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SoRoLib: Library of Building Blocks for Pneumatic Shape Changing in Soft Robotics

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Abstract

Soft Robotics, as a specific research area in robotics, is attracting widespread interest due to its various application areas where conventional rigid robots are not viable. They offer the unique opportunity to provide flexible and adaptive, as well as safe interfaces for user interaction. In this thesis, we present a soft pneumatic actuator made entirely of a highly compliant elastomer, that is intended to be employed in a range of application areas such as assistive wearable devices (e.g. smart and interactive jewellery). We focus on the geometry of the pneumatic network consisting of embedded air chambers and the material properties of the actuator itself in order to control the change in shape by combining basic motions. These motions include bending in two directions and extending, and can be of parallel or additive nature. Although current designs of soft pneumatic actuators in other studies achieve these type of motions, they are limited to only one type at a time and mostly comprise an inextensible component. We examine dimensional parameters that facilitate the customization of soft pneumatic actuators and their effects. These parameters are then put into a geometry space with the aim of creating a library of building blocks for pneumatic shape changing in soft robotics. Moreover, we provide the foundation for this library by introducing a simple geometry of the pneumatic network that is applied to our actuator. Furthermore, we investigate the fabrication process and evaluate the actuator based on its performance with respect to its range of motion.

Überblick

Aufgrund diverser Anwendungsgebiete, in denen herkömmliche starre Roboter nicht eingesetzt werden können, ziehen weiche Roboter als Untergruppe in der Robotik ein weit verbreitetes Interesse auf sich. Sie bieten die einzigartige und besondere Möglichkeit, sowohl flexible und anpassungsfähige, als auch sichere Schnittstellen für die Interaktion mit Nutzern zu realisieren. In dieser Arbeit präsentieren wir einen weichen pneumatischen Aktor, der vollständig aus einem äußert flexiblen Elastomer besteht. Dieser Aktor ist für den Einsatz in einer Reihe von verschiedenen Anwendungsbereichen, wie zum Beispiel den Bereich der tragbaren technischen Hilfsmittel, konzipiert. Wir konzentrieren uns auf die Geometrie des pneumatischen Netzwerks von Luftkammern im Inneren des Aktors und die physikalischen Eigenschaften des Materials, um die Veränderung seiner Form mit Hilfe von elementaren Bewegungen kontrollieren zu können. Zu diesen elementaren Bewegungen gehören das Krümmen und das Dehnen, die sowohl parallel, als auch additiv kombiniert werden. In anderen themenverwandten Arbeiten werden diese Bewegungen ebenfalls untersucht, jedoch sind die dort präsentierten Aktoren auf einen Typ der beiden Bewegungen beschränkt. Zudem untersuchen wir dimensionale Parameter, die das Entwerfen von weichen pneumatischen Aktoren erleichtern, und ihre Auswirkungen. Ziel dieser Untersuchungen ist eine Sammlung von Bausteinen für die pneumatische Formgebung im Bereich der Soft Robotics. Darüber hinaus legen wir mit der in unserem Aktor verwendeten Geometrie des pneumatischen Netzwerks den Grundstein dieser Sammlung. Des Weiteren beschreiben wir den Herstellungsprozess beginnend bei der Modellierung der nötigen Gussformen und evaluieren den Aktor hinsichtlich seiner Fähigkeit, die Form zu ändern.

Acknowledgements

I would like to thank all people who spent their time on helping me to fulfil this thesis. I gratefully acknowledge their help and their constructive comments.

Furthermore, I thank my supervisor Anke Brocker who gave me much valuable advice throughout all stages of this thesis.

Conventions

Throughout this thesis we use the following conventions.

The whole thesis is written in British English.

For reasons of politeness, unidentified third persons are described in female form.

Chapter 1

Introduction

1.1 Soft Robotics

Soft Robotics as a research area in the rapidly growing field of robotics is attracting widespread interest due to the increasing number of various tasks that can not be accomplished by conventional rigid robots. Especially when operating in human friendly environments or directly in collaboration with humans, as in the application area of assistive wearable devices, soft robots benefit from their unique opportunity to provide flexible and adaptive, as well as safe interfaces for user interaction. Sebastian et al. [2017] benefit from these advantages by developing a novel soft robotic haptic device for neuromuscular rehabilitation of the hand. During the rehabilitation process, strengthening the patient's motor skills requires multiple objects of varying stiffness in order to offer a wide range of strength training due to the rigid components. The need for varying stiffness is then addressed by employing a soft pneumatic structure whose stiffness can be adjusted by the user. Even though conventional rigid robots are well suited for controlled, constraint and human-unfriendly environments Martinez et al. [2012] and hence dominating most of the application areas of robotics, such as factory assembly lines or surgery Ilievski et al. [2011], they lack in flexibility and the ability to adapt to their environment. For instance, they are limited in moving across an unknown, irregular and

Soft robots provide flexible and adaptive, as well as safe interfaces.

shifting terrain due to their metal structural elements and conventional joints that are actuated by electric motors, or pneumatic or hydraulic systems Ilievski et al. [2011]. In contrast, soft robots are able to adapt autonomously to different shapes and can therefore handle fragile objects such as fruits or even internal organs. Ilievski et al. [2011] state that soft robots are promising for applications that require robotic interactions with delicate objects. While conventional hard robotic grippers concentrate stresses on a small area on the object of interest, soft robotic grippers are able to distribute the stress evenly over the entire area of contact. Since soft pneumatic actuators do not consist of articulated joints, they can have different local curvatures on different contact areas which allows them to closely follow even irregular shapes along their length. The medical profession can benefit from these features as soft robots can be employed alongside surgeons in order to assist them during a surgery, e.g. a heart transplantation. The robot's tasks can then range from temporarily storing the heart to navigating around different structures in the human body by adjusting its form. Soft robots can also be found in the field of bio-mimicry. For instance, they are designed to mimic deep sea creatures such as octopuses in order to efficiently maneuver through water and to explore the ocean. One can differentiate between two types of soft robots. Soft robots of the first type are composed of multiple rigid components that are able to mimic soft-robotic behaviour and properties by operating in harmony, e.g. in Crespi et al. [2005], while soft robots of the second type are actually made of soft materials Ilievski et al. [2011]. However, advances in smart and specifically soft materials promote the use of the second type since they allow for creating interactive devices that are not only flexible but continuously deformable, meaning that their ranges of motion are limited only by the material's properties. There exist various shape-changing mechanisms that can be applied in order to develop an interactive device whose shape can be controlled and reconfigured on demand. According to Qamar et al. [2018] these shape-changing mechanisms can be categorized into stretchable structures, e.g. elastomers, deployable structures, such as foldable structures, variable stiffness materials, e.g. anisotropic structures, and shape memory materials. In this thesis, we focus on stretchable struc-

Soft robots adapt autonomously to different shapes.

One can differentiate between two types of soft robots.

Soft robots allow for creating interactive devices that are continuously deformable.

tures and especially on highly compliant elastomers since they are considered to be part of the most applicable materials to Human Computer Interaction. For example, Weigel et al. [2015] introduce an input surface for mobile Human Computer Interaction on the human body to the field of assistive wearable devices. The so called *iSkin* is a customizable overlay that consists of multiple layers of thin, flexible and stretchable silicone which can be worn directly on the skin. A silicone-based organic polymer is also employed in *Stretchis* by Wessely et al. [2016]. They are particularly interested in ultra-thin, stretchable and fully-customizable user interfaces that can embed a rich user interaction onto a wide variety of physical objects and fabrics.

Hihgly compliant elastomers are stretchable structures that are the most applicable to HCI.

1.2 Soft Pneumatic Actuators

We present a soft pneumatic actuator made of a highly compliant elastomer that is intended to address a range of application areas including assistive wearable devices. Soft pneumatic actuators are responsible for motions that allow for a user interface to change its shape or to provide haptic feedback. These motions are typically quite slow and weak in comparison to motions created by rigid robots which are often designed to apply large forces or to move at high speed. Soft pneumatic actuators consist of a soft material, such as silicone, and an internal pneumatic network of elastomeric channels (PneuNet) that is connected to a source of pressure. Changes in pressure then result in contraction or extension of the pneumatic network which can be observed as motion. Compressed air is a widely used energy source since it has a low viscosity and permits rapid actuation. Additionally, air is easy to store, light and environmentally friendly Ilievski et al. [2011]. The speed of actuation then depends on the rate of inflation, the geometry of the internal channels and exterior walls, and the properties of the structure Mosadegh et al. [2014]. Other types of actuation include hydraulic actuation, which is well suited for applications that require greater force, incompressible components or a specific density, or using electroactive polymers. In this thesis we focus on pneumatic actuation. Another advantage can be observed when part of a distributed pneu-

Soft pneumatic actuators are responsible for motions.

Soft pneumatic actuators consist of a soft material and an internal pneumatic network.

matic network malfunctions because the internal channels are blocked. In this case the remaining part is still able to function properly. Additionally, they do not need a power supply continuously providing power as the pneumatic network can be closed by a valve in order to keep the pressure and hence keep the actuation. However, soft pneumatic actuators deflate over a period of time since it is hard to connect a source of pressure while retaining a leak-proof connection. According to Martinez et al. [2012], soft pneumatic actuators are the most useful when they satisfy three conditions. First, they should be flexibly controllable in direction and force. Second, they should take advantage of its non-linearities to simplify the accomplishment of functions that are difficult with linear actuators. And third, they must be easily incorporated into designs that are practical to fabricate, inexpensive and functional. We discuss several parameters, e.g. the thickness of walls, that affect the nature of motion. Moreover, we focus on the geometry of the pneumatic networks and the material properties of the actuator in order to achieve controlled anisotropic behaviour when pneumatically actuating the component. Furthermore we develop a soft pneumatic actuator with a pneumatic system that provides controlled anisotropic behaviour while keeping the number of required pressure sources at a minimum of one. By using embedded sheet or fiber structures or other stiff materials that can guide the motion of the actuator in direction, other researchers move away from unlimited flexibility since these embedded materials are flexible but not stretchable. On top of that, their actuators are mostly designed to accomplish a single function that requires one type of motion. In contrast, we eliminate all stiff components and present an actuator that is entirely made of a highly compliant elastomer. This enables a wide range of behaviours and allows for multiple types of motion, i.e. bending and extending and combinations of both.

Soft pneumatic actuators should satisfy three conditions.

We provide controlled anisotropic behaviour.

1.3 Outline of the Thesis

The introductory chapter is followed by seven further chapters. The second chapter presents the related work that was done in the field of soft pneumatic actuators. Following the related work, the third chapter aims to put the technical part of soft pneumatic actuators in the context of Human Computer Interaction. We demonstrate various features that are beneficial to the Human Computer Interaction community with the help of several examples of use. In the fourth chapter, we take a deeper look on the materials that are used within our study and the studies of other researchers. Especially the material's properties are examined to discover their human interactive potential. The fifth chapter deals with the modeling of molds and the fabrication of our soft pneumatic actuator. We present rapid prototyping techniques and the software that facilitates the process of modeling. Furthermore, we provide step-by-step instructions for modeling the required molds and casting the actuator. Chapter six describes the development process of forming the geometry of the pneumatic network which provides promising results with respect to the actuator's deformation. The seventh chapter then aims to put a set of parameters that facilitates the customization of pneumatic networks into a geometry space in order to provide the foundation for a library of building blocks for pneumatic shape changing in soft robotics. Moreover, we describe the value assignment to these parameters that provides the most promising results for our developed actuator and present the resulting deformations. Last but not least, chapter eight summarizes our key findings and the contribution of this thesis and presents ideas for future work.

