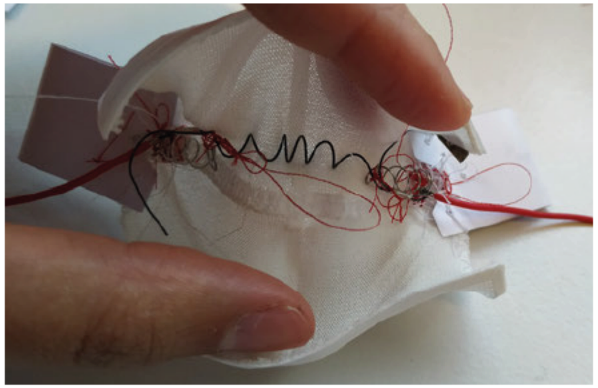












Movement 2 - Crawling

Configuration 1

Two springs are used to recreate the movement shown by the participant. In this movement, the top of the arch is pushed in, but this is not possible to recreate using SMA wires. For this reason, another configuration of wires was proposed. Spring A is attached to the top and back of the structure, aimed and pulling the top down. The resulting movement actually pulls the end upwards.

Configuration 2

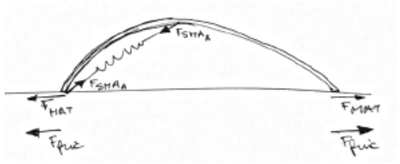
To include an inching movement to configuration 1, an additional spring was implemented between both ends. This created a movement that would best work with a separate control of the actuation of the springs: A on - B on - A off - B - off. The hind part would have a higher friction, so that by lifting the back, an incremental step forward can be made.

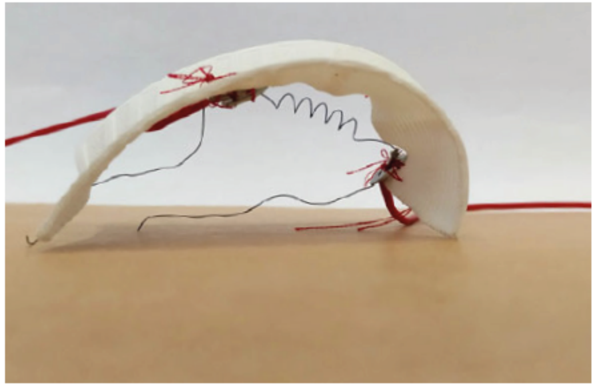
A control system that was able to drive both springs separately was missing, so only the movement of the separate springs could be seen respective of each other.

Configuration 1

1x 0.25mm
SMA spring

$F_{SMA\text{-}A}=0.2$ N
$F_{SMA\text{-}B}=0.1$ N
$F_{FR\,C}=0$ N
$F_{MAT}=0.2$ N

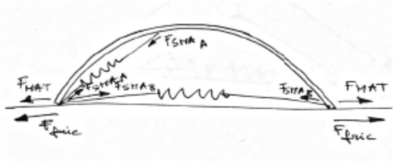


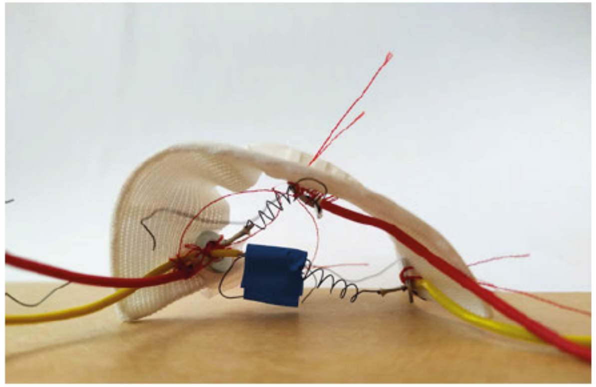


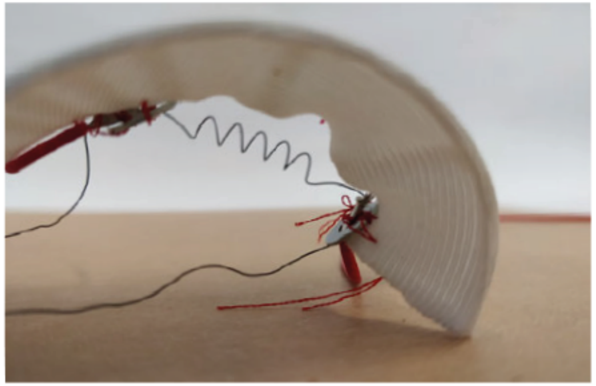
Configuration 2

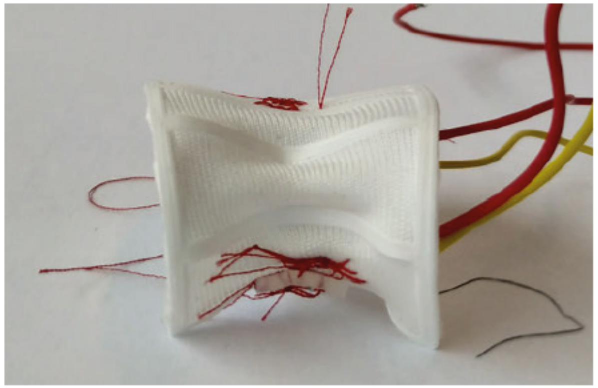
2x 0.25 mm SMA
spring

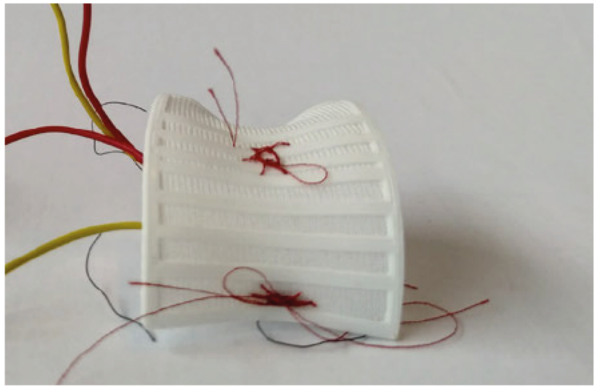
$F_{SMA\text{-}A}=0.2$ N
$F_{SMA\text{-}B}=0.1$ N
$F_{FR\,C}=0$ N
$F_{MAT}=0.2$ N

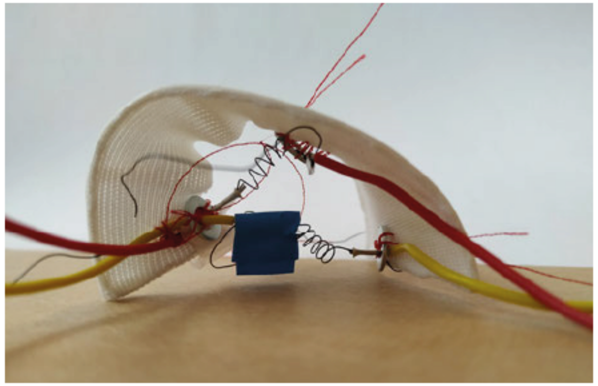


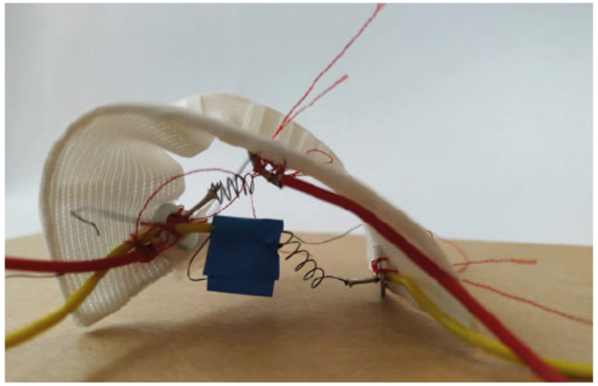












Section 11.3 Development of Silicone SMA Composites

Movement 1 - Stretching

Configuration 1

Dragon skin is a stretchable material, movement 1 takes advantage of this material characteristic. In configuration 1, it was explored if a SMA hinge can even stretch the material. A 0.3 mm thick dragon skin sheet was taken and sewn around an SMA hinge, designed to open up to 180°.

The hinge was not able to exert enough force on the silicone to stretch it out to 5 mm. However, it was observed that the material did change from a relaxed to a stretched state.

Configuration 2

The same principle as in configuration 1 was applied to configuration 2, this time with a 0.3 diameter wire that was trained to become flat (180°) and woven into the silicone with a shorter length. In this way, the SMA could only revert back to its trained shape by moving the dragon skin sample outwards.

The hinge was however not exerting enough force on the material sample, because there were too many degrees of freedom for the wires.

Configuration 3

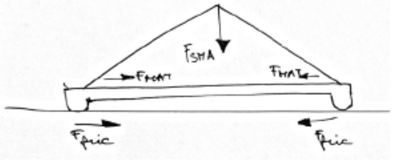
This time around, the wires were sown onto the material structure, so that there were less degrees of freedom. The resulting movement of the dragon skin material was stretching it out upwards. In a sense, a compromise was made between the silicone and the SMA: the wire wants to move straight and so moves the silicone up, at the same time the silicone stretches upwards because of the movement.

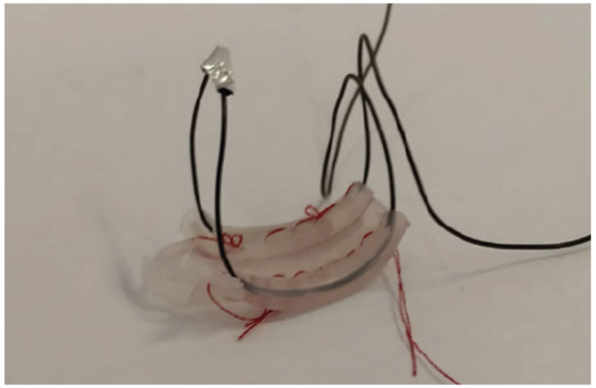
Paper was used to spread the wires out and keep them from touching and creating a short circuit.

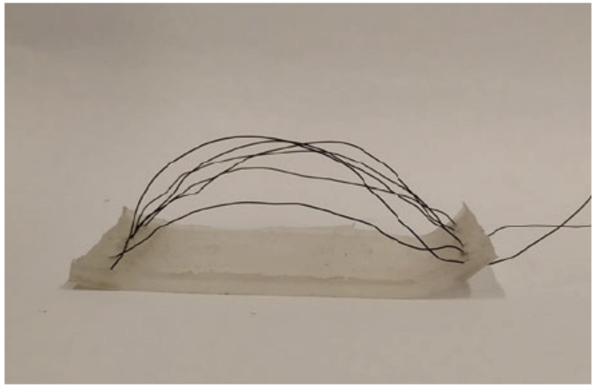
Configuration 1

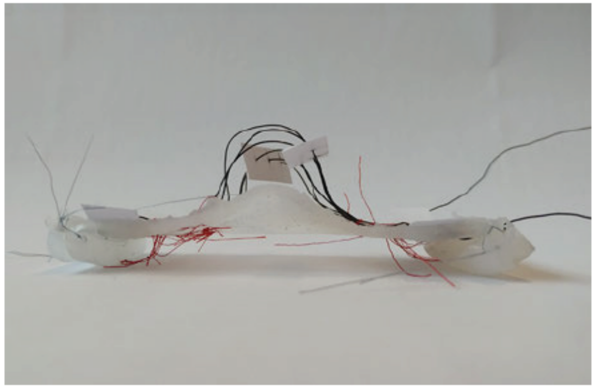
Bending 0.5 mm
SMA hinge

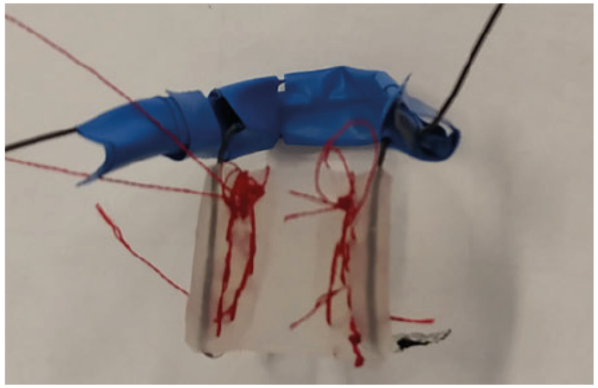
$F_{SMA} = 0.1$ N
$F_{FR\,C} = 0$ N
$F_{MAT} = 0.2$ N

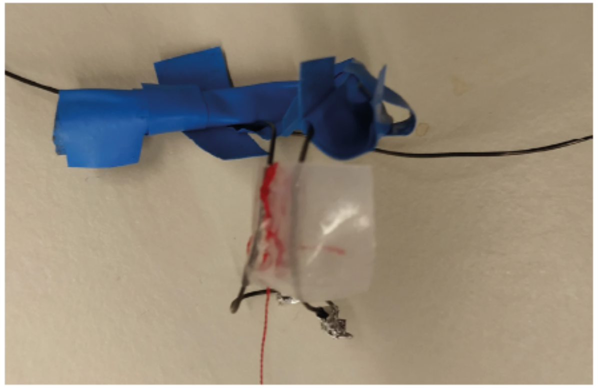


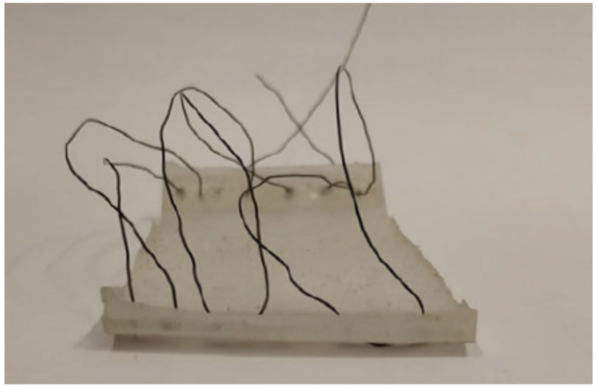


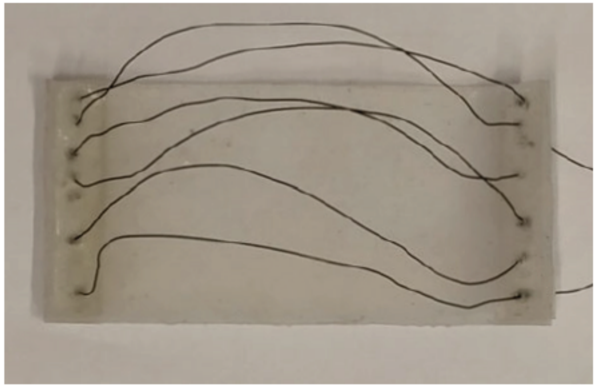


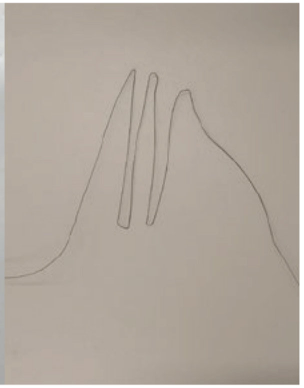


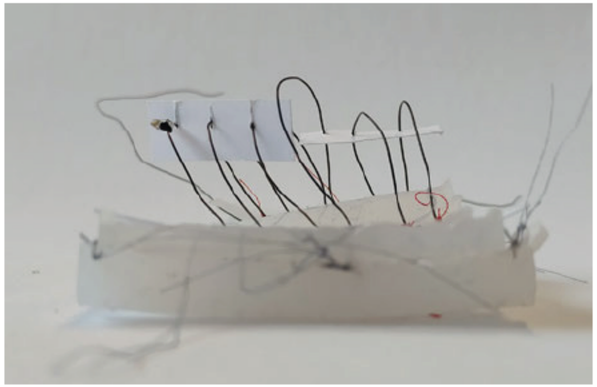


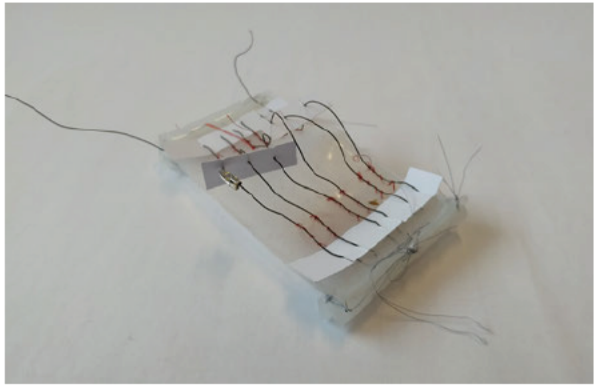












Movement 2 - Rolling
Configuration 1

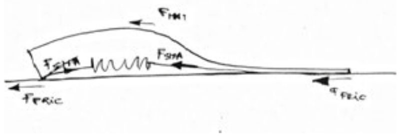
The movement of the back part to the front is facilitated by a 0.5 mm diameter spring. The spring is attached to the end of the material. The second half of the sample is supposed to continue the bending motion of the first half in a rolling fashion. From the mid point the wire is attached to the sample by hand sowing it.

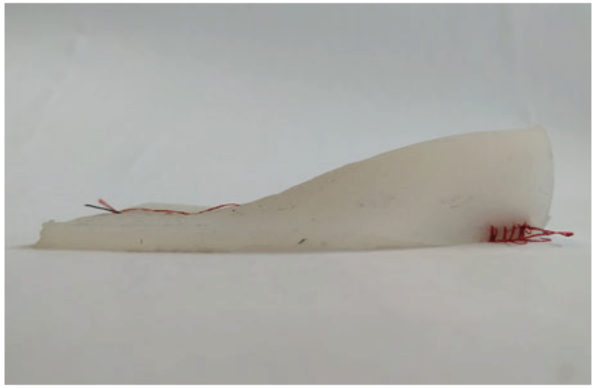
When the SMA spring is actuated the back part moves forward which curves the material. The other half of the material however does not continue the movement. Without the wire embedded in the silicone, the material does roll forward. From this it was deduced that the SMA wire is too stiff and inhibits the movement.

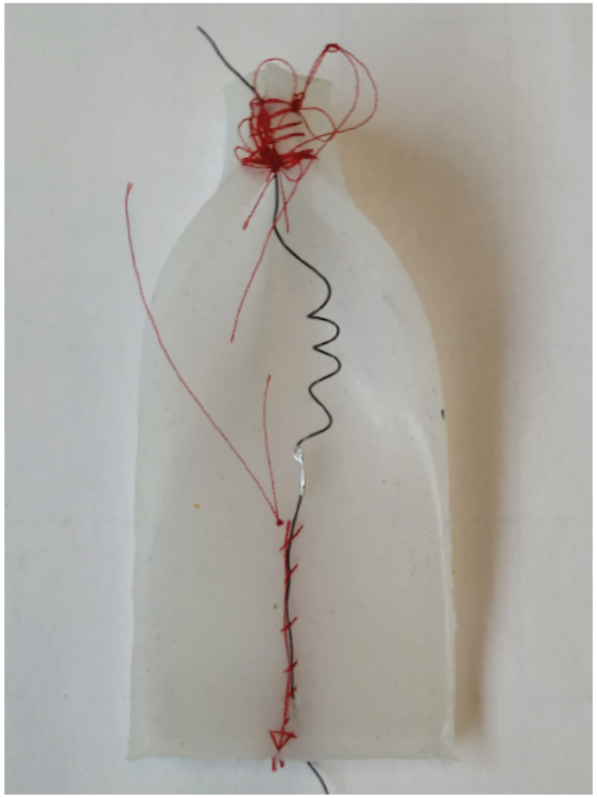
Configuration 1

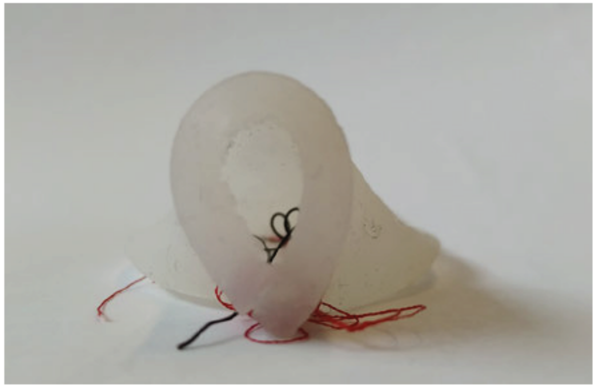
1x 0.5 mm
SMA spring

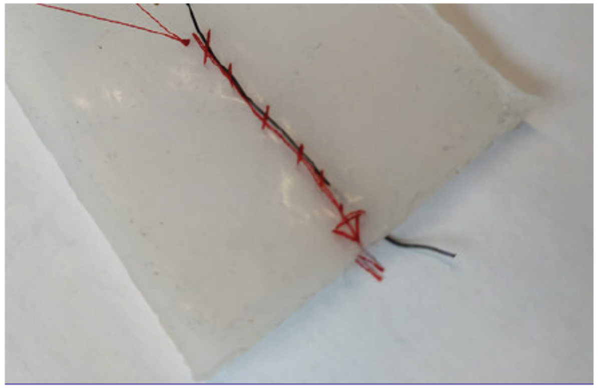
F_{SMA} = 0.2 N
$F_{FR C}$ = 0.1 N
F_{MAT} = 0.1 N

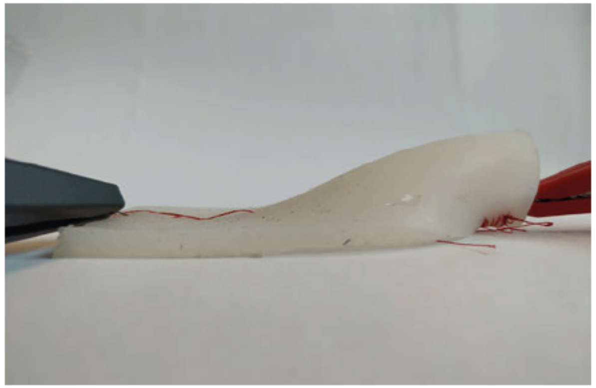






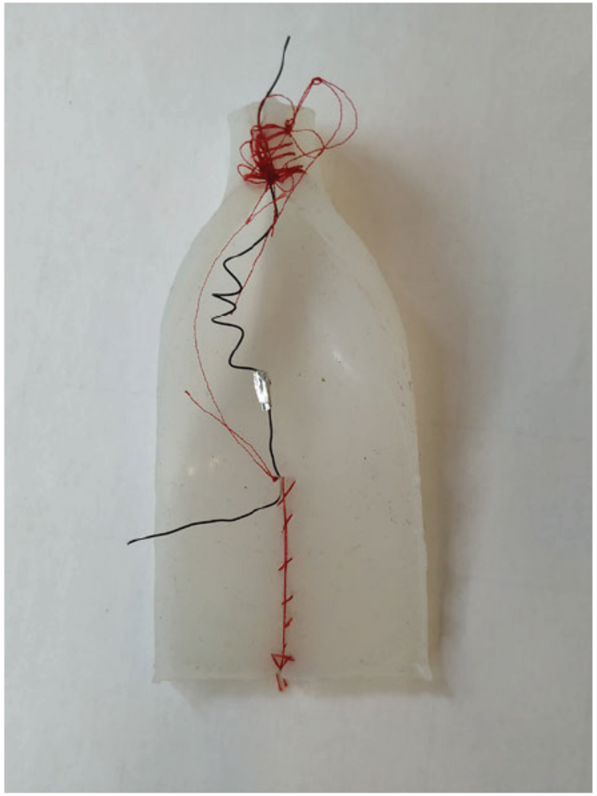


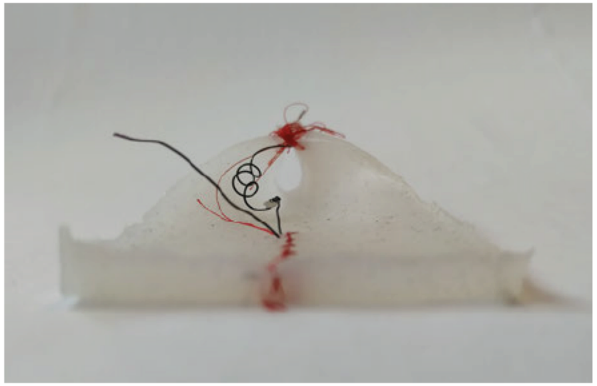


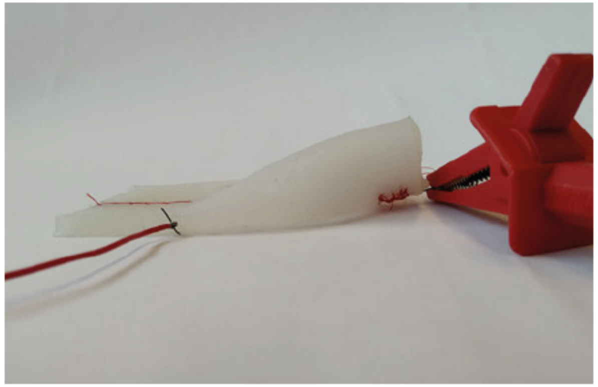


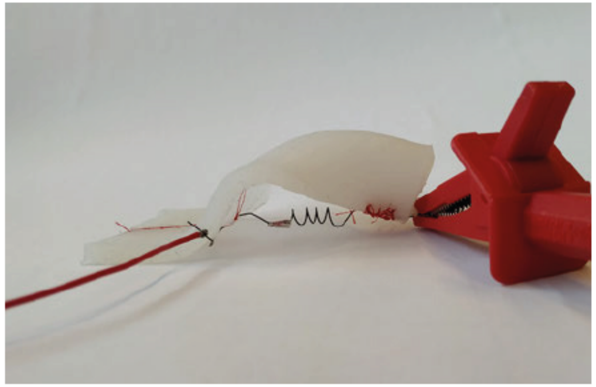
Configuration 2

Another method for attaching the SMA wire to the mid-point was by weaving it in at the start of the second part. This ensure that the spring was securely connected, while also giving the second part the freedom to move.
Upon activation the first part was moving forward, and the second part would spontaneously move itself forward. This happened quite unpredictable, almost as if the material needed to harness all the energy from the first motion before it could move forward.
The rolling motion was observed minimally since the motion was very abrupt and fast.



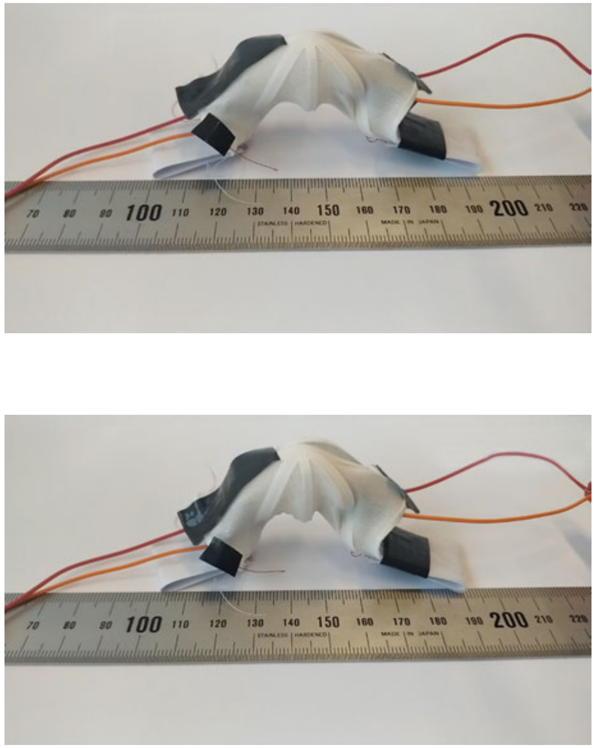




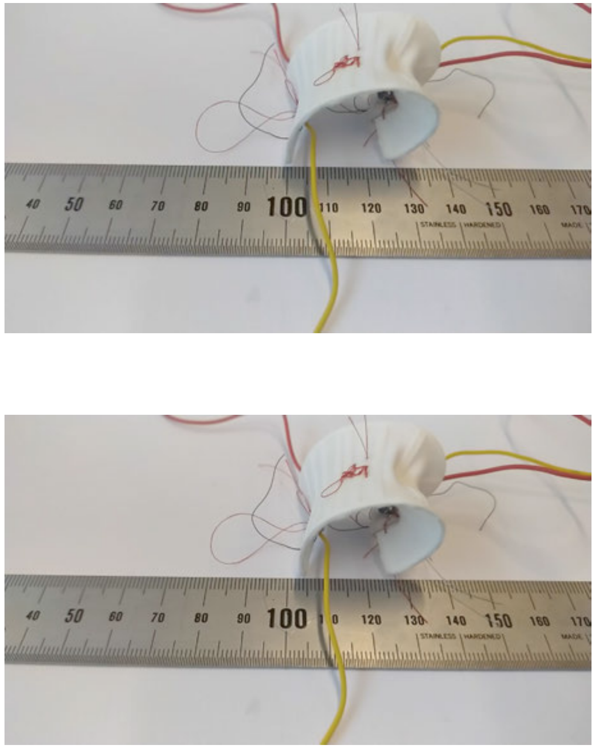


Section 11.4 Movement of Material

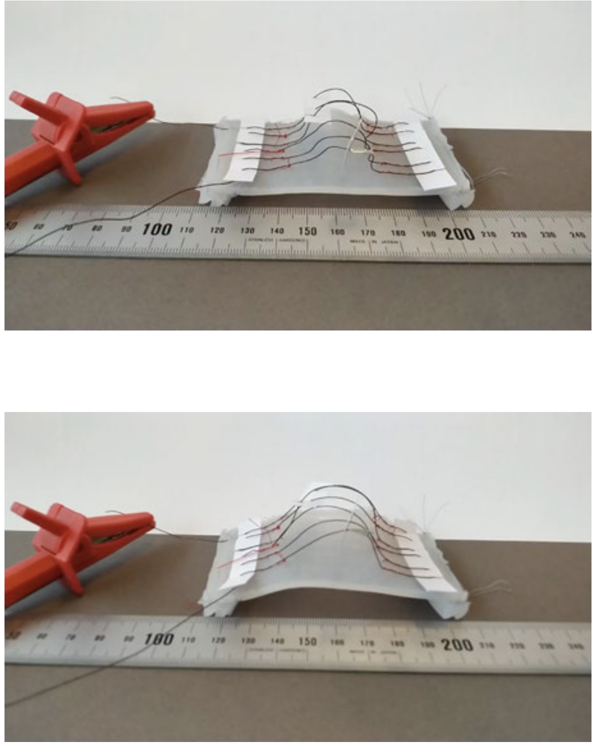
An overview of the material composites that best convey the intended movement are listed here. By scanning the QR code, the movement can be reviewed in detail. The activation time and cooling time are described for each material.

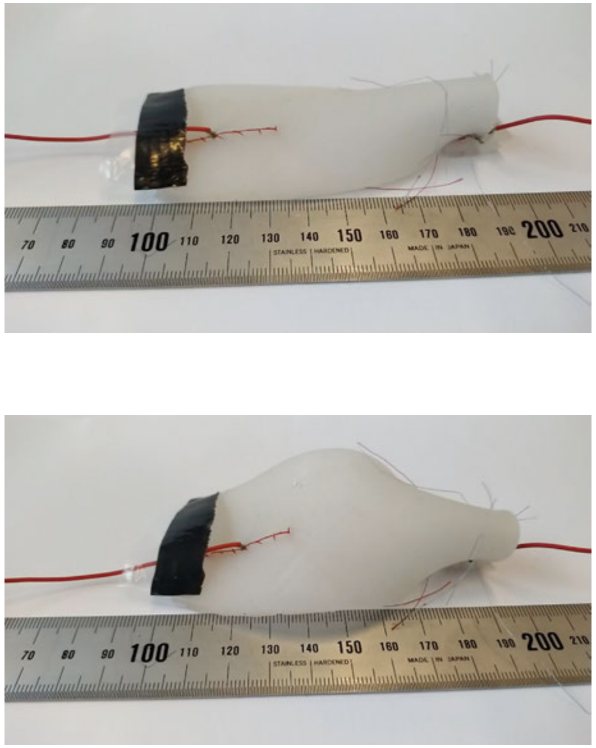


Name: Crawly
Cycle time: Activation (13sec) / Cooling (47 sec)



Name: Springle
Cycle time: Activation (7 sec) / Cooling (19 sec)





Name: Levity
Cycle time: Activation (35 sec) / Cooling (40 sec)

Name: Sluggo
Cycle time: Activation (50 sec) / Cooling (55 sec)

Section 11.5 Selection

To select one of the SMA based composites to continue with the weighted objectives methods is used. This method typically used when concepts are evaluated and a decision should be made on which concept should be developed into a detailed design (WikiD, 2019). This is an evaluation method for comparing design concepts based on an overall value per design concept. Compared to the Harris profile or Datum method, this gives a clear score for each concept on which a comparison on the value can be made. The criteria on which the assessment is based can have different levels of importance. To take this into consideration, weights are assigned to the different criteria.

To assess the developed material structures, the needs and wishes from the list of requirements from Chapter 6, were used. All material structures were driven by SMA and are controllable using the power circuit, for this reason these points were not taken as criteria. At this stage of the project, the forward moving requirement has also been kept out of the assessment, and will be further developed in the next stage.

The three needs: to have a resetable, modular and caterpillar-inspired moving material were equally important and therefor given a weight of 4 out of 5. The wishes being slightly less important were given a weight of 3 out of 5 with the exception of meaningful.

Crawly

The material structure of Crawly makes it return to its original shape as the SMA springs cool down. This ensures the material can be actuated again. It was observed that sometimes the material would have the springs stuck in between the fabric, leaving the material slightly more compressed. The overall shape and actuation is modular and caterpillar like, and so scores 5 out of 5. The material features two separate springs making the composition more complex.

Out of all cycle times, Crawly has the second fastest actuation and cooling time making the cycle time 4 out of 5. Finally, the movement is deemed as inspirational based on the idea that it makes the spectator feel something and meaningful because of the different applications that can be imagined with this type of movement.

Springle

Just like Crawly the material structure of Springle is modular and resets the material to its original shape as the SMA cools down, although with decreasing effectiveness over time, hence the 4 out of 5. The overall shape is deemed less caterpillar-like compared to Crawly. The material features two separate springs making the composition more complex. The cycle time of Springle is the fastest out of all material concepts. While the movement is deemed inspirational, the meaningfulness of this material movement is deemed low.

Levity

After actuation the material remains in the same position as right after actuation, meaning the material is not reset completely. Although the material is modular, the shape does not resemble a caterpillar in comparison to the other material concepts, for this reason a 2 out of 3 is given.

The SMA component inside the material is made up of one long wires, trained into a zig-zag pattern. Thought the assembly of SMA with material is complex, making the complexity on average a 3 out of 5. Based on the ranking in cycle time, Levity scores a 3 out of 5. Finally, the movement of the material found inspirational, especially considering the material upside down. This way the silicone surface seems to stretch itself and push itself upwards. Next to this the types of interactions that can be envisioned with this material movement are deemed as meaningful.

Sluggo

The material is quite unstable, sometimes falling down and other times the material does not completely respond to the actuation of the SMA and remains in an arched position This positions it will not be reset-able for further actuation. Next to this, the shape of the material is not symmetric and therefor not modular, nor does it resemble the shape of a caterpillar. However, the complexity is very low since it is only actuated by one spring. The cycle time of the actuation of the material is the lowest out of all 4 and in addition is not as inspirational and meaningful in comparison to the other materials.