Chapter 2

Related Work

Due to its increasing importance in the field of robotics, the topic of soft robotics arouses the interest of several Human Computer Interaction and robotic researchers that have started designing, prototyping, and evaluating shape changing devices. Since there are various techniques for achieving shape change in interactive devices, we want to review some of the most important and closey related studies on soft actuators that are pneumatically actuated.

2.1 Soft Robotic Gripper

Complex motion depends on appropriate distribution, configuration and size of the pneumatic networks.

Ilievski et al. [2011] aim to employ advances in material science and chemistry in the development of fully soft robots. They describe a type of design for soft pneumatic actuators that can be used to test different materials and fabrication methods for soft robots. The design makes use of embedded pneumatic networks with a series of air chambers arranged in parallel providing a range of behaviours. Learning from intuition and empirical experimentation results in prototypical structures that provide complex motion where appropriate distribution, configuration and size of the pneumatic networks determine the resulting motion. For instance, expanding structures were modeled by using finite element analysis. During their studies, Ilievski et al.

Stiffness of the material affects the behaviour upon actuation and allows for programming the direction of motion.

[2011] discovered that the choice of material in combination with the design of the pneumatic network determines the non-linear responses to actuation. Their studies show that the pressure that is required to cause actuation scales with the stiffness of the material. Composite structures consist of multiple materials that are joined during the process of fabrication meaning that different layers of the component are made of materials that differ in stiffness. These differences in stiffness result in changes of the behaviour upon actuation. While actuators made of a single material expand at the most compliant regions, composite structures expand at the regions that are made of a softer and more elastic material allowing the researchers to program the direction of actuation. They demonstrate their findings with the help of fully soft robotic grippers. The grippers consist of an inactive layer made from polydimethylsiloxane (PDMS) between two active layers made from Ecoflex 00-30 in which the internal pneumatic networks are embedded. The two active layers are then sealed by the inactive layer. Figure 2.1 shows the actuator's response to actuation and how the layers are joined. The resulting composite prototype can change its curvature from concave to convex upon actuation of the two active layers pattered in Ecoflex. Moreover, it should reliably represent soft structures of the studied kind. The prototypes, specifically the used materials, are not suitable to handle heavy objects. However, the methods are versatile and can still be used with appropriate materials in order to face this challenge.

2.2 Elastomeric Origami: Programmable Paper-Elastomer Composites as Pneumatic Actuators

Martinez et al. [2012] move away from the idea of a pneumatic actuator entirely made of soft materials. Instead, they describe the development of soft pneumatic actuators that consist of elastomers, specifically Ecoflex 00-30, with embedded sheet or fiber structures that are flexible but not extensible or stretchable. In this case, the motion can be guided in direction by the embedded sheet or fiber struc-

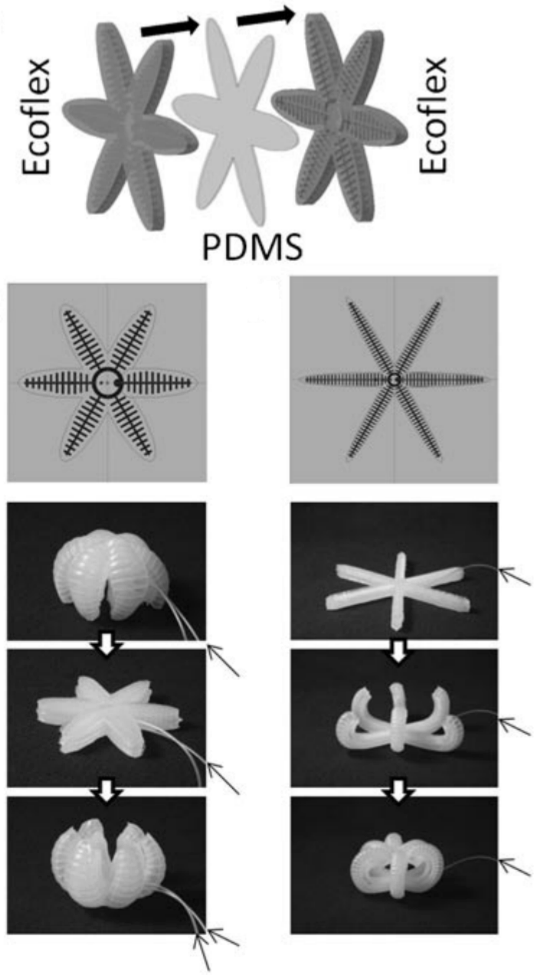

Figure 2.1: The soft robotic gripper comprises multiple, independently prepared, and joined layers made from Ecoflex and PDMS. The sequences of pictures demonstrate the geometry of the pneumatic network and the response to actuation. Ilievski et al. [2011].

ture resulting in controlled anisotropic behaviour in the response of elastomers to actuation. Figure 2.2 demonstrate how encapsulated paper sheets affect the direction of motion upon actuation. They present methods based on molding and casting for fabricating such composite structures and their results in form of various motions including extension, contraction, twisting, bending, and combinations of these. The molds can be easily modeled with computer-

Embedded sheet or fiber structures guide the motion in direction.

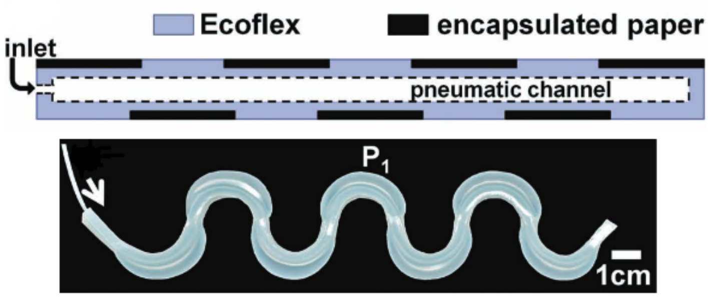

Figure 2.2: Top: The schematics of the design showing the layout of the pneumatic channel and the paper. Bottom: One actuated state. Martinez et al. [2012].

aided design tools and built with 3D printing. The resulting casted open-channel structure can then be joined with a layer of Ecoflex with encapsulated paper sheets. As a result, the paper introduce a flexible and inexpensive solution to the problem of constructing simple, low-cost and lightweight soft actuators made of the silicone elastomer Ecoflex 00-30 and a polyester/cellulose blend paper. The tested actuators are again limited in manipulating heavy objects and especially fragile and susceptible to damage by puncture or cutting when stretched.

2.3 Micro Pneumatic Curling Actuator "Nematode actuator"

Soft pneumatic actuators facilitate tasks on the micro scale level.

Especially medical and biotechnological fields benefit from micro rubber pneumatic actuators due to their low mechanical impedance providing high safety. In general, the presented advantages of soft pneumatic actuators facilitate tasks on the micro scale level, for instance handling biologic tissue, such as cells, or minimally invasive surgery. Ogura et al. [2009] face the challenge of developing a micro rubber pneumatic actuator that could realize simple structures and that is both highly flexible with large displacement, and easy to fabricate and suitable to downsizing on micro range. The authors renounce the use of reinforced fiber as it hinders the fabrication process and hence the downsizing of the actuator. Instead, only silicone rubber was used. The actuator was then designed by non-linear finite element method and produced with the help of rubber bonding technology with an excimer lamp in order to achieve an optimal actuator design. Because the resulting motion resembles the motion of a nematode, commonly known as roundworms, the authors call it "Nematode actuator". The actuator realizes a large curling deformation upon actuation which allows it to handle and hold objects and experiments show that the resulting motion is similar to the motion of real nematodes. Furthermore the motion can be guided in direction by applying either positive or negative pressure.

2.4 Towards a Soft Pneumatic Glove for Hand Rehabilitation

Soft pneumatic actuators can simulate the flexing motion of fingers and support the rehabilitation process.

Another application of soft robotic technology in the medical field and especially in rehabilitation can be found in the studies of Polygerinos et al. [2013]. They describe the design, development and evaluation of a hand rehabilitation glove that serves the execution of repetitive task practice in order to improve hand strength, accuracy and range of motion while suffering from the loss of the ability to partially or totally move the fingers. Their studies include the integration of soft elastomeric actuators that can achieve bending motions similar to the flexing motion of human fingers into a neoprene glove. The conceptual function of the soft robotic glove for hand rehabilitation and the corresponding characteristic rehabilitation exercises can be seen in figure 2.3 Due to the advantages of air over fluid the bending motion of the actuator is caused by inflating integrated channels that function as pneumatic network. The resulting behaviour is geometrically analyzed and validated using the finite element method prior to fabrication. In order to provide a generic design of the actuator, the authors identify a number of geometrical parameters that directly affect the performance and behaviour. In their studies Polygerinos et al. [2013] explore a subset of these parameters includ-

Geometrical parameters provide a generic design.

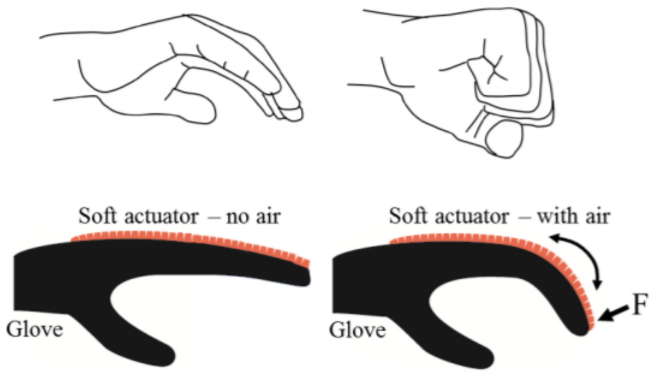

Figure 2.3: Top: Characteristic rehabilitation exercise where the fingers go from an open state (left) to a closed state (right). Bottom: Conceptual function of the proposed soft robotic glove. Left: the soft actuator with no air pressure; fingers are in the open state. Right: the soft actuator with air pressure; fingers are assisted to move to the closed state. Polygerinos et al. [2013].