Conclusion

The resulting values per material structure based on the LoR needs can be found in Table 11.1. Crawly and Springly score very close to each other. For this reason another table, which includes the wishes of the LoR has been established, depicted in Table 11.2. In both tables, Crawly has the highest score. For this reason it was decided to continue with this material structure in the development of the computational composite.

Table 11.1
Weighted criteria method on the needs from the list of requirements.

	Resetable	Modular	Caterpillar-like	Low complexity	Cycle time	Inspirational	Meaningful	
	4	4	4	3	3	3	2	
Crawly	4	5	5	2	4	5	4	56
Springle	4	5	4	2	5	5	3	52
Levity	3	5	2	3	3	4	4	40
Sluggo	3	1	3	5	2	3	3	28

Table 11.2
Weighted criteria method on the needs and wishes from the list of requirements.

	Resetable	Modular	Caterpillar-like	Low complexity	Cycle time	Inspirational	Meaningful	
	4	4	4	3	3	3	2	
Crawly	4	5	5	2	4	5	4	97
Springle	4	5	4	2	5	5	3	94
Levity	3	5	2	3	3	4	4	78
Sluggo	3	1	3	5	2	3	3	64

Section III:

Computational Composite Development

Chapter 12

Computational Composite Overview

An overview is given of the elements to a computational composite. The inputs to the computational composite and the resulting output are defined in Section 12.1 and 12.2, respectively. The analysis of these inputs and the required computation and control system are explained in Section 12.3.

Section 12.1 Input

The approaches to user input as defined in Chapter 4 are: none, indirect and direct. To fit the development of this computational composite, the interaction method of directly touching the composite may be restrictive to the eventual output of the composite, which is forward movement. For this reason, the user interaction is defined as indirect.

The means of interacting with the computational composite in an indirect way can be by influencing the environment, data streams and interacting with connected elements.
At this stage of the development of the computational composite, it is chosen to first develop a composite that responds to the user input with a push button. In this way the user can perceive that their actions influence the computational composite.

Section 12.2 Computational Control

The drawbacks to using this system are the inability of controlling two SMA wires separately and the bulkiness of the heating element and the electrical cables. Next to this, the method of supplying the voltage is uncontrollable.
The effectiveness of supplying voltage to the SMA wire can be improved by using a PWM curve. Instead of continuously supplying the SMA with electricity, the signal is periodically alternated between on and off, where the width of the signal can be defined from 0 - 100%. The oscillating power allows the heat in the wire to be more evenly distributed, by heating up the cold spots (Images Scientific Instruments, 2019). This gives better control of the activation of the SMA over longer periods of time.

The following electrical circuit was suggested by Images Scientific Instruments (2019) to send a controllable electrical current with duty cycle over the wire, illustrated in Figure 12.1. After replicating the circuit and connecting an SMA wire as can be seen in 12.3a, the electrical signal over the wire was measured, which resembled a the curve illustrated in Figure 12.2.

To use it for each SMA wire individually within the composite structure, the circuit board was miniaturized and soldered on a matrix board., depicted in Figure 12.3b. Initially, the aim was to manufacture this module, but after some research it was found that a Grove Mosfet module would provide the same functionalities, though the Mosfet can only drive one SMA wire at a time.

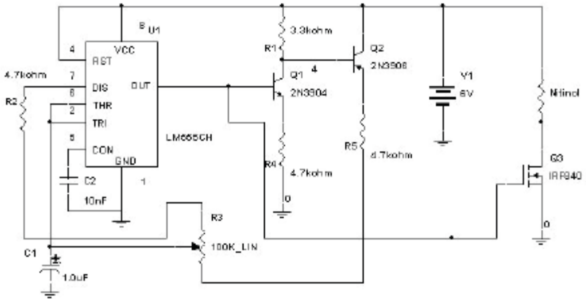
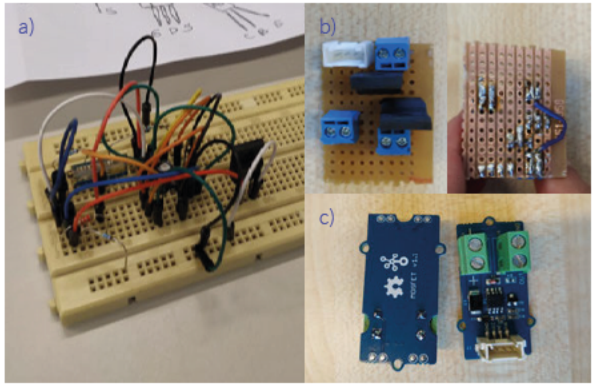


Figure 12.1
Electric circuit for PWM current on SMA wire
(Images Scientific Instruments, 2019).

Figure 12.2
Square wave duty cycle (PWM)
(Images Scientific Instruments, 2019).

Figure 12.3
a) electrical Circuit on breadboard,
b) miniaturised version of circuit and
c) Grove Mosfet modules.



The Grove Module was programmed using the Seeed studio system. The PWM signal was defined in a Seeeduino Lotus, this integrated system of a controller and breadboard, allows the system to be easily connected. Each PWM output on the Seeeduino is capable of supplying 300mA. Dependent on the SMA wire this current would be enough to heat it to activation temperature.

Control System

The control system of the multiple SMA wires within the composite structure is depicted in Figure 12.4. Each SMA wire is individually addressed. The duty cycle and activation loop time are empirically determined based on the desired output and measured temperature of the wire. In the loop, the wire will go through an heating period and a cooling period.

A push button is connected to the system to serve as the user interaction point. Pushing the button activated the heating of the SMA wires and makes the composite move forward. The button must be pressed continuously for the loop to be working. Once the button is let go, the loop will be stopped and the system is reset, such that the heating period is always started once the button is pressed again.

Figure 12.4
Control of SMA wires through grove mosfet driven by the Seeeduino.

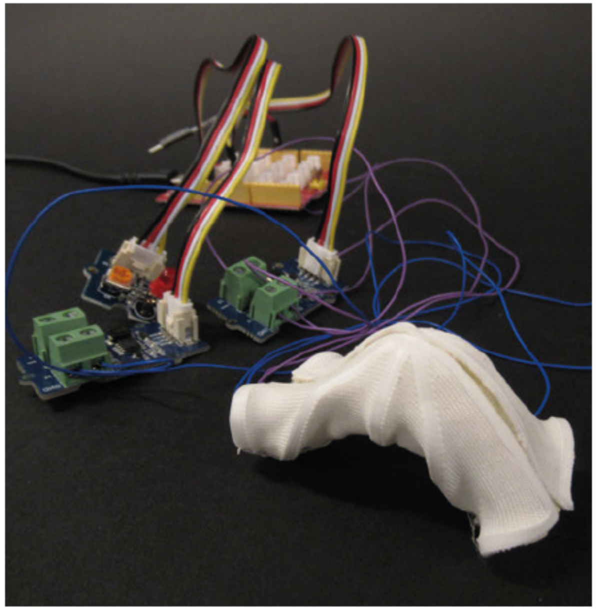
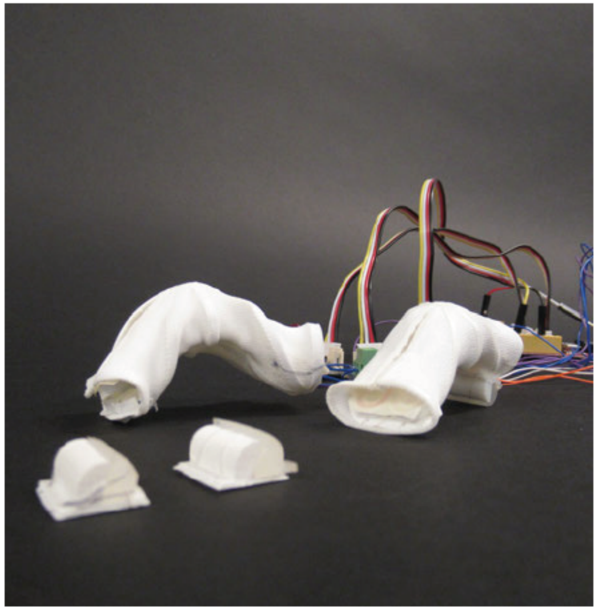


Figure 12.5
Several Variables showing PLA and ABS printed material and the small and big frictional feet.



Section 12.3 Output

The output for this computational composite was based on the initial movement that was demonstrated by the user as caterpillar-like, and is the movement of the developed SMA composite.

The output for the computational composite will be a forward translational movement, as it is the aim of this project. The moving SMA composite, Crawly, that was developed in Chapter 11 would at that stage contract and expand symmetrically. As a result, the material would not move forward in any direction. A few improvements have been made to this material and each variable is discussed in Section 12.3.1. The effect of certain variables on the translational movement is investigated and described, as seen in Figure 12.5.

12.3.1 Material Variable Overview

Several aspects are involved in the making of the computational composite material. Some variables were already investigated in the development of the 4D printed material, such as the type of fabric and the pattern and thickness of the 3D printed part. An overview is given in Figure 12.5 and each component is described below.

Fabric & 3D Printed Structure

The stretchiness of the fabric influences the shape the material takes on after being printed on. More elastic and stretched materials take on a more curved shape. Comparing different fabrics also showed that the desire, or forcefulness, of the 4D printed material to return to its original shape was dependent on the fabric type. Next to this, the structure that is printed on top of the stretched fabric influences the type of shape that is created. An overview of the resulting shapes from different patterns, print thickness and fabric is given in Appendix C. The effect of different filament materials, PLA and ABS was investigated. It was observed that the type of filament influences the stiffness of the 4D printed material.

Frictional Foot

Anisotropic frictional feet are developed so that the structure will move freely in the forward direction but the backwards movement, as the SMA wire relaxes, is inhibited. The component is 3D printed in PLA which acts as the smooth edge and as the support structure for the sticky part: dragon skin silicone. The dragon skin part is first cast into a semi-circular mold. Afterwards it is cut to shape and sewn attached to the 3D printed component.
Several composition of the PLA and dragon skin were tried by changing the angle in the semi-circle. Different angles for the PLA component of the friction feed were tried: 90 °, 95° and 100°. The silicone component was adjusted to accommodate to the angle of the PLA component. The protrusion of the silicone from the mold was also varied from 0 to 1 mm.

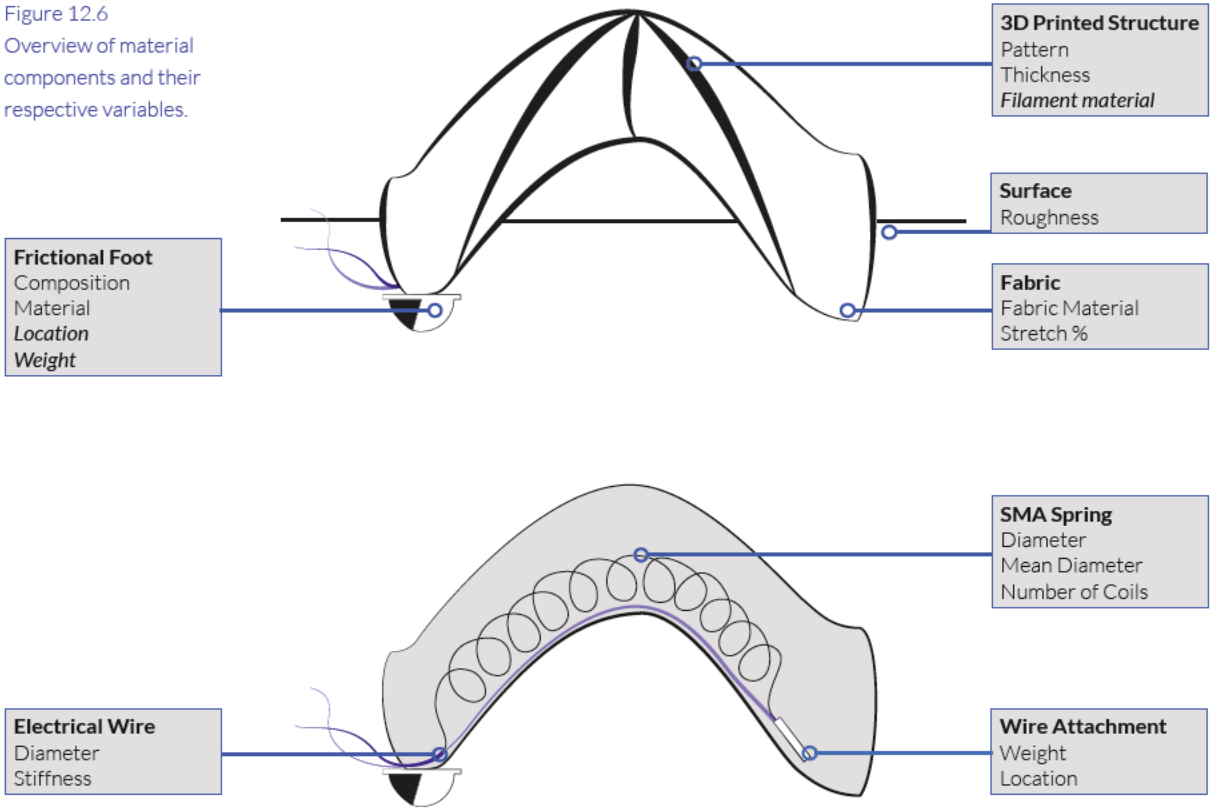
Surface

The roughness of the substrate may have an effect on the frictional force at the foot, it is therefor chosen to use two types of surfaces: course paper and a smooth plastic surface.

Electrical Wires

By changing the diameter of the electrical wires from 3 mm to 1 mm thick, as significant change was observed in the stability of the material. With the thicker and stiffer wires, the orientation of the wire compared to the material would determine if it would stay up or would fall over. It can also be assumed that the stiffness played a role in the inhibition of movement. With the thinner wires this effect has been diminished, but it can not be ruled out completely.

Figure 12.6
Overview of material components and their respective variables.



Wire Attachment

At the end of the material, the electrical wires are circled back to return all the wires at one end. The wires are secured by pushing them into the 3D printed component depicted in Figure 12.7, which is sown into the material. Another benefit is that SMA does not slide anymore.

SMA Spring

The SMA spring has a number of variables that influence the force and stroke that is ideally used in a design. The relation between these variables has been discussed in Chapter 3. The influence of these springs has not been further investigated, although it can be noted that initially the 0.2 mm could not exert enough force on the material with frictional foot to move it forward. For this reason it has been chosen to use a 0.35 mm spring.

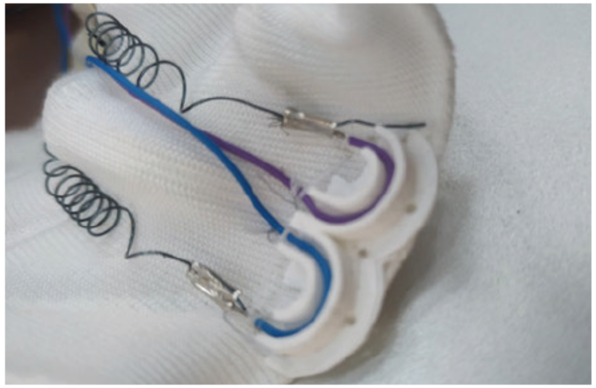


Figure 12.7
Wire holder sewn inside the material structure.

Filament material 1: ABS
Friction Foot: Small
Configuration: Friction foot at electrical wires, 0°

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Paper	0	-1.0	0.0	-1.0
	15	-0.2	0.0	-0.2
	30	0.0	0.0	0.0
Polystyrene	0	-1.7	-0.3	-1.4
	15	0.0	0.0	0.0
	30	0.0	0.0	0.0

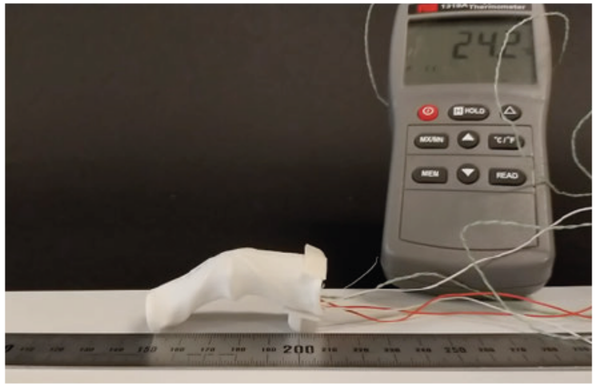
Filament material: PLA
Friction Foot: Small
Configuration 1: Friction foot at electrical wires, 0°

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Polystyrene	0	2.2	5.4	-3.3
	15	0.3	1.6	-1.4
	30	0.0	0.0	0.0

Filament material: PLA
Friction Foot: Small
Configuration 1: Friction foot at electrical wires, 10°

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Paper	0	1.5	12.8	-11.3
	15	-0.3	4.0	-4.3
	30	-0.7	0.7	-1.3
Polystyrene	0	0.3	3.2	-2.9
	15	-0.3	2.9	-3.1
	30	-0.5	0.5	-1.0

Figure 12.8
Test set-up consisting of a thermocouple, ruler and SMA composite.



12.3.2 Material Variable Influence

Due to the number of changes made to the computational composite material and the number of variables each new component has, it was important to investigate the influence each variable has on the movement of the material.

Test Setup

The composite made of the 4D printed structure and the wire holder and two 0.35 mm SMA springs was connected to the Seeeduino and placed next to a ruler, depicted in Figure 12.8. For each variable that was changed 3 tests were conducted that lasted 3 actuation cycles.

The changes that were made to the composite started with the 4D printed filament material, then the position of the friction foot and finally the weight put on the friction foot.

Filament material 1:
PLA
Friction Foot:
Big
Configuration:
Friction foot at electrical wires, 0°

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Paper	0	1.5	2.8	-1.3
	15	-1.5	0.0	-1.5
	30	-0.3	0.0	-0.3
	45	0.0	0.3	-0.3
Polystyrene	0	-0.7	1.5	-2.2
	15	-1.7	0.3	-2.0
	30	-0.5	0.0	-0.5
	45	0.0	0.0	0.0

Filament material:
PLA
Friction Foot:
Small
Configuration 2:
Friction foot at wire holder, 0°

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Polysterene	0	0.0	0.0	0.0
	7	-0.5	-0.5	0.0
	15	0.0	0.0	0.0
	22	0.0	0.0	0.0
	30	0.0	0.0	0.0
	45	0.0	0.5	-0.5

Filament material:
PLA
Friction Foot:
None

Surface	Weight [g]	Average Distance [mm]	Activation Distance [mm]	Cooling Distance [mm]
Paper	0	-0.6	7.2	-7.8
	7	-1.9	5.8	-7.8
	15	0.0	4.1	-4.2
Polystyrene	0	-0.2	7.8	-7.6
	7	-3.8	4.1	-7.9
	15	-0.3	3.4	-3.8

Insights

From analyzing the results per cycle it became clear that all of the tests had an initial peak of transversed distance during the first cycle. This may be because the test starts with a fully relaxed material which has cooled down to room temperature, compared to the 'cooled down' material in between cycles that is still around 5 °C higher than room temperature. For this reason it can not be assumed that the material has completely expanded at this point, but extending the cooling time would reduce the actuation speed.
To take this initial offset in distance into consideration the average is taken starting from the second cycle. An overview of the resulting average transversed distance and average activation and cooling movement of the materials is given per variable.

It can be seen that the composite from ABS transverses in a negative direction on both a paper and polystyrene surface. However, with increasing weight on the frictional foot the composite does not move anymore. Contrastingly, the composite from PLA a polystyrene surface with a weight on the foot of 0 to 15 grams moves forward.

The angle at which the foot is attached to the material also allows the PLA composite to move, with up to 30 grams attached to the foot, although transversed distance is backwards and the activation and cooling distance has diminished compared to the foot having an angle of 0° and a load of 0 to 15 grams. Surprisingly, this configuration of the composite moves forward on a paper surface but with an increased weight on the frictional foot will move backwards.
The same effect is observed with frictional foot B, which also only moves forward in that set-up. Overall, the transversed distance with frictional foot B for each weight has been increased, even though the average activation and cooling distances have diminished. This is a good example of how the contraction and expansion of the material partially cancel each other out, and how an imbalance in these values results in a transverse motion.

Changing the configuration of the smaller frictional foot from attached at the electrical wires to the other end of the material has resulted in for the most part no translational movement. Initially, the composite was unbalanced and the electrical wire end was lifted from the ground. Even balancing the composite out by adding weights at the electrical wires did not result in a translational movement.

Finally, the configuration without a frictional foot surprisingly resulted in the largest translational movement of an average of 3.8 mm per actuation. This was mainly unexpected since 'Crawly' the moving material from Chapter 11, would contract and expand symmetrically over the center. It may be that the addition of the wire holder and having all the wires come out at one end of the sample is responsible for this unsymmetrical behavior.

12.3.3 Final Translational Movement

Based on the study of the influence of each component on the movement of the material, it was found that the most effective configuration for translational movement was PLA filament, without a frictional foot and with a weight on the electrical wires of 7 grams. Over the course of 11 cycles and 5 minutes and 44 seconds the material traveled 38 mm, resulting in a speed of 0.11 mm/sec or 6.6 mm/min. The full movement can be viewed by scanning the QR code.

Translational
Movement
Video

Translational
Movement
Video
Shortened Version

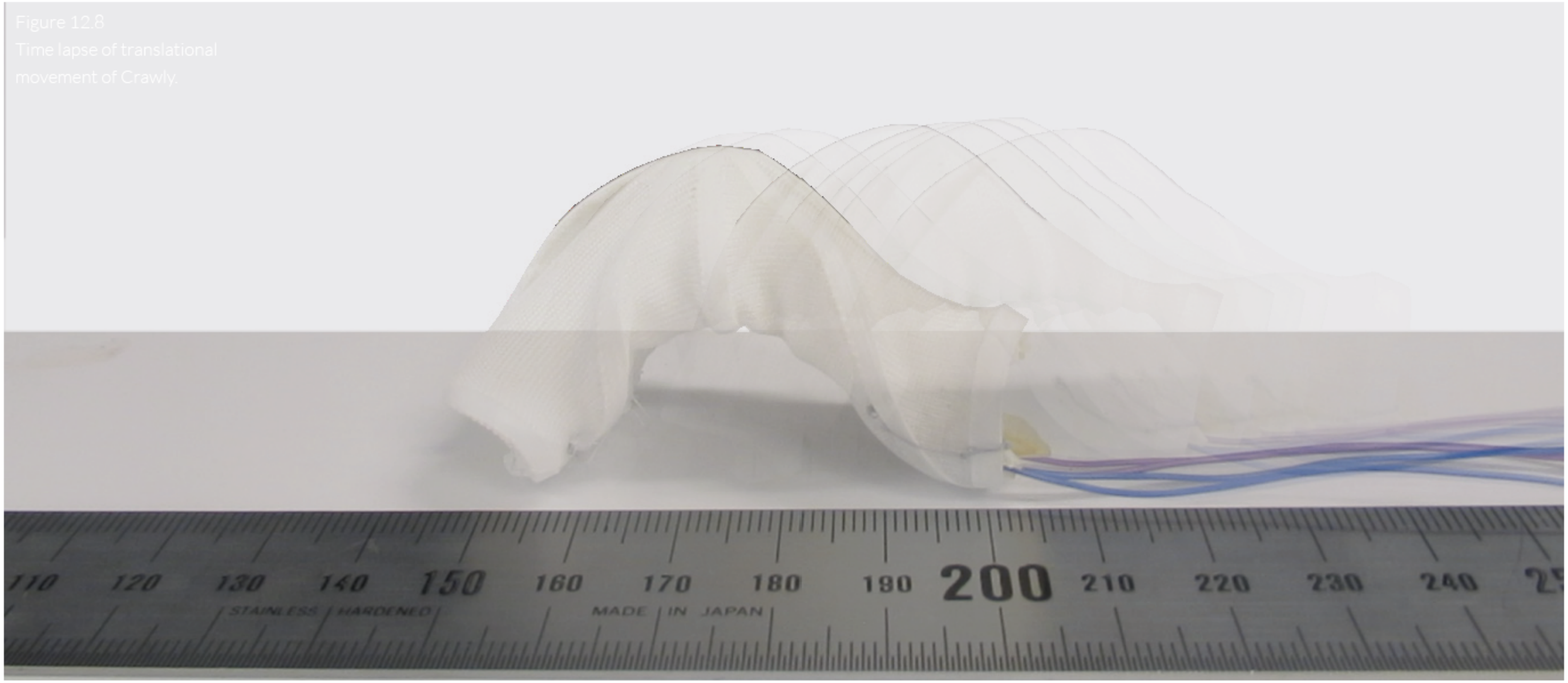


Figure 12.8
Time lapse of translational movement of Crawly.

Chapter 13

Conceptualization

To create a material experience vision the experiential characteristics are first investigated in Section 13.1. Together with the technical characteristics the material experience vision is formulated in Section 13.2. A creative session was organized to get inspiration on new areas of application which are presented in Section 13.3, followed by the ideation phase in Section 13.4 Finally, three concepts were further developed in Section 13.5. Final recommendations for the development of these concepts and the computational composite in general are described in Section 13.6.

Section 13.1 Experiential Characterization

Goal

The goal of this user study is to define the experiential characteristics of the moving SMA-based composite. In the previous user test, an emphasis was put on the performative level of user experience of a wide range of material samples. In this stage, the other experience levels are also recorded and reflected upon to create a material experience vision. In this study 'Crawly' is assessed on four experiential levels: sensorial, interpretative, affective and performative.

Method

Participant with little experience or knowledge about the material or project will be asked to take part in the study. Before conducting the test, participants are asked to sign a consent form and a release form of the recorded audio and video footage during the test. First, the purpose of the study will be explained to the participant: to characterize the material in experiential levels. The test set-up can be seen in Figure 13.1.

Part 1: Material
The Ma2E4 tool will be used to score the material (Figure 13.2):

1. Exploring the performative qualities of the material | The participant is asked to freely explore the material. The actions are noted on the map by the facilitator. Additional questions are asked: 'how do you move the material', 'how do you touch the material' and 'how do you hold the material'.
2. Exploring the sensorial qualities of the material | The participant is asked to rate the material & movement according to the scale.
3. Exploring the affective qualities of the material | The participant is asked to select at least 3 emotions form the affective vocabulary and to place them in the graph according to the axis: pleasant/unpleasant and intensity.
4. Exploring the interpretive qualities of the material | Using the interpretive vocabulary, three meanings they think the material evoke are chosen by the participant. The participant is asked to reflect on those three words. A set of interpretive pictures is used to specify what they meant exactly (Figure 13.3 .

Part 2: Moving Material
An adapted version of the Ma2E4 tool is used to score the material movement, illustrated in Figure 13.2. The same order of questions is used. A new set of pictures related to movement is made to support the interpretative section.

Figure 13.1
Material characterization
test set-up.

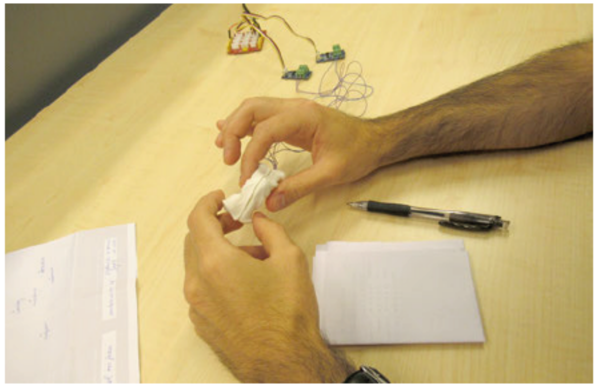


Figure 13.2
Ma2E4 toolkit with the adjusted sensorial level characteristics that describe movement used in the second part of the test.

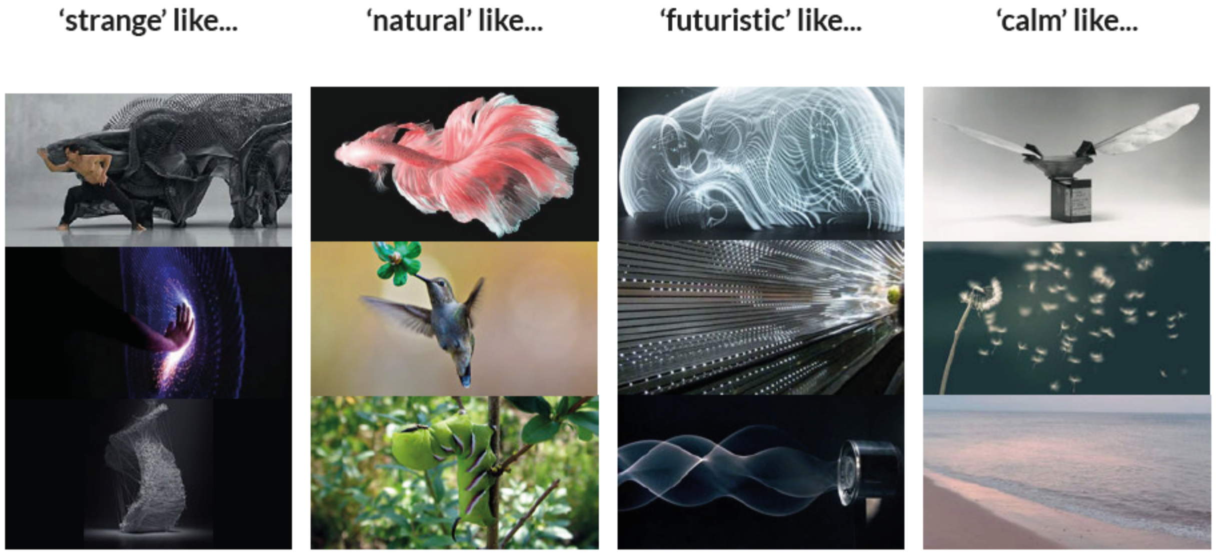
Results

Part 1: Material

Most participants would immediately lift the material up and hold it at both ends, touch the material by pushing it with their finger at the top. After gaining more confidence with the material, participants would bend the material to see what it's limits were and even twist it around.

Participants did not agree about the softness of the material, some suggested since it is a mixture of something hard (3D printed structure) and soft (textile) it was in between soft and hard. Whereas others thought the overall material was soft.

Figure 13.3
Pictures set for meanings related to strange, natural, futuristic and calm movement.



Overwhelmingly the material evokes ***curiosity*** by all participants. ***Amusement***, ***comfort*** and ***fascination*** is felt by at least two participants, as well as ***confusion*** and ***doubt***. A mixture of ***confusion*** and ***curiosity*** was felt because people did not understand what was inside the material, and were interested to find out. The unfamiliarity with the material and the unknowingness of its purpose lead to a sense of doubt.

Four out of six participants attributed ***futuristic*** to the material due to the novel approach to a structure with the composite composition. The second most common meaning was ***calm***, because the material seems relaxing and close to nature. The curvy shape lead to interpretations such as ***calm***, ***cozy*** and ***feminine***. On the other hand the material was also described as ***strange*** because of its insect like shape and combination of high-tech and cute.

Since the composite brings out wonder and curiosity, play-full/toy-like aspects were seen as pleasant qualities, next to flexibility and softness. The most disturbing qualities of the material is that it looks fragile and passive. The combination of materials was seen as the most unique aspect of the material.

Part 2: Moving Material

With the activation of the material, participants were asked to first observe the movement and then to freely explore the material. Most participants were reluctant to move the material themselves, because they did not want to interfere with the movement of the material. The participants would hold the material in the palm of their hands and squeeze it slightly. One participant remarked that having the material squeeze the index finger felt like a baby grabbing their finger.

Notably, some participants defined the movement as not just the activation phase but the activation and cooling phase. Consequently, the movement was not rated as continuous by all participants because during the cooling phase the material seems to be standing still. Keeping this in mind, the movement may also be perceived as jerky because of the intermittent stops. Most participants thought the material moved continuously and smooth. All participants thought the movement was patterned and slow.

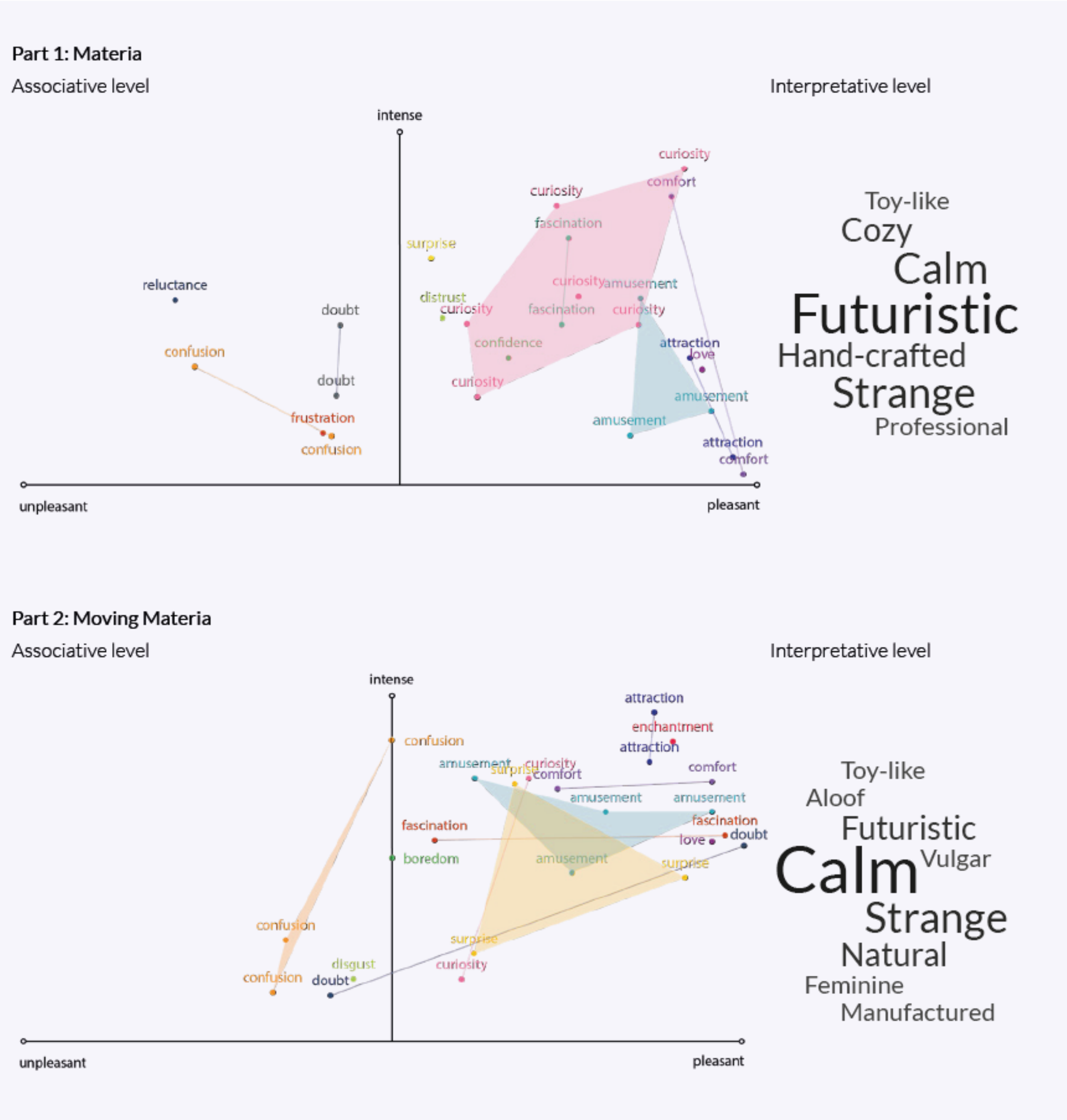
The amount of participants that felt ***curious*** was lowered and replaced by ***surprise*** and ***amusement***.

Overall, the pleasant emotions were all felt with more intensity. In one instance, ***confusion*** was also ranked high in intensity, because the technology for moving the material was still unclear.

For five out of six participants, ***calm*** was one of the first meanings they attributed to the movement. Most related the pattern or rhythm of the movement to the tides of the sea. ***Strange*** was attributed because of the uncertainty in the pattern of the movement and the novelty of having a silent actuation. For the same reasons, ***futuristic*** was also used to describe the moving material. Finally, some participant also saw a natural aspect in the movement and even related it to a caterpillar.

Based on the qualities described by the participants, it was found the most positive quality would be the calm movement, whereas the negative qualities are that it is slightly aloof and boring because it moves quite slow. The most interesting qualities were the intimacy the material evoked and the balance between the actuation of the material and the return to its original shape because of the structural rigidity of the material.

Figure 13.4
Illustrations of the associative and interpretative results from the experiential study for the material and moving material.



Section 13.2 Material Experience Vision

Looking at the results from the material characterization, what are the technical/experiential qualities that should be emphasized in the design of a computational composite?

Solely focusing on the material, the emotion it elicits are curiosity, amusement, fascination and comfort. At the same time, the material was described as futuristic, calm, cozy and strange. Depending on the context, these characteristics can be applied in different ways. For instance, when designing an interface with the material, the futuristic yet strange characteristics may be elevated in the design to evoke a combination of curiosity and confusion. Coupling these emotions may lead to a meaningful experience of the material.
At the same time, the feeling of comfort can be enhanced by accentuating the calm and cozy sides of the material. These characteristics may be more suitable in close and long-lasting relationships between the user and material, where trust and affection should be developed.

Taking into consideration the movement and the moving material, the most important insight was the hesitation participants exhibited to further manipulating the material as it was moving. Therefore, a suitable application would not make the user do anything to the material as it is activated and to experience it passively. Furthermore, the moving material was overwhelmingly described as calm and related to the tides of the sea. Next to this, the material creates a warm and pressured feeling when it is placed around the skin. The moving material made people feel surprised and amused.

From the experiential study it was found that the material elicits many contradictions. The material is cozy yet strange and people may feel curious and confused at the same time.

Combining these characteristics the following material experience vision was developed:

> “The material will express calmness and comfort in people’s life allowing them to acquaint themselves with the unknown and strange through passive interaction”

The material serves as a first encounter to the new age of computational composites. Employing it in a daily object will reduce the barrier for people to approach the material. In addition, it lets people reflect on the way computational composites have replaced the traditional material and invites them to re-imagine other aspects of their lives with computational composites. As a moving material, surprising and amusing applications can be found that allow the user to open up to the material.

The ultimate purpose would be for the material to sensitize people to the idea of a world where materials move from passive objects to active elements in our daily lives.

Section 13.3 Creative Session

The composite that was created features a range of pleasant, disturbing and unique qualities. By doing the experiential characterization, these qualities were uncovered and the emotions and meanings that the material elicits were mapped. A material vision was derived from these insights. Next to this, the movement was designed to be translational, but given another context it can also be seen as gripping or pinching. A creative session was organized to find other ways of using the material and new areas of application for the material.

Goal

The composite that was designed during the project has unique qualities which were found using the experiential characteriation map of the Ma2E4 toolkit. Based on 6 participants, qualitative insights were gained on the meanings, emotions and sensorial qualities the material has. These qualities were taken as the basis of finding a suitable application. The creative session is used to gain inspiration and explore various opportunities for an product or application.

Setting

Four participants, who also already gained experience with the material through the experiential characterization map, were asked to join the creative session. The background of these participants is in industrial design.

Set-up

Using the Creative Problem Solving Process (CPS) by Buijs and Tassoul (2005), the session will go throught 3 phases: problem statement, idea generation, and concept development. Due to time constraints, the concept development is excluded from this creative session.

Introduction & Ice-breaker (20 min)

To start off, the problem statement was introduced: ‘What product or applications can be made from this material that can change shape?’

An introduction of the material was given by means of a demonstration. The participants were free to touch and interact with the activated material. Based on the results of the experiential characterization, the descriptions that were found were presented.

Idea generation (30 min)

To clear the mind of associations, the participants were asked to create a flower association for the words: calm, strange and futuristic.

A brainstorm was done on the verbs associated with movement. Up to know, the movement is seen as forward translation. Can this be re-imagined?

From these verbs, three were used to reformulate the initial problem statement to: ‘What product or applications can be made from this material that communicates/swims/grows?’

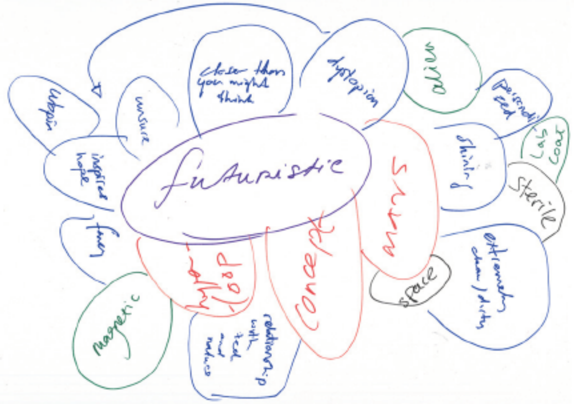
The whole group then brainstormed using these three questions.

Clustering (25 min)

Finally, the ideas were clustered together. The resulting groups were: environmental, symbiosis, consumer, health, practical, exploration and extending human capacity.

Closure (5 min)

Each participant was asked to shortly comment on the session and for any recommendations.



Insights

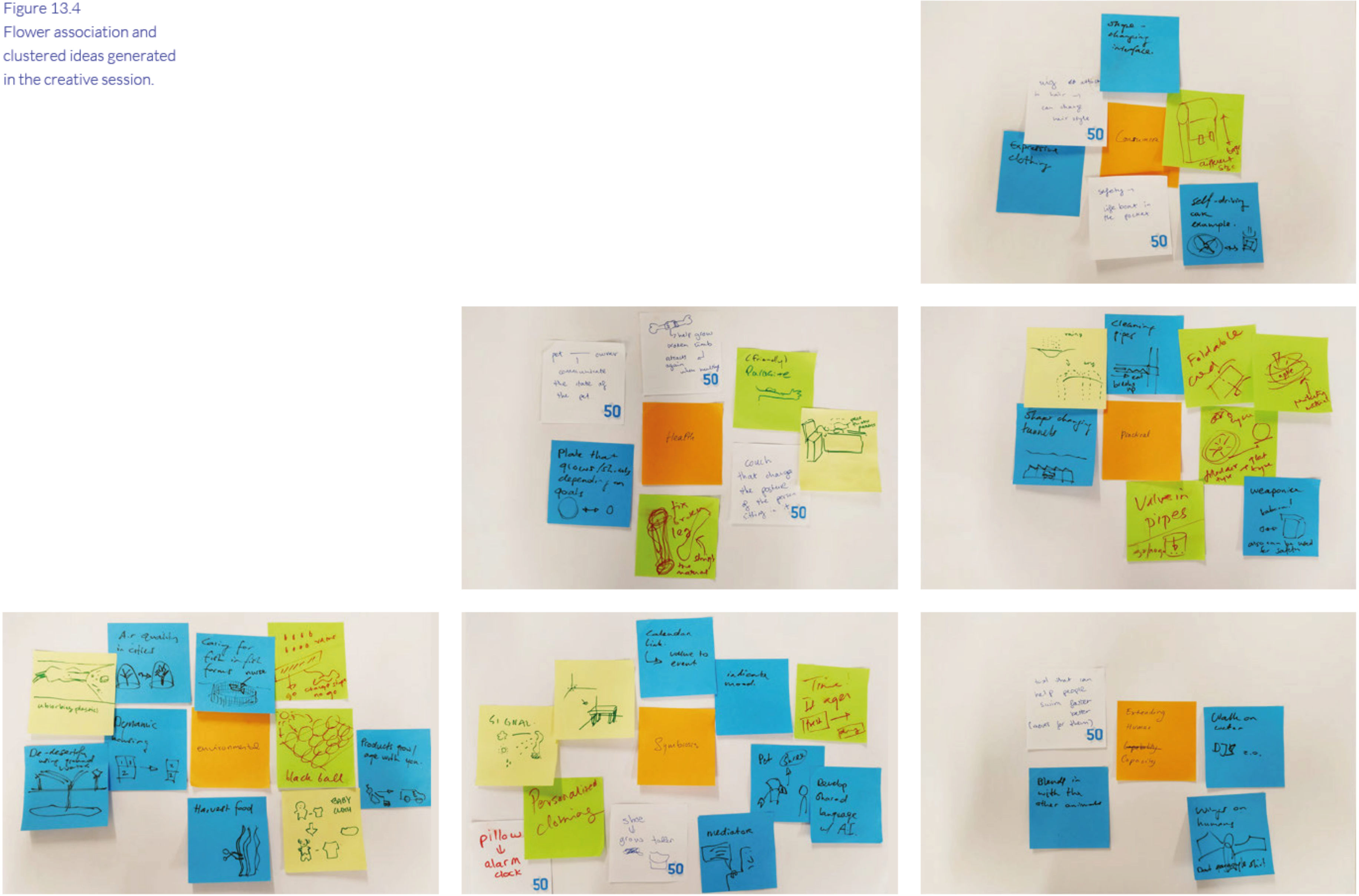
Taking into consideration only the translational movement of the material, the range of applications was quite limited, with some of the most innovative ideas being a no-tire vehicle or drug delivery systems inside the human body.

Some interesting applications surfaced from the creative session, by defining the movement in a different or abstract way. First of all, the idea of a symbiosis as close and long-term interaction between the person and the material brought about a couple of interesting ideas connected to the interaction suitable to the computational composite. Next to this, it also seems suitable to the qualities the material possesses: calm, warm, cosy.

Another surprising area of application was in the health sector, with anxiety relieving product, heating applications to combat cramps, muscle-aches or the cold.

Finally, leaning into the cosy, strange and calm aspect of the material, applying it in the sleep or relaxation related context fitting. The comfort associated from the enveloping material structure and movement may be suitable for body wrapping furniture or blankets.

Figure 13.4
Flower association and clustered ideas generated in the creative session.



Section 13.4 Ideation

Based on the new areas of application found in the creative session, another round of generating ideas was done individually. As a warm up, flower association chains were made with the meanings for the material as starting point: strange, futuristic and calm. Furthermore, to fit the scope of computational composites, two more flower associations were done on how to express and to communicate with a movement. Finally, the area's of application from the creative session we used to ideate further on.

Consumer products

Ideas range from relaxation and care products to furniture. In particular, the moving lamps, either shape changing or moving around the room adopt the materials technical characteristics. The activation of the material by warm objects was also an interesting direction for a consumer product, such as the tea cup holder to protect the hands.

Exploration

Perhaps a new way of exploring our earth and outer space can be envisioned using this material in slow and soft robots. Geometridae caterpillars translates to earth-measuring for a reason, and the locomotion can be applied to this purpose of exploration and data gathering. Several scenarios were imagined: a single robot or within an inter-communicating swarm.

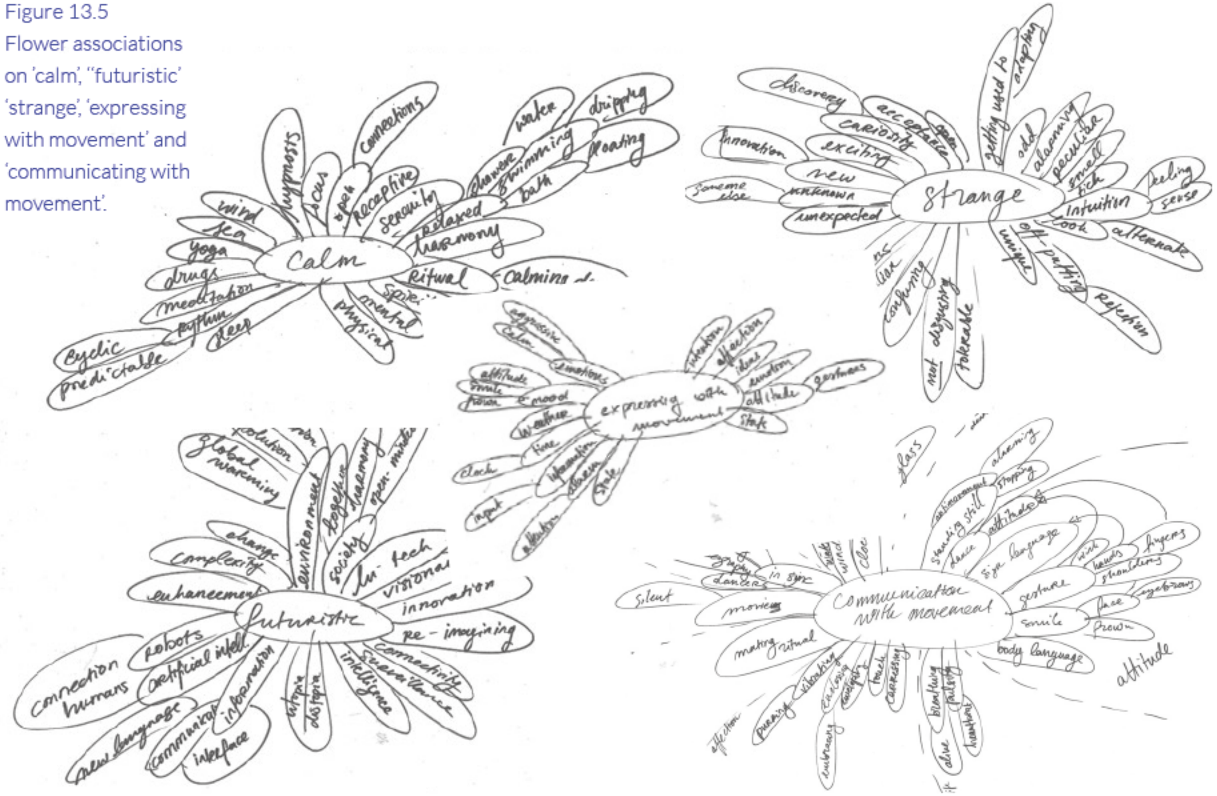
Medical

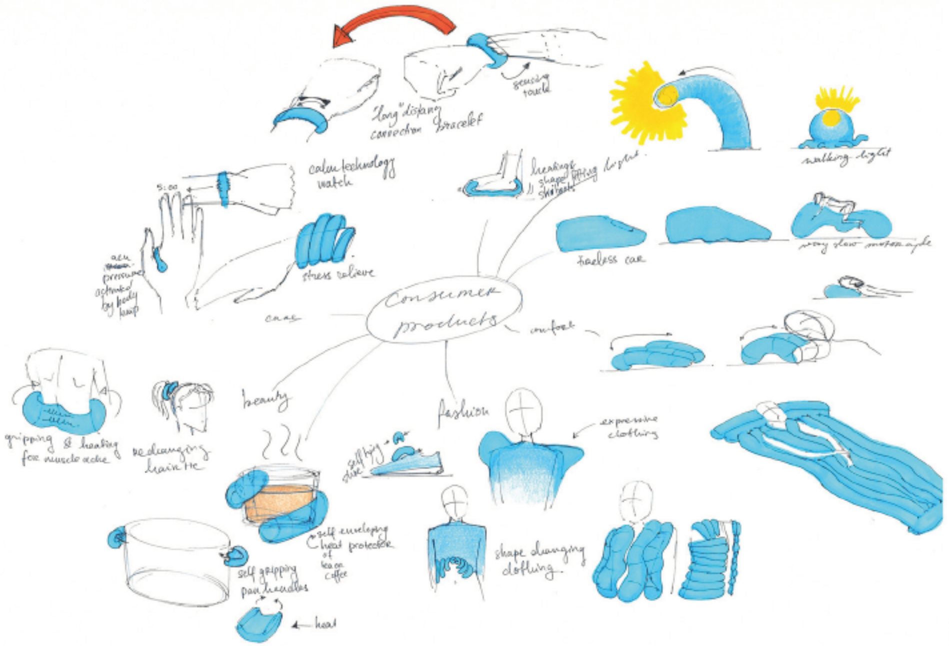
Heat and pressure are two of the most relevant aspects of the material in the medical field, to provide relaxing massages or to heat up the body. Next to this, the mental health aspect was also considered: loneliness, stress, exhaustion. Perhaps the material can be designed to be more life-like, acting as a buddy. A sleeping buddy is proposed, which cuddles the user and mimics the breathing pattern of a sleeping organism. More innovative ideas are finger prostheses and a vitality checking material that crawls over the body.

Symbiosis

To have a close and long-term interaction, or symbiosis, between the person and the material there should be a benefit for the user. The envisioned way is by creating an intimate relationship, which can be as a companion to the user. The buddy could even help communicate certain emotions to others. Another way of looking at symbiosis is as a supporting environment. Structures from the material may organize themselves around the wishes of the user, as self assembling furniture or moving walls. Finally, support can also be by showing progress and achievements, or communicating near events by incorporating data streams into the computational composite.

Figure 13.5
Flower associations on 'calm', ''futuristic' 'strange', 'expressing with movement' and 'communicating with movement'.

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care
Consumer products
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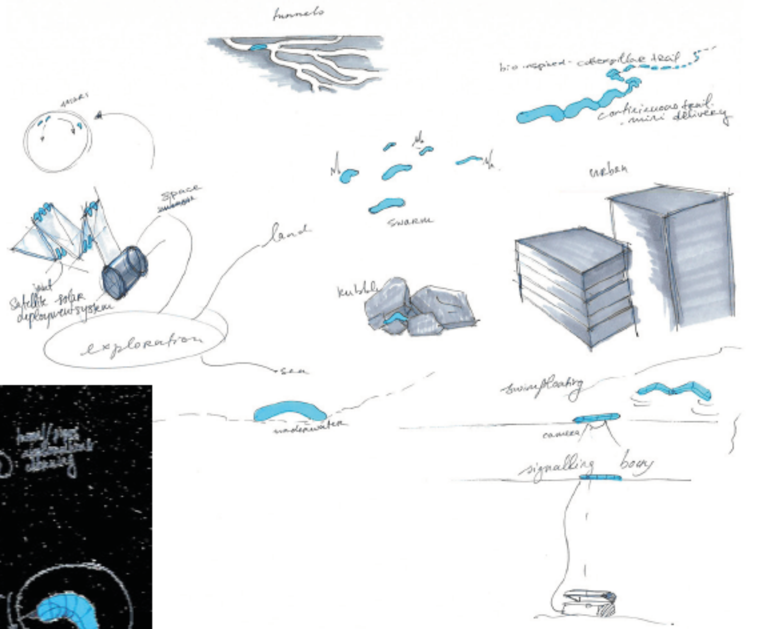
self tying shoe
self enveloping heat protector of tea or coffee
self gripping pan handles
heat
shape changing clothing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continuous trail - mini delivery
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swarm
urban
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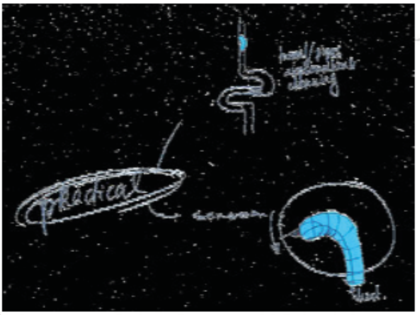
practical
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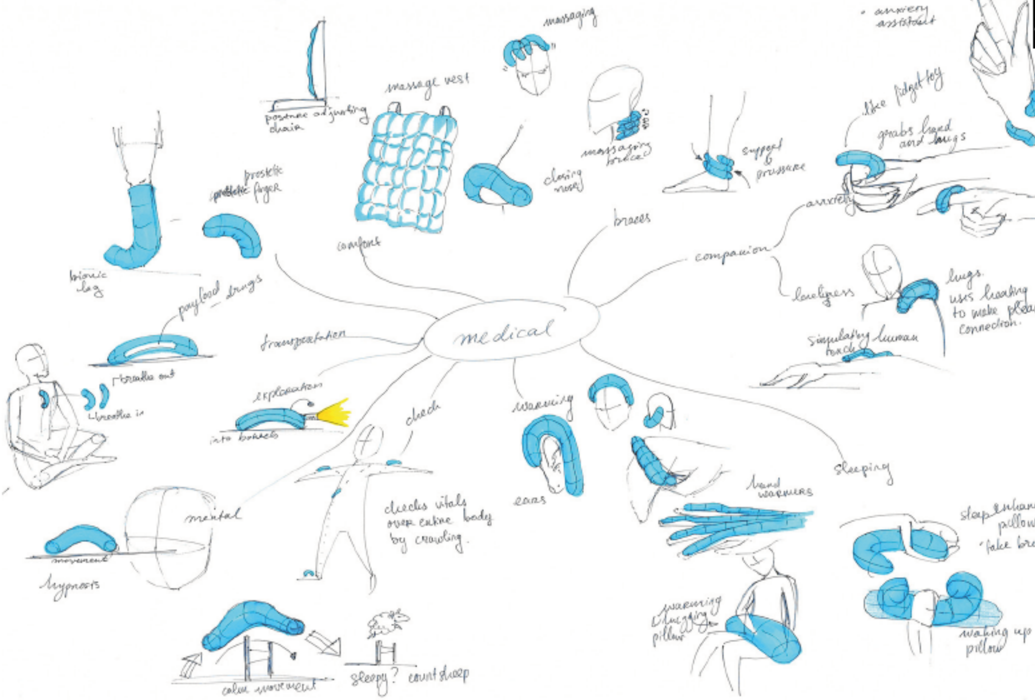
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massaging
massage vest
posture adjusting chair
massaging brace
closing nose
support & pressure
like fidget toy
grabs hand and hugs
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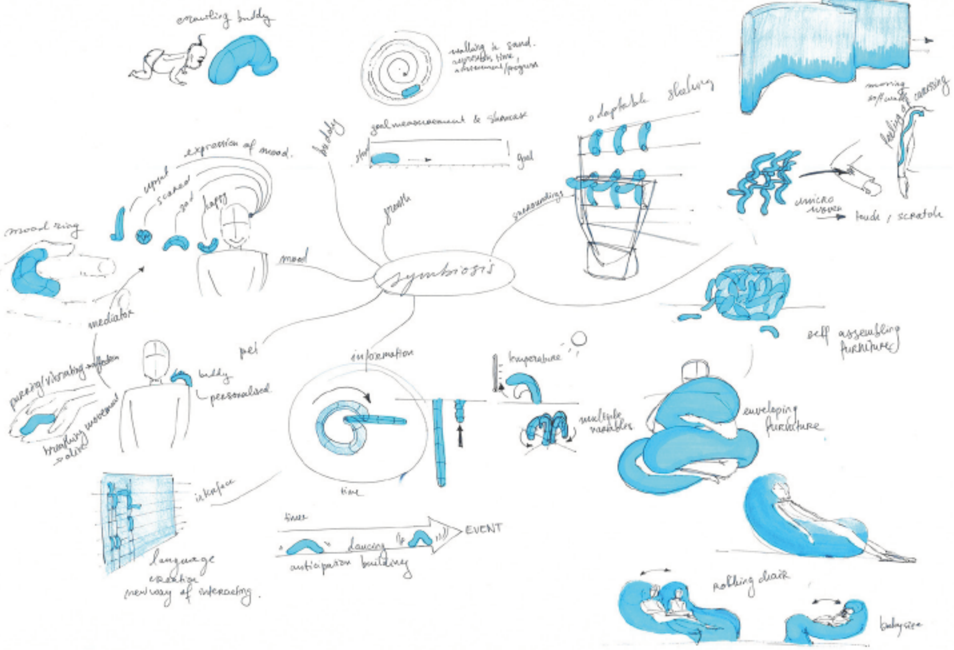
prostetic finger
bionic leg
comfort
braces
companion
loneliness
hugs. uses heating to make personal connection.
simulating human touch
payload drugs
transportation
medical
breathe out
breathe in
exploration
into bowels
check
warming
ears
hand WARMERS
sleeping
mental
movement
hypnosis
checks vitals over entire body by crawling.
sleep enhancing pillow
fake breath
warming hugging pillow
waking up pillow
calm movement
sleepy? count sheep


crawling buddy
walking in sand. represents time, achievement/progress
goal measurement & showcase
start
goal
buddy
adaptable shelving
moving softwall
feeling & caressing
expression of mood.
upset
scared
sad
happy
mood ring
growth
surroundings
unicro woven
touch / scratch
mood
symbiosis
mediator
self assembling furniture
pet
purring/vibrating reflection
buddy personalised
treating wound
information
temperature
multiple variables
enveloping furniture
interface
time
timer
dancing
EVENT
anticipation building
language creation
new way of interacting.
rolling chair
baby size

Idea Selection

To select ideas to further develop into concepts, the c-box method was adopted to map the ideas based on innovativeness and feasability. This way an the understanding of the solution space ins enhanced and it gives a rough distinction between the ideas in four groups.

The ideas which fall under the innovative and immediately feasible sector are:
moving light, anticipation building product, expressive clothing, long distance relationship bracelet, meditation guide, anxiety relief bracelet, wake-up pillow and ankle brace.

To further categorize these ideas, the levels of interaction in a computational composite discussed in Chapter FIXME was taken as a starting point.

No user interaction

Inputs are not related to the user interaction and may be influenced by the environment of the material which can be detected using sensors.

wake-up pillow, ankle brace, moving light

Indirect user interaction

Indirect user interaction is based on implicit interaction, as described by Rasmussen et al. (2012): when users may not realize their actions or even online data are being used as input.

anticipation builder, expressive clothing, anxiety relief bracelet, meditation guide

Direct user interaction

The user interacts intentionally with the system through directed manipulation, such as creating a specific sound, manipulating light and direct touch.

long distance relationship bracelet

For each type of interaction, one idea is selected to further develop into a concept. Ideas were selected that could also showcase the designed SMA-based composite in an inspiring and meaningful way to designers.

Based on the way the technical and mechanical characteristics of the material and the insights from the experiential characterization the following ideas were selected: wake-up pillow, meditation guide, the long distance relationship bracelet.

Figure 13.6
Ideas sorted between innovation and feasibility.

Section 13.5 Concept Development

Concept 1: Neowake - *Wake-up Pillow*

At the heart of Neowake is the idea that there is a better way of waking up, leaving the ringing of the alarm clock behind and moving past set hours. Neowake uses the soundless moving technology of the computational composite and applies it at the surface of the pillow to slowly caress the face in order to wake up.

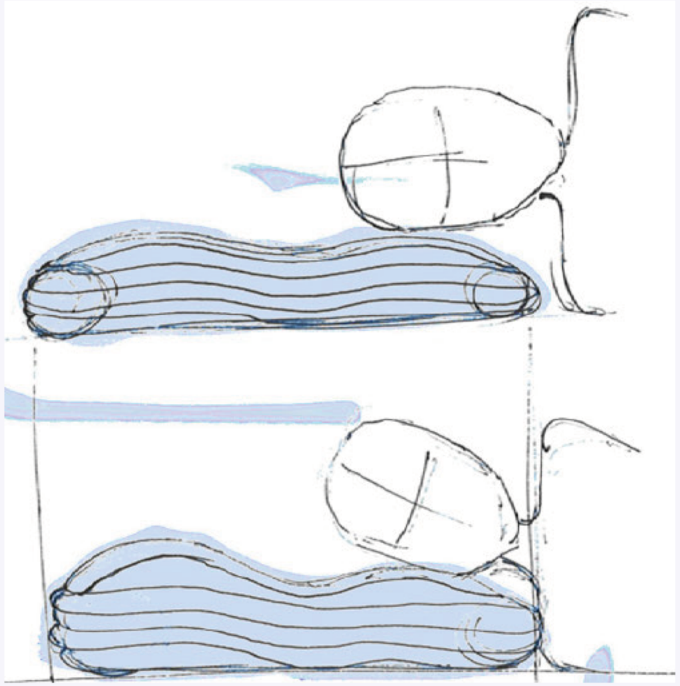
Computational Composite

Input Following the no user interaction scenario, the input for starting the movement of the computational composite should respond to impulses from the environment. A fitting input would be the sunrise, as the brightness of the surroundings increases over time.

Output The resulting output is the slow and soft movement of the surface of the pillow. The pattern for this movement, may change over time. It can be actuated more frequently, by decreasing the actuation and cooling time. Furthermore, the intensity of actuation can be varied from a smooth to a very bumpy surface.

Computation The relation between input and output is determined by the computational step in between. To fit the purpose of the product - waking the user up as the sun rises - it seems fitting to have the movement of the product start slowly with a low intensity when a minimum level of brightness is registered from the surroundings. The movement of the surface gradually increases to a fast and high intensity as the brightness increases, to ensure the user eventually wakes up. An maximum wake-up timer may also be embedded in the computation.

In this case the material is used in this application to introduce a new way of experiencing an ordinary object in our daily lives, the pillow, with the incorporation of a computational composite. By applying a material that is unfamiliar and strange in a context of comfort, it gives the user the chance to become intimate with the material. Furthermore, with the habitualization of the wake-up routine, the user become more and more used to the idea of having thinking and acting materials to support our daily lives.



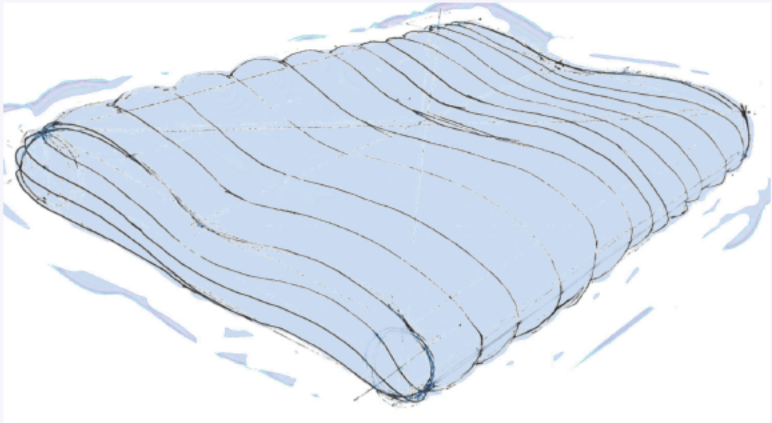


Figure 13.7
Sketches of Neowake.

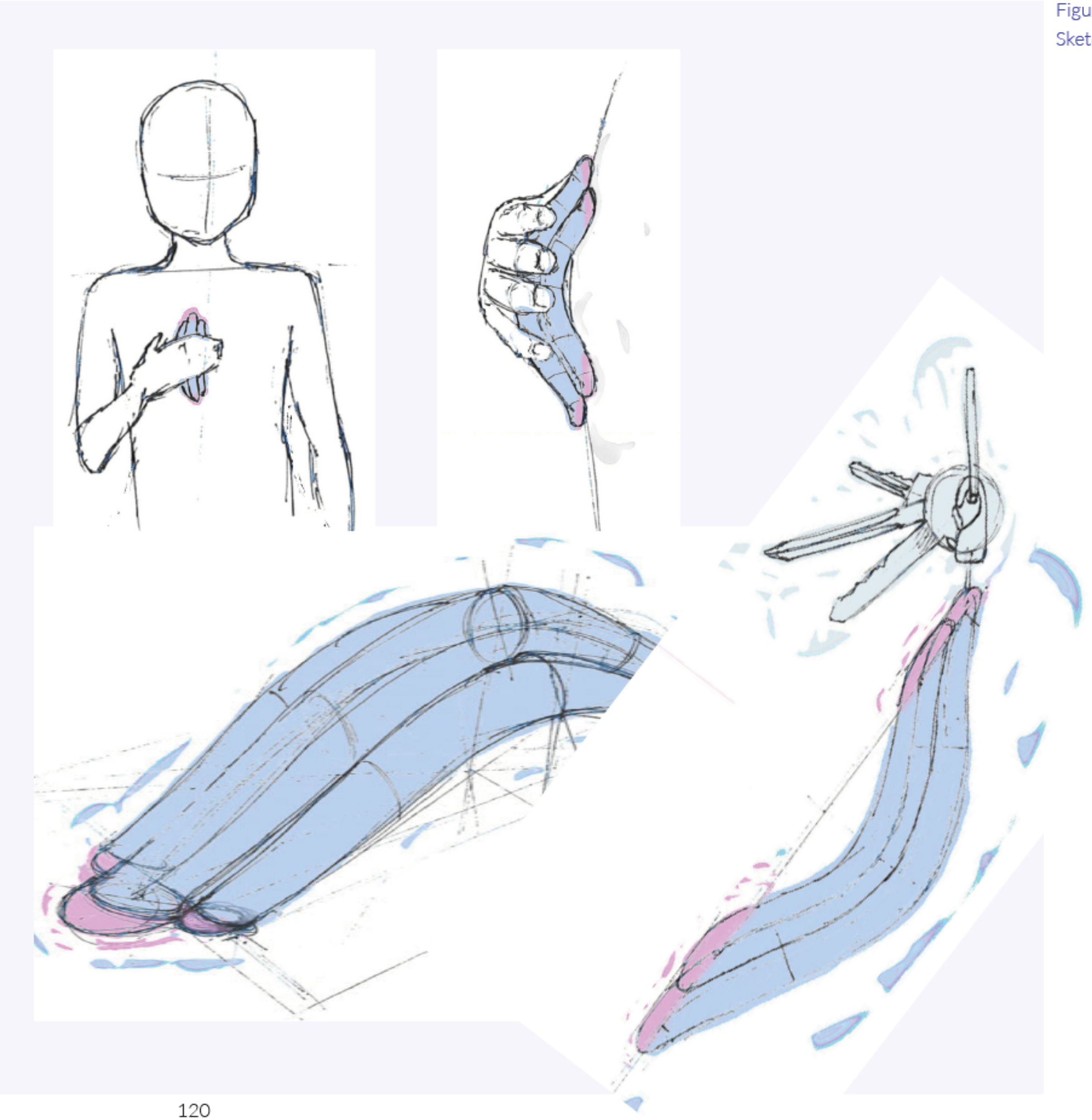


Figure 13.8
Sketches of Exobreathe

Concept 2: Exobreathe - *Anxiety Keychain*

In a state of stress, the sympathetic nervous system is activates, leading to an increased heart rate and shallow breathing. When the user feels anxious or stressed, they can press the exobreathe on their chest. Exobreathe will start to guide the breathing of the user by making it synchronize with the simulated breathing of the material.

Computational Composite

Input As part of the indirect user interaction scenario, the user may not realize that their actions are taken as input. Although the user interacts directly with the product by placing it on their chest, the input that activates the material is considered indirect and outside the scope of direct influence of the user: the heartbeat of the user.
Output The material should imitate the breathing movement of the collapsing and rising chest, while following the regular and relaxed breathing frequency. Pressure is applied to the chest by means of the frictional ends.
Computation The activation of the material is related to the input of a heartbeat sensor. Based on the level of the heart rate different breathing frequency can be taken as a starting point. The breathing frequency is gradually slowed down to the slow breathing: 4 - 10 breaths per minute. Once the heart rate has reached the normal level for a certain amount of time the breathing sequence is stopped which communicates that the Exobreathe is done synchronizing.