Soft lithography is used as fabrication method.

ing the height of the pneumatic network, length, number of pneumatic networks and wall thickness while keeping all other geometrical parameters constant. The manufacturing process can be described as follows. First, a two-part mold is created using rapid prototyping techniques. After pouring the activator and the silicone into the molds, the molds were put in a vacuum and then in a pressure chamber which ensures that the casted elastomer is free of any trapped air bubbles that could decrease the performance of the actuator or even lead to failure. Last but not least, the actuator is closed with an elastomeric layer with an encapsulated paper sheet that facilitates the bending motion by preventing the actuator from extending. Figure 2.4 shows the different layers of the actuator and its internal pneumatic network. Experiments show that one actuator that is responsible for one finger can bend more than 320 degrees. In addition to that, it provides enough force in order to assist passive human fingers meaning that it is strong enough to push or pull an impaired finger with some or no stiffness when closing or opening the hand respectively allowing the user to grasp objects of varying size and stiffness. As stated by Polygerinos et al. [2013] the design ensures a smooth distribution of contact pressure over the entire length of the

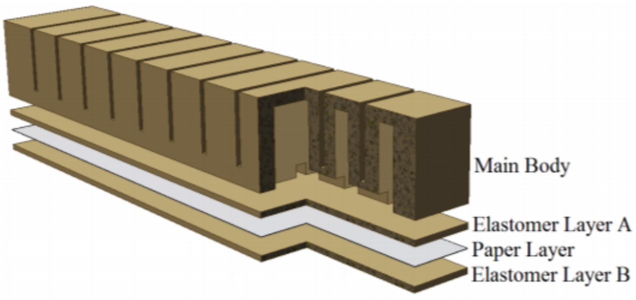

Figure 2.4: Exploded view of the generic soft actuator design. In cross section view: the pneumatic networks connected through the air channel. Polygerinos et al. [2013].

fingers minimizing concentrated pain effects and hence discomfort.

2.5 Pneumatic Networks for Soft Robotics that Actuate Rapidly

Design of pneumatic network determines the speed of actuation.

Type of motion depends on the rate of inflation.

Mosadegh et al. [2014] describe the development of a new design for pneumatic networks that can increases the speed of actuation while retaining motions with large amplitudes by decreasing the amount of gas needed to inflate the actuator. They demonstrate their design with the help of a soft pneumatic bending actuator that also provides a new mode of actuation resulting in different motions with different rates of inflation. At low rates, the actuator bends into approximately a circle while all chambers are evenly inflated. Further, the actuator curls upon itself with the chambers at its tip inflating first when applying high rates of inflation. Next to the increased speed of actuation, the design offers the benefits that the actuator's volume does not increase significantly upon actuation and that the stress that is put on the material is minimized resulting in a longer operating lifespan. Previous designs as in Ilievski et al. [2011] consist in general of an extensible top layer and an inextensible but flexible bottom layer in combination with an internal pneumatic network. The new design, however, is similar to the actuators that are deployed on the soft

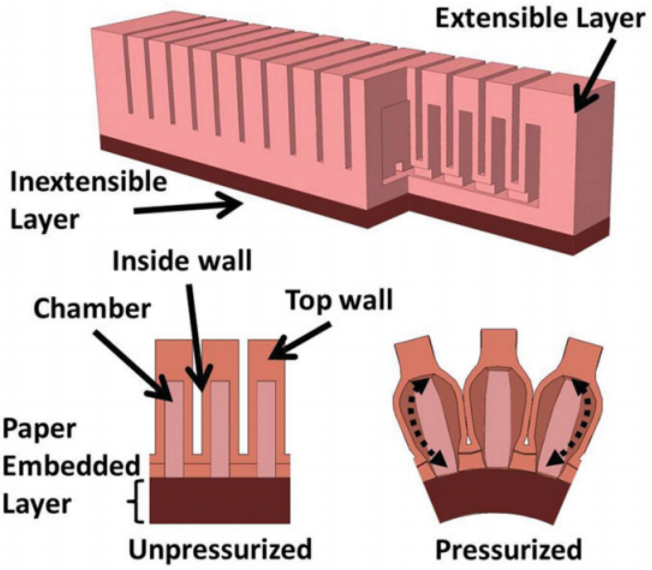

Figure 2.5: The design of a rapidly actuating pneumatic network. Mosadegh et al. [2014].

pneumatic glove for hand rehabilitation Polygerinos et al. [2013]. Gaps between the inside walls of each chamber that are designed to be thinner and to have greater surface area than the exterior walls allow for minimizing the stress on the exterior walls since the inside walls are now preferentially expanded. Figure 2.5 shows the design of such a rapidly actuating pneumatic network. During their studies Mosadegh et al. [2014] examine amongst others different dimensions, including the number, height and wall thickness of the chambers, and different materials. The resulting actuators are 25 times faster, and 1.4 times stronger than actuators build with the prior design. Furthermore, the inflated state is 8 times smaller. In order to present the new inflation-rate-dependent mode of actuation the authors attached four of them on an electronic piano to play a tune where the movements remind of human fingers playing the piano. However, two limitations have to be noted. First, when being in the idle state, the gravity causes the actuators to bend slightly towards the ground due to the thin and hence weak connections between each chamber. Second, the chambers do not expand evenly when further inflating the actuator after the maximum bending amplitude

Soft pneumatic actuators are comparably weak.

is reached.

2.6 Multigait Soft Robot

Shepherd et al. [2011] demonstrate the advantage of soft robots being systems in which simple types of actuation produce complex motion with the help of a unique class of locomotive robot consisting of five actuators. The robot is inspired by marine animals and does not consist of any hard endo- or exoskeleton but exclusively of elastomeric polymers, i.e. Ecoflex 00-30 or Ecoflex 00-50. As a popular fabrication method soft lithography is used due to its simplicity and compatibility with the pneumatic network architecture. The pneumatic network in concert with a pneumatic valving system allows to independently control each leg and the torso in order to create a crawling behaviour. Additionally, the robot is able to navigate a difficult obstacle. During their studies Shepherd et al. [2011] examine several parameters , i.e. orientation, size, and number of the pneumatic network's chambers, in order to achieve the most effective bending motion. Figure 2.6 shows a cycle of pressurization and depressurization of pneumatic networks in the presented locomotive soft robot that result in a crawling behaviour.

Soft lithography is simple and compatible with the pneumatic network architecture.

Several parameters have an impact on the motion.

2.7 Characterization of Silicone Rubber Based Soft Pneumatic Actuators

While all studies introduced by now focus on the design, fabrication and evaluation of the developed soft pneumatic actuators, Sun et al. [2013] address the lack of effective methods to characterize and understand soft pneumatic actuators, specifically to measure the force and torque output, range of motion and the speed of actuation. They aim to provide the basis for customizing soft pneumatic actuators such that given requirements like the speed of actuation are met. Due to the infinite number of configurations the authors limit their work to two types of actua-

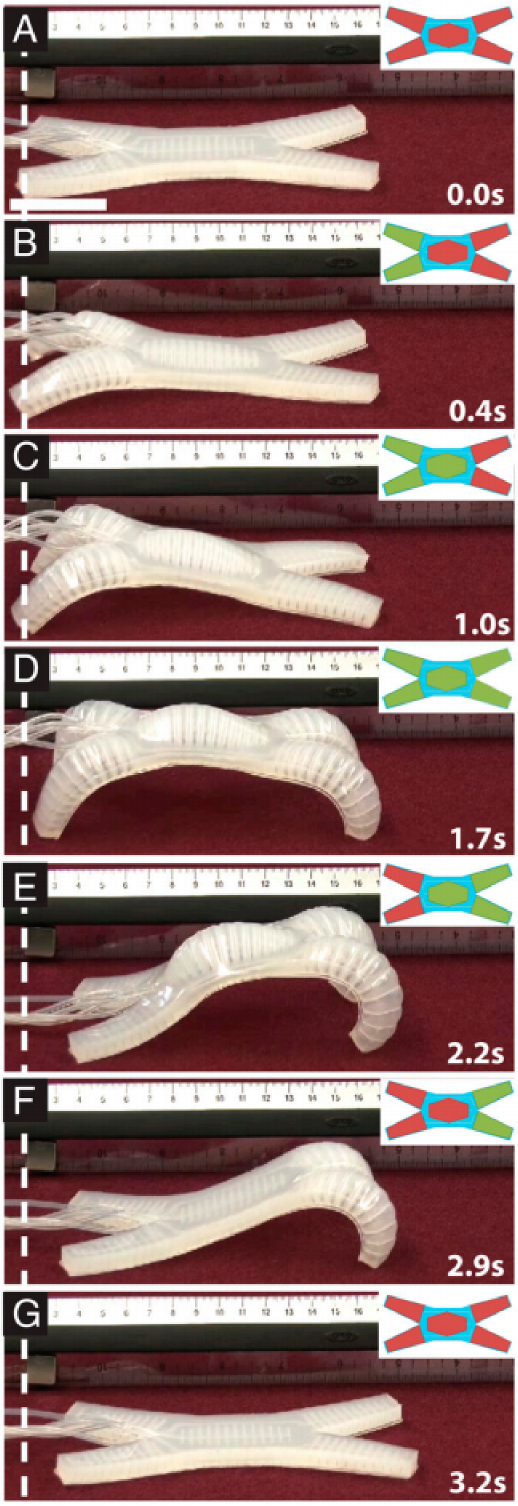

Figure 2.6: *(A–G)* Cycle of pressurization and depressurization of pneumatic networks that results in undulation. The particular pneumatic network(s) pressurized in each step are shown *(Insets)* as green, and inactive pneumatic network(s) are shown *(Insets)* as red. The scale bar in A is 4 cm. Shepherd et al. [2011].

tors, namely multi-chambered bending soft pneumatic actuators and multi-chambered rotary soft pneumatic actuators, following the principles of pneumatic networks for design and soft lithography for fabrication. Furthermore, the authors characterize the discussed actuators with respect to their force and torque output by using two developed measurement setups. The results provide a platform process for selecting design parameters for creating customized actuators of the presented types.

2.8 Research Question and Contributions

This chapter presented research projects dealing with the development and evaluation of soft pneumatic actuators. However, these projects move away from unlimited flexibility by embedding inextensible layers that are flexible but not stretchable, e.g. the paper layer in Polygerinos et al. [2013]. These layers can guide the motion in direction in order to create the desired behaviour which, in the end, limits the actuator to one single type of motion. We suggest an iterative approach to the exploration of various parameters, that affect for instance the geometry of the pneumatic network with the aim of creating a soft pneumatic actuator that provides more than one motion while comprising only materials that are flexible as well as stretchable. Our research question can therefore be defined as follows.

We iteratively modify parameters to provide more than one motion.

- What are meaningful dimensional parameter values for soft pneumatic actuators that provide more than one motion?

Furthermore, we describe the detailed modeling and fabrication process in order to offer the opportunity to easily replicate the resulting soft pneumatic actuator which serves as the foundation of a library of building blocks for pneumatic shape changing in soft robotics.

We describe the detailed modeling and fabrication process.

Chapter 3

Soft Pneumatic Actuators in HCI

This chapter aims to put soft pneumatic actuators in the context of Human Computer Interaction.

3.1 Dynamic Physical Affordances and Multimodal Feedback

Soft pneumatic actuators offer shape changing user interfaces that provide haptic feedback.