The use of the material as computational composite in this type of application means that a complex system of electronics to generate a breathing like movement and design of a soft movable exterior can be omitted and instead the material acts as actuator and exterior.

Concept 3: Adora - *Thinking-of-you bracelet*

Adora incorporates the material in wearable technology. The aim of Adora is to allow you to let someone out of reach know you're thinking fondly of them, instantly. Utilizing the materials ability to contract and heat up as it is activated, the product can give a warm squeeze to the recipient as a way of saying hello.

Computational Composite

Input The user's direct interaction with the product is kept simple and defined as the action of touching the bracelet, measured by a capacitive touch sensor can be applied. Standard sensors can be applied, although it would also be possible to employ SMA wires as a capacitive sensor, also demonstrated by the Sprout I/O (Coelho & Maes, 2008).

Output The output of the material, is the contraction of the three curves in the bracelet, which imitate the squeezing of the wrist. Another output of the material is the increase in heat around this area due to the heating of the SMA for activation.

Computation The input of one computational composite is in this case transferred to another linked and remote computational composite, where the input is reproduced. This entails that the duration and intensity of the initial touch input is related to an equally long and intense squeeze on the receiving end. Even the movement of the finger can be taken as an input, which relates to the frequency of the squeezing pattern.

This computational composite clearly shows the advantage of using a single material to sense and actuate and highlights the possibility of interconnectedness between material, provided with the necessary supporting IoT hardware.

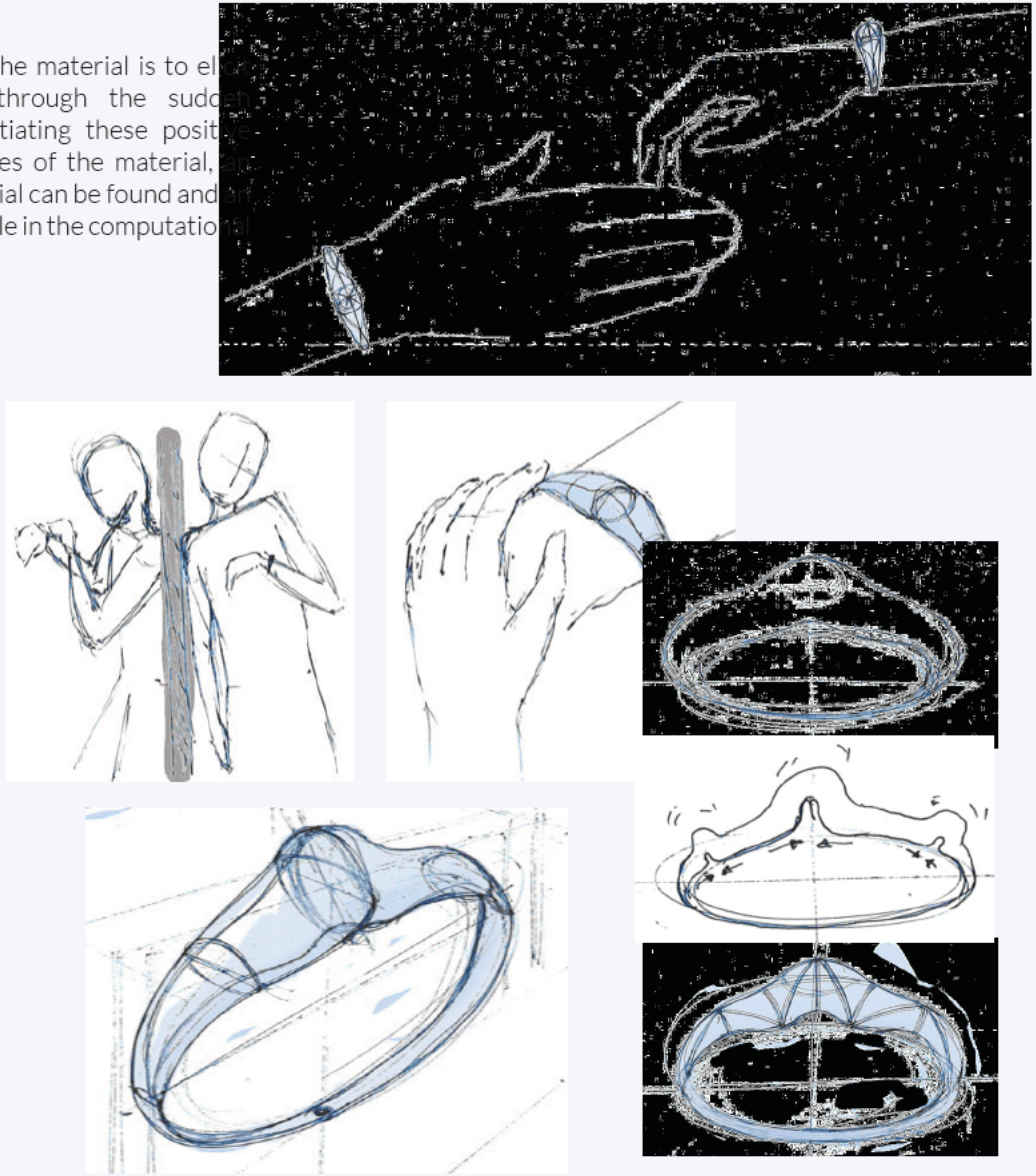


Figure 13.9
Sketches of Adora

The aim of the actuation of the material is to elicit surprise and amusement through the sudden movement. Hopefully by initiating these positive passive and active experiences of the material, an acceptance for the new material can be found and an understanding of the user's role in the computational composite can be established.

Section 13.1 Further Development

The composite that was developed up to this point is capable of changing shape and returning to its original shape because of the balance that was achieved between the SMA actuators and the exterior 4D printed material. A thorough study of the influence of the several components in the working prototype lead to the improvement of the translational motion the material is capable of.

Finally, the experiential characteristics of the material were investigated and a material experience vision was derived, which served as a guide during the ideation and conceptualization phase for the computational composite. In the end three concepts for a computational composite were developed for different user interaction scenarios to highlight the types of user experiences possible.

On the basis of the research done, it is proposed to further develop these concepts into working prototypes to demonstrate the changes made to our daily objects using computational composites. The experience of the user can then truly be mapped and it can be validated if the material experience vision was successfully applied.

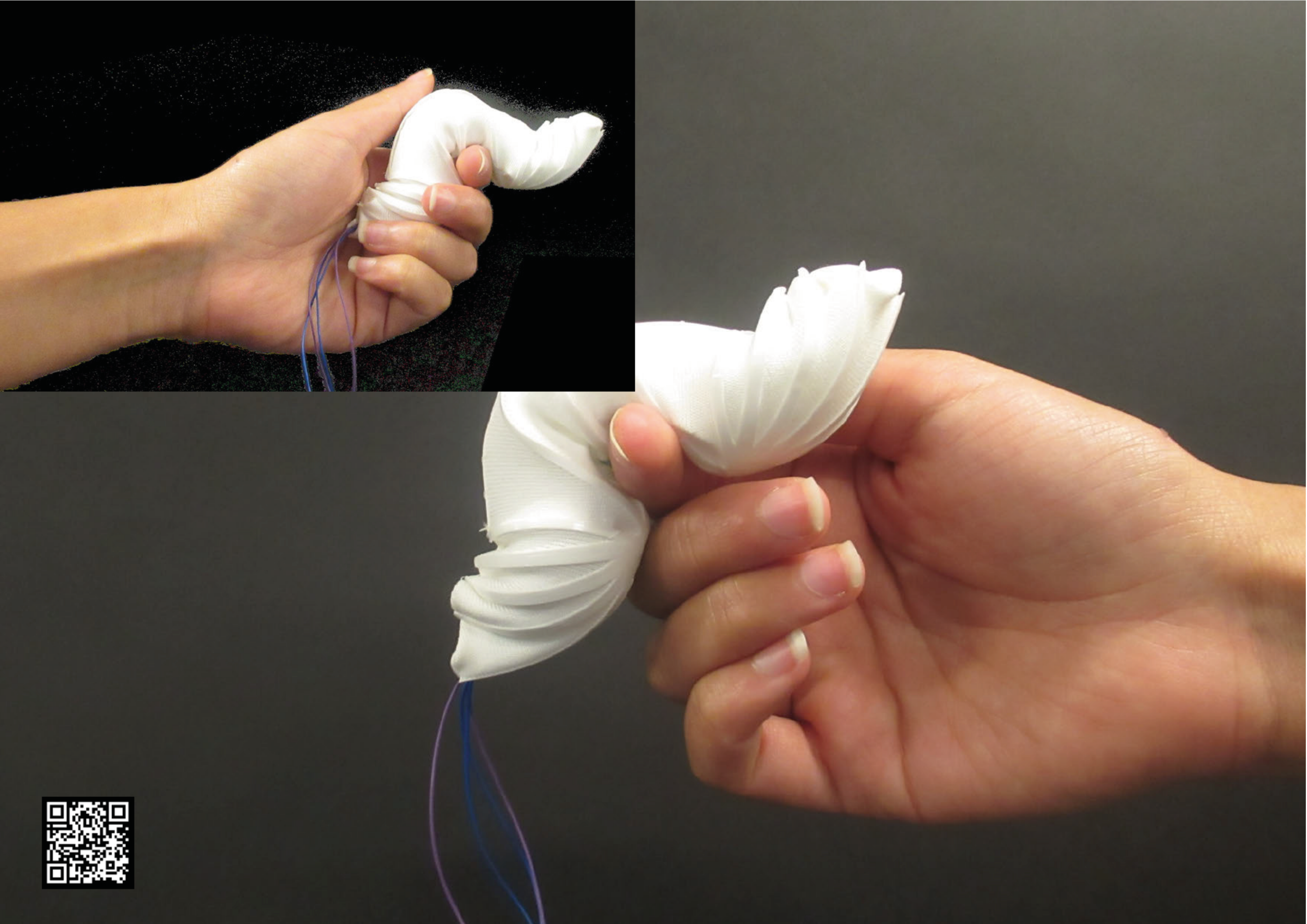
More functionalities may be added to the current concepts, for instance Adora might also be activated through a smart phone App. It is important that the aim of these concepts is kept in mind: to demonstrate the role of the user in the output of the computational composite. Adding multiple layers of interaction makes this understanding more complex but on the other hand also expresses the multi-level capabilities of computational composites and that it does not have to be dependent on just one input.

Next to this, the translational movement the material is capable of may be further developed. A possible research direction would be the use of two or more segments of Crawly. Furthermore, the application of the translational movement to a suitable field be further investigated.

The manufacturing of the computational composite may also be improved upon. For example, at this point the assembly of the composite with the holding components and the SMA wires is done manually. A possible solution would be looking into 3D printing the wire holder component and the shape pattern on the stretched fabric in one time, reducing the need to sew it in at a later stage.

In addition, the 4D printed shape may be changed based on the several shapes experimented with in Appendix C and even beyond them. Different shapes and ways of actuation can be imagined with the composition of SMA and 4D printed textile as a basis.

The ultimate purpose for the material would be to sensitize people to the idea of a world where materials move from passive objects to active elements in our daily lives. Next to letting people experience the material in daily object, this vision can also be realized by a larger installation, such as an interface made of the computational composite. The materials futuristic yet strange characteristics may be elevated in such a design to evoke a combination of curiosity and confusion. Coupling these emotions would lead to inspirational and meaningful experiences of the material, which hopefully leads to acceptance.



Section IV:

Evaluation

Chapter 14

Discussion & Recommendations

An overal reflection on the project outcomes and the combination of the MDD and bioinspired approach is given in Section14.1. A personal reflection is given in Section 14.2.

Section 14.1 Project Evaluation & Reflection

At the start of the project the following aim was defined: to design and prototype a soft-bodied mechanism driven by a novel computational composite. It was expected that with the development of the computational composite an identity and meaning can be given to the material by adopting a Material Driven Design (MDD) approach. This project embarked on combining MDD with a bio-inspired design approach and applying it to the development of a shape changing material, illustrated in Figure 14.1.

Project process

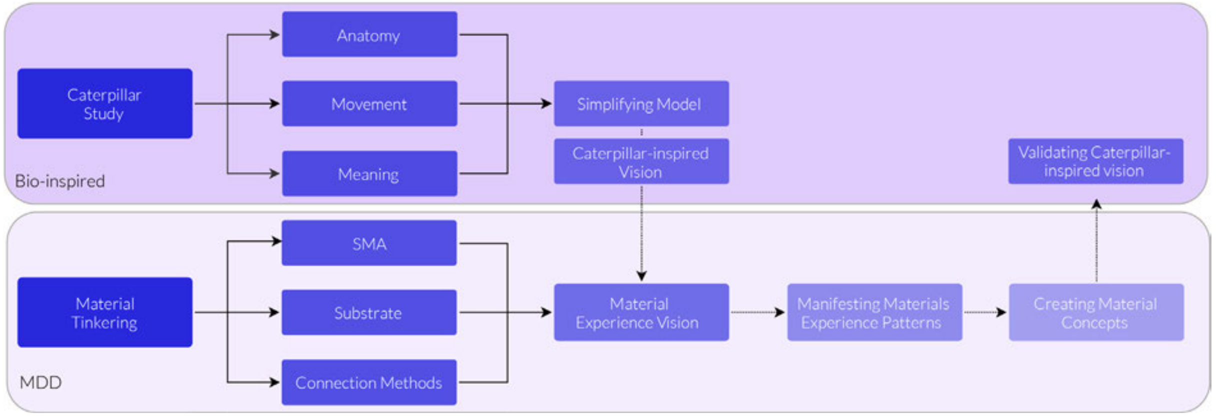
Looking back on the project, the previously planned steps of development were not followed in this sequence. During the literature review on both the caterpillar anatomy and locomotion and a benchmark of SMA-based composites a fit between both researches was not immediately apparent. Finally, the link between a moving mechanism made from a material and caterpillar inspired movement was found in developing computational composites.
The project, being more technologically driven due to the desire to mimic the locomotion of a caterpillar, went through an extensive material tinkering phase in which silicone and 4D printed textile samples were developed. Instead of using the caterpillar inspired vision to develop a material vision, the material was used in a user test to develop caterpillar inspired movements, which were then programmed into the material to make moving material samples. From these samples one was selected for further development into a working prototype.
Based on this prototype the technical and experiential characterization could be performed to develop a material vision. This was used as the starting point for an ideation phase, creative session and finally concept development for a computational composite based on the developed material and movement.

In hindsight, this step from understanding the technical and experiential characteristics to further ideation and conceptualization might have been too fast. In between, the step of benchmarking with other materials and manifesting material experience patterns would have been valuable. For this reason I would also not claim to have followed the MDD approach and instead only the tools offered to determine the material characteristics. However, I do think the ideation and conceptualization were applicable to the development of the computational composite out of the material. In this way I got the chance of suggesting what a computational composite made up from this material could look like.

Combination of approaches

Although it was initially very optimistically planned to have both the bio-inspired and MDD approaches running parallel to each other, in practice both approaches were harder to combine.
Starting the project with the desire to take the locomotion of the caterpillar as the movement the material should express, was limiting to the material development process. Instead of taking movements that might be natural to the material, the movement was already limited by the caterpillar. Reflecting back on the project process it can be seen that instead of taking the movement of a caterpillar and applying it to the material it was chosen to take a reverse approach, this was done to try and incorporate the materials intrinsic qualities such as elasticity.
Afterwards, the material was further developed and the aim was to develop a segmented prototype which was unfortunately not realized. Personally,

Figure 14.1
Proposed combination of Bio inspired with MDD approach.



I do not see this as failure in terms of the project, because by taking the single segment of the moving material as an inspiration point, the ideation and creative session led to a more diverse range of ideas for future applications. Similarly, although the aim of the project was to develop a SMA-composite capable of translational movement, seeing the movement in a more abstract way, such as squeezing or pushing, gave more freedom for ideas for possible applications.

The MDD approach and the tools given in the approach helped with the formulation of a vision for the material. Unfortunately they could only be applied once a SMA-based composite was developed. For this reason, the experiential study was done at a later stage in the project and product concepts were only suggested and not worked out into a prototype.

I personally think that taking inspiration from caterpillar locomotion in the development of the movement of a shape changing composite lead to an interesting material and movement. Only once the material prototype was working and I started ideating on possible products and applications did I understand the real benefit of starting from a material towards the application. Using this material driven approach to product design, new interactions and products can be thought of, especially on the innovative end of the spectrum: computer interface design, human touch technology and anxiety relieving mechanisms.

For this reason I do think that combining the MDD and bio-inspired approaches may lead to innovative ideas, provided the designer is aware that the approaches do not naturally come together. To apply the MDD approach a clear idea on the composition of the material should be available, so that the technical and experiential material studies can be much more focused. At the same time, bio-inspired design may become constricting and a loose definition may help to balance the material and bio-inspired movement. On the other hand, bio-inspired materials and the MDD approach would probably go hand in hand. Perhaps the disconnect was that using the material driven design method the material was developed and using the bio-inspired approach the movement was determined, finally bringing both aspects together was not as intuitive as initially expected.

Section 14.2 Personal Reflection

I started the project off knowing very little of both the bio-inspired and MDD approach and even less about SMA, silicone and 4D printing. Nonetheless, during the project I learned a tremendous amount in all of these topics and even added computational composites to the complexity of the project Luckily, the supervisory team suggested me to map everything out in the taxonomy.

For a long time I was confronted with the struggle of combining a defined movement to an unknown material composite. The constant tinkering with new compositions of the material taught me the importance of a well described plan and documenation of what works and what doesn't. Taking a structured path in the development of the composite was something I learned over the course of the project.

One of the goals I set for myself was to acquire expertise on SMAs, soft materials and electrical control elements, which I learned through a the hands-on project. I would say the research I did of SMA was elaborate as I also did technical characterization of the SMA wire in tensile and cyclic tests and tried to uncover the micro-structure of both material phases.

As a designer, I think my prototyping skills have improved and having gone through the ideation phase with a material as starting point my conceptualization skills even more so. This was the first opportunity I had to organize and facilitate a creative session.

I think the project has given me many learning opportunities and the guidance of my supervisory team has ensured I was continuously challenged and supported in my growth as a design engineer.

References

Albright Technologies. (2019). Types and Properties of Moldable Silicone Rubber. Retrieved from https://albrightsilicone.com/types-and-properties/

Andrianesis, K., & Tzes, A. (2015). Development and Control of a Multifunctional Prosthetic Hand with Shape Memory Alloy Actuators. Journal of Intelligent Robotic Systems, 78(2), 257-289.

Atieh, A. (2012). Design, Modeling, Fabrication and Testing of a Piezoresistive-Based Tactile Sensor for Minimally Invasive Surgery Applications. Concordia University,

Baumeister, D., Tocke, R., Dwyer, J., Ritter, S., & Benyus, J. M. (2014). Biomimicry : Resource Handbook : A Seed Bank of Best Practices. Missoula, Montana: Biomimicry 3.8.

Baz, A., Chen, T., & Ro, J. (2000). Shape Control of Nitinol-Reinforced Composite Beams. Composites Part B: Engineering, 31(8), 631-642.

Bengisu, M., & Ferrara, M. (2018). Materials That Move: Smart Materials, Intelligent Design: Springer.

Bergstrom, J., Clark, B., Frigo, A., Maze, R., Redstrom, J., & Vallgårda, A. (2010). Becoming Materials: Material Forms and Forms of Practice. Digital Creativity, 21(3), 155-172. doi:10.1080/14626268.2010.502235

Brackenbury, J. (1997). Caterpillar Kinematics. Nature, 390(6659), 453.

Brackenbury, J. (1999). Fast Locomotion in Caterpillars. Journal of insect physiology, 45(6), 525-533.

Coelho, M., & Maes, P. (2008). Sprout I/O: A Texturally Rich Interface. Paper presented at the Proceedings of the 2nd international conference on Tangible and embedded interaction.

Coelho, M., & Zigelbaum, J. (2011). Shape-Changing Interfaces. Personal Ubiquitous Computing, 15(2), 161-173.

Coyle, S., Majidi, C., LeDuc, P., & Hsia, K. J. (2018). Bio-Inspired Soft Robotics: Material Selection, Actuation, and Design. Extreme Mechanics Letters.

Duvall, J., Granberry, R., Dunne, L. E., Holschuh, B., Johnson, C., Kelly, K., . . . Joyner, M. (2017). The Design and Development of Active Compression Garments for Orthostatic Intolerance. Paper presented at the 2017 Design of Medical Devices Conference.

Follador, M., Cianchetti, M., Arienti, A., & Laschi, C. (2012). A General Method for the Design and Fabrication of Shape Memory Alloy Active Spring Actuators. Smart Materials Structures, 21(11), 115029.

Gilbertson, R. G. (2005). Muscle Wires: Project Book: A Hands-on Guide to

Amazing Robotic Muscles That Shorten When Electrically Powered. San Rafael, CA: Mondo-tronics.

Gillott, C. (2005). Entomology: Springer Science & Business Media.

Gomes, A., Nesbitt, A., & Vertegaal, R. (2013). Morephone: A Study of Actuated Shape Deformations for Flexible Thin-Film Smartphone Notifications. Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

Guberan, C., Demaine, E. , Carbitex LLC, Autodesk Inc. (Producer). (N.D.). Programmable Materials. Retrieved from https://selfassemblylab.mit.edu/programmable-materials/

Han, X. J., Dong, Z. Q., Fan, M. M., Liu, Y., li, J. H., Wang, Y. F., . . . Zhang, S. (2012). Ph⍰Induced Shape⍰Memory Polymers. Macromolecular rapid communications, 33(12), 1055-1060.

Hughes, C. L., & Thomas, J. B. (2007). A Sensory Feedback Circuit Coordinates Muscle Activity in Drosophila. Molecular Cellular Neuroscience, 35(2), 383-396.

Images Scientific Instruments. (2019). Activating Nitinol Wire with Pulse Width Modulated (Pwm) Electrical Current. Retrieved from https://www.imagesco.com/articles/nitinol/07.html

Ishii, H., Ren, S., & Frei, P. (2001). Pinwheels: Visualizing Information Flow in an Architectural Space. Paper presented at the CHI'01 Extended Abstracts on Human Factors in Computing Systems.

Johnson Matthey. (2019). Nitinol Technical Properties. Retrieved from https://matthey.com/markets/pharmaceutical-and-medical/medical-device-components/resource-library/nitinol-technical-properties

Johnston, R., Consoulas, C., Pflüger, H., & Levine, R. B. (1999). Patterned Activation of Unpaired Median Neurons During Fictive Crawling in Manduca Sexta Larvae. Journal of experimental biology, 202(2), 103-113.

Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material Driven Design (Mdd): A Method to Design for Material Experiences. Retrieved from WorldCat.org database. Chinese Institute of Design.

Kate, M., Bettencourt, G., Marquis, J., Gerratt, A., Fallon, P., Kierstead, B., . . . Trimmer, B. A. (2008). Softbot: A Soft-Material Flexible Robot Based on Caterpillar Biomechanics. In (Vol. 2155): Tufts University, Medford, MA.

Kellogg's Research Labs. (2019). How Much Electric Current Do I Need to Actuate Nitinol? Retrieved from https://www.kelloggsresearchlabs.com/nitinol-faq/

Kim, H., Song, S., & Ahn, S. (2012). A Turtle-Like Swimming Robot Using a Smart Soft Composite (Ssc) Structure. Smart Materials and Structures, 22(1), 014007. doi:10.1088/0964-1726/22/1/014007

Koh, J.-S., & Cho, K.-J. (2013). Omega-Shaped Inchworm-Inspired Crawling Robot with Large-Index-and-Pitch (Lip) Sma Spring Actuators. IEEE/ASME Transactions On Mechatronics, 18(2), 419-429.

Laschi, C., Cianchetti, M., Margheri, L., Follador, M., Dario, P., & Mazzolai, B. (2012). Soft Robot Arm Inspired by the Octopus. Advanced Robotics, 26(7), 709-727. doi:10.1163/156855312X626343

Leary, M., Jani, J. M., Gibson, M. A., & Subic, A. (2014). A Review of Shape Memory Alloy Research, Applications and Opportunities. Materials & Design (1980-2015), 56, 1078-1113.

Lin, H., Leisk, G. G., & Trimmer, B. A. (2011). Goqbot: A Caterpillar-Inspired Soft-Bodied Rolling Robot. Bioinspiration & biomimetics, 6(2), 026007.

Losertova, M., Stencek, M., Stefek, O., Drapala, J., Matysek, D., th Joint Seminar Development of Materials Science in, R., & Education, D. (2017). Microstructure Evolution of Heat Treated Niti Alloys. IOP Conference Series: Materials Science and Engineering, 266(1). doi:10.1088/1757-899X/266/1/012008

Majidi, C. (2014). Soft Robotics: A Perspective—Current Trends and Prospects for the Future. Soft Robotics, 1(1), 5-11.

Meza, L. R., Das, S., & Greer, J. R. (2014). Strong, Lightweight, and Recoverable Three-Dimensional Ceramic Nanolattices. Science (New York, N.Y.), 345(6202), 1322-1326. doi:10.1126/science.1255908

Nassar, J. M., Rojas, J. P., Hussain, A. M., & Hussain, M. M. (2016). From Stretchable to Reconfigurable Inorganic Electronics. Extreme Mechanics Letters, 9, 245-268.

Papakonstantinou, N. (Producer). (2015). Fabricflation _ Structuring Textile Techniques. Retrieved from http://www.iaacblog.com/programs/fabricflation-_-structuring-textile-techniques/

Prescott, T. J., Lepora, N., & Verschure, P. F. M. J. (2018). Living Machines: A Handbook of Research in Biomimetics and Biohybrid Systems: Oxford University Press.

Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., & Hornb, K. (2012). Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Austin, Texas, USA.

Rodrigue, H., Wang, W., Bhandari, B., Han, M., & Ahn, S. (2015). Sma-Based Smart Soft Composite Structure Capable of Multiple Modes of Actuation. Composites Part B: Engineering, 82, 152-158. doi:https://doi.org/10.1016/j.compositesb.2015.08.020

Rodrigue, H., Wang, W., Kim, D.-R., & Ahn, S.-H. (2017). Curved Shape Memory Alloy-Based Soft Actuators and Application to Soft Gripper. Composite Structures, 176, 398-406.

Rodrigue, H., Wei, W., Bhandari, B., & Ahn, S.-H. (2015). Fabrication of Wrist-Like Sma-Based Actuator by Double Smart Soft Composite Casting. Smart Materials and Structures, 24(12), 125003.

Rydarowski, A., Samanci, O., & Mazalek, A. (2008). Murmur: Kinetic Relief Sculpture, Multi-Sensory Display, Listening Machine. Paper presented at the Proceedings of the 2nd international conference on Tangible and embedded interaction.

Šittner, P., Heller, L., Pilch, J., Curfs, C., Alonso, T., & Favier, D. (2014). Young's Modulus of Austenite and Martensite Phases in Superelastic Niti Wires. Journal of materials engineering performance, 23(7), 2303-2314.

Smooth-On. (2019). Dragon Skin™ Fx- Pro. Retrieved from https://www.smooth-on.com/product-line/dragon-skin/

Song, W., Onishi, M., Jan, L. Y., & Jan, Y. N. (2007). Peripheral Multidendritic Sensory Neurons Are Necessary for Rhythmic Locomotion Behavior in Drosophila Larvae. Proceedings of the National Academy of Sciences, 104(12), 5199-5204.

Suresh, K. S., Lahiri, D., Agarwal, A., & Suwas, S. (2015). Microstructure Dependent Elastic Modulus Variation in Niti Shape Memory Alloy. Journal of Alloys and Compounds, 633, 71-74. doi:10.1016/j.jallcom.2015.01.301

Tassoul, M. (2009). Creative Facilitation (3th ed. ed.). Delft: VSSD.

Teh, Y. H., & Featherstone, R. (2004). A New Control System for Fast Motion Control of Sma Actuator Wires. Paper presented at the The 1st International Symposium on Shape Memory and Related Technologies.

Terriault, P., Viens, F., & Brailovski, V. (2006). Non-Isothermal Finite Element Modeling of a Shape Memory Alloy Actuator Using Ansys. Computational Materials Science, 36(4), 397-410.

Trimmer, B. A., & Issberner, J. (2007). Kinematics of Soft-Bodied, Legged Locomotion in Manduca Sexta Larvae. The Biological Bulletin, 212(2), 130-142.

Trimmer, B. A., & Lin, H. (2014). Bone-Free: Soft Mechanics for Adaptive Locomotion. In: Oxford University Press.

van Griethuijsen, L. I., & Trimmer, B. A. (2010). Caterpillar Crawling over Irregular Terrain: Anticipation and Local Sensing. Journal of Comparative Physiology, 196(6), 397-406.

van Griethuijsen, L. I., & Trimmer, B. A. (2014). Locomotion in Caterpillars. Biological Reviews, 89(3), 656-670.

van Manen, T., Janbaz, S., & Zadpoor, A. A. (2018). Programming the Shape-Shifting of Flat Soft Matter. Materials Today, 21(2), 144-163. doi:10.1016/j.mattod.2017.08.026

van Spijker, M. (2016). Exploring Dynamic Behaviour of Shape Memory Alloy Composite. (Integrated Product Design), Delft University of Technology, Delft, The Netherlands.

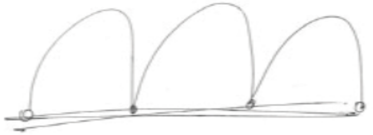
WikiD. (2019). Weighted Objectives Method. Retrieved from http://wikid.io.tudelft.nl/WikID/index.php/Weighted_objectives_method

Woods, W. A., Fusillo, S. J., & Trimmer, B. A. (2008). Dynamic Properties of a Locomotory Muscle of the Tobacco Hornworm Manduca Sexta During Strain Cycling and Simulated Natural Crawling. Journal of experimental biology, 211(6), 873-882.

Zhakypov, Z., Heremans, F., Billard, A., & Paik, J. (2018). An Origami-Inspired Reconfigurable Suction Gripper for Picking Objects with Variable Shape and Size. IEEE Robotics and Automation Letters, 3(4), 2894-2901. doi:10.1109/LRA.2018.2847403

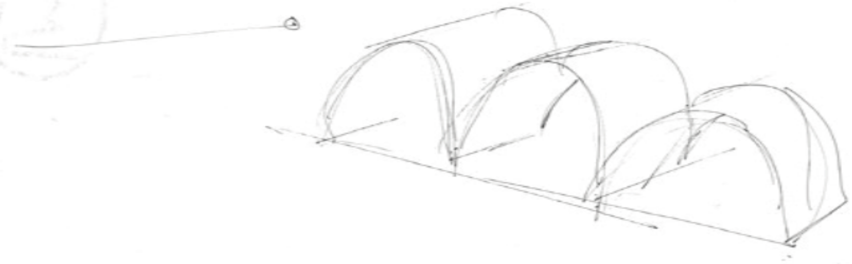
Appendix A:

Caterpillar Movement Ideation


3 hinge crawling


hollow

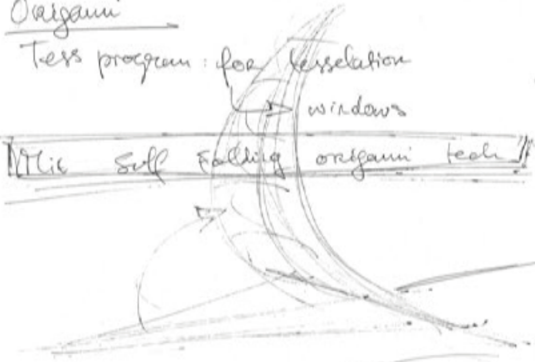
flat

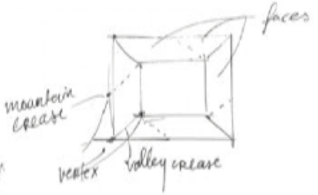


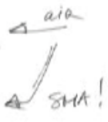
Origami

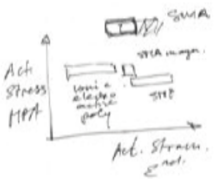
Tess program: for tesselation
↳ windows

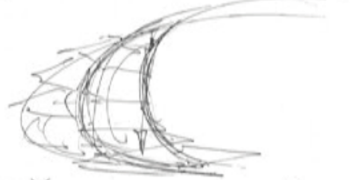
Mic Self Folding origami tech



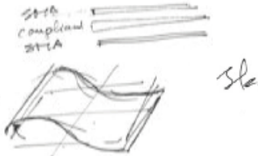








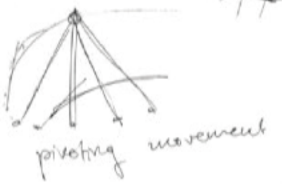
Rus [102, 103]
↳ Design & programming guide.



skeleton based

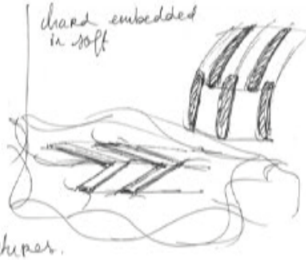
what do I want from origami structures?


controlled contraction

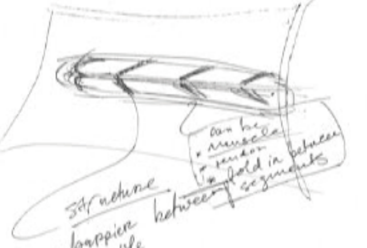

pivoting movement

Textile structures

advantages
- flat fold?
- flexible
- soft
- feels comfortable
- may exhibit stretch


hard embedded in soft

what do I want out of textile structures.



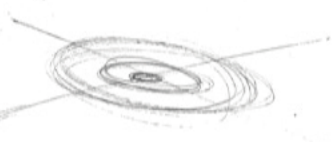
- happier between SMA & textile

↳ PLA melting temperature

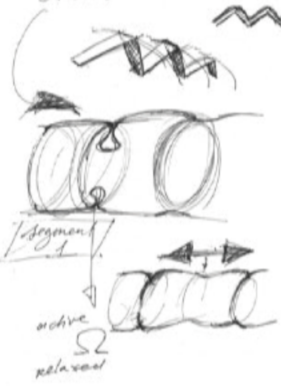
180°C - 220°C	60-65°C
	glass trans. temp

" providing a 'skeleton' for the material to stretch on and work around. "

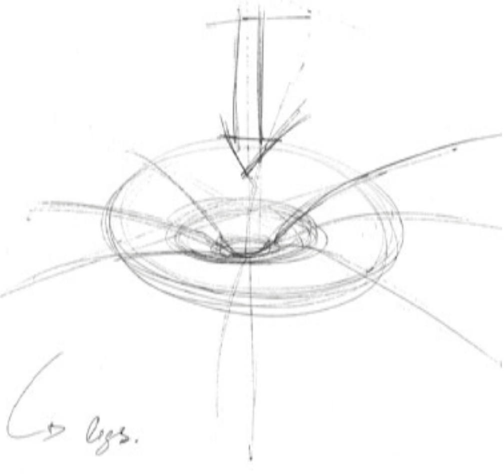
in this way
- control the overall shape of caterpillar (not flimsy

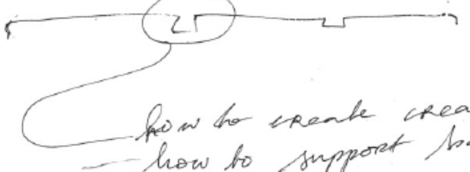


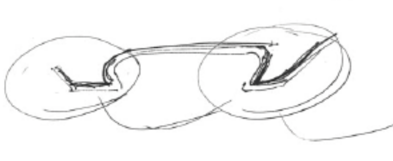
how to make crease in cilinder



origami x textile

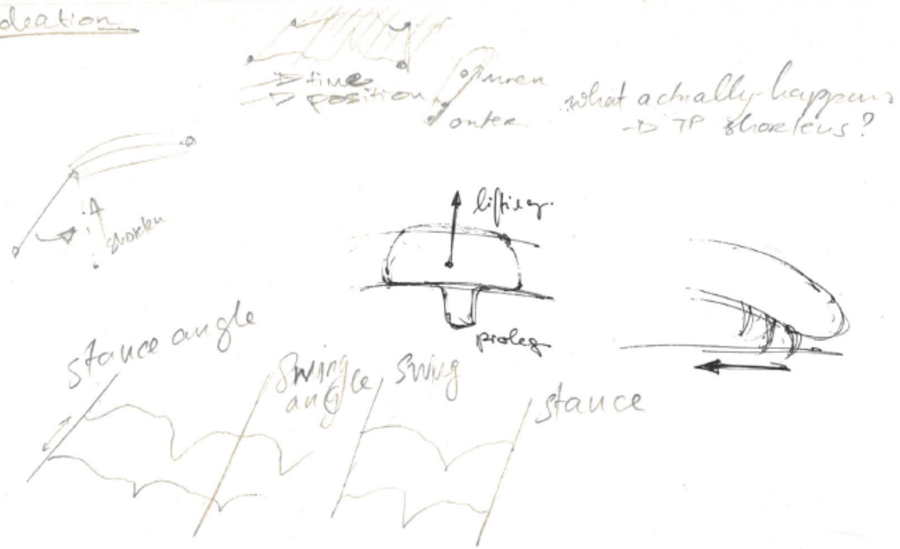

↳ legs.



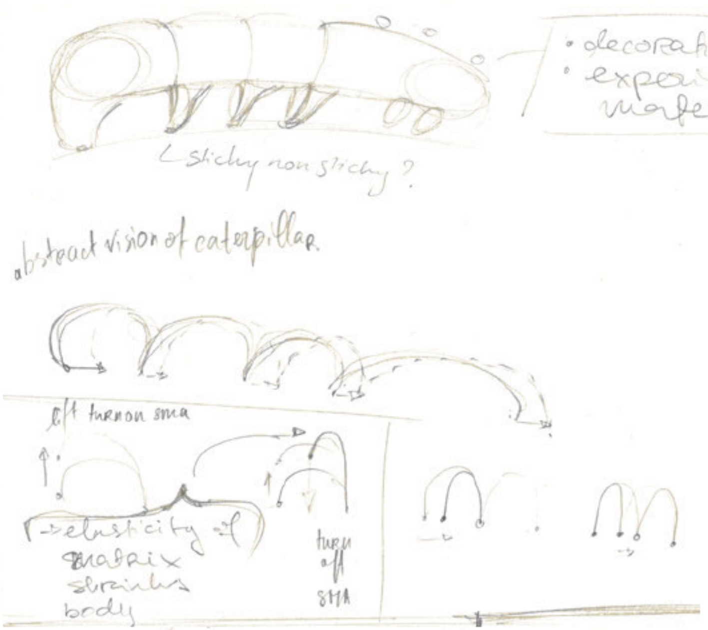


- how to create creases?
- how to support body structure?
- how to bias tensioning in such a way that prolegs can be adapted.

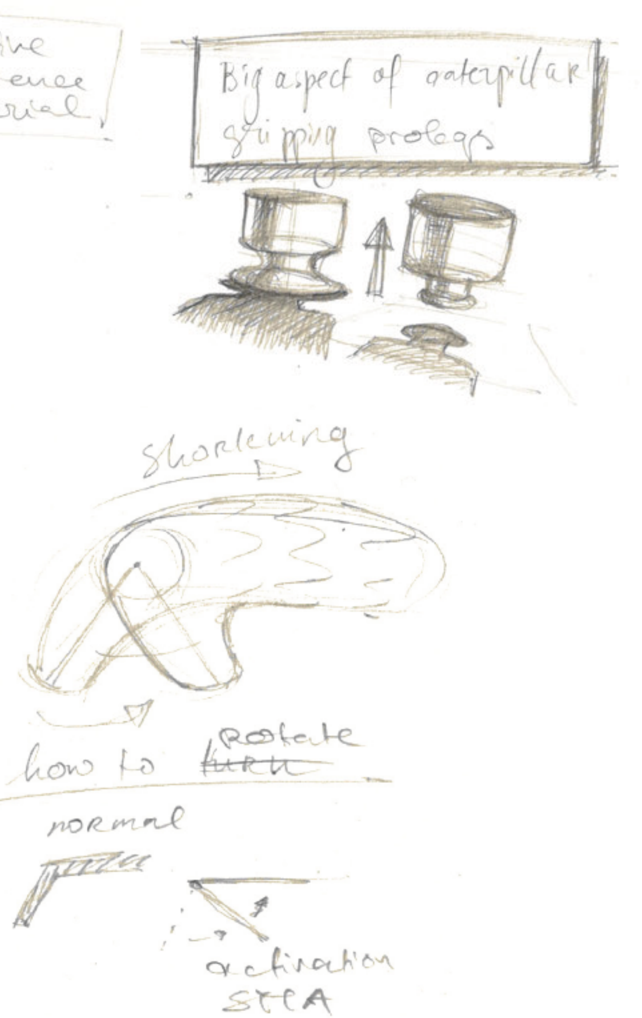
deation



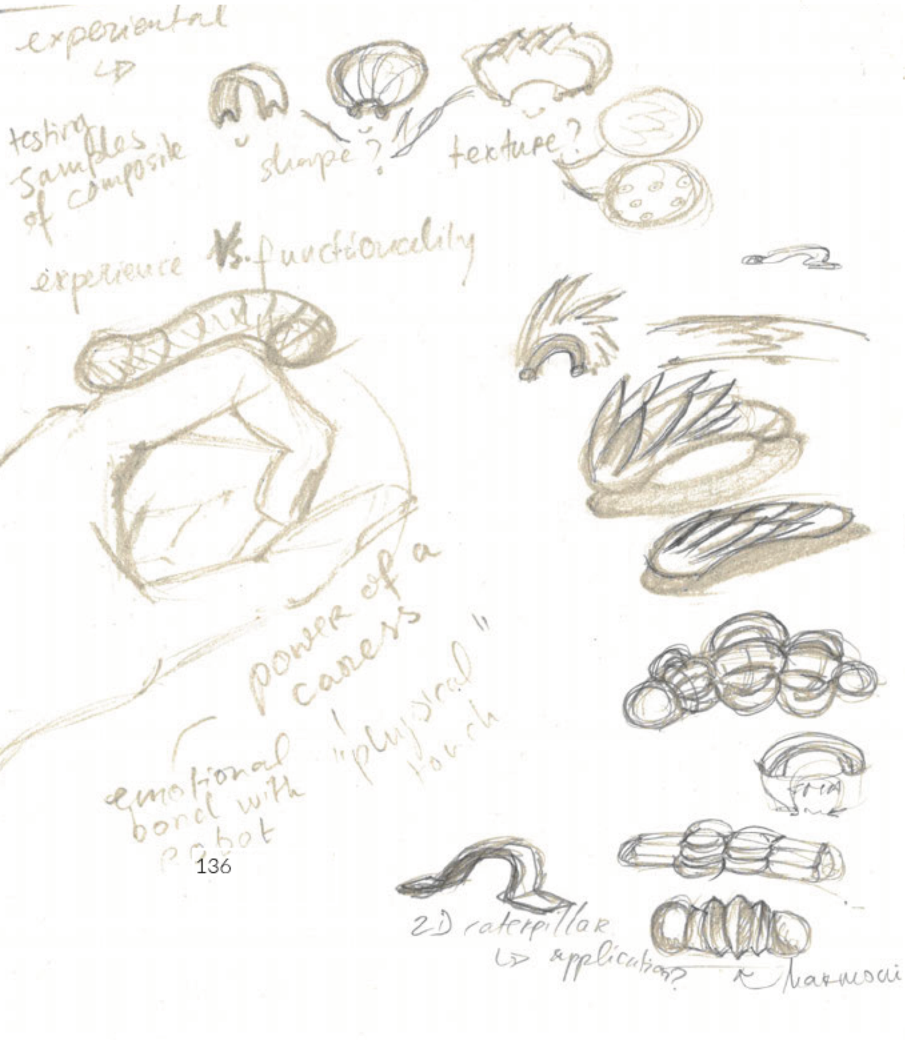
▷ time
▷ position
inner
outer
what actually happens
-▷ TP shortens?
shorten
lifting
proleg
stance angle
swing angle
swing
stance



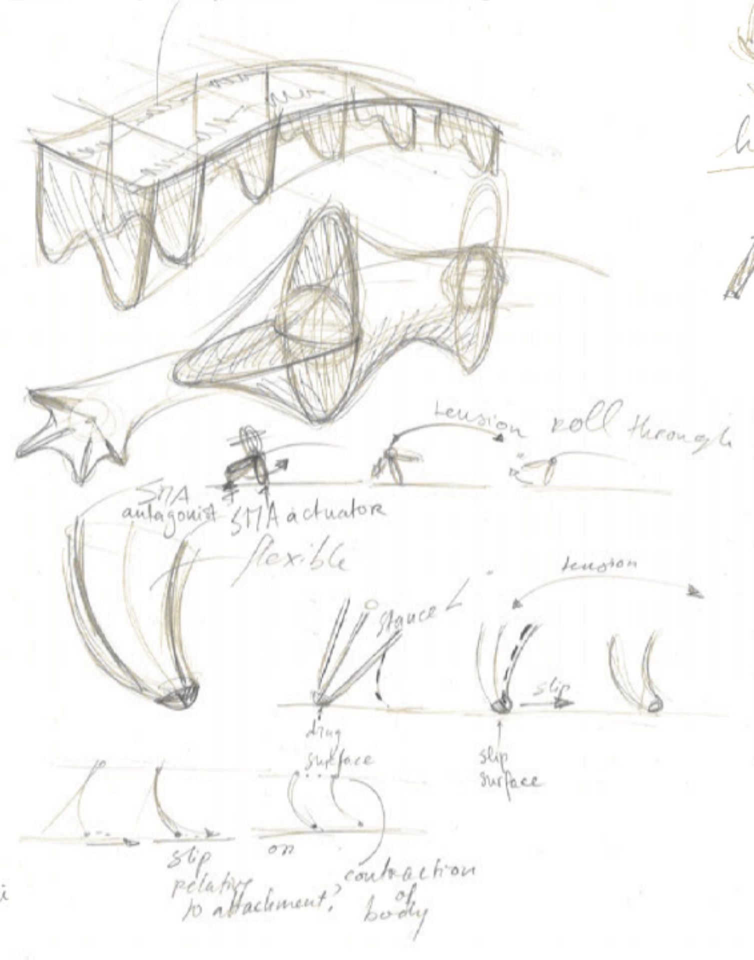
sticky non sticky?
• decorative
• experience
material
abstract vision of caterpillar
lift turn on sma
elasticity of matrix shrinks body
turn off SMA



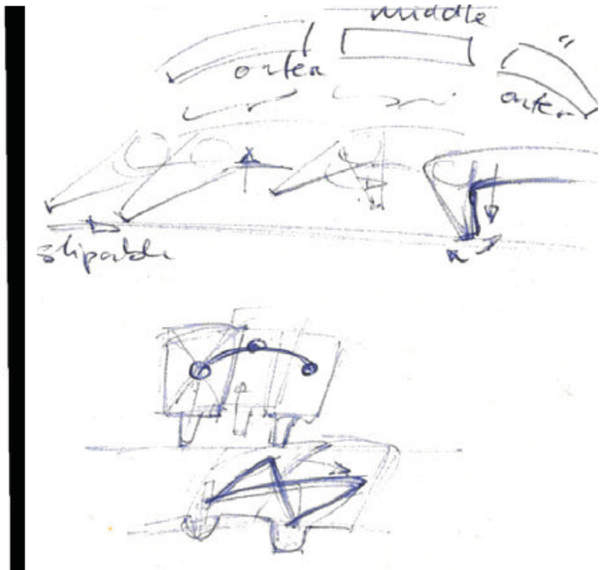
Big aspect of caterpillar
gripping prolegs
shortening
how to ~~turn~~ rotate
normal
activation SMA



experiental
testing samples of composite
shape?
texture?
experience vs. functionality
power of a caress
emotional bond with robot
"physical" touch
SMA
2D caterpillar
▷ application?
harmonic



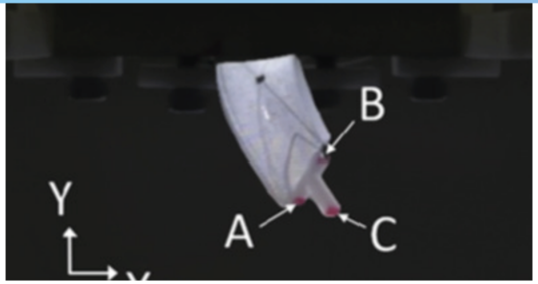
tension
roll through
SMA antagonist
SMA actuator
flexible
tension
stance
slip
drag surface
slip surface
slip relative to attachment?
on
contraction of body



middle
outer
outer
slip patch

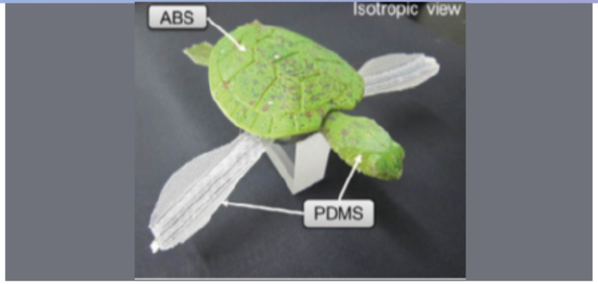
Appendix A:

SMA Composite Benchmark



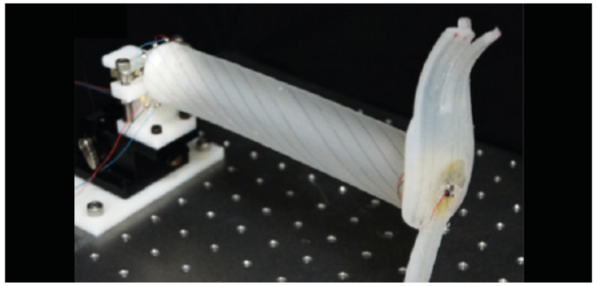
Name project: SMA-based smart soft composite structure capable of multiple modes of actuation. (Rodrigue, Wang, et al., 2015)

Name project: Soft Robotic Arm Inspired by the Octopus (Laschi et al., 2012)

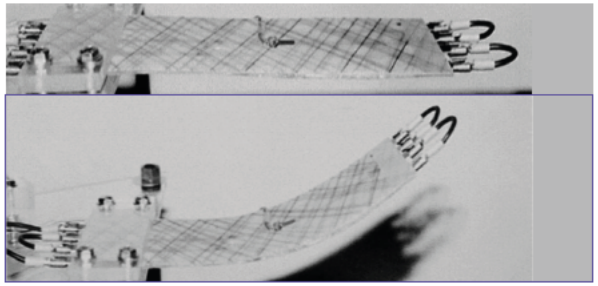


Name project: A turtle-like swimming robot using a smart soft composite (SSC) structure. (Kim, Song, & Ahn, 2012)

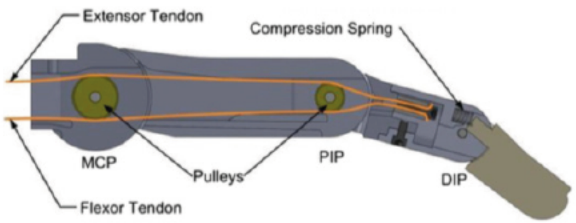
Materials	PDMS matrix + Dynalloy 0.15 mm SMA wires	0.2mm SMA wire + UHMWPE + braided sleeve	PDMS matrix + Dynalloy 0.15 mm SMA wires
Fabrication	ABS mold with holes where SMA wires are positioned, pre-strained and mechanically fixed on a jig using bolts.	Springs/coils are made from the SMA wire with an internal diameter of 1mm and around 6-10 coals. a 50-µm PTFE sheath was used to cover the SMA wires. A module consists of eight SMA springs. 12 Modules are attached to the conical braid.	ABS mold with holes where SMA wires are positioned, pre-strained and mechanically fixed on a jig using bolts.
Actuation	Activated by Joule heating using 0.65 A, A+B or C+D for bending. A + D or B+C for torque.	The SMA account for the cylindrical deformation of the arm.	Activated by Joule heating using 0.65 A, A+B or C+D for bending. A + D or B+C for torque.
(Dis)advantages	+ Multiple modes of actuation within one actuator gives versatility and flexibility to the actuator. - One end is free moving in this paper. The effects are not registered with a restriction or reaction force on that end.	+ This is a clear example the muscular hydrostatic principle being reproduced by a soft robot. - SMA coils are not the only actuation method used into this system adding to the complexity of the product.	+ Multiple modes of actuation within one actuator gives versatility and flexibility to the actuator. - One end is free moving in this paper. The effects are not registered with a restriction or reaction force on that end.



Name project: Wrist-like SMA-based actuator by double smart soft composite casting (Rodrigue, Wei, Bhandari, & Ahn, 2015)

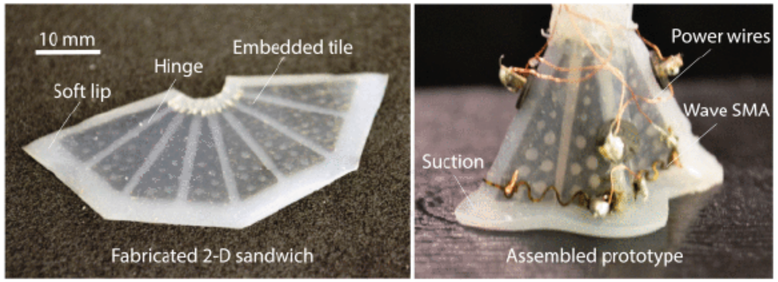


Name project: Shape control of NITINOL-reinforced composite beams Composites Part B: Engineering (Baz, Chen, & Ro, 2000)



Name project: Development and Control of a Multifunctional Prosthetic Hand with Shape Memory Alloy Actuators (Andrianesis & Tzes, 2015)

Materials	PMDS matrix + SMA wire + ABS mold	Fiberglass composite beam made of 8 plies of unidirectional BASF 5216 prepreg + 1.2x1.25mm SMA strips	SMA wire + Mechanical Hinge
Fabrication	ABS mold is fused deposition modeled (Stratasys Dimension SST 768). SMA wire is positioned into parallelogram shaped mold at an angle to the base. PMDS is poured on top of this. This component is then placed into a hollow tube shaped mold where PMDS is again poured into the mold. The resulting shape is a circular actuator with SMA wires at an angle.	SMA Strips are pre-trained to remember the parabolic curve. When inserted into the fiberglass beam, the whole beam is prestrains the strips in such a way that the initial flat position can be achieved.	As the movement is determined by the design of the mechanical hinge for the prosthetic fingers, the movement is actuated by SMA wires. To fit all the wire inside the tight dimensions of the finger, the wire is turned into an N shape by attaching it to two plates to using screws. This allows the actuation force of the SMA wire to be increased as well, since they are essentially placed parallel.
Actuation	Upon actuation of the SMA wires, the tube is capable of uni-directional twisting, where the direction of twisting is dependent on the direction of the SMA wires. And the magnitude of the of twist angle is dependent on the amount of wires actuated.	Upon actuation of the SMA strips, the whole beam is moved upwards until an equilibrium can be found between both beam and wire moments.	The finger can be actuated using opposing tendons: the flexor and extensor tendons. Activation of the SMA wires moves these tendons over the guidance pulleys.
(Dis)advantages	+ Novel method for creating tube shaped actuators with non-axial positioning of the wire. - The actuator can only perform twist. And at low values of force it will buckle (2N)	+ The flexural rigidity of the beam acts as a bias spring against the SMA actuator, essentially moving the beam back into the original position at temperatures below the austenite start temperature. Nitinol 5 wil increase in flexural stiffness upon activation, in contrast to nitinol fibers 1-3. - One end is free moving in this paper. The effects are not registered with a restriction or reaction force on that end. The hinge created here is of a stiff nature, which limits the application in a flexible, adaptable system.	+ Folding the wire over can give it extra actuation force output as well as extending the length of the wire, making the strain of the wire bigger. - The SMA wires are used to actuate an external rigid mechanical hinge using a pulley system, where the complete possibilities of SMA are not necessarily exploited. The system is quite complex and big.



Name project: Compression Garment for Medical Applications (Duvall et al., 2017)

Name project: Origami-Inspired Reconfigurable Suction Gripper (Zhakypov, Heremans, Billard, & Paik, 2018)

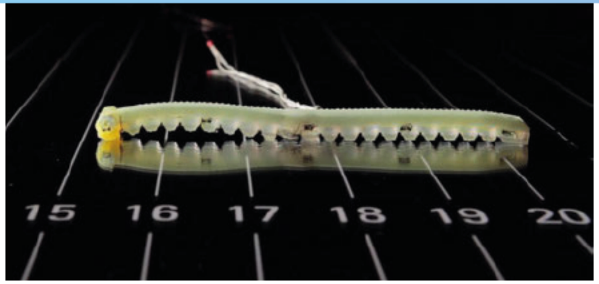
Materials	SMA coil + ripstop nylon	SMA wave (thin film) & coil + Dragonskin + Glass fiber tiles + PET mold
Fabrication	Three different attachment method were developed fro the SMA coils to the garment:using metal hooks, fibreglass electrical tubing and fibreglass webbing loops.	PET mold is used to cast the silicone layers. Laser cut glass fibrer tiles are placed inside the mold after the first layer is cured and then another layer of dragon skin is added. Cut-outs are made in the tiles to ensure the top and bottom silicone layer can bond, to avoid delamination. Bridge spacers are used to ensure the tiles stay at a fixed instance from each other and are cut out after the tiles are cured into place. SMA is attached. Silicone glue is used to connect both ends to create a conical shape and to attach the vacuum tube. SMA waves were cut out of a 0.15mm thick Nitinol sheet. SMA coils are formed from 0.25 mm Nitinol wire around a diameter of 1 mm.
Actuation	By joule heating, the SMA wires are activated and contract leading to dynamic control of the degree of compression, timing of compression, type and site of compression.	The actuation of the waves and coils is done to shape the gripper in different operating modes for large, small and narrow openings. The vacuum pump creates the suction effect. Combined it allows the gripper to puck long and narrow objects up.
(Dis)advantages	+ Different embedding options for SMA are explored. -	+ The combination of a soft silicone with glass fiber tiles shows how a versatile hinge can be created, and the added benefit of hard & soft materials together. The application of different types of SMA (coil and wave from thin film) is also highlighted, with a explanation of the different effects. - This type of actuator still needs an external vacuum pump to be attached in order to fulfill its function.

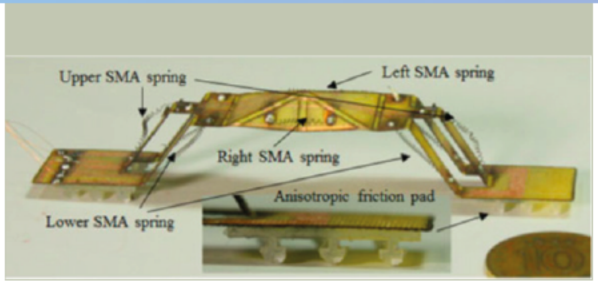
Name project: Curved shape memory alloy-based soft gripper (Rodrigue, Wang, Kim, & Ahn, 2017)

Name project: Morephone (Gomes, Nesbitt, & Vertegaal, 2013)

Name project: Shutters (Coelho & Zigelbaum, 2011)

	Curved shape memory alloy-based soft gripper	Morephone	Shutters
Materials	0.2 mm SMA wire + PDMS + Glass fiber + ABS mold	0.15 mm SMA wire + Cardboard + Copper substrate + E ink display	Felt sheet and SMA strips
Fabrication	An ABS mold with a inner volume of 1.25 x 15 mm and 99.5 mm is used to position the SMA wire. The wires are pre-strained with 1kg and attached to a jig using bolts. The mold is filled with PDMS. This rectangular and straight composite is then put into a curved mold. In the middle a glass fibre plate is positioned with on either side a mixture of PDMS. The sample with SMA wire is positioned in the direction of the bending moment.	Copper substrate allows current to be passed to the sensors and SMA wires. Two 0.15 mm SMA wires are stitched into a each corner of the cardboard using Kevlar thread.	Attached SMA strips to cut out pieces of fabric.
Actuation	By joule heating the inserted wire contracts and bends the structure. The bending is found to be for a flat structure at maximum 90° and for an actuator melded at 90°, the maximum bending angle is 180°.	By joule heating, the SMA wires are activated and contract leading to a bending moment of the material.	By joule heating, the SMA wires are activated so that the shutters open.
(Dis)advantages	+ Having a larger maximum bend angle can be useful, as well as proving that having an initial bending angle does not influence the maximum bending angle achievable compared to a flat actuator. In addition, the actuator can be shaped differently, while still achieving the same bending angle. - One end is free moving in this paper. The effects are not registered with a restriction or reaction force on that end.	+ A simple method for connecting SMA wire to the substrate is given, as well as the connection between SMA wires. The paper also proposes interesting direction that van be taken with shape morphing surfaces in relation to user interaction. - At the current stage this does not seem to be implementable in the current market.	+ A simple method for shape morphing materials in relation to user interaction. - Constant power must be supplied to maintain the SMA strips in the lifted position





Name project: GoQBot: a caterpillar-inspired soft-bodied rolling robot (Lin, Leisk, & Trimmer, 2011)

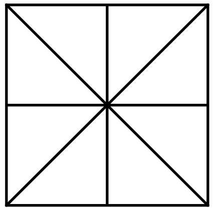
Name project: Omegabot - Inchworm-Inspired Crawling Robot (Koh & Cho, 2013)

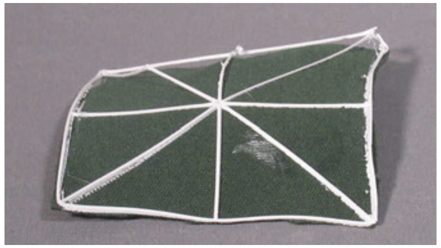
Materials	SMA coils + Dragonskin 20 + VTV800 + ABS Mold	Glass-fiber composite + Copper-laminated Kapton film + SMA coils
Fabrication	ABS mold is 3d printed (Stratasys). Silicone first vaccuum treated before it is poured into the mold. After curing 2 long SMA coils of a diameter of 0.1 mm and 0.5 coil diameter. The coils are preloaded using 100mN. At the midpoint a copper ring is attached that forms the stimulation ground, so that current can be passed through each side of the coil independently.	Composite is lasercut. Copper-laminated Kapton film is cured. SMA wires and pads are attached to structure.
Actuation	Each coil is activated by resistive / joule heating using pulses of current similar to muscle tetanus.	Two four-bar linkages are used to bend the robot body and shape it into an omega. Steering is controlled by a six-bar linkage system. Frictional pads at the bottom of the head and tail segments ensure either segment remains stationary while the other is being moved by the actuator. Antagonistic coil SMAs are used.
(Dis)advantages	+ Two types of silicone rubber are used, with different shapes. The shape of the upper layer and the cut outs in the lower part are made to predispose the body to bend in a ventral direction. The composite gives a structure to the actuator, holds the SMA wires and also influences the actuation movement. - After a ballistic roll, the system is not able to recover. Making the shape dorsal-ventral symmetric would allow the system to roll over both sides of the body.	+ The body is made of a single part and does not need assembly of different mechanisms for the body structure. Use of frictional pads is interesting in the crawling locomotion of a caterpillar. -Exterior is not soft and has not been implemented in a series formation for a crawling locomotion yet.

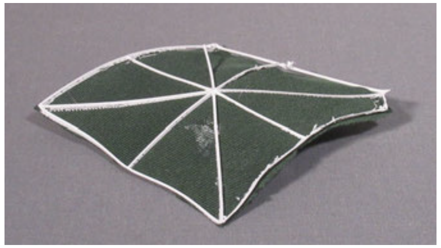
Appendix A:

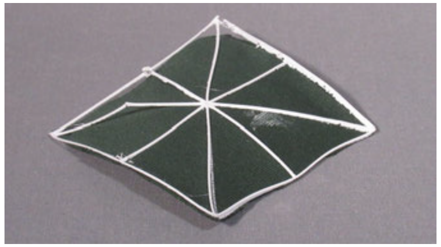
Material Sample Pictures

Material: Polyester Viscose
Filament: PLA
Height 1.0 mm Width: 0.5 mm

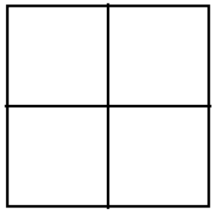
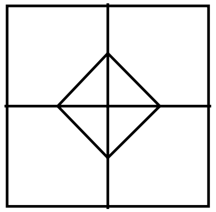
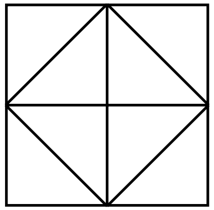
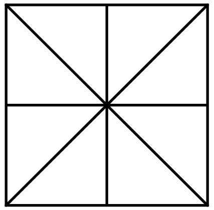


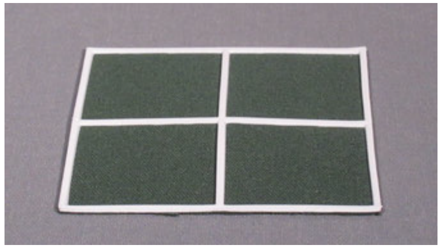
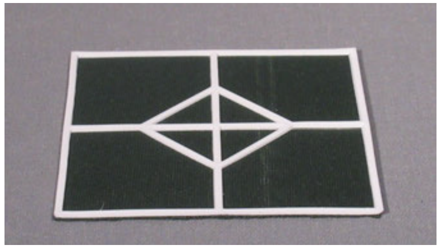
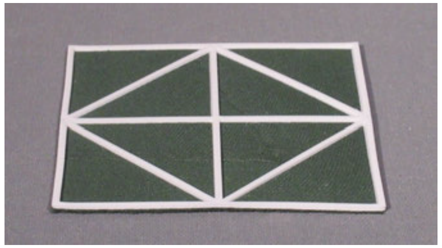
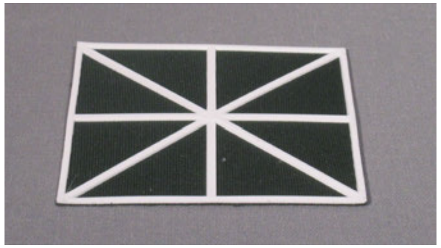


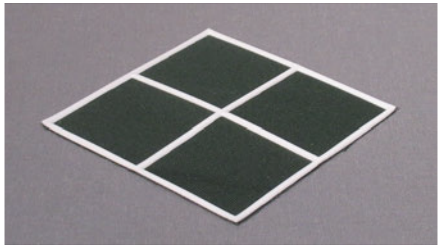
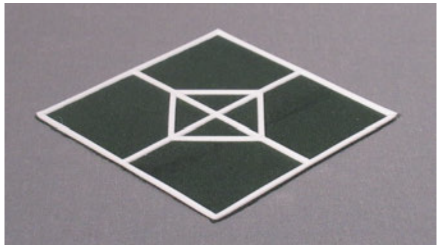
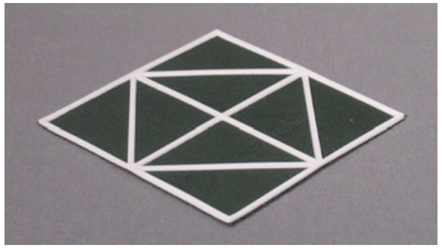
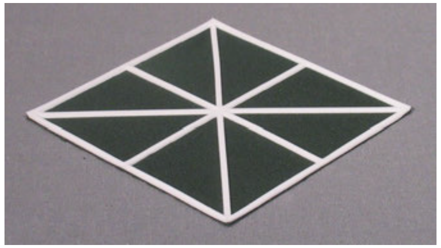




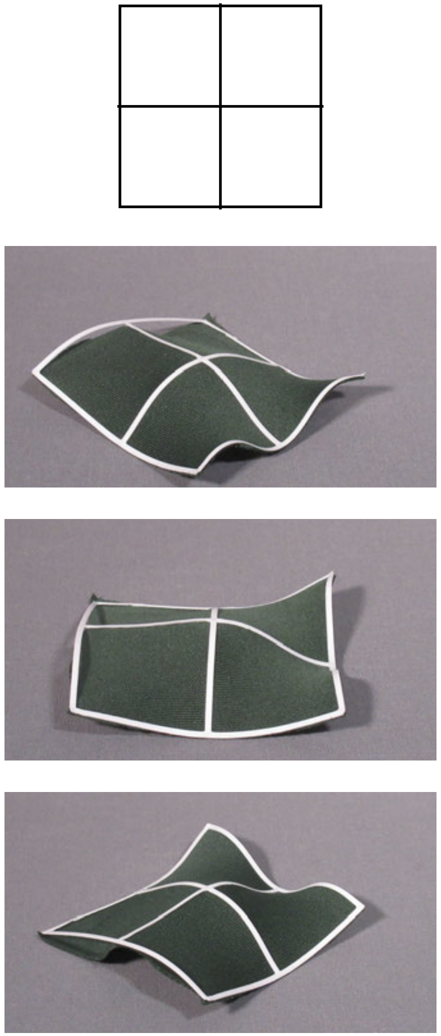
Material: Polyester Viscose
Filament: PLA
Height: 1.0 mm Width: 1.5 mm