Due to their advantage of being completely soft, these actuators are well suited for operating in human friendly environments. Taking a step further, they can even offer shape changing user interfaces that provide haptic feedback to get in direct touch with the user. Haptic feedback expands the communication between the computer and the user because, so far, electronic devices communicate with the user using predominantly just two human senses: sight and hearing. Haptic feedback makes the change by simulating the sense of touch meaning that not only can you touch a computer or an electronic device, but it can touch you. However, shape changing user interfaces in Human Computer Interaction are still not highly developed as several techniques for shape change are being explored. According to Rasmussen et al. [2012] the types of shape change can be categorized as orientation, form, volume, texture, viscos-

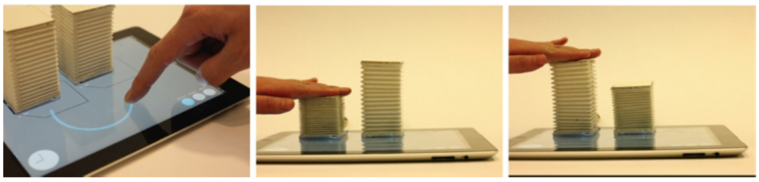

Figure 3.1: Height changing tangibles. Yao et al. [2013].

ity, spatiality, adding/subtracting and permeability. Pneumatic actuation as a technique for shape change enables soft pneumatic actuators to offer an alternative to rigid interface elements and create a space for the development of novel user interfaces where a user interacts with the computer or an electronic device through physical objects in the real world. The communication between physical objects such as tangibles or buttons and digital has usually been a one way street since only the user can change digital information through physically interacting with the objects. By introducing dynamic shape changing objects, we allow the digital world to affect the shape of interface elements Poupyrev et al. [2007] by creating and animating three-dimensional physical shapes, generating motion and providing new means for user input Gohlke et al. [2016]. This way, the user is able to experience dynamic physical affordances as well as multimodal feedback in form of simultaneous visual and tactile output. Soft pneumatic actuators are as well able to generate anisotropic output which is hard to achieve with rigid robots.

The digital world can affect physical properties of interface elements.

Soft pneumatic actuators provide dynamic physical affordances and multimodal feedback.

3.2 Tangibles

Soft pneumatic actuators enable active motion and programmable features to static tangibles.

Next to fully soft and flexible tangibles as shown in figure 3.1, soft pneumatic actuators can also be used to take conventional static tangibles to the next level by implementing joints that can be manipulated through pneumatic actuation. For this purpose Niiyama et al. [2015] propose to add free-form actuators on existing materials and objects, such as paper or fabric, that support tangible interaction but do not provide active motion or programmable features. They

Figure 3.2: "Sticky actuators" are used to open and close a box. Niiyama et al. [2015].

develop planar soft actuators called "sticky actuators" that consist of inflatable bladders with an adhesive back which allows the user to simply attach and detach the actuators to any object. For example, employed in a fantasy table top game, the actuators can be used to close and open chests or boxes, as in figure 3.2 depending on the state of the game.

3.3 Conventional Input Devices

3.3.1 Buttons

Physical buttons are usually static interface elements that offer intuitive affordances.

Touchscreen technologies provide flexible user interfaces but no tactile clues.

Physical buttons are easy to find and use and do not require high attention or visual contact by offering intuitive affordances. However, they are often designed to be static elements of user interfaces with respect to configuration, appearance, and tactile expression limiting them to only one type of functionality. This results in one button having multiple functions during different states of the system. On the other hand, touchscreen technologies offer the opportunity to provide multiple flexible user interfaces on demand, while suffering from the lack of intuitive tactile clues since they are only presenting a uniform flat surface. Harrison and Hudson [2009] aim to occupy the space between these two extremes. They develop dynamic physical pneumatically actuated buttons that are designed to provide the flexibility of touch screens while retaining the benefits of static physical buttons. This technique allows for instance

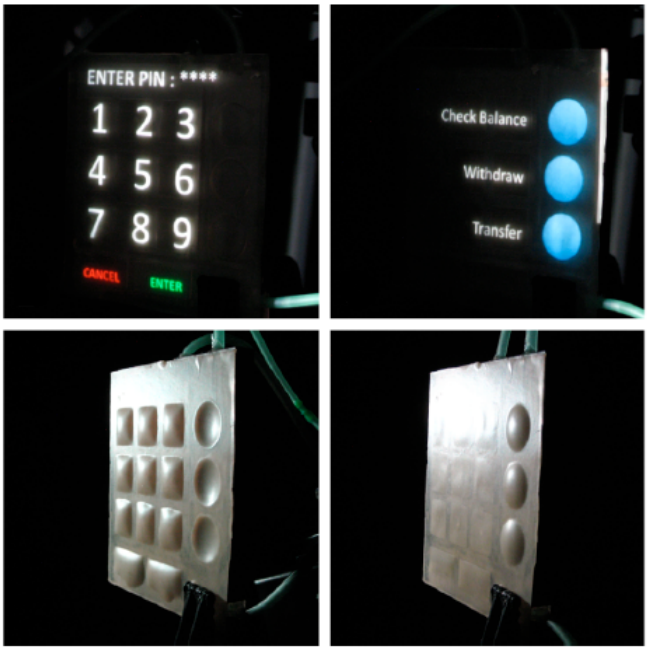

Figure 3.3: Two different states of an ATM and the corresponding user interface. Harrison and Hudson [2009].

to make buttons appear and disappear on demand or even to change between distinct interface elements that occupy the same physical space at different times. In figure 3.3, two different states of an ATM are shown and how the user interface, i.e. the keypad, evolves according to the corresponding state. Buttons that are not needed disappear in order to minimize the number of wrongly pressed buttons.

3.3.2 Mouse

Computer mouse remains typically static.

As the most iconic pointing device for computers, the mouse is an essential element in Human Computer Interaction. However, the physical nature of the user interface offered by a computer mouse typically requires it to remain static, just like the physical buttons. Pneumatic actuation provides new possibilities not only for laptop users to have access to a pointing device with high portability as well as high performance but also to apply pressure-based interaction techniques. Kim et al. [2008] propose a design for an inflatable mouse where the user can choose between a flat shape for portability and an easy-to-grasp shape for usability by changing the volume of injected air respectively. The ability to change the pressure can as well be used to deform the mouse while being held by the user in order to provide haptic and visual feedback which can be applied for instance in surgery simulation games where the mouse keeps the user up to date with the patient's health condition by simulating the heart beat. Additionally, by sensing the pressure inside the mouse, the pressure is the key to another bi-directional input technique. As stated by Kim et al. [2008], previous pressure-based input devices have allowed only half-dimensional input, meaning that the user can apply pressure in only one direction. For example, a pen that senses the pressure applied to the surface is not able to measure any pressure that is applied to the opposite direction whereas the inflatable mouse can be squeezed at its sides and pressed on the top allowing one-dimensional input. Various potential appplication scenarios are discussed by the authors. Their approach has the potential to facilitate the navigation of documents and web pages, i.e. to perform scrolling, zooming and other operations. Figure 3.4 demonstrates how different tasks such as zooming in and out can be accomplished by applying pressure to different contact areas of the device.

Pneumatic actuation enables pressure-based interaction.

Deformation of the mouse provides visual and haptic feedback.

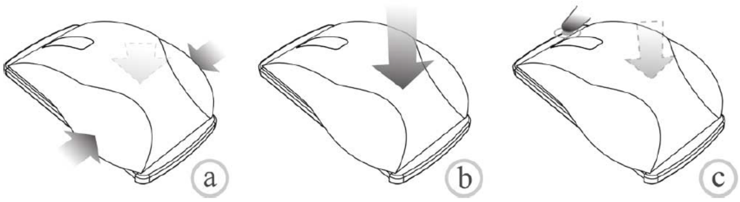

Figure 3.4: (a) Zooming in with squeezing, (b) Zooming out with pressing, and (c) Maintaining the current depth by touching the mouse frame during zooming. Kim et al. [2008].

3.4 Virtual Reality

Virtual reality is limited to visual and audible feedback.

Soft pneumatic actuators introduce tactile feedback to virtual reality.

Moving on with modern technologies in Human Computer Interaction, we investigate how soft pneumatic actuators can be applied in virtual reality. Virtual reality is a great way to put a user into completely new, exciting and entirely customizable worlds. However, experiencing these worlds is with head-mounted displays only again limited to visual and audible feedback, sometimes resulting in confusion because the user can not map what she feels to what she sees. By introducing human-computer interface gloves for providing tactile feedback in virtual environments, the desire to directly touch and experience virtual objects is satisfied. A common method to realize tactile feedback is to install actuators that provide mechanical stimuli since they are well suited for precisely reproducing the actual texture of an object. On the downside, with vibrotactile stimulation one is not able to reproduce the surface shape of an object. Song et al. [2019] address this issue by introducing a novel soft pneumatic actuator for providing tactile feedback. When the user gets in touch with a virtual object, the actuators that are placed on the fingertips of the hand start to inflate

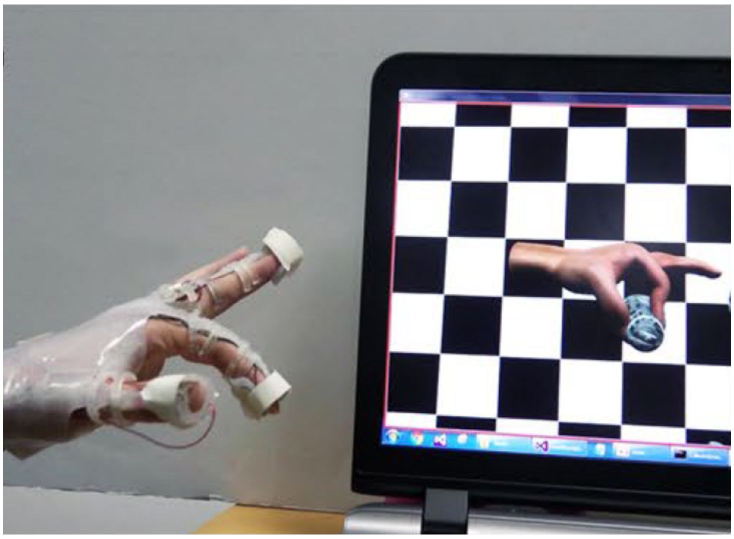

Figure 3.5: Glove for user interaction with tactile feedback in virtual reality. Song et al. [2019].

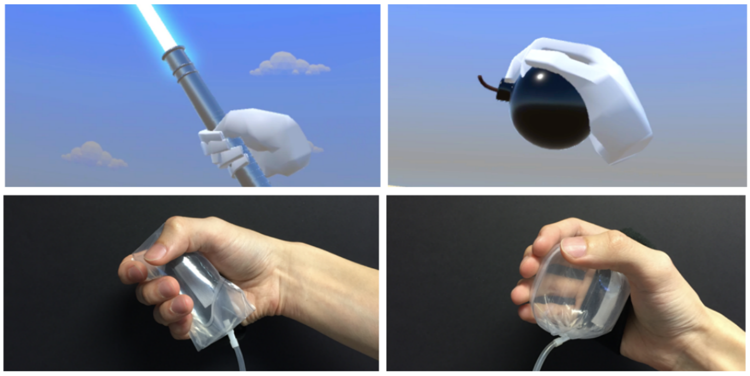

Figure 3.6: Grasping emulation of picking up a virtual Lightsaber with a cylindrical PuPoP and throwing a virtual bomb with a spherical PuPoP. Teng et al. [2018].

simulating the physical collision with the virtual object. On the other hand, the actuator that we are presenting in this thesis can function as object in the real world while representing an object of the same shape in the virtual reality that can change its shape. This virtual object can be for example a dowsing rod in a scenario where the user finds herself in search of water in a desert. The actuator can then replace a rigid controller and bend alongside with the virtual dowsing rod towards the water in case there is water in the user's proximity. Teng et al. [2018] present "Pop-up Prop on Palm" (PuPoP), a light-weight pneumatic shape-proxy interface worn on the palm that pops several airbags up with predefined primitive shapes for grasping (figure 3.6). When the user grasps or touches an object in virtual reality, an airbag with an appropriate shape is selected and inflated in order to provide haptic feedback and the full sensation of touch.