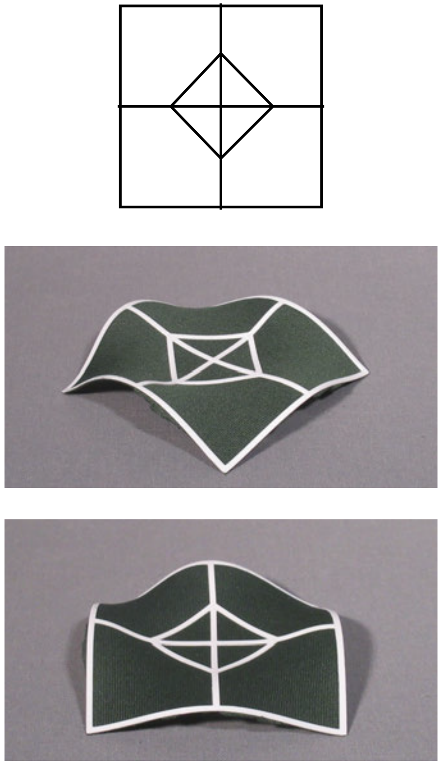





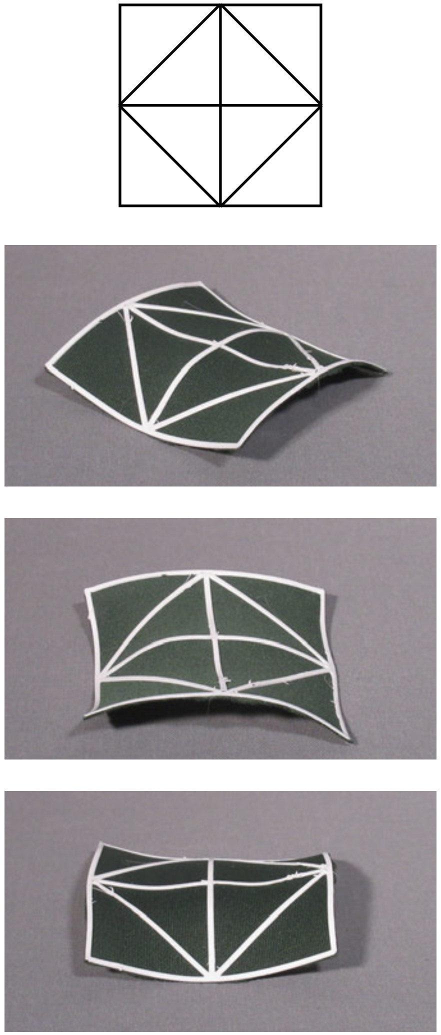





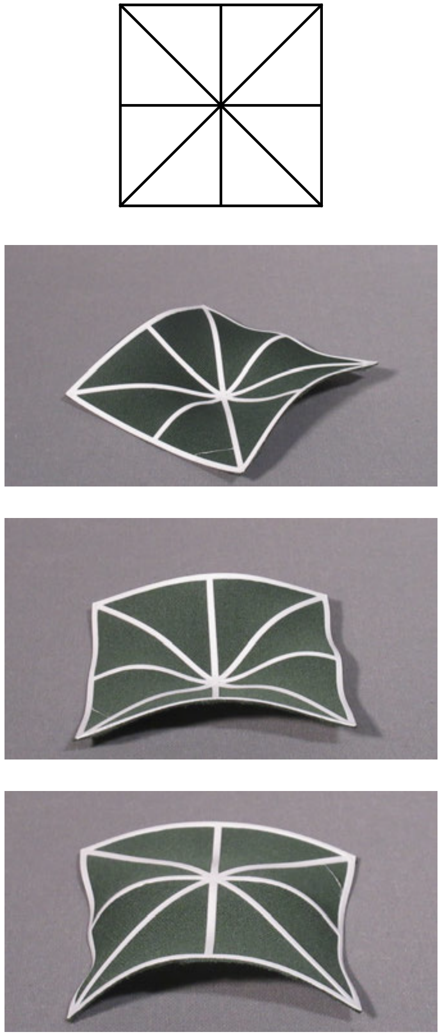





Material: Polyester Viscose
Filament: PLA
Height: 0.5 mm Width: 1.5 mm

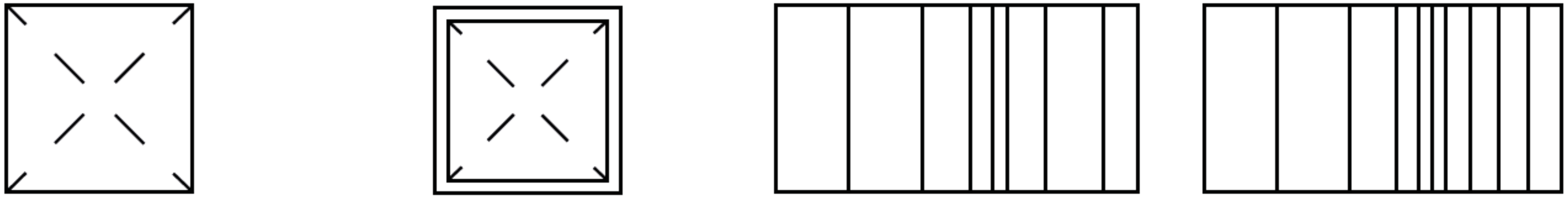


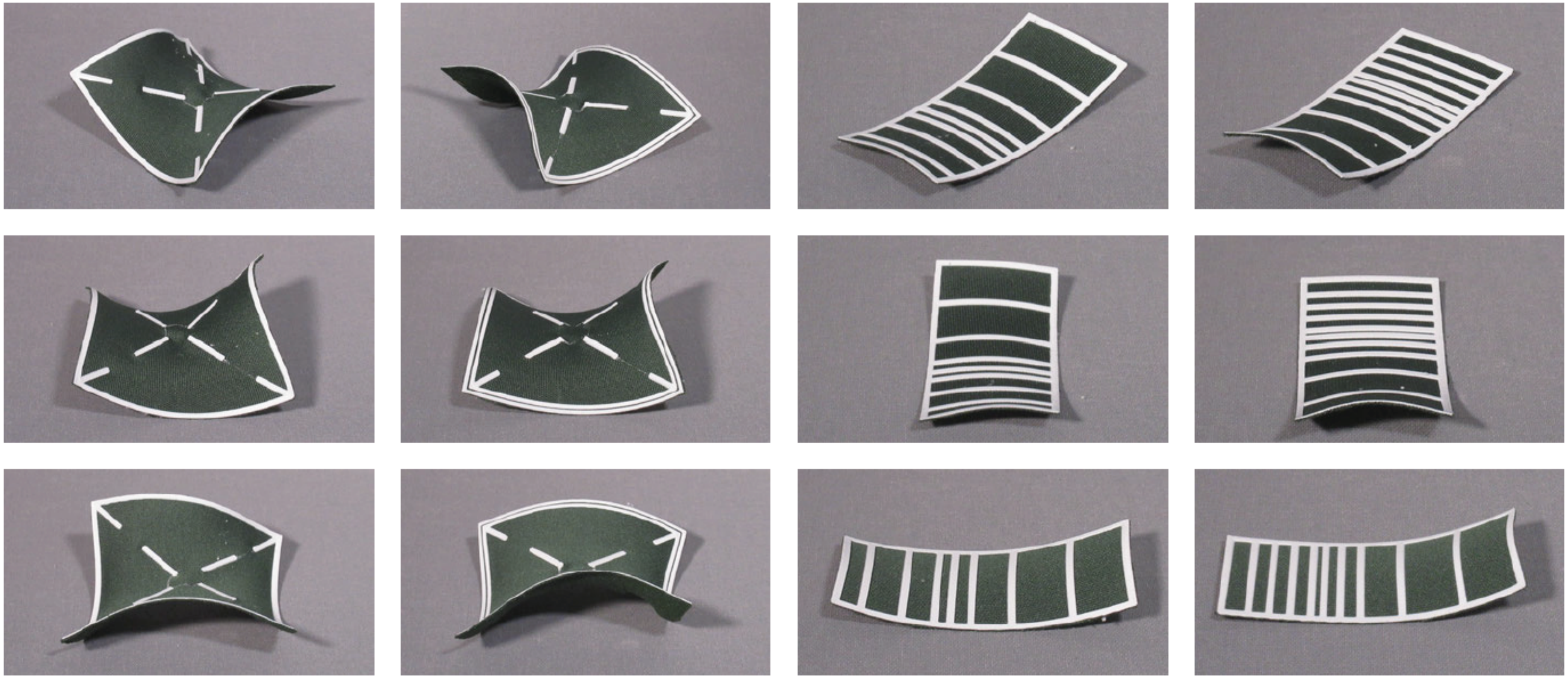




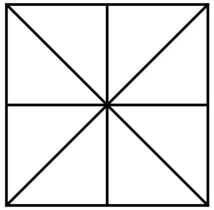


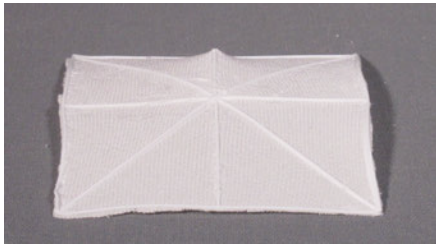
Material: Polyester Viscose
Filament: PLA
Height 0.5 mm   Width: 1.5 mm

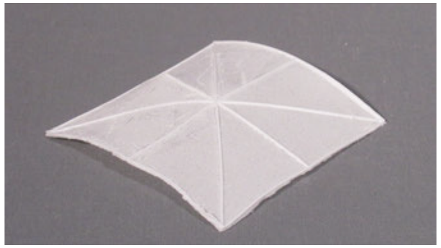




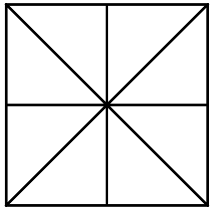
Material: Polyester Lycra
Filament: PLA
Height 1.0 mm   Width: 0.5 mm

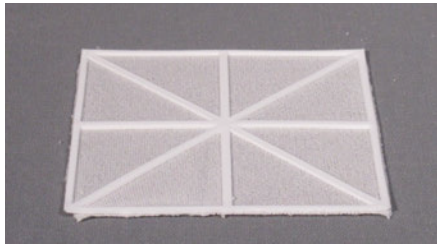




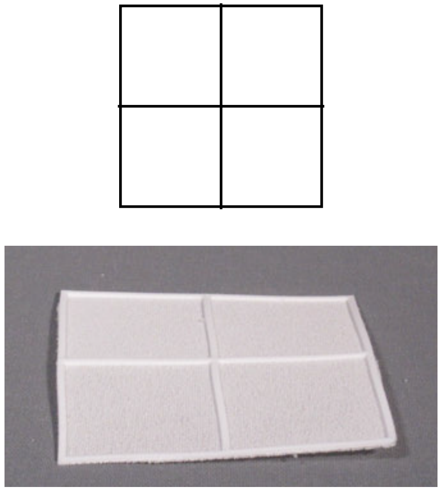


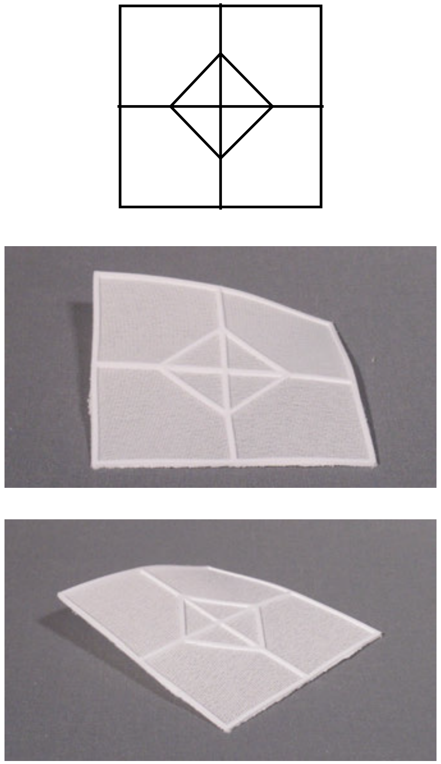
Material: Polyester Lycra
Filament: PLA
Height: 5.0 mm   Width: 0.5 mm

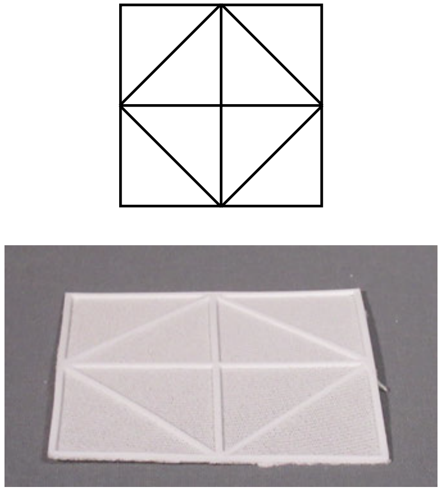


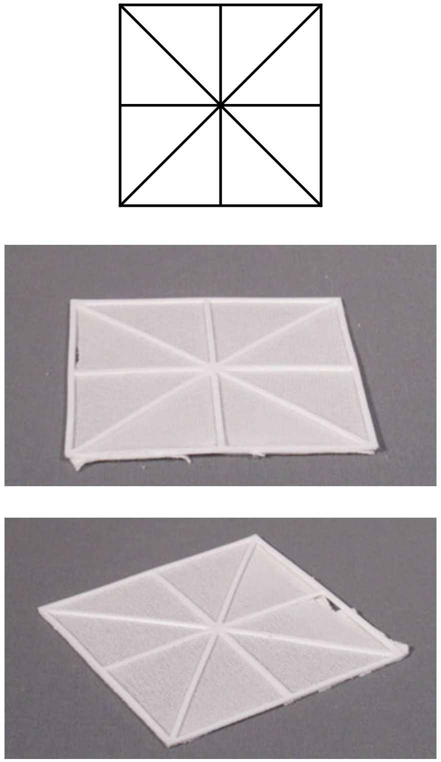


Material: Polyester Lycra
Filament: PLA
Height: 1.0 mm   Width: 0.5 mm

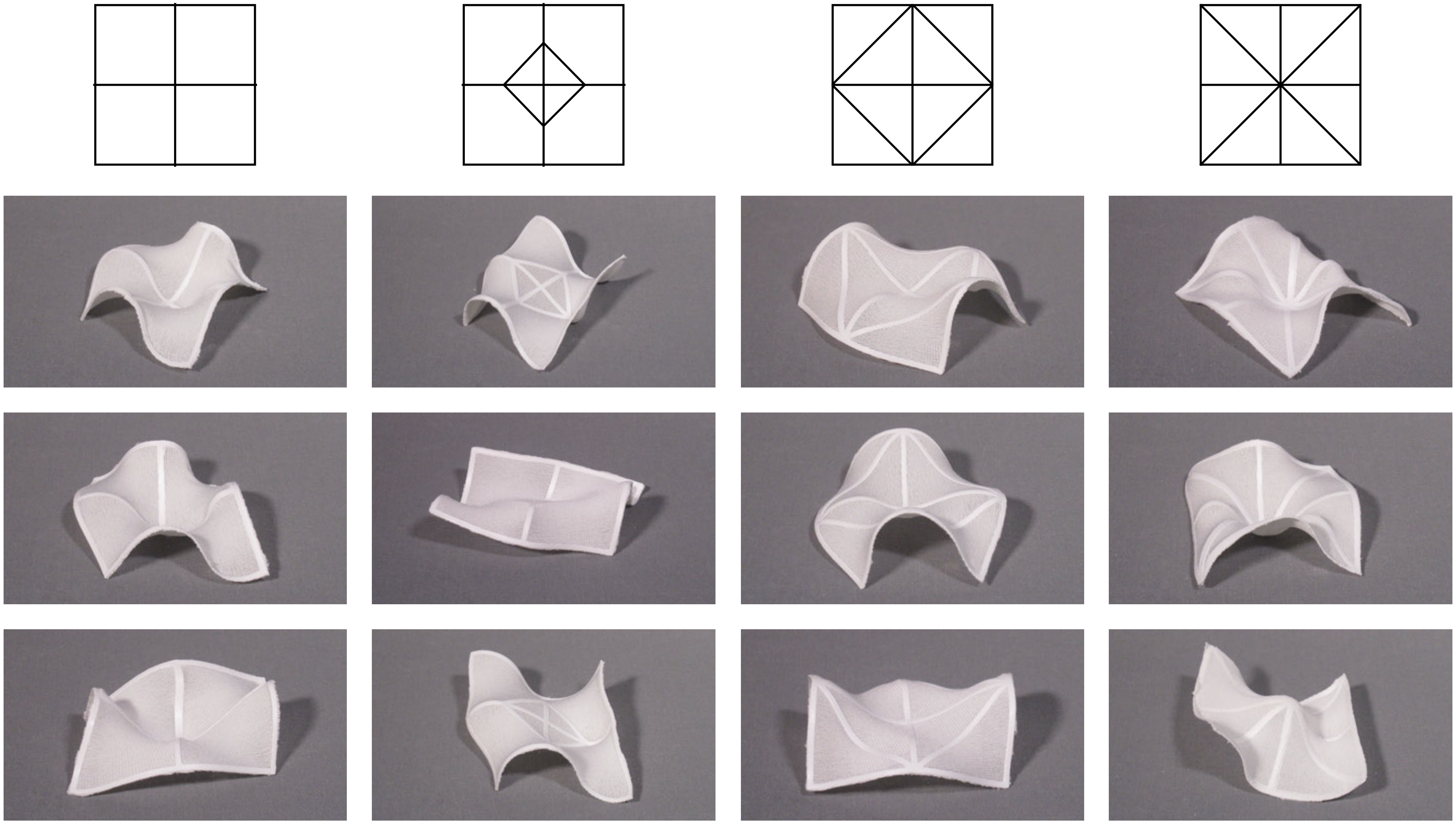






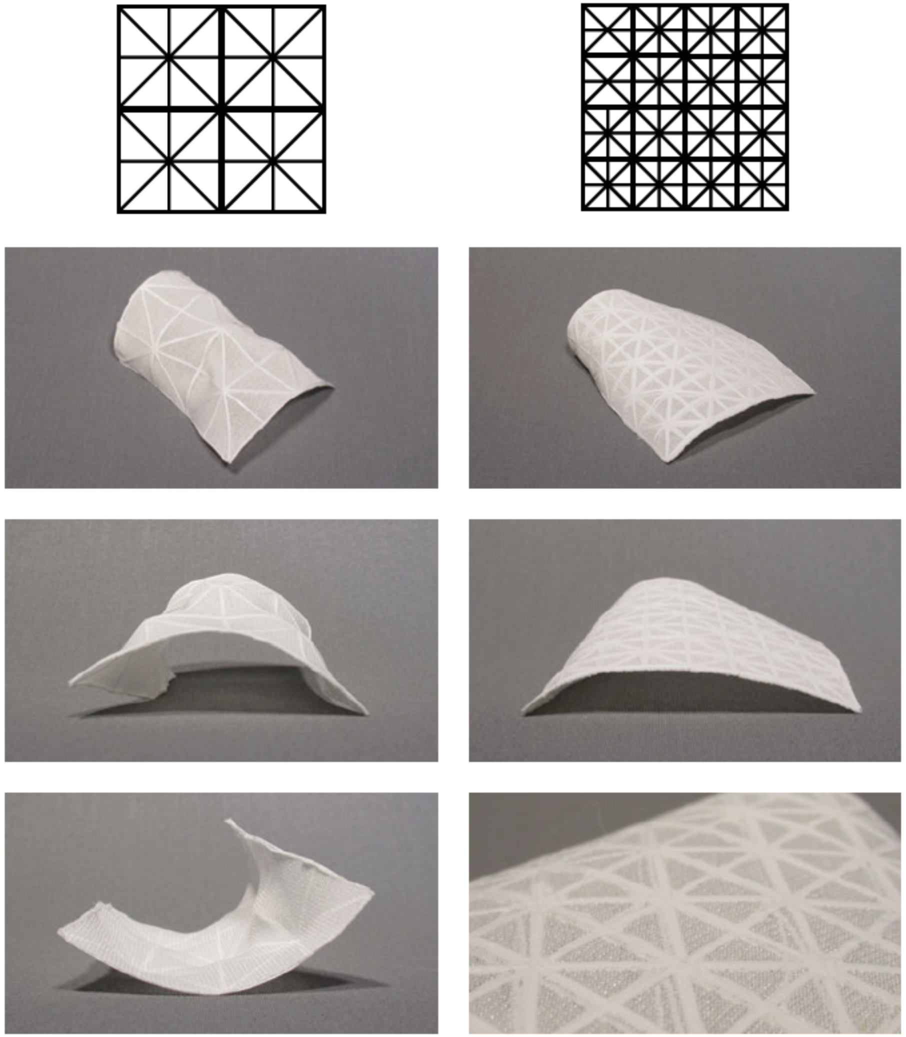


Material: Polyester Lycra
Filament: PLA
Height: 0.5 mm   Width: 1.5 mm

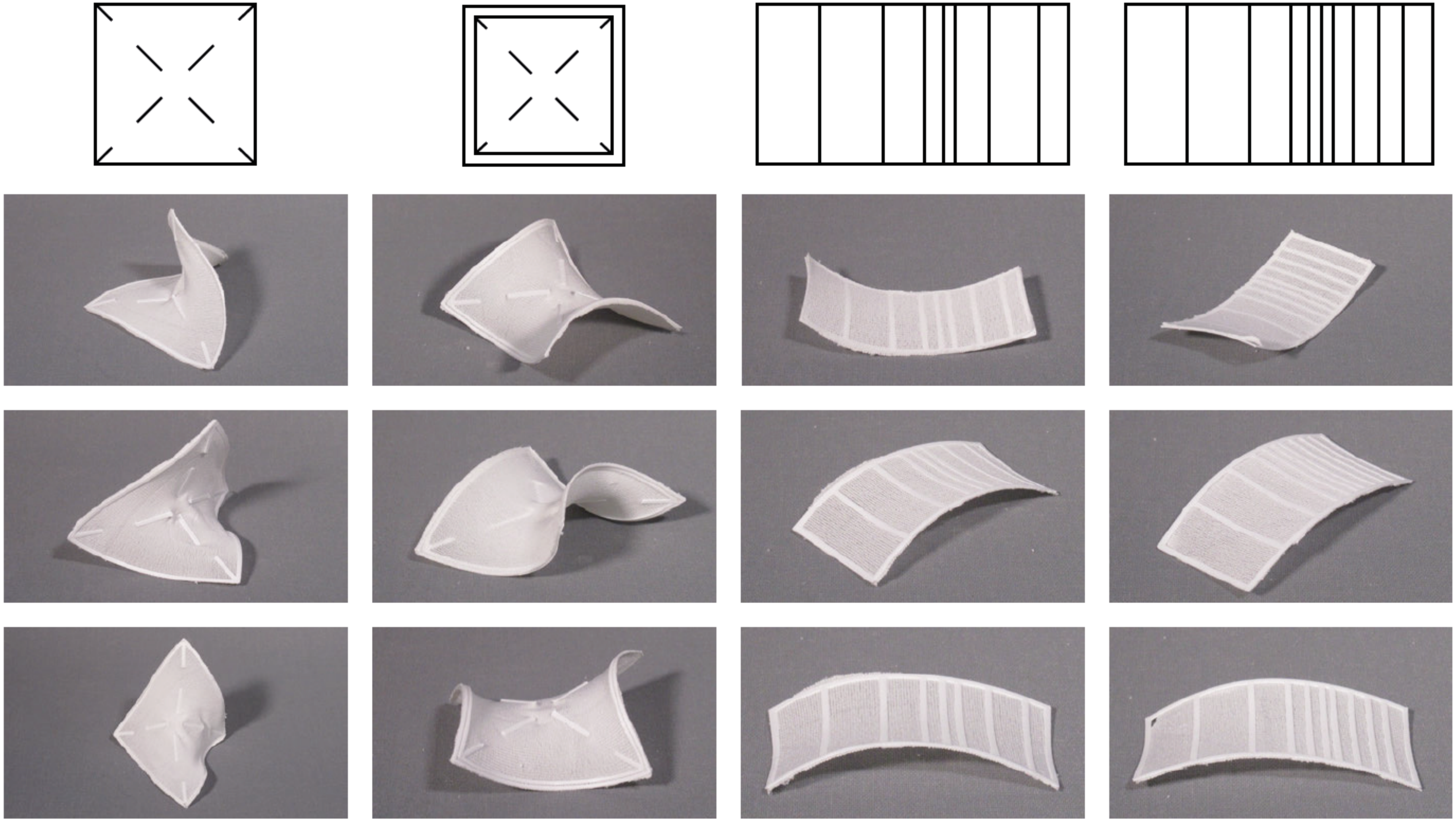


Second ‘plopped’ state

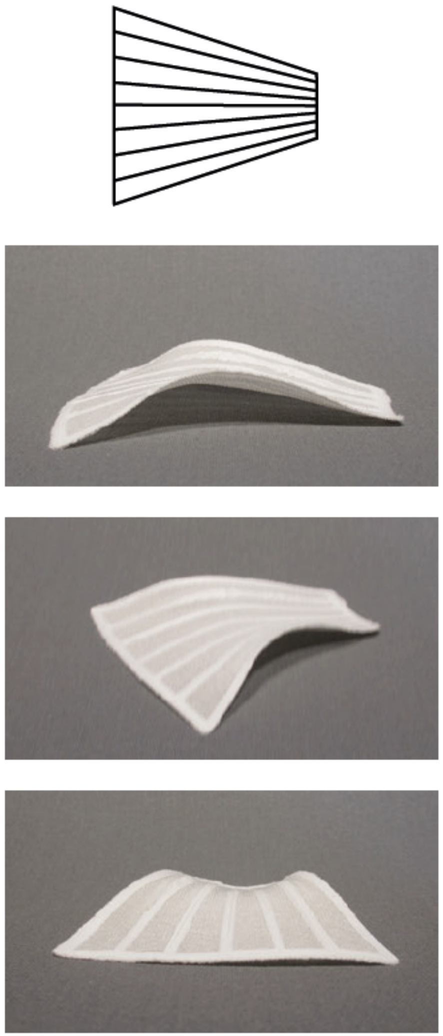
Material: Polyester Lycra
Filament: PLA
Height 0.5 mm   Width: 1.5 mm

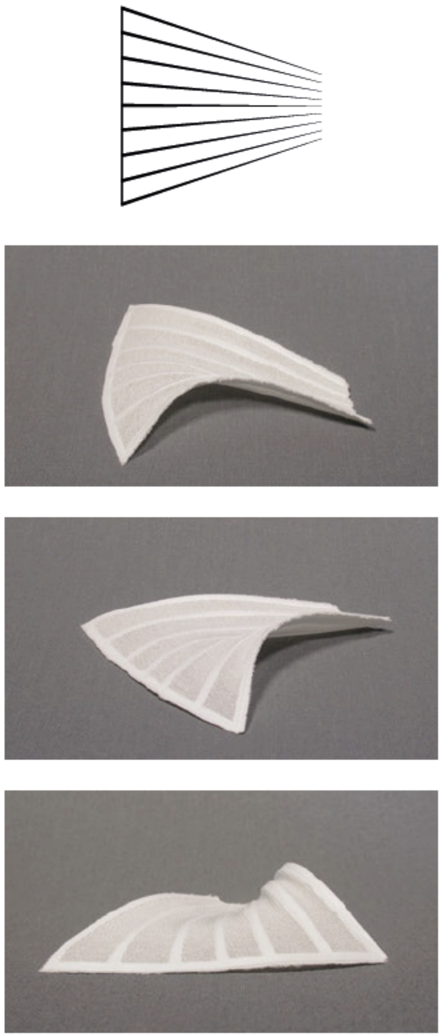


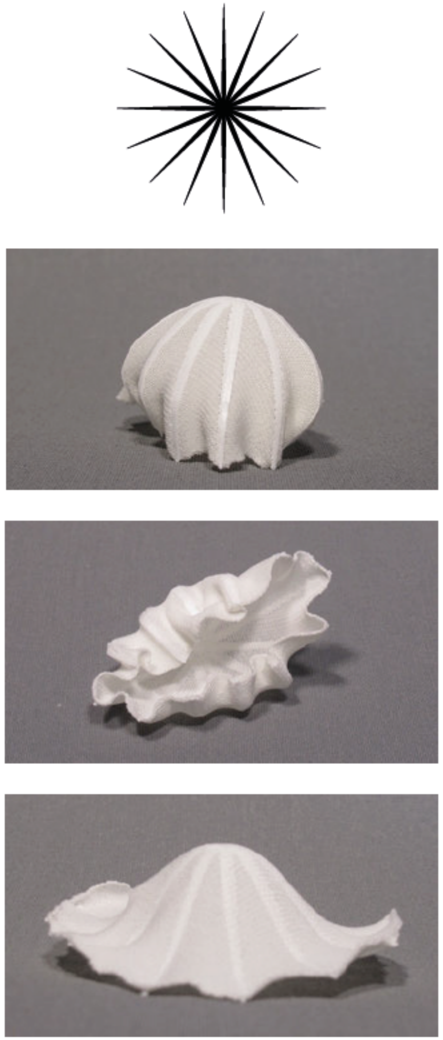
Material: Polyester Lycra
Filament: PLA
Height 0.5 mm Width: 1.5 mm

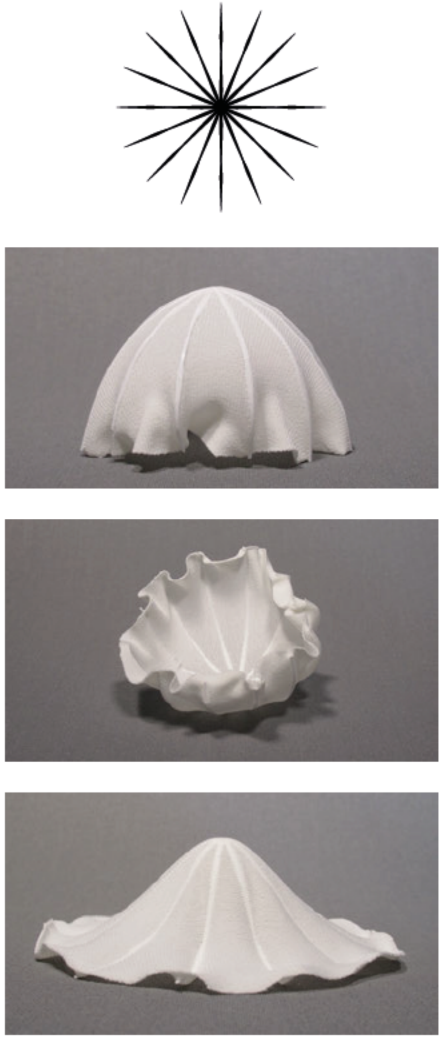


Material: Polyester Lycra
Filament: PLA
Height: 0.5 mm   Width: 1.5 mm

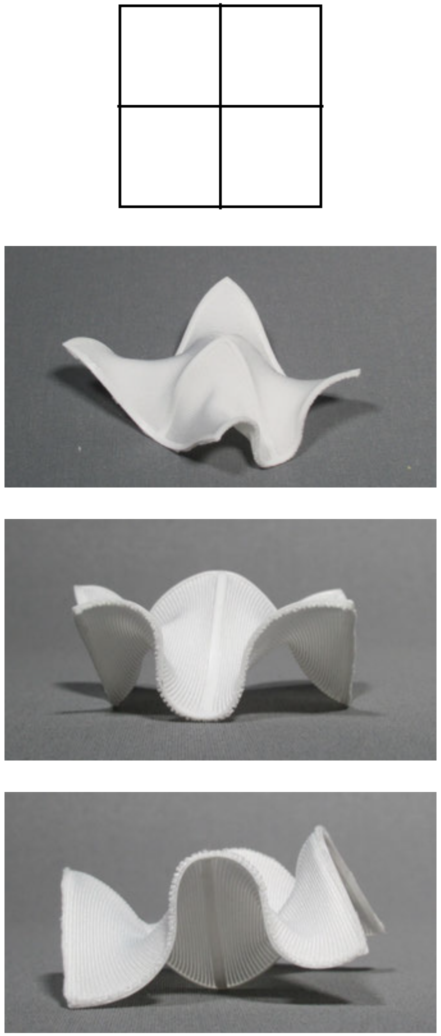


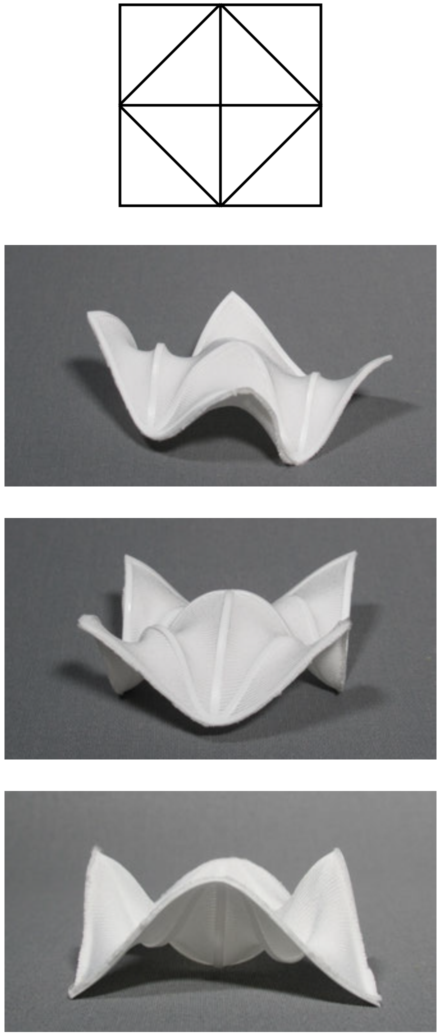




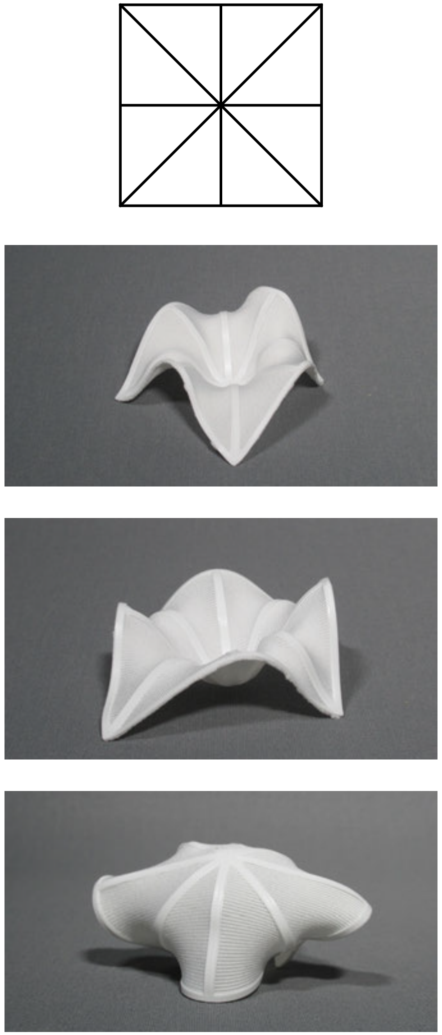


Material: Lycra
Filament: PLA
Height: 0.5 mm Width: 1.5 mm



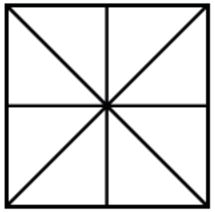


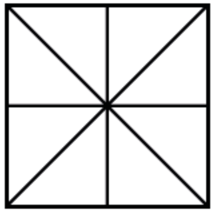
Upside down

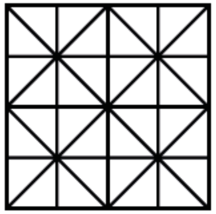


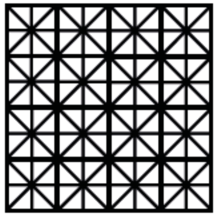
Second ‘plopped’ state

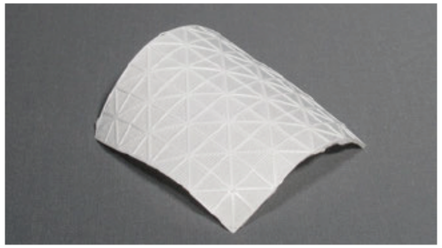
Material: Lycra
Filament: PLA
Height 0.5 mm Width: 1.5 mm