Chapter 4

Material Science

In this chapter we want to take a look on the materials that are applied within the Human Computer Interaction community and specifically in our studies on the interactive devices side. In order to create physical affordances that unleash the human interactive potential of shape changing user interfaces by exploiting material properties, we first require a deeper appreciation of these material properties. According to Qamar et al. [2018] stretchable structures are amongst others the most applicable to the context of Human Computer Interaction as they are the basis of shape changing devices. One type of stretchable structures that allow for large-scale deformation and changes in surface area are elastomers, e.g. silicone which is our material of choice. They can be found in everyday objects such as seals and adhesives, gloves and tyres and offer various advantages from which the Human Computer Interaction community can benefit. They are safe in their end form, widely available and easy to manipulate. Their most attractive feature is certainly their low resistance to being stretched due to their weak intermolecular structure that allows for easy large-scale deformation. Furthermore they return to their original shape when the stretching force is removed. Depending on the surrounding temperature and how quickly the material is stretched, different shape-changing responses can be observed indicating a non-linear behaviour which makes it difficult to ensure repeatability and minimal degradation of the material without tightly controlled user conditions. The

Stretchable structures are the most applicable to HCI.

Elastomers offer various benefits.

Elastomers have a non-linear behaviour.

Figure 4.1: The two components (Left: Basis. Right: Catalyst.) of “TFC silicone rubber type 1 impression silicone soft 1: 1 NV Troll Factory RTV”. Troll Factory.

temperature indeed plays an important role in the use of elastomers due to the so called glass transition temperature which determines the temperature below which the physical properties of elastomers change to those of a glassy or crystalline state. However, above their glass transition temperature elastomers behave like the desired rubbery material. Hence, elastomers can only be used at a temperature above their glass transition temperature in order to provide the characteristics that can be exploited for shape change.

Silicone is durable and compatible with soft lithography.

Silicone has proven to be beneficial for the development of pneumatically actuated soft robots because of its durability and compatibility with soft lithography making it very easy to create pneumatic networks. However, there is always a trade-off between strength and flexibility to be considered. Very flexible materials such as Ecoflex 00-30 that require a low force to being stretched are typically very weak. Hence, they are not able to put up resistance to external forces and at extremes not even to carry their own weight. During our studies we use “TFC silicone rubber type 1 impression silicone soft 1: 1 NV Troll Factory RTV” sold by “Troll Factory” which is an easily accessible two-component silicone rubber that does not require any specific skills or equipment other than the ability to mix two components in a specified ratio.

Shore value indicates the stiffness of the material.

The silicone has a shore value of A20 indicating the hardness of the material, i.e. the material’s resistance to indentation where the shore A scale measures rubbers that range from soft and flexible to hard with almost no flexibility in a range from 0 to 100. RTV is the abbreviation of Room Temperature Vulcanizing meaning that the process of vulcanization takes place at room temperature. Vulcanization relates to the process of cross linking where the viscous silicone mixture turns into a permanently elastic rubbery solid mass without heat of reaction, a so called elastomer. Peroxides, metal oxides or sulfur compounds serve as cross linking agents that allow the mixture to vulcanize by developing molecular compounds that are responsible for the elastomer's flexibility. The silicone is made by mixing the basis and the catalyst together in a specific ratio where the composite of these components has a high flowability, i.e. it is easy to pour. The resulting product promises to provide a great strength before tearing, high flexibility and very high detail in reproduction.

Chapter 5

Modeling and Fabrication

This chapter describes the detailed development process from a theoretical design to a fully functional soft pneumatic actuator. Moreover, we review techniques and tools that facilitate the development process.

5.1 Rapid Prototyping

Rapid prototyping refers to the process of quickly fabricating a scale model of a physical component or assembly using three-dimensional computer aided design tools and usually 3D printing. Using rapid prototyping technologies allows to choose an iterative rather than an analytical approach, e.g. FEM analysis, to evaluate new designs, parameters etc., because it is easy to fabricate new prototypes. Engineers and designers can benefit from these technologies since they are able to execute inexpensive, quick and frequent revisions of their designs and creations. Furthermore, it helps you discover design mistakes at the earliest stages of the development process.

Rapid Prototyping facilitates the development process.

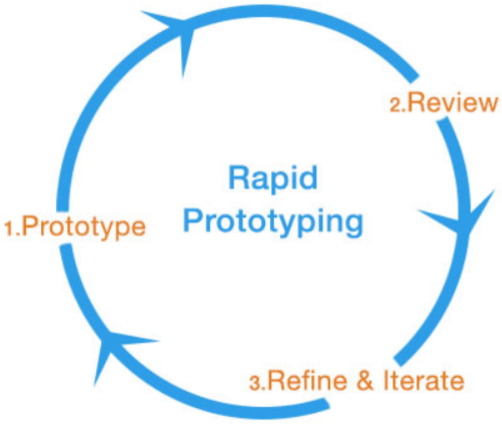

Figure 5.1: Process of rapid prototyping. UsabilityGeek.

5.1.1 Autodesk Fusion 360

Fusion 360 is used to design the molds for the fabrication process.

Autodesk Fusion 360 is a cloud-based universal tool for CAD, CAM and CAE which stand for computer-aided design, manufacturing, and engineering. It is our tool of choice because it offers a lot of benefits to this thesis. First of all it is free to use for students. Furthermore, the Fusion 360 freeform modeling environment allows the designer to realize their specific idea by exploring shapes, iterating, and repeating until what appears on the screen is what they were led to by their imagination. The design can then be furher edited with parametric solid modeling tools or analyzed with respect to different conditions. Fusion 360 keeps track of all the changes by integrating data management which allows not only for working with the most current version of the component but also to go back to previous versions. In our study, we use Fusion 360 to design the molds for fabricating the soft pneumatic actuators. For this purpose, the sketch feature which is used to create the base 2D profiles for creating solid models, surfaces, and T-spline forms fits our needs the best. It is the 2D geometry that supports the creation of the 3D part which, in the end, can be exported as a stereolithography file format (STL) that can be fed to a 3D printer slicing application. Sketches consist of two-dimensional entities such as lines, rectangles or points whose positions can be locked with dimensions or constraints. Additionally Fusion 360 allows the user to dynamically resize these entities on demand.

5.1.2 Ultimaker Cura and 3D Printers

After designing and creating 3D models of the molds, we use Ultimaker Cura as an open source 3D printer slicing application. This "slicer" converts a model into a series of thin layers and produces specific instructions, including for instance linear movements of the printer's extruder, which are then tailored to a specific type of 3D printer in a G-code file. We choose the layers to be 0.1mm high in order to provide a high printing resolution and to avoid imperfections on the actuator's surface which could lead to misleading results or even failure. Our 3D printer of choice is the Ultimaker 2 Extended+ which is well suited for robust single extrusion 3D printing as well as rapid prototyping and concept modeling. The printed molds are made of polylactide (PLA).

5.2 Modeling

This section contains step-by-step instructions for making a solid model of our soft pneumatic actuator molds in Autodesk Fusion 360. The actuator is composed of two identical components that are responsible for the direction and type of motion. Each component consists of the main body which expands when inflated and a base layer which serves to close the pneumatic network. Furthermore, the base layers function as connection layers in order to form the complete actuator. The main body and the base layer are casted separately and will be combined in the end. There are plenty of designs for the actuator's morphology, i.e. its shape, with various dimensions that affect the behaviour upon actuation such as wall thickness or spacing of the chambers. However, these dimensions and their effects are discussed in detail in the following chapters. Here, we present the modeling and fabrication of an actuator whose pneumatic network resembles the structure of a fishbone.

We model molds for the base layer and the main body.

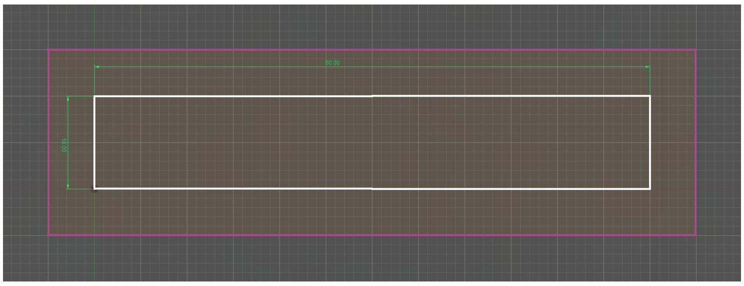

Figure 5.2: Outline of the mold for the main body without the pneumatic network.

The actuator's morphology and its dimensions are described.

The outline of the mold for the main body is sketched.

The outline of the pneumatic network is sketched.

The sketches are extruded.

Each of the two identical components is 60mm long, 10mm wide and 7mm high. Moreover, they have 18 chambers that are connected by a central channel with a distance of 2mm between the chambers. Each chamber is 8mm long, 1mm wide and 3mm high. The central channel is also 1mm wide, 3mm high and widened at the start to facilitate the insertion of the tube. The resulting pneumatic network is vertically as well as horizontally centered within one component. We start with sketching the outline of the mold for the main body as seen in figure 5.2. The area that is enclosed by the white rectangle will be filled with silicone whereas the area between the white and the purple rectangle serves as frame of the mold. Next, we sketch the outline of the pneumatic network that is embedded in the actuator according to the given dimensions (figure 5.3). Note that the pneumatic network does not intersect with the frame. This is very important, because otherwise the casted actuator will not be closed leading to leaking air and failure. Last but not least, the "Extrude" function from Fusion 360 provides the desired functionality to create a 3D model from the 2D sketch. We start with area 1 from figure 5.3 and extrude it to a height of 5mm. This is the ground of the mold. Next, we extrude area 2 to a height of 8mm in order to complete the ground and to form the pneumatic network. The mold is finished with the extrusion of area 3 to a height of 10mm. The height of the main body is now the difference from the height of area 1 and area 3 which is in our case 5mm. It is also important that the height of area 3 is greater than the height of the other areas. Otherwise, the actuator will not be closed on the top. We choose these dimensions

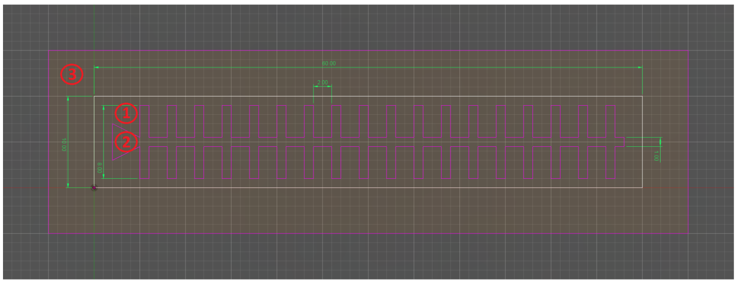

Figure 5.3: Adding the outline of the embedded pneumatic network and three areas that have to be extruded in order to form the mold's 3D model.