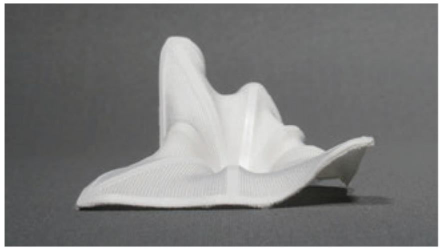


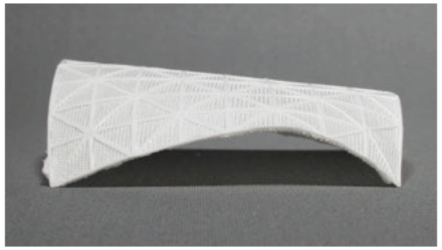




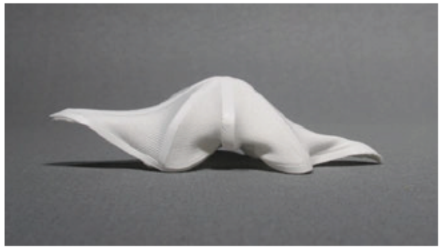




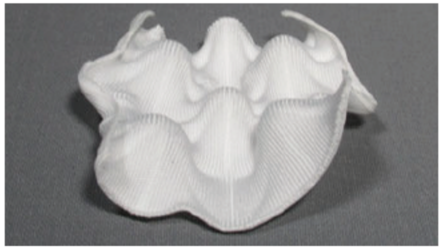


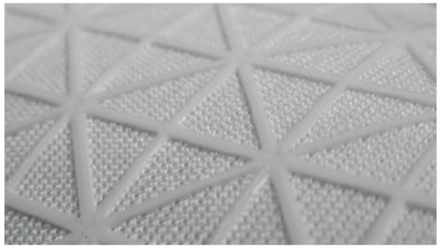


Second 'plopped' state

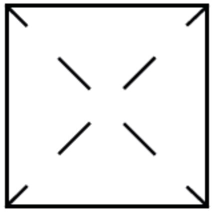


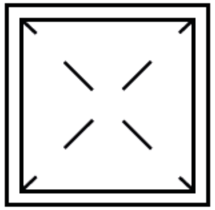
Second 'plopped' state

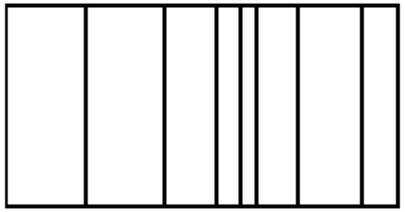


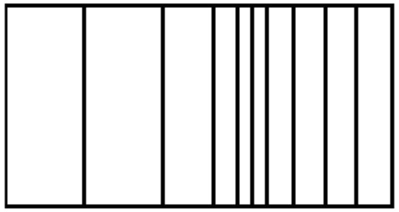


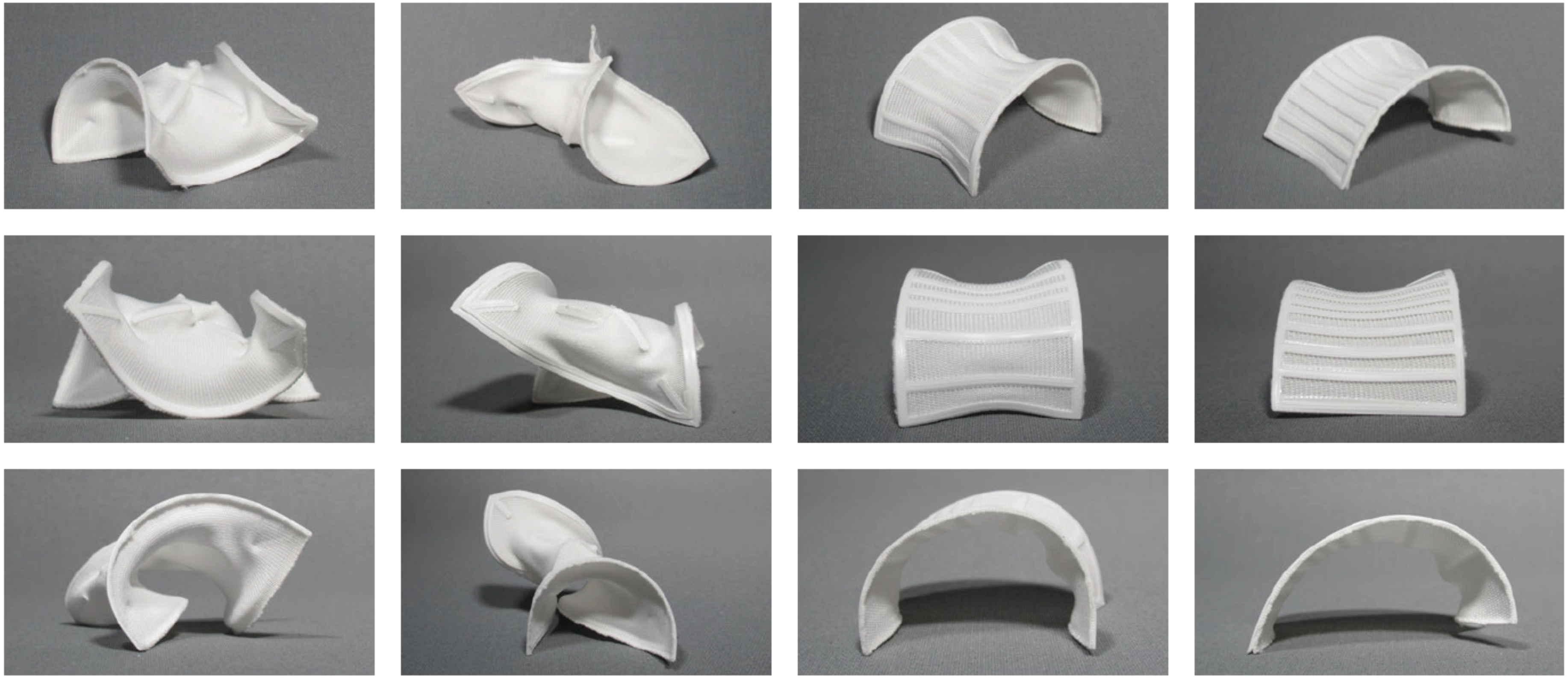
Material: Lycra
Filament: PLA
Height 0.5 mm Width: 1.5 mm



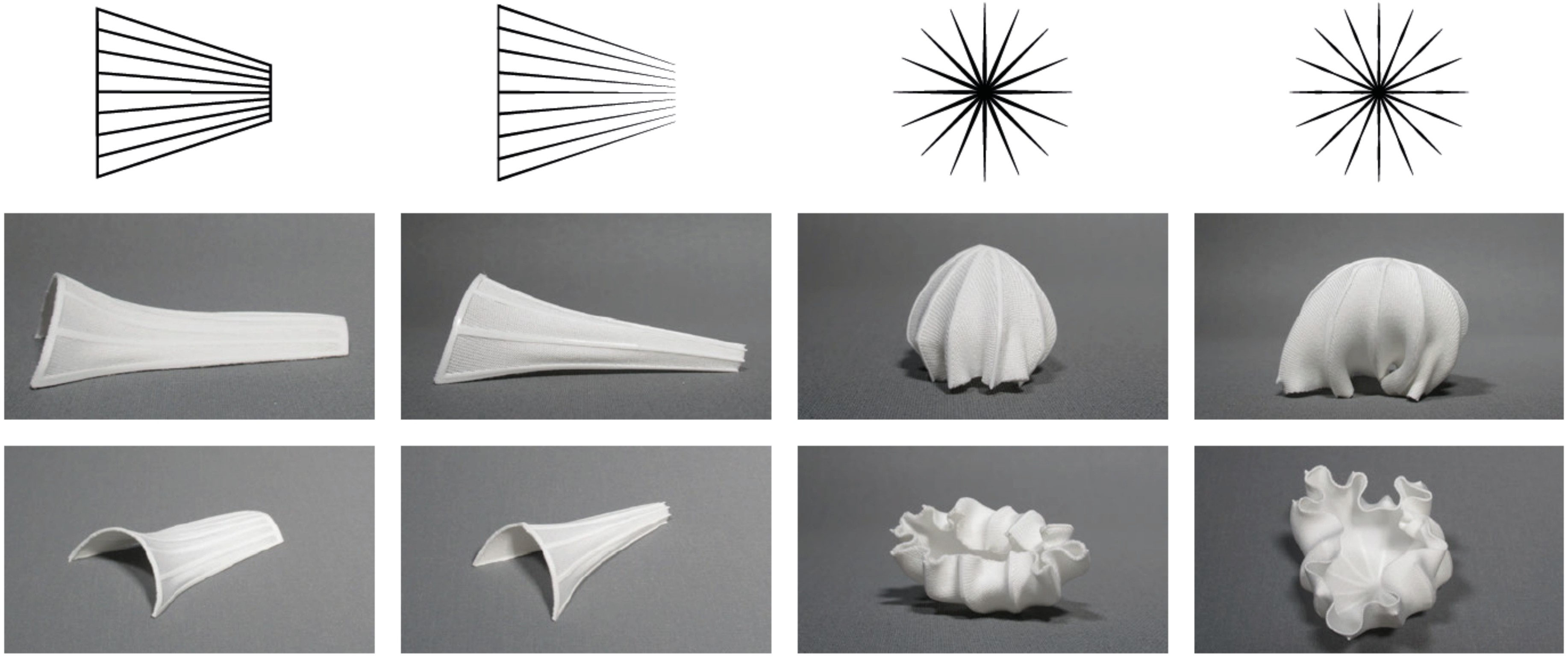






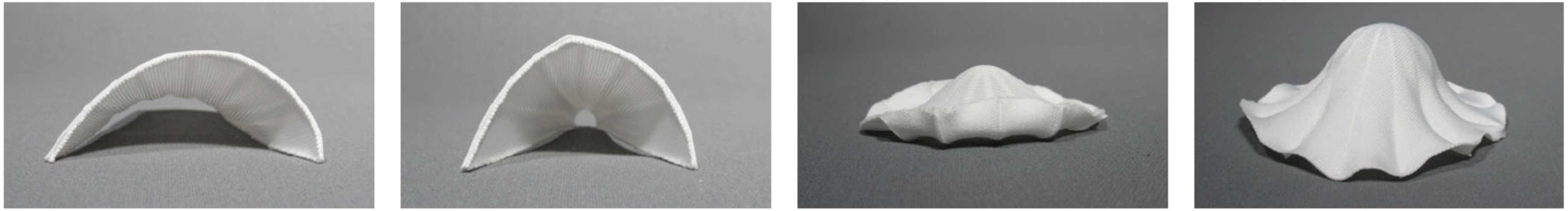


Material: Lycra
Filament: PLA
Height: 0.5 mm Width: 1.5 mm

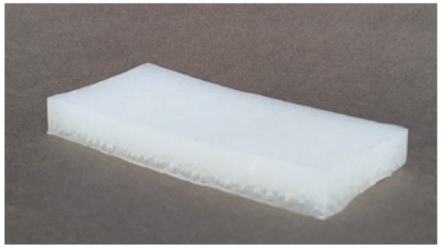


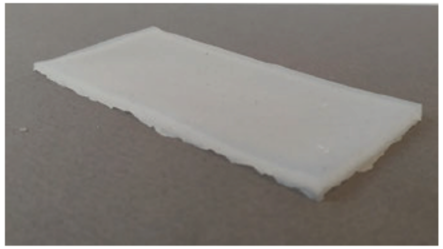
Second ‘plopped’ state

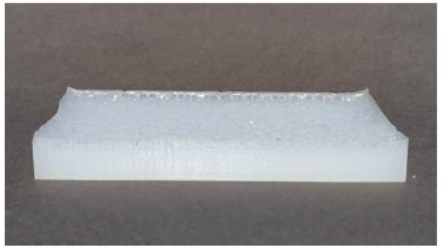
Second ‘plopped’ state

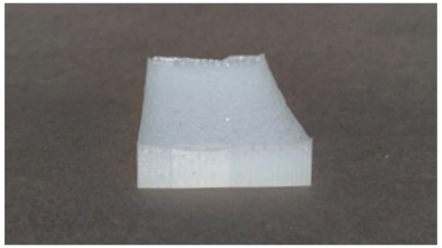


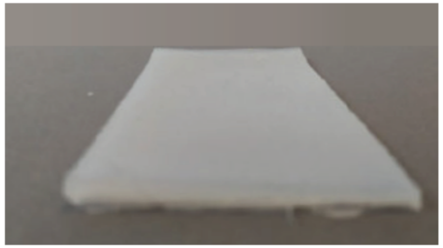
Dragon Skin Silicone - multiple surface patterns and thicknesses

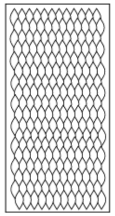


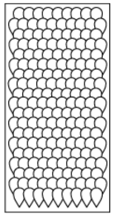


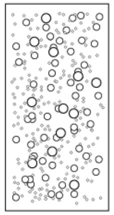


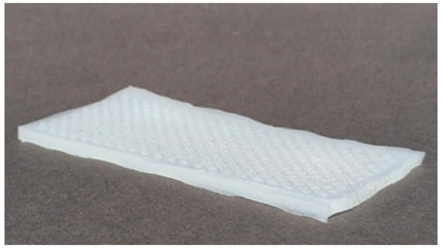


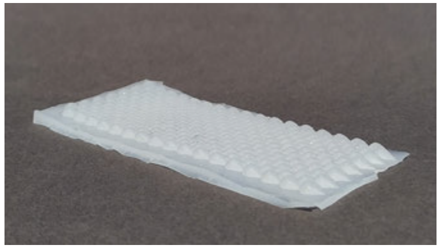


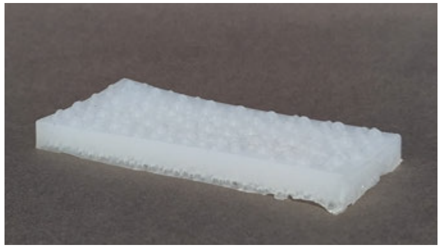


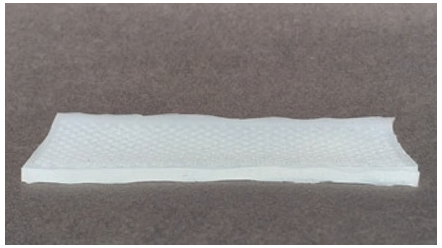


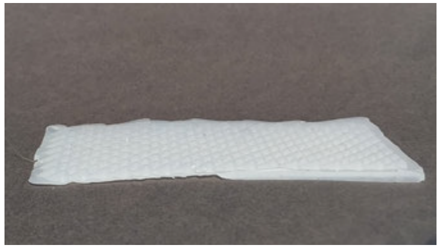


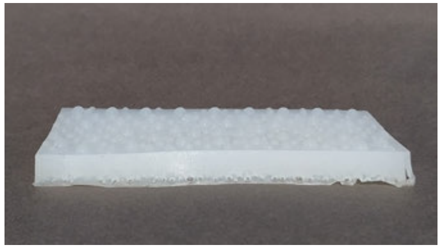


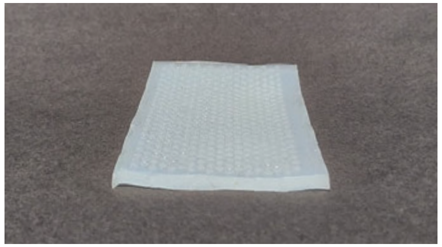


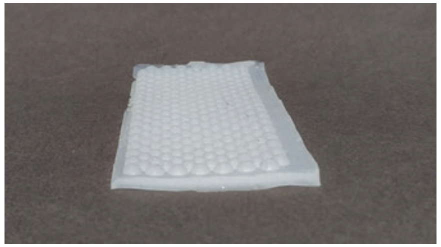


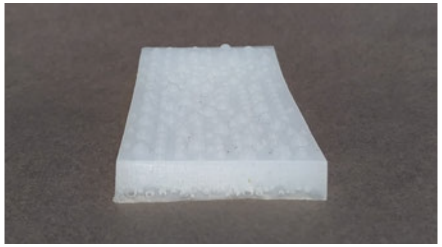








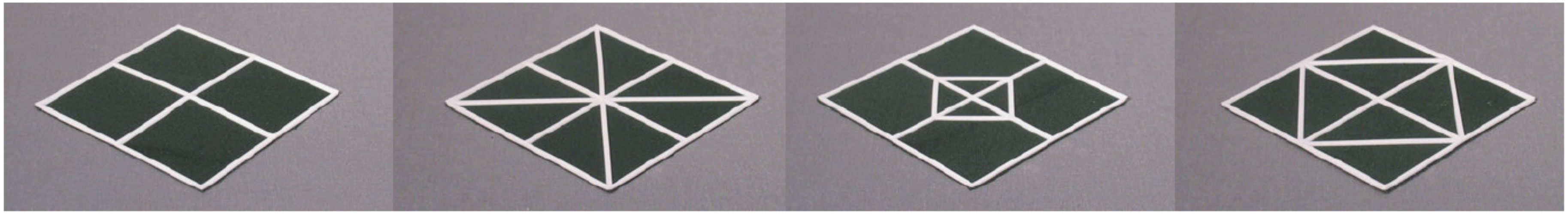




Appendix A:

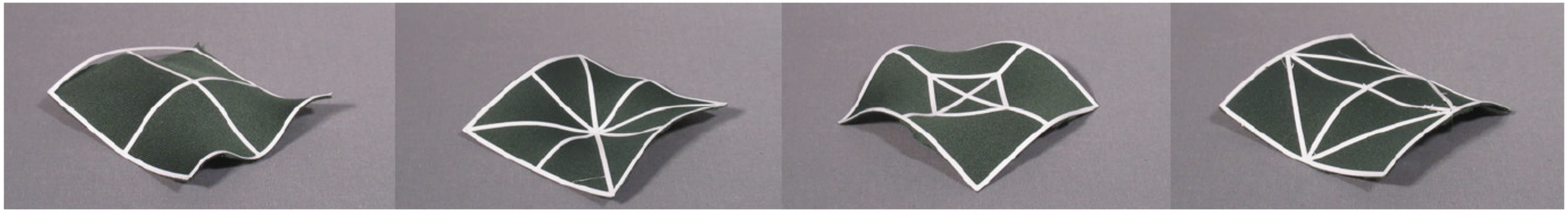
User Test

Polyester Viscose - H1.0 - W1.5



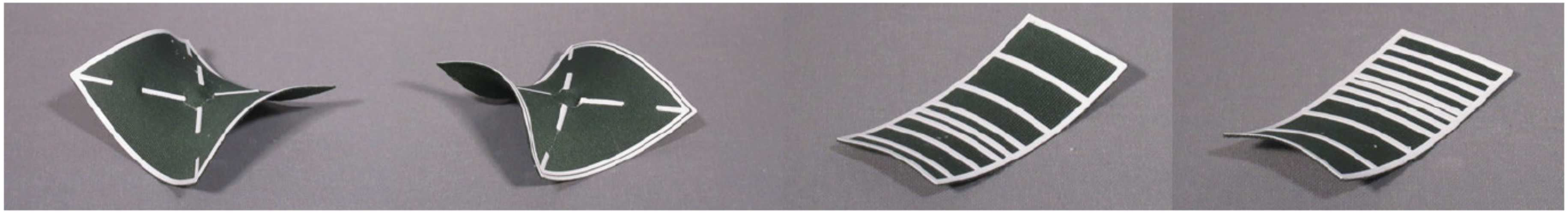
Participant 1	**Action:** 1) Bending of the sample using two hands and releasing 2) Tries to fold corners together, pushing two fingers together using the surface below it **Thoughts:** Quite Flexible and strong		**Action:** 1) Bending of the sample using two hands and releasing	**Action:** 1) Tries to fold it Thoughts: If I fold it I think I will break the filament. Would be interesting to be able to fold it and have a new structure
Participant 2	**Thoughts**: I don't see how useful these shapes are	**Thoughts:** I don't see how useful these shapes are	**Thoughts:** I don't see how useful these shapes are	**Thoughts:** I don't see how useful these shapes are
Participant 3	**Action:** Flopping the center part back and forward by alternating the pinched corners **Association:** On-off switch, abrupt transition Does not relate to anything seen in nature. **Thoughts:** I don't see a direct connection to caterpillar: it is flat and not flexible whereas the caterpillar is	**Thoughts:** I don't see a direct connection to caterpillar: it is flat and not flexible whereas the caterpillar is	**Thoughts:** I don't see a direct connection to caterpillar: it is flat and not flexible whereas the caterpillar is. This is the most flexible one and has the switch effect.	**Thoughts:** I don't see a direct connection to caterpillar: it is flat and not flexible whereas the caterpillar is
Participant 4	**Thoughts:** I don't see a movement or a caterpillar in these shapes because it is too flat and regular			

Polyester Viscose - H0.5 - W1.5



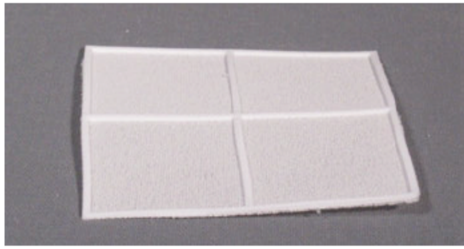
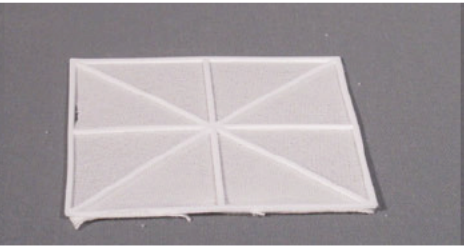
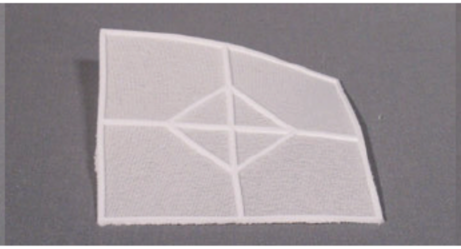
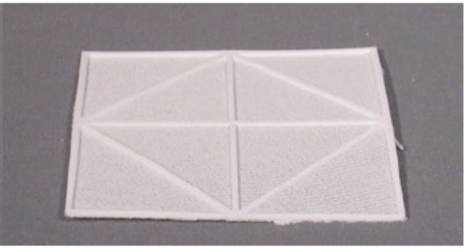
Participant 1	**Thoughts:** It is not as strong as the Lycra samples, so it is not as interesting. It is between the flat 1mm samples (stubborn) and the springy ones). They are also not soft enough to play with			**Action:** 1) Folding two sides down & release (jumps away) 2)
Participant 2	**Action:** Pushing bump **Thoughts:** The fabric does not move a lot, i would prefer the other Lycra		**Action:** Pushing on edges to compress and release	
Participant 3	**Action:** Pushing the bump. Pinching the material to bend and move like inching	**Action:** Pushing bump. 2) Inching movement by pinching.	**Action:** 1) Folding both sides to create tube, moving one side and other in an inching way 2) Moving feet with 4 fingers towards and away from each other (like walking) **Thoughts:** Same folding is possible as with the >,	**Action:** Folding **Thoughts:** 1) It is quite sturdy but also flexible. It seems too restricted because the diagonal lines inhibit the material to form a curved shape, opposed to the smaller triangle shape. 2) The shape and material do not call for the movement of a caterpillar.
Participant 4	**Action:** Pushing corners to the ground and inching it. **Thoughts:** The less regular and curved shape seems more organic.			

Polyester Viscose - H0.5 - W1.5

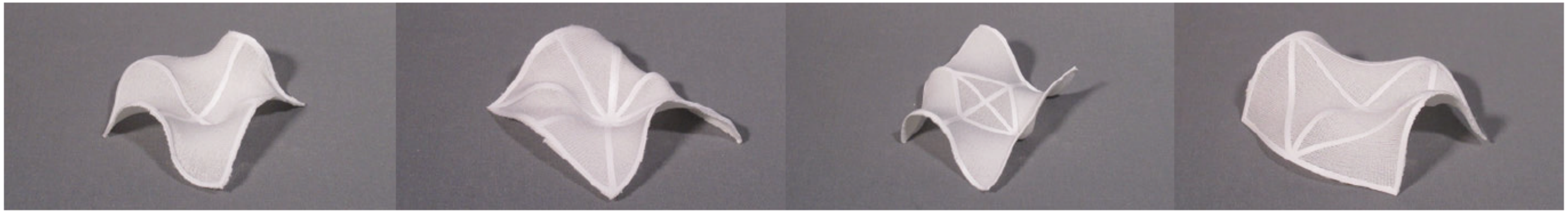


Participant 1	**Action:** 1) Folding sides together 2) Crumpling it up into a ball (squeeze it) **Thoughts:** It is so soft! I am not afraid I will break it because it seems so flexible and soft. I love them!	**Action:** 1) Folding sides together 2) Crumpling it up into a ball (squeeze it) **Thoughts:** It is so soft! I am not afraid I will break it because it seems so flexible and soft. I love them!		**Thoughts:** It is not as strong as the Lycra samples, so it is not as interesting. It is between the flat 1mm samples (stubborn) and the springy ones)
Participant 2		**Action:** Moving center and corner together		**Action:** Bending two edges together
Participant 3			**Thoughts:** Does not really look like a caterpillar, but the shape does.	
Participant 4				

Polyester Lycra - H0.5 - W1.5

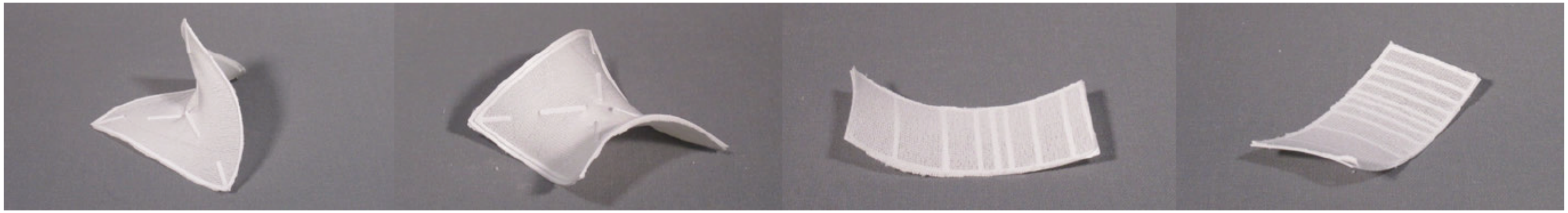
				
Participant 1	**Action:** Pulled two sides so that the shape would be straight but it broke instead. **Thoughts:** It looks like a parallelogram, but I do not think it is supposed to look like that		**Action:** 1) Pushing center in and out while holding two opposing corners in one hand	**Action:** Pushing two corners down to the substrate & releasing
Participant 2	**Action:** 1) Pulling two opposing corners away from each other 2) Bending two connected corners together using two hands			
Participant 3	**Action:** 1) Pulling two opposing corners away from each other 2) Bending two connected corners together using two hands **Thoughts:** Sample has no performance	**Action:** Flexing sides. **Thoughts:** Less flexible, not as interesting because lycra does not have a function.	**Action:** 1) Pulling two opposing corners away from each other 2) Bending two connected corners together using two hands **Thoughts:** No performance	**Action:** Flexing sides
Participant 4	**Thoughts:** The shapes are too flat to really see a movement with it.			

Polyester Lycra - H0.5 - W1.5



Participant 1		**Action:** 1) Pushing bulge (plop) 2) pushing two sides away from each other (counteracting plop) **Thoughts:** Interesting performance		
Participant 2	**Action:** Pushing bump with one finger	**Action:** Bending from two sides using two hands 2) Pushing two opposing edges with two fingers to create forward motion	**Action:** Pushing curled side down with one finger **Thoughts:** if i keep the square on the bottom, once the front moves, it has to be fixed and the other side has to move.	
Participant 3	**Action:** Pulling opposite corners away 2) Pinching sides together and again. 3) Pushing bump with finger. **Thoughts:** 1) Offers more freedom, the lack of the inner square makes the movement of that sample not as possible with this sample. 2) The options are less guided in what I should do with it 3) Curvature and lack of some diagonal ribs make the structure a bit more stretchy/flexible and can account for caterpillar expansion/contraction	**Action:** Pushing bump (plop, moving corner (de-plop), Moving corners together. **Thoughts:** Seems like a mix between the star and the small square. The added curves feel nice. Moving corners together for caterpillar movement.	**Action:** Bending opposing corners together 2) bending two opposing sides together **Association:** Circular flexible frisbees, Shape reminds me of a manta ray (flat and a little bit curved) **Thoughts:** 1) I like that one plane is weirdly curves in the fabric (feels nice) 2) Surprising how quick it snaps back after bending 3) Folding corners to the center is hard, they move to the side 4) Pushing down and forward slightly, it moved in that direction 5) Difficult to move like a caterpillar	**Action:** 1) Folding both sides to create tube, moving one side and other in an inching way **Association:** Toys you can flip inside out and you put them on the surface and let go and then.they jump up 2) Tube body: Literal translation to caterpillar body shape **Thoughts:** Flexing the middle feels nice. Interesting Movement: Rolling the structure and making a tube, then it can move like a caterpillar. Interesting how a square can easily fold to a caterpillar like shape.
Participant 4		**Action:** pushing corners down and moving similar to inching Association: Spider **Thoughts:** The belly is touching the ground, it seems more like a spider		**Thoughts:** This is the most interesting as a body shape. it can be moved into a crawling pattern because the corners are nicely pointed to the floor and the belly is lifted from the surface

Polyester Lycra - H0.5 - W1.5

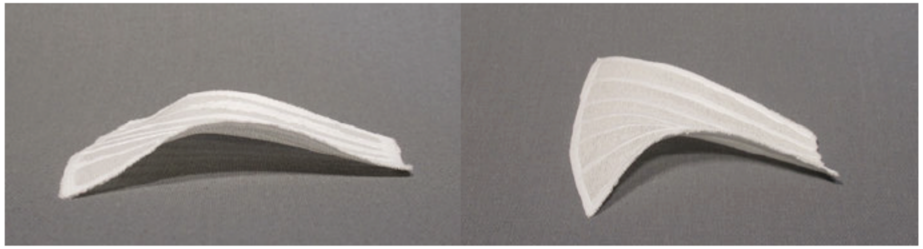


Participant 1				
Participant 2	**Action:** 1) Moving corners away 2) Twisting **Thoughts:** It is nice and flexible, but i like feeling of the stiffer and more curved structures more	**Action:** Twisting like a bowtie 2) Bending sides together. 3) Bending twice like a piece of paper. **Thoughts:** You can pull the sides away from each other, more flexible and can also move the corners away and towards each other. Flexible but less structure, so most work has to be done by yourself and movement is not immediately apparent. The other shape offer a frame to work within.	**Action:**1) Bending two hands 2) Twisting it **Thoughts:** 1) rigid laterally, but easily movable in twist and bending 2) Not as imaginative, very straightforward movement	**Action:** Creating wave over surface with two hands **Thoughts:** feels less flexible on one side because of extra ribs. The impact of the ribs is not necessarily clear. Doesn't seem very different from the similar shape
Participant 3		**Action:** Stretching sides away from each other. Folding sides together (also diagonally). Laying it flat. **Thoughts:** feels thicker. Behaves in a similar way, folds pretty nicely. Shape and material don't necessarily give me a caterpillar feel.		**Action:** 1) Inching (bending two edges together). 3) Twisting. 3) Bending over lateral axis. **Association:** Straightforward translation of caterpillar.
Participant 4			**Action:** 1) Inching 2) Creating a rolled wave movement over the surface **Thoughts:** It is the most similar to a caterpillar	

Polyester Lycra - H0.5 - W1.5

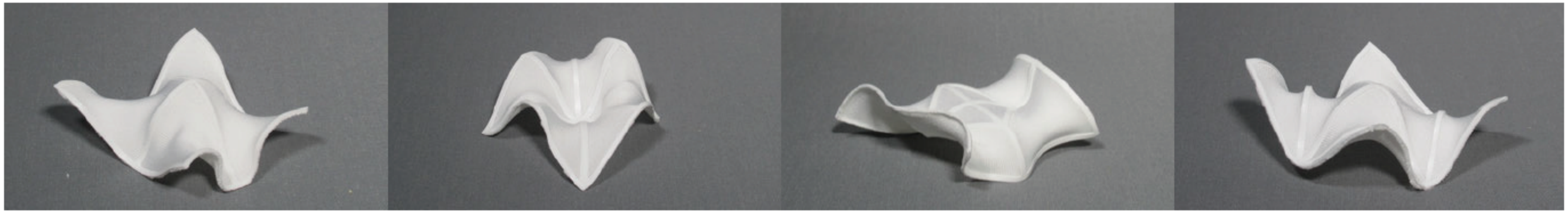
Participant 1		**Action:** 1) Pushing bulge (plop) 2) pushing two sides away from each other (counteracting plop) 3) Forming it over the fist again 4) Moving it with two hands and popping it repeatedly by bending the centre Association: **Thoughts:** 1) Love it (still favourite piece) You can see two beautiful states of the material, without deformation 2) Deformation is dependent on the shape of the substrate, if it does not have a flat surface it does not plop. 3) I feel like it can embrace my fist (Feels good)		**Action:** Pushing sample down to the substrate and releasing 2) folding it with two hands 3) squeezing it 4) Moving between both hands 5) Rolling it & releasing it 6) Rolling it the other way around **Thoughts:** I like how thin it is because it seems like a whole piece. I feel like i can squeeze or roll it. I can do something to it! (doesn't go back to its original shape after rolling) (negative feeling: disappointment)
Participant 2	**Action:** 1) Pushing the bump with one finger 2) Moving it with two hands and popping it repeatedly by bending the centre		**Action:** Pushing with one finger at the center	
Participant 3	**Action:** Moving it outwards (pop) **Association:** Smaller jellyfish, Turning it inside out is cool. I like it can change its shape from dome to pointy flower. **Thoughts:** inviting to explore, sparks wonder. Shape guides it to a certain use.	**Action:** Caressing the bump upwards. Squeezing inwards over surface to mimic walking forwards. Flipping sides outwards. **Association:** Jelly fish, Flower **Thoughts:** I like how it feels. Inviting to explore, sparks wonder	**Association:** Bendable lighter than plastic. 'new material' **Thoughts:** Interesting, but not as interesting as the circles because it has less shape. The flexibility of the material is not really used. More adaptable to different products.	**Thoughts:** Same as smaller size,
Participant 4				

Polyester Lycra - H0.5 - W1.5



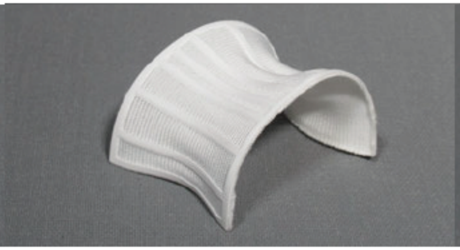
Participant 1		
Participant 2	**Action:** Bending, harmonic effect on the ribs, inching pattern over long side of material. **Association:** Reminds me of fish fin, Convertible car, Carnaval attraction 'de rups'	**Thoughts:** 1) Does not remind me of a caterpillar, but i like that it can change its shape. 2) Seems fragile.
Participant 3	**Action:** Grabbing both sides and pushing it to the ground in inching way. **Association:** Ribs/bones of an animal	
Participant 4		

Lycra - H0.5 - W1.5

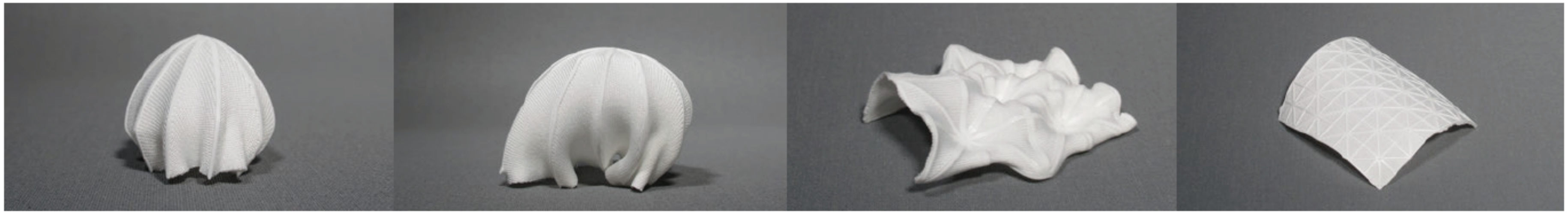


Participant 1		**Action:** 1) Pushing at the center (plops) 2) Pushing and the lifted sides **Thoughts:** The printed structure is regular, but the shape on different samples random and organic		
Participant 2	**Action:** Pushing bump -> moving it slightly forward **Thoughts:** Can the bump be made eccentric so that the flexing of the structure is more proportional to one side			
Participant 3	**Action:** Pushing the sides that are pointing downwards - jumps up. Pushing only two diagonal corners down - jump up. 3) Pulling corners away from each other. **Association:** Game with plastic frogs	**Thoughts:** Bends quite well. Croissant bend, Transforms easier, but also has less pressure		**Action:** 1) Folding sides in. 2) Folding sides in to the surface making a moving leg shape. **Association:** Croissant.
Participant 4	**Association:** Feet of caterpillar, bump to the bottom. Corners are the feet. The bump is too low, its touching the bottom. **Thoughts:** All the shapes with a clear structure inside, become less flexible.	**Action:** Holding the sides and moving it in an inching way, two other sides touching the ground represent the feet. **Thought:** The bends on the sides could be as feet, the bump in the bottom is not touching the ground. having multiple in parallel with the two feet at the side. *(asymmetric one)* **Action:** moving corners in inching way. **Association:** looks like manta ray.	**Action:** Grabbing both sides, moving in an inching pattern **Association:** Belly of the caterpillar. I see it as the ring of a caterpillar in between segments. **Thoughts:** Doing something diagonal seems the best, because the cross makes it hard to move, it might break the textile. But i see the shape in the other way.	**Action:** Grabbing both sides, moving in an inching pattern **Thoughts:** The belly is a bit up, the 4 corners are the feet.

Lycra - H0.5 - W1.5

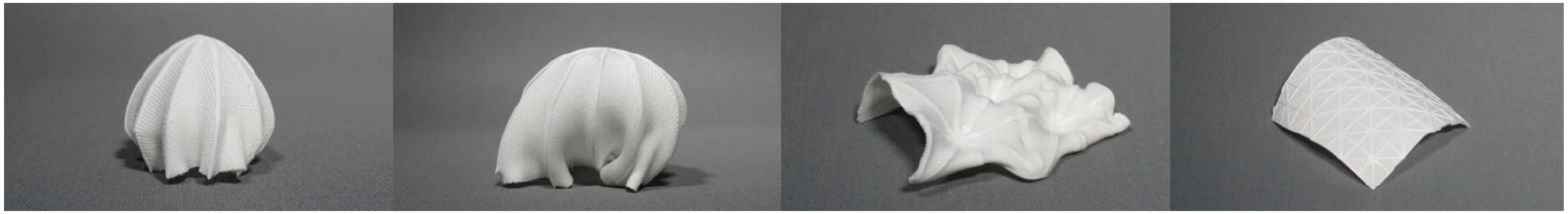
				
Participant 1	**Action:** 1) Pulling the two corners away from each other 2) Pulling on the sides 3) Putting it on the wrist			**Action:** 1) Holding it with one hand and bending with the other hand and letting go 2) Pusing one finger on one side of the sample to propel it forward Association: **Thoughts:** Surprisingly has a quite quite strong memory of its original shape
Participant 2	**Action:** 1) Rolling 2) straightening 3) pulling two facing corners away and closer (like a swimming motion) 4) moves it like a butterfly **Association:** Horse saddle **Thoughts:** Could mimic the movement of a swimming		**Action:** 1) Bending with both hands 2) Holding it with one hand and bending with the other hand and letting go 3) Pushing it on the top middle on top of a surface **Thoughts:** 1) I think it deflects like a caterpillar, but it should be followed by something which is not as flexible as this (stick and slide) 2) It is stiffer at one side because more filament 3) Concave curvature is not necessary for a caterpillar - Perhaps add axial ribs to provide flexural stiffness	**Action:** 1) Bending with both hands 2) Holding it with one hand and bending with the other hand and letting go 3) Pushing it on the top middle on top of a surface **Thoughts:** I think it deflects like a caterpillar, but it should be followed by something which is not as flexible as this (stick and slide) 2) It is stiffer at one side because more filament
Participant 3		**Actions:** Warping **Thoughts:** The shape is more warped that the other sample The shape is maybe also bistable. Has too little structure to represent a caterpillar.	**Thoughts:** Similar to other fabrics, always come out similar. This fabric is more springy.	**Thoughts:** Similar to other fabrics, always come out similar. This fabric is more springy.
Participant 4	**Actions:** Grabbing two sides and moving it in an inching way **Thoughts:** I am looking for a arch shape, this one does not really get that arch when I move it. Due to the lacking complete lines, the structure is more flexible	**Thoughts:** This one is too bend to really look like the caterpillar and not as flexible as the other one. The shape is too closed.	**Action:** Grabbing both sides, moving in an inching pattern **Association:** Caterpillar, because it is long, rectangular and it is easy to inch. **Thoughts:** Making the bottom more arched like the squares gives it more of a caterpillar look. This is more flexible in both directions	**Action:** Grabbing both sides, moving in an inching pattern **Thoughts:** This one seems to have more of a direction because one side is more flexible. So the highly flexible part should be at the front.

Lycra - H0.5 - W1.5



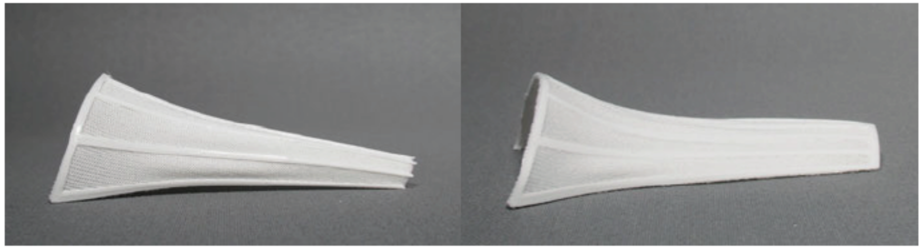
Participant 1	**Action:** Pushes the bulge on the tip of the finger with the other hand, after it plops tries to have it enveloping the finger	**Actions:** 1) Want to drop it from the sky (interested to see how it behaves) 2) Putting it on the wrist and pushing the bulge (plopping it) 3) folding the open flower over the wrist as if it embraces it **Associations:** 1) Umbrella of a Mushroom, structure resemble the fiber. 2) Parachute Folding it open and closed with hands (because it allows for it) **Thoughts:** 1) It does not go back to its original shape. 2) When i press it on my skin, the filament pierces the skin, it is a bit painful (in a good way) 3) If it could embrace my body it would be more similar to a creature than a dead material	**Action:** Pusing one finger on one side of the sample to propel it forward because it bounces **Association:** A frog, reminds them of frog toy that jumps forward by pushing the back side	**Thoughts:** The texture is very regular, but the shape it not. It is intriguing why this happens.
Participant 2	**Action:** 1) Pushing the bulge with one finger (plop) 2) Grabbing it with two hands and moving the centre up and down -> repeatedly plopping **Association:** Starfish - Leg of a caterpillar, extending and contracting **Thoughts:** This is fancy! Perhaps the surface area and sticky-smooth material can be altered, to facilitate movement	**Association:** Leg of a caterpillar	**Action:** Pushing bumps on surface with fingers	**Action:** Rolling it up **Association:** The covering/skin of the caterpillar **Thoughts:** This could be nice for the texture

Lycra - H0.5 - W1.5



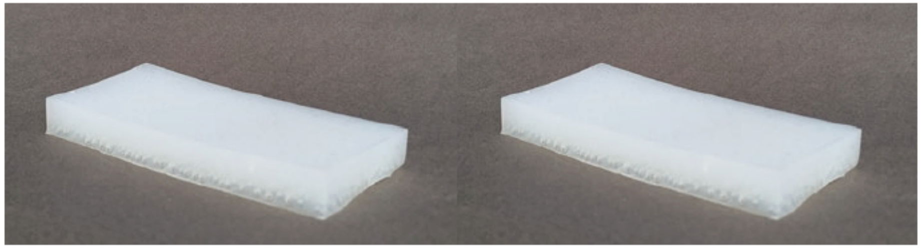
Participant 3	**Association:** Reminds me of jelly-fish	**Association:** Reminds me of jelly-fish thoughts: not very different from other materials.	**Association:** Bubble wrap, almost same satisfaction. Similar movement & sound.Relation to caterpillar hard.	**Action:** rolling, bending folding Thoughts: similar to rectangular, but not as springy
Participant 4	**Action:** 1) Grabbing both sides, moving in an inching pattern 2) pinching sides together **Association:** Spider, Jellyfish	**Association:** Ghost or flower. Not a caterpillar	**Association:** Surface is irregular seems like a caterpillar **Thoughts:** I like that when it contracts the surface created is more uniform. it seems more realistic	**Association:** Not a caterpillar **Thoughts:** It is too regular, not natural shape. Could be a surface. I think non-uniform is nicer.

Lycra - H0.5 - W1.5



Participant 1		**Thoughts:** This one is softer on the side without filament than the other one
Participant 2	**Action:** Tapping the top surface	
Participant 3	**Thoughts:** The points can be pushed together a bit more. If the movement at the ends were bigger, it would be more interesting to me	**Action:** Rolling, Pulling **Thoughts:** I thought it would be more flexible because the fabric is thicker, but its not.
Participant 4	**Action:** Arching sides and then releasing a side **Association:** Muscle **Thoughts:** Too uniform. Structure seems very strong and reminds me of a muscle.	**Thoughts:** Not as flexible

Dragon Skin Silicone - multiple surface patterns and thicknesses

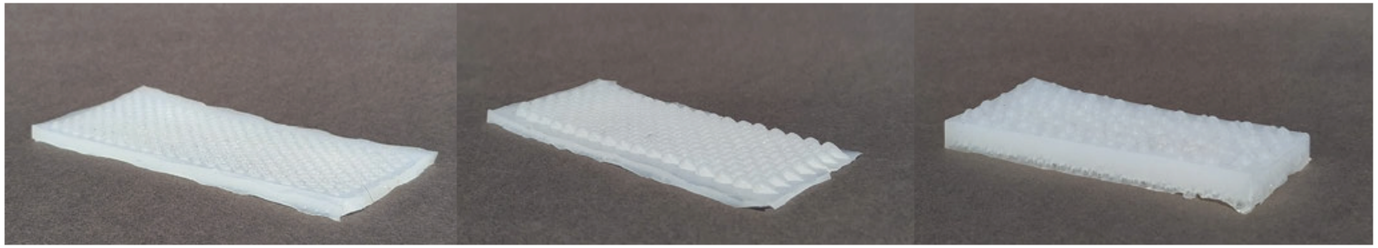


Participant 1	**Actions:** 1) Folding it over to stretch all the bubbles 2) Caressing the hand 3) Smelling 4) Flipping it over **Associations:** 1) It reminds me of an orange **Thoughts:** I think some people might be afraid of this texture because of the small and crowded holes, but I think it is fascinating. 2) The material doesn t have any smell, but I could imagine it having a smell like orange juice or meat: something totally different 3) The rectangular shape does not seem organic apart from the texture, it seems very passive	**Action:** 1) Stretching long side 2) Stretching short side 3) Stretching over head 4) Stretching over hand **Associations:** It is like stretching somebody s face **Thoughts:** 1) It is interesting that there is a hidden pattern into the silicone. 2) It s very stretchy 3) I would like it to be even more stretchy so you can make a big movement
Participant 2		
Participant 3	**Action:** 1) Twisting it 2) Pinching sides together 3) Folding the material over **Thoughts:** I like the thick slap, but I feel like if the surface was less sticky it would be easier to move the caterpillar around. Sliding the material is hard because of the stickiness.	**Action:** 1) Stretches both sides with two hands 2) Creating an inching pattern by placing two sides on the surface and sliding them 3) Rolling the silicone up. 4) Placing two sides on the surface, stretching and releasing one side. **Association:** Workout band **Thoughts:** 1) If it has less friction inching would work better. 2) When I release the material and let it bounce back it seems like an aggressive caterpillar. 3) Moving this material in an inching way with propagating a wave is more difficult because it is thinner

Participant 4

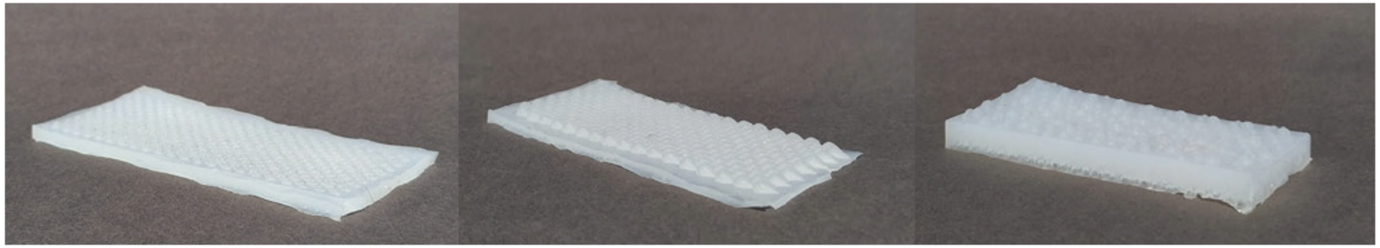
Actions: Inching sample by moving short sides 2) Bending 3) Rolling **Associations:** Meat **Thoughts:** 1) I find the material more natural. it feels like a piece of meat because of the consistency and thickness. 2) It does not remind me of a caterpillar, it is nice that it is so flexible and i can see the movement of the caterpillar because the movement is fluid 3) I like to see the vacuum air bubble edge, it really reminds me of a caterpillar	**Action:** 1) Folding it over 2) Stretching it out **Associations:** none **Thoughts**: This one doesn t remind me of a caterpillar

Lycra - H0.5 - W1.5



Participant 1	**Action:** Caressing **Thoughts:** This one is more regular, I don t like it because they look like an imitation of a plastic material, like an anti-slip mat 2) They are not exciting since there is no change along the length. 3) They seem more dead than alive	**Action:** Caressing **Thoughts:** This one is more regular, I don t like it because they look like an imitation of a plastic material, like an anti-slip mat 2) They are not exciting since there is no change along the length. 3) They seem more dead than alive	**Action:** Caressing 2) Sliding it over the 3) Bending both edges together **Association:** It is like a massage thing **Thoughts:** I want to caress it because it seems like i need to do this. 2) If the balls would be harder it could be used for massage
Participant 2	**Thoughts:** Changing the pattern over the length of the sample may make it more controllable or affect the movement	**Action: 1)** Bending 2) Stretching 3) Caressing 4) Inching by moving two sides together. 4) Pushing one 5) Flapping it around **Thoughts:** Changing the pattern over the length of the sample may make it more controllable or affect the movement	**Action:** Bending long sides of caterpillar together 2) Tying the sides together. 3) Stretching 4) Rolling the shape up **Thoughts:** perhaps the sides can be put together to create a more 3d shape. With such a thick slab, maybe having the edges thicker than the middle can enhance the movement. 2) I think the material is able to stretch enough, but then to translate this movement is challenging. Stretching is the first step. 3) Using a second layer you might be able to roll the silicone up, creating a bump which moves the top layer up like an inching movement

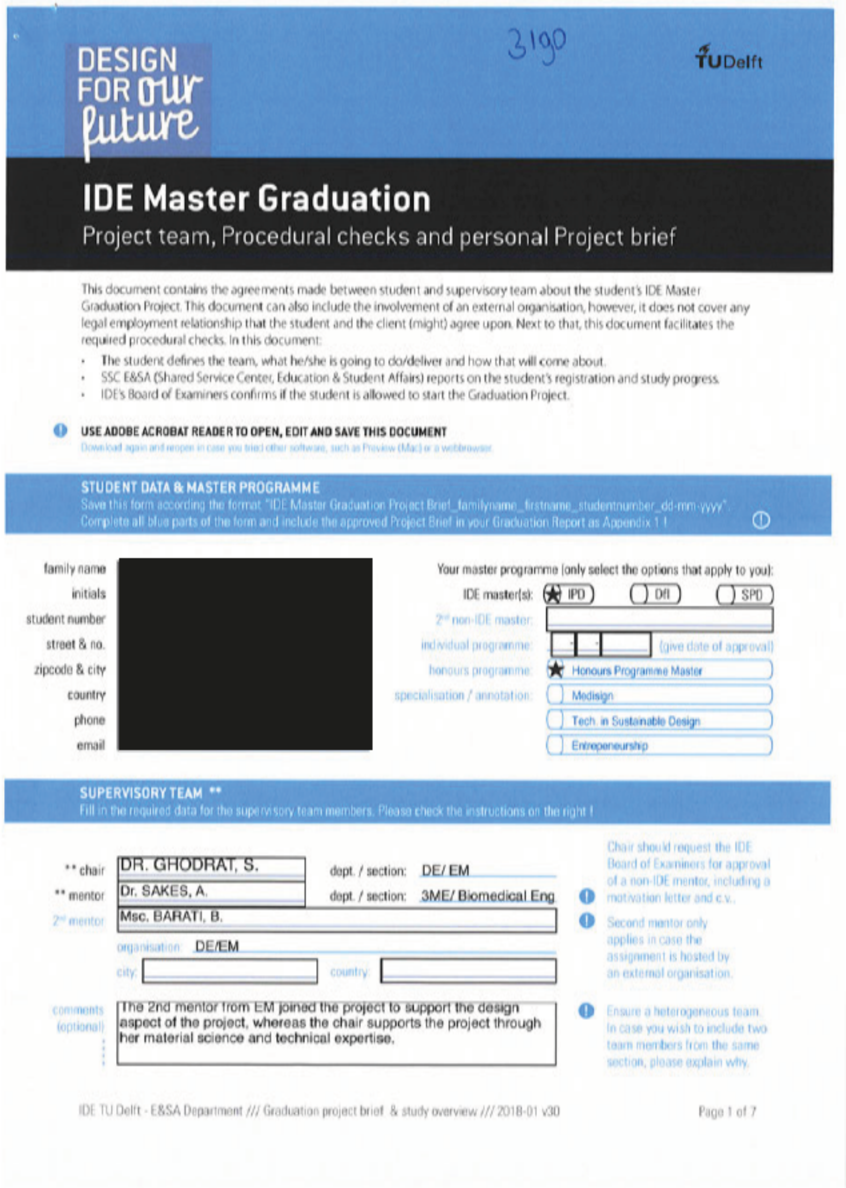
Dragon Skin Silicone - multiple surface patterns and thicknesses



Participant 3	**Action:** 1) Caressing the surface of the 2) Inching pattern 3) Rubbing the textured side on itself 4) Folding the sample over **Association:** Snake skin, the back of a toothbrush to scrape the tongue **Thoughts:** 1) I like that this one has a texture. There is a noise created by rubbing both sides over each other! 2) Because this one is thicker, the end doesn t roll over and I can move it in an inching way without 'catapulting the structure.	**Action:** Stretching it out **Thoughts:** This texture is nicer because the shape has a direction. They also stretch in an interesting way.	**Action:** 1) Caressing it 2) Slapping it 3) Squishing it 4) Inching pattern 5) **Association:** A children s toy which was shaped like a silicone banana slug The material really reminds me of a slug, also because of the air bubble finish. **Thoughts:** The pattern is random which makes it seem a bit weird. 2) Oh, these air bubbles also feel weird. You can create interesting noises by squishing it.
Participant 4	**Association:** Snake skin	**Action:** 1) Folding 2) Bending **Association:** Snake skin **Thoughts:** The thicker samples remind me more of a caterpillar than the thinner ones. The rolling movement is more translated using a thicker surface.	**Action:** 1) Caressing 2) Inching **Thoughts:** 1) If i were to touch the material without looking, it would really seem like a caterpillar or animal. Although I have never touched a caterpillar. 2) This texture reminds me more of a caterpillar than flat. 3) These material slabs don t really have feets, the edge on the surface, acts as feet.

Appendix A:

Graduation Project Brief



DESIGN FOR our future

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TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name
initials
student number
street & no.
zipcode & city
country
phone
email
[redacted]

Your master programme (only select the options that apply to you):
IDE master(s): ● IPD ○ Dfl ○ SPD
2nd non-IDE master:
individual programme: __ - __ - __ (give date of approval)
honours programme: ● Honours Programme Master
specialisation / annotation: ○ Medisign
○ Tech. in Sustainable Design
○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: DR. GHODRAT, S. dept. / section: DE/ EM
** mentor: Dr. SAKES, A. dept. / section: 3ME/ Biomedical Eng
2nd mentor: Msc. BARATI, B.
organisation: DE/EM
city:
country:
comments (optional): The 2nd mentor from EM joined the project to support the design aspect of the project, whereas the chair supports the project through her material science and technical expertise.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

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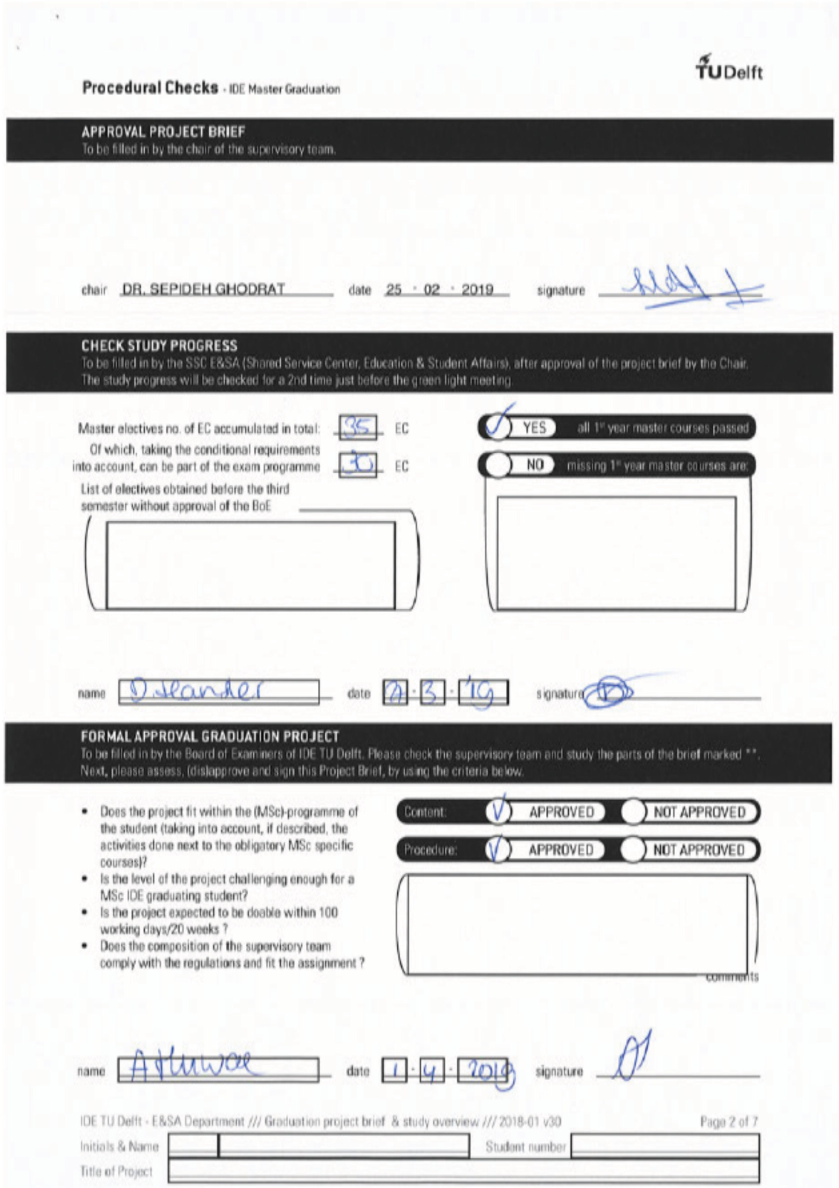

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Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: DR. SEPIDEH GHODRAT date: 25 - 02 - 2019 signature:

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 35 EC
Of which, taking the conditional requirements into account, can be part of the exam programme: 30 EC
List of electives obtained before the third semester without approval of the BoE:

☑ YES all 1st year master courses passed
○ NO missing 1st year master courses are:

name: D.Jlander date: 2 - 3 - 19 signature:

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ☑ APPROVED ○ NOT APPROVED
Procedure: ☑ APPROVED ○ NOT APPROVED
comments:

name: Atluwae date: 1 - 4 - 2019 signature:

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7
Initials & Name: Student number:
Title of Project:

Designing a locomotive device driven by a shape memory alloy-based composite:
a mimicry of the caterpillar movement

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 25 - 02 - 2019

29 - 07 - 2019 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The gestation period of new materials before their market introduction is typically 20 years or more. In the case of shape memory alloys it took 30 years before it was applied commercially in the medical field in the 1990s. Currently, the application of Shape memory Alloys (SMAs) is also in the aerospace, automotive and robotics industry

SMAs are able to change shape and have certain characteristics that make them exceptionally attractive for human-machine interactions. Therefore, we are not only talking about materials that are able to respond to stimuli and react correspondingly but also facilitate interactions through external drivers. This sense of interacting is important because it generates a relationship between the material and the user; consequently we are looking to know which factors in this human action and reaction scenario are relevant to generate the desired morphing behavior.

Furthermore, SMAs are also implemented in biomimetic and humanoid robots. The advantages of having SMAs as actuators is the reduced complexity and size of the mechanism. Composites from SMAs and soft materials can be flexible and adapt to their environment better, compared to traditionally rigid mechanisms. A balance has to be achieved between the lay-out of the actuators and the soft exterior to recreate the mechanism found in nature.

There are numerous projects involving bio-inspired soft robotics, such as the caterpillar-inspired GoQBot which is made of an SMA-based soft composite. The FILOSE robot was developed to gain a greater understanding of fish locomotion and sensing. The Festo bionic handling assistant, inspired by an elephant trunk, has proven to create a safer interaction between man and machine while in direct contact. It is an example of how a bio-inspired approach and soft actuators open up the doors to safe human-machine interaction.

A better understanding of the SMAs in combination with soft materials can lead to innovation in their application in robotics and consequently consumer products. For instance, how can SMA-based composites be applied to improve man-machine interaction? What type of experience can be evoked with SMA-based composites? What applications are suitable for SMA-based composites based on the technical characteristics?

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introduction (continued): space for images

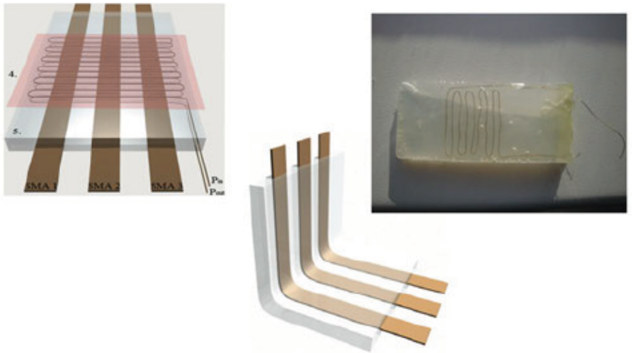


image / figure 1: Example of SMA/SMP composite actuator (Lelieveld et al., 2016)

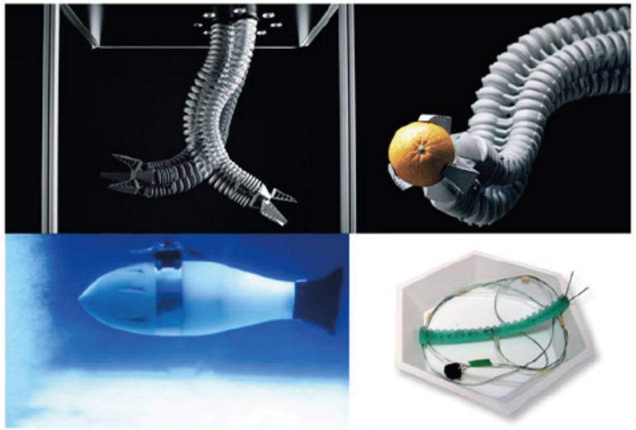


image / figure 2: Bio-inspired soft robots: Festo assistant handeler (top), FILOSE (left) & GoQbot (right)

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Information about the Shape Memory Effect (SME) of SMAs is already documented, but they are strongly dependent on chemical composition, dimensional characteristics and the loading conditions. In the case of SMAs combined with soft materials such as silicone, their response as a composite can be manipulated even more, though it may be more complicated. The main question is then, to what extend do the material choice, lay-out and positioning of such composites influence its response to activation of the SMA? And how can multiple actuators be combined to create a controllable movement?

Material Driven Design (MDD) is a systematic tool developed by Elvin Karana et al. (2015) in which our understanding of materials (experientially as well as experimentally) is of crucial importance for innovative and multisensory design of a product. MDD can be applied to determine the technical and experiential characteristics of the SMA-based composite. The combination of a bio-inpired design approach and this method has not been documented yet, and poses the question how MDD should be adapted to incorporate a bio-inspired vision, such as the movement of a caterpillar. Taking inspiration from a caterpillar's locomotion gives a good starting point since its locomotion is unique and well described.

And finally, given that the SMA-based composites are relatively unknown as a material, how can designers be inspired to embed SMAs in a soft matrix to form a composite structure?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

A soft-bodied mechanism is developed that mimics the crawl of a caterpillar, using a composite made of SMA embedded in a soft matrix. The behaviour of SMA-based composites are first explored to identify interesting patterns. A controllable, segmented robot will be designed and prototyped which will demonstrate the application of the designed SMA-based composite in an inspiring and meaningful way to designers.

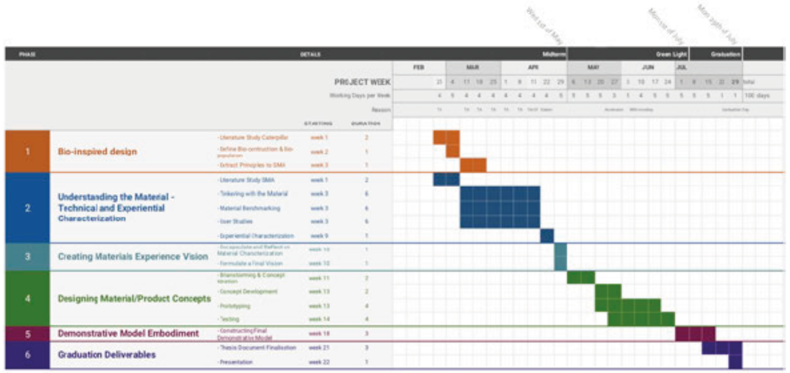
The aim of the project is to design and protype a soft-bodied mechanism driven by a novel SMA-based composite. By having a prototype an identity and meaning can be given to the material.
This project will embark on combining a bio-inspired design approach together with a material driven design approach applied to the development of a SMA-based soft-bodied mechanism using a hands-on approach. The compatibility of both approaches is assessed through prototyping and testing of material samples. For a bio-inspired design approach, the locomotion of a caterpillar is first studied. Then the mechanical principles inspired by the caterpillar are translated to SMA-based composites, which are further explored in the first stage of MDD understanding the material. A combined material vision is made based on the vision for the bio-inspired mechanism we want to embody and the experiential characteristics of the composite. From this vision patterns are manifested to evoke the envisioned materials experience and concepts are designed and created. The context for these concepts is unknown at the start of the project and will be developed using the bio-inspired and MDD approach, it could for example be the medical field or for search & rescue.

The process of the adaption of the MDD approach with bio-inspired vision will be documented and described to give a reference point to future researches and designers. Secondly, the prototype derived from the research serves as an example of how the SMA-based composite can be controlled and applied to a soft-bodied caterpillar-like design, and how bio-inspired design can be embodied.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date ☐ - ☐ - ☐ ☐ - ☐ ☐ end date



As can be seen in the Gantt chart, the project is first started with a literature study regarding the movement of caterpillars and similar organisms, parrallel to a study of SMA (composites).

The insights are then incorporated in the first MDD block technical and experiential characterization of the material, where different types of composites are developed and tested.
In the second MDD block creating a materials experience vision, both the bio-inspired vision and the insights gathered from the composite's (experiential) characteristics are integrated to find a cohesive vision, which is then further explored in the third MDD block manifesting material experience patterns. In the fourth MDD block material concepts will designed. At the end of the conceptuation and prototyping phase a final demonstrative model is made.

In the first quarter 4 days a week will be dedicated to the project instead of 5, since 1 day is spend as a TA for the D4135-16 Modelling course.

The following days have been considered non-working days, according to the TU Delft Academic Calendar 2018/2019 19th April, 22nd April, 30th-31st May,10th June.

Important dates
Kick-off meeting 25-02-2019
Mid-Term meeting 2-05-2019
Green-Light meeting 1-07-2019
Graduation ceremony 29-07-2019

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

During my Bsc in Aerospace Engineering was already interested in material science and it's development towards innovation. Over the course of the PD master rekindled this interested and pursued it in more depth during my Erasmus at Politecnico di Milano. When the opportunity presented itself to have a hands-on work experience with this material dove right into it. see this project as the perfect chance to apply both a Material Driven and a Bio- nspired Design Approach, two methods have never had the chance to follow yet.

find this an invaluable experience to prepare myself for a carreer as a Design Engineer, providing the bridge between material scientists and design. As a designer, opening up to the experiential qualities a material has goes beyond what is traditionally researched by material scientists. Adopting a MDD approach gives me the chance to already experience how to manage such a project, but also a sense of what experiential characteristics are and how they can provide new insights.

also have a keen interest in bio-inspired design and wonder how our society can benefit from solving current challanges by looking in nature for solutions. What have learned up untill now from PD is that a good methodology is needed to develop technology driven design. Just like technology, methodology should constantly be evolved and refined. would like to combine both design approaches to see if it leads to an innovative and impactful change in how the material is applied.

My main learning objectives concern
- mproving my knowledge concerning the Material Driven Design approach.
- mproving my knowledge concerning Bio- nspired design.
- Acquiring expertise on SMAs, soft materials and electrical control elements through a hands-on approach.
- Gaining experience on how to document the process of developing SMA-based composite materials.
- Developing additional skills necessary to built a working prototype.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.