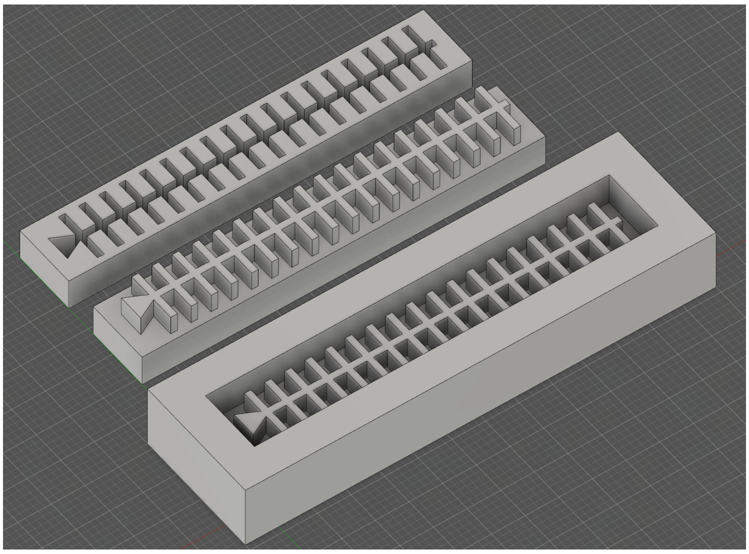

Figure 5.4: From top to bottom: The extrusion of area 1, 2 and 3 from figure 5.3 result in the mold for the main body.

in order to provide an actuator that is as small as possible while allowing to be crafted with easy accessible devices and technologies. The single extrusion steps and their results can be observed in figure 5.4. Since the base layer is simply a flat piece of silicone that is joined with the main body, the mold is very easy to create in comparison to the main body's mold. Creating a sketch that looks like figure 5.2 and using the same method as before yields a 3D model for the base layer mold (figure 5.5). We decide to design the base layer as thick as the layer above the pneumatic net-

The mold for the base layer is modeled.

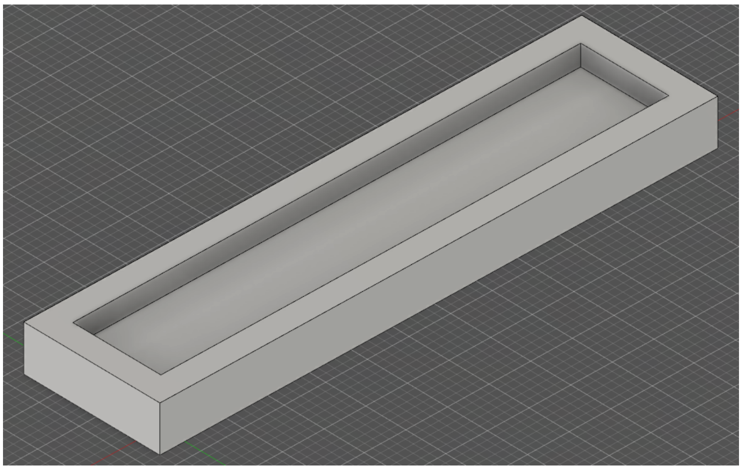

Figure 5.5: The base layer mold.

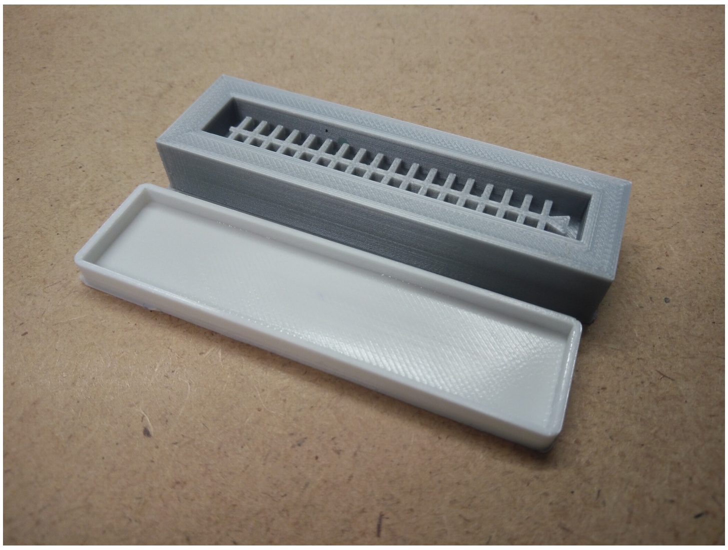

Figure 5.6: 3D-printed molds for the main body and the base layer.

work, that is 2mm, for symmetrical reasons. The resulting 3D-printed molds for the main body and the base layer are shown in figure 5.6.

5.3 Fabrication

This section aims to describe the detailed process of casting the soft pneumatic actuator.

5.3.1 Bill of Materials

We start with a list of items that are used within the process of fabrication. These items are however examples that fit our needs the best and each can be substituted with any other item.

- Molds for the main body and the base layer
- Silicone rubber (e.g. TFC silicone rubber type 1 impression silicone soft 1: 1 NV Troll Factory RTV)
- Mass scale
- Mixing cups and rod
- Needles of syringes and the corresponding pneumatic tubes
- Air pump (e.g. DC 12V Micro Vacuum Pump)

5.3.2 Process

The silicone is prepared by mixing the two components and then poured into the molds.

We use the mixing cups, the rod and the mass scale in order to mix the basis and the catalyst in a ratio of 1:1, measured by weight (figure 5.7), with the aim of creating a pourable silicone rubber. At a surrounding temperature of 23 degrees Celsius, the two components need to be mixed for one minute. Afterwards, they are processable for six to eight minutes. Note that any values regarding the temperature, the ratio or other concerns depend on the used material and are usually given by the manufacturer. In the next step, we pour the silicone rubber in the molds for the main bodies and the base layers. The main bodies' molds should be filled completely while the base layers' molds should be

Figure 5.7: Mixing the catalyst and the basis of the silicone rubber

Trapped air decreases the performance.

filled to half of the depth. It is important to evenly fill the molds in order to achieve the best functionality. Furthermore, it is essential to remove all bubbles of air that appear after pouring the silicone by simply poking them until no new bubbles form. Figure 5.8 shows the molds after being filled with silicone rubber where bubbles have drawn to the surface. Trapped air bubbles decrease the performance of the actuator or even lead to failure. When the silicone has cured, we are ready to join the main bodies with the base layers. For that purpose, we remove the main bodies from their molds. At this point, one can observe the air chambers that form the pneumatic network. Next, we pour another layer of silicone rubber in the already halfway filled molds

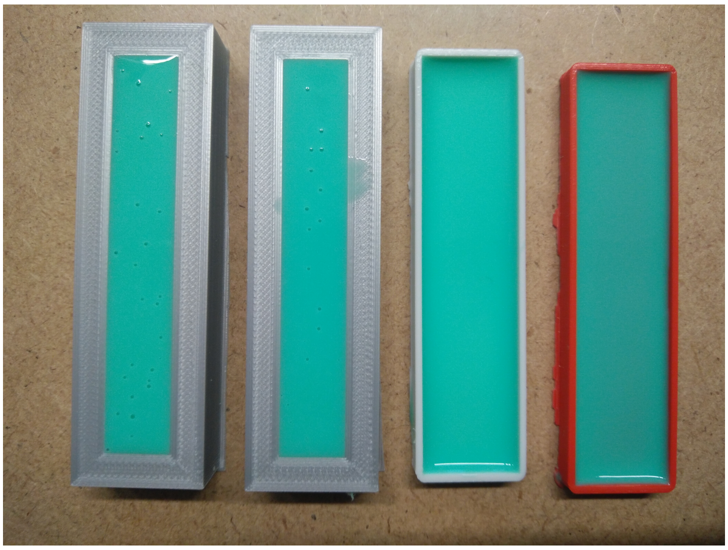

Figure 5.8: Molds filled with silicone rubber.

It is essential that the actuator is closed and that the channels are not blocked.

for the base layers and place the main bodies on top with the pneumatic network facing the base layer so that it settles into the uncured silicone rubber. It is important that the bond between main body and base layer is complete so that the air does not leak upon actuation. However, the pneumatic system must not be filled with the freshly added silicone rubber. Otherwise, the channels are blocked after the silicone rubber has cured and the actuator does not work properly. We now have two identical components that need to be joined by using the same method. We add another layer of silicone rubber and put one component on top of the other as shown in figure 5.10. Last but not least the actuator needs to be connected to a source of pressure. As introduced before, we use air provided by a micro vacuum pump. The needles of syringes are well suited for our purpose, because on the one hand they can be easily connected with the internal pneumatic network due to their design that allows for easily penetrating the silicone rubber without harming it. On the other hand, they come with pneumatic tubes that prevent the air from leaking on the way to the actuator. We reinforce the inserted needles with a stiffer silicone rubber (the yellow material in figure 5.10) that serves to prevent the needles from jiggling and tearing the material when inflating the actuator. Furthermore,

Figure 5.9: Joined main body and base layer.

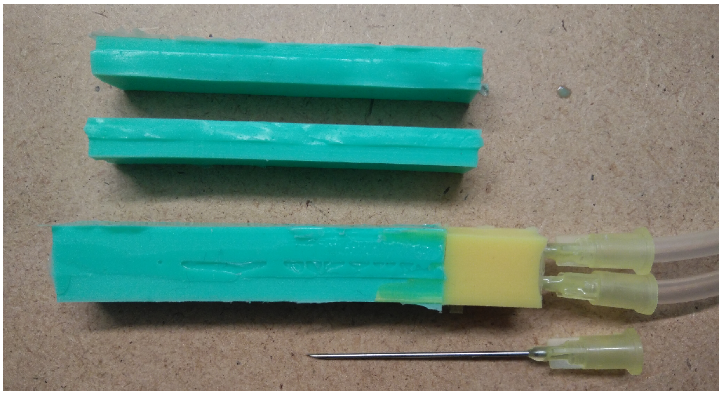

Figure 5.10: Completed soft pneumatic actuator.

A system of valves allow for controlling the inflation of each pneumatic network.

we deployed a system of two solenoid-operated valves between the source of pressure and the actuator. The first valve determines the direction of pressure meaning that opening and closing the valve leads to negative or positive pressure respectively. The second valve determines which component of the actuator is addressed since the actuator consists of two identical components as presented in section 5.2.

Chapter 6

Shaping Geometry

This chapter deals with the development process of forming the geometry of the inner pneumatic networks that are responsible for changing the actuator's shape. As discussed in previous sections, the presented actuator comprises two identical components that each contain a pneumatic network which are again identical. The desired result that we want to come closer to with each iteration of design is a geometry that evenly expands the corresponding component of the actuator in order to achieve the maximal deformation. However, this expansion should only be in the direction of motion, that is along the central channel as shown in figure 6.1. This expansion can then be observed as elongation. Furthermore, it is sufficient for the pneumatic network to only elongate the corresponding component, because it is possible to create an additional motion, i.e. bending, by installing two such pneumatic networks in one actuator as described in section 5.3. Since we suggest an iterative approach to finding the geometry that fits our needs the most, we describe how new designs aim to solve the problems from previous designs and the challenges that we have to face during the process. Since our goal is to achieve a maximal deformation by evenly expanding one or both components of the actuator, we start with a symmetric design consisting of one single air channel. Furthermore, we keep the height of the pneumatic network constant at a value of 3mm in order to satisfy the desire to develop a functional actuator that is as small as possible. In

The maximal deformation can be achieved by an evenly distributed expansion in the direction of motion.

The combination of two pneumatic networks enables different types of motion.

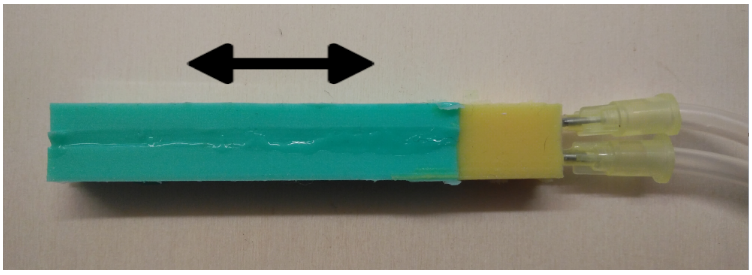

Figure 6.1: Direction of expansion.

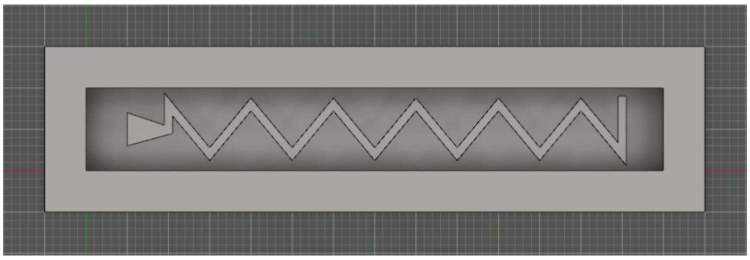

Figure 6.2: Development of the pneumatic network's geometry: Design 1.

The first design offers too much resistance to being deformed.

general, we do not change the exterior dimensions of the actuator, that is its length, width and height. Figure 6.2 shows the serrated pattern of our first design where the widened inlet on the left aims to facilitate the connection with the source of pressure. At this point, we already face a significant challenge, because the used air pump is not capable of providing enough pressure to achieve a deformation when inflating the chamber. Moreover, we can exclude the possibility that the channel was blocked during the fabrication process as we could observe the complete pattern picturing on the components surface upon actuation. Consequently, the next designs should increase the space occupied by the pneumatic network and therefore decrease the resistance to being deformed. The second design addresses exactly this problem by applying a dense snake-like pattern as shown in figure 6.3. It increases the size of the resulting pneumatic network to approximately one seventh of a component's volume while retaining a symmetric and repeating structure. This allows for easily expanding the component to almost twice its original length. The channel as well

The second design increases the size of the pneumatic network.

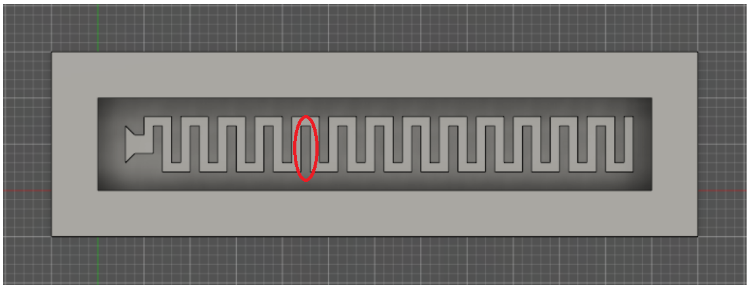

Figure 6.3: Development of the pneumatic network's geometry: Design 2.

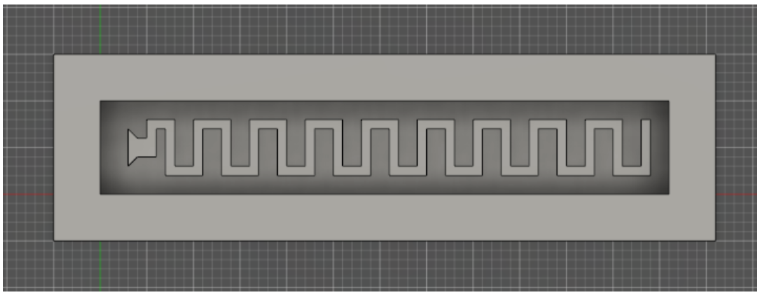

Figure 6.4: Development of the pneumatic network's geometry: Design 3.

as the distance between the areas that are nearly enclosed by the pneumatic network and that are directly joined with the base layer is 1mm wide whereas the distance to the sides is 2mm. In figure 6.3 we marked one representative with a red oval for a better understanding of which areas we are talking about. However, these areas turn out to be the weak spots of this design. Their weakness is their lacking strength when inflating the pneumatic network which forces them to tear off from the base layer. This way, we lose the structure of the network and end up with one single hollow space that behaves like a conventional balloon when inflating. In addition, it is important to keep the same distance to each side to prevent the pressure from concentrating on a side causing it to burst. In the third design, we strengthen the critical areas and increase their width to a value of 2mm while keeping everything else unchanged as shown in figure 6.4. As a result, the interior design provides enough strength to withstand the pressure. Unfortunately,

The structure of a pneumatic network which is too big tears upon actuation.

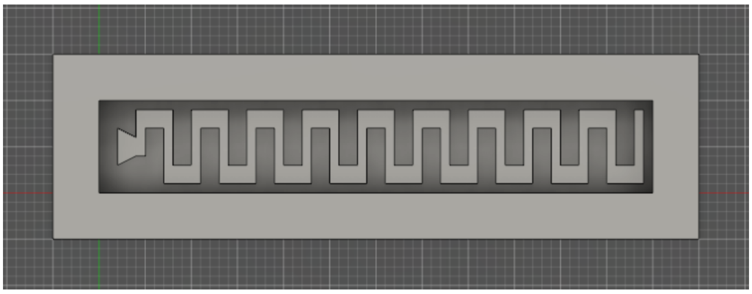

Figure 6.5: Development of the pneumatic network's geometry: Design 4.

We aim for creating a geometry that provides both enough strength and a small resistance to being deformed.

the problem from the first design recurs. We therefore have to make a new design that provides both enough strength to withstand the pressure and a small resistance to being deformed. Nevertheless, we keep the width of the critical areas at a value of 2mm as it is crucial to not destroy the pneumatic network. Instead, we set the width of the channel on its horizontal segments to be 2mm while keeping the width of 1mm for the vertical segments. The distance to the sides is now accordingly 1mm. The resulting geometry can be observed in figure 6.5. At first glance, the actuators that are build with this type of design yield promising results in several test runs with respect to stability and deformation. Since all prior actuators either do not deform or burst immediately after inflating the pneumatic network, we are now able to observe the actuator's behaviour upon repeating actuation and increasing pressure. On the one hand, the actuator keeps deforming with an increasing pressure. On the other hand the pressure is not evenly distributed over the length of the actuator. Instead, we observe a trend towards the end of the channel with a descending pressure towards the inlet which eventually causes the actuator to burst at high pressure. Our assumption for the cause of this phenomenon is the structure of the geometry reminding of a dead end leading to congestion. As response, the fifth design comprises one central channel with two outgoing bypass channels that head back to the inlet as shown in figure 6.6. The central channel is 2mm wide while the bypass channels measure 1mm in width. The distance from a bypass channel to the central channel is 2mm and from the bypass channels to the sides it is 1mm. A suchlike structure

The pressure is not evenly distributed.

We aim for achieving air circulation.

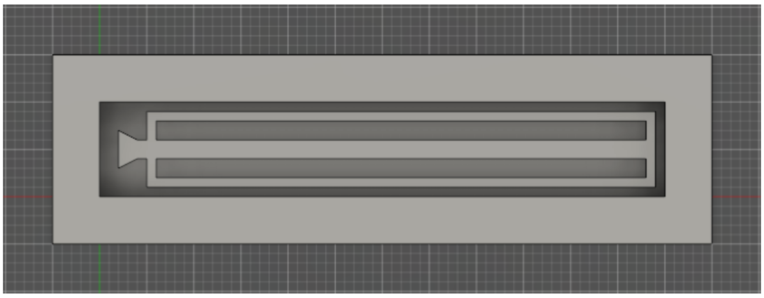

Figure 6.6: Development of the pneumatic network's geometry: Design 5.

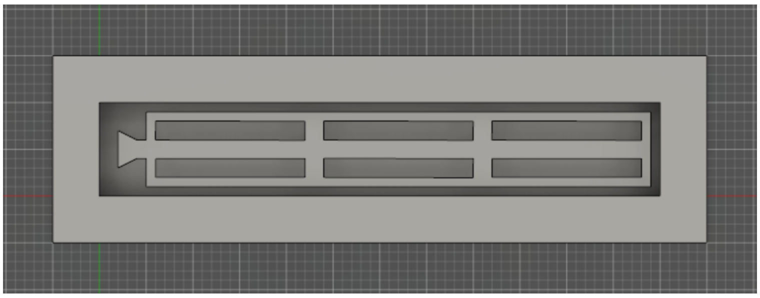

Figure 6.7: Development of the pneumatic network's geometry: Design 6.

intends to create a circular airflow that prevents the air from congesting. Yet, there is still a lot of pressure on the end of the actuator to be observed. We modify the fifth design by inserting two vertical channels, measuring 2mm in width, that connect the central channel and both bypass channels in order to create multiple circuits. The modification yields the sixth design which is demonstrated in figure 6.7. Unfortunately, the intersections that are created by inserting the connecting channels turn out to be the weak spots of our geometry as the pressure concentrates on these points preventing the actuator from evenly expanding. Finally, our seventh and last design satisfies the desired behaviour and proves itself to be the most effective and durable. We seize the idea of employing one single central channel and the principle of congestion in dead ends. Unlike the third design, which yields promising results, we do not create a single dead end but plenty of them in form of chambers that

Areas with a high concentration of pressure lead to failure.

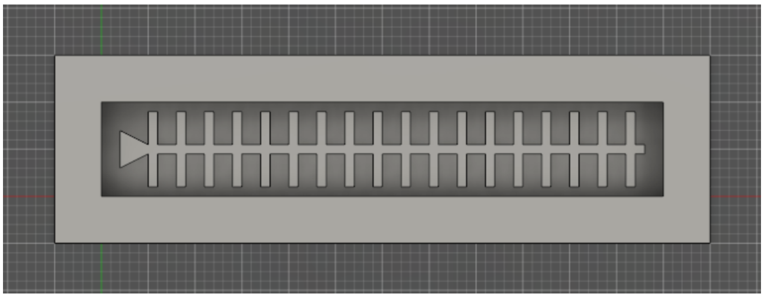

Figure 6.8: Development of the pneumatic network's geometry: Design 7.

periodically go off from the central channel. The central channel as well as the outgoing chambers are 1mm wide while keeping a distance of 1mm from the end of the chambers to the sides. By doing so, we are able to evenly distribute the pressure on each chamber which is facilitating the control of changing the shape of the actuator. The detailed modeling of the design, which is recapitulated in figure 6.8, is discussed in the prior chapter.

Chapter 7

Geometry Space and Results

Throughout our study, we have examined a set of parameters that affect the behaviour of a soft pneumatic actuator. In this chapter, we want to put these parameters and their effects into a geometry space with the aim of creating a library of building blocks for pneumatic shape changing in soft robotics. First of all, we provide the foundation for this library by introducing a simple geometry with a symmetric and repeating pattern that allows for an even expansion of the employed actuator. The dimensions of the pneumatic network's geometry as well as the silicone rubber parts of the actuator can then be adjusted with specific parameters in order to transform the expansion into desired motions. In our study, we consider the following parameters with respect to the final design of the pneumatic network's geometry presented in chapter 6. A visual representation of the parameters is shown in figure 7.1 and figure 7.2.

The examined parameter and their effects are described and put into a geometry space with the aim of creating a library of building blocks.

- Parameters affecting the pneumatic networks
    - Number of pneumatic networks
    - Number of air chambers and their positions
    - Spacing between the air chambers
    - Width, length and height of air chambers

- Parameters affecting the silicone rubber parts
  - Thickness of silicone around the pneumatic network, i.e. base layer, side walls, top surface
- Parameters affecting the material's properties
  - Number of different materials
  - Stiffness of the material

There are inverse relationships between parameters.

Based on a soft pneumatic actuator with a length of 60mm, a width of 10mm and a height of 7mm comprising only one pneumatic network according to the mentioned design, table 7.1 and table 7.2 show the effects of the listed parameters. Note that changes in one parameter consequently lead to changes in other parameters as the presented actuator aims to satisfy a set of constraints. For example, keeping the height of the whole actuator fix while increasing the thickness of the base layers and the top surfaces forces the height of the pneumatic network to decrease. This indicates the presence of inverse relationships, meaning that as one parameter increases the other parameter is forced to decrease and vice versa.

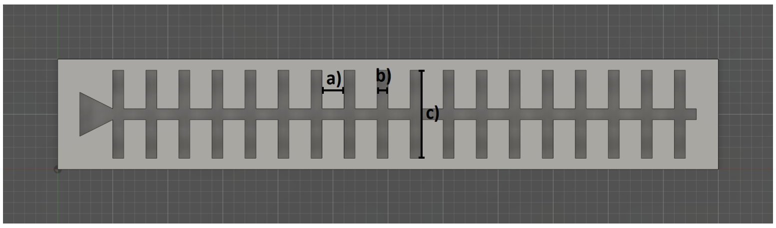

Figure 7.1: Cross section along the pneumatic network and the affecting parameters: a) Spacing between the air chambers b) Width of the air chambers c) Length of the air chambers.

7.1 Parameters Affecting the Pneumatic Network

7.1.1 Number of Pneumatic Networks

The number of pneumatic networks offers the opportunity to create actuators that can provide a wide range of motions by combining their effects upon actuation. Furthermore, the actuator can be divided into several sections where each section has a corresponding pneumatic network allowing to change the shape of only a section of the actuator while keeping different shapes in other sections. On the downside, however, each pneumatic network should be able to be actuated independently for maximum control which requires either multiple sources of pressure or a valve system.

Multiple pneumatic networks can work in concert.

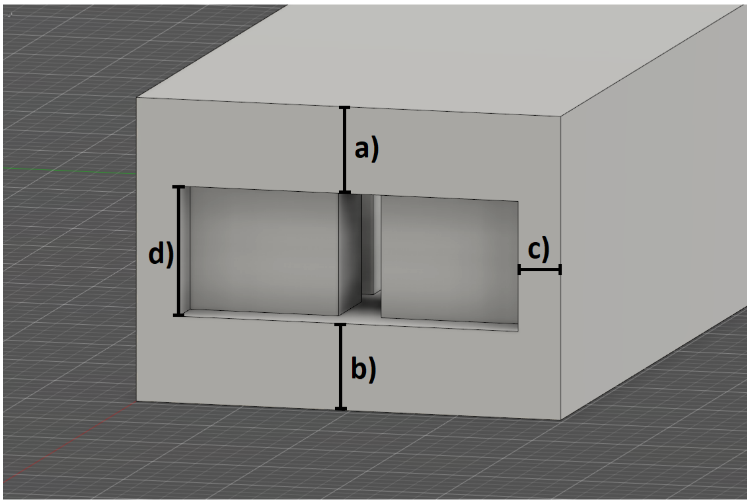

Figure 7.2: Cross section of a component and the affecting parameters: a) Thickness of the top surface b) Thickness of the base layer c) Thickness of the side walls d) Height of the air chambers.

7.1.2 Number of Air Chambers and Their Positions and Spacing

The design of the air chambers determines the pressure distribution.

The number of air chambers and their positions can be used to control the concentration of pressure within the actuator. A large number of chambers that are symmetrically and periodically positioned in the pneumatic network result in an evenly distributed pressure and a smooth deformation when inflated. Furthermore, their spacing is important to retain the stability and durability of the pneumatic network as the areas between the chambers must not tear. Otherwise, the pneumatic network is destroyed and the actuator becomes unusable.

7.1.3 Width, Length and Height of the Air Chambers

The width, length and height of the air chambers have a significant impact on the actuator's behaviour. They can be used to control the concentration of pressure by varying the size of the pneumatic network along different sections of the actuator. Furthermore, they are, along with the thickness of the parts made from silicone rubber, responsible for the speed of actuation and the extent of expansion.

7.2 Parameters Affecting the Silicone Rubber Parts

7.2.1 Thickness of Silicone

The thickness of silicone determines the speed of actuation and the extent of expansion.

The thickness of silicone surrounding the pneumatic network determines, next to the dimensions of the air chambers, the speed of actuation and the extent of expansion. A high ratio of the size of the pneumatic network to the amount of silicone correspond to a rapid actuation and a great extent of expansion due to the low resistance offered by the thin silicone. However, actuators that feature this ratio tend to break under high pressures and lack in strength. On the other hand, actuators with a low ratio of the size of the pneumatic network to the amount of silicone are stronger but not as flexible since a greater pressure is required to deform the components. Moreover, the thickness of different layers, such as the base layer and the top surface, can be used to manipulate the type of motion upon actuation and to guide the resulting motion in direction. That is due to the fact that silicone deforms in the most compliant regions. For instance, designing the top surface to be thinner than the base layer causes the component to bend towards the base layer and vice versa.

7.3 Parameters Affecting the Material's Properties

7.3.1 Number of Different Materials and Their Stiffness

A varying stiffness can guide the motion in direction and control the concentration of pressure.

In order to guide the motion in direction or to control the concentration of pressure, one can also apply different materials with different degrees of stiffness. Just like a thicker layer of silicone, a layer made from a stiffer material than the material used for the remaining component offers a greater resistance to being deform while inflating the component. Similar to the thickness of the silicone, when designing the base layer to be stiffer than the remaining component, the component bends towards the base layer and vice versa. The soft robotic grippers presented in Ilievski et al. [2011] make use of this technique in order to create a bending motion. They comprise multiple layers that are made from Ecoflex and PDMS where PDMS has a greater stiffness than Ecoflex.

Next, we describe the value assignment to the introduced parameters that provides the most promising results for the actuator developed in our study.

Table 7.1: Listing of parameters and their effects (1)

Thickness of the top surface $\mathrm{w_t}$, the base layer $\mathrm{w_b}$ and height of the air chambers $\mathrm{h_c}$	
$w_t > w_b$	Causes the actuator to bend towards the top. The degree of bending depends on the difference $\Delta w = \lvert w_t - w_b \rvert$. The degree of bending increases with an increasing value of Δw. However, with big Δw the actuator tends to burst due to high pressure acting on the base layer.
$w_t < w_b$	Causes the actuator to bend towards the bottom. The degree of bending depends on the difference $\Delta w = \lvert w_t - w_b \rvert$. The degree of bending increases with an increasing value of Δw. However, with big Δw the actuator tends to burst due to high pressure acting on the top surface.
$w_t = w_b$	Causes the actuator to extend without bending.
Small $\frac{h_c}{w_t+w_b}$	Increases stability, but decreases flexibility, i.e. the ability to bend or extend. With decreasing $\frac{h_c}{w_t+w_b}$ the pressure that is required for actuation increases.
Big $\frac{h_c}{w_t+w_b}$	Results in smaller resistance to the extension and bending of the actuator. However choosing $\frac{h_c}{w_t+w_b}$ to be too big causes the actuator to burst.

Thickness of the side walls $\mathrm{w_s}$ and length of the air chambers $\mathrm{l_c}$	
Small $\frac{w_s}{l_c}$	Results in smaller resistance to the extension and bending of the actuator. However choosing $\frac{w_s}{l_c}$ to be too small causes the sidewalls to pop due to high pressure acting on the walls.
Big $\frac{w_s}{l_c}$	Increases stability, but decreases flexibility, i.e. the ability to bend or extend. With increasing $\frac{w_s}{l_c}$ the pressure that is required for actuation also increases.

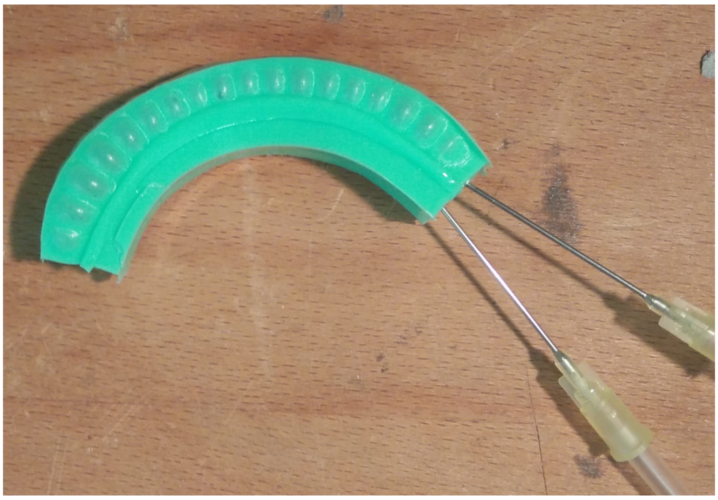

Figure 7.3: Presented actuator bending to the left.

7.4 Results

First of all, our actuator consists of two identical components that comprise one pneumatic network each. We apply to each component the same value assignment to the parameters. Both, the thickness of the top surface and the base layer measures 2mm which causes the component to extend without bending. The air chamber's height is 3mm resulting in enough flexibility of the component to function properly with a small amount of pressure required. The thickness of the side walls is set to be 1mm while the length

The applied dimensions provide enough flexibility as well as stability.

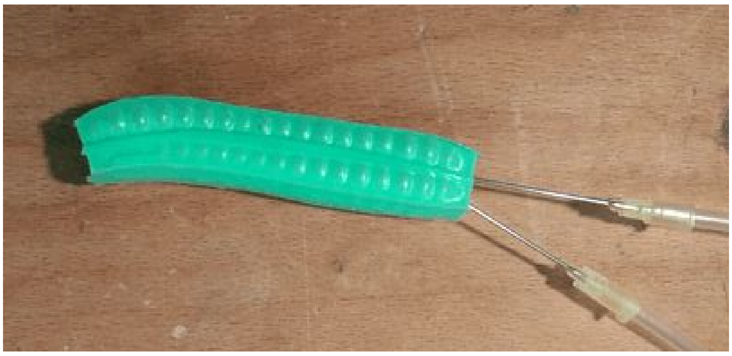

Figure 7.4: Presented actuator in its extended state.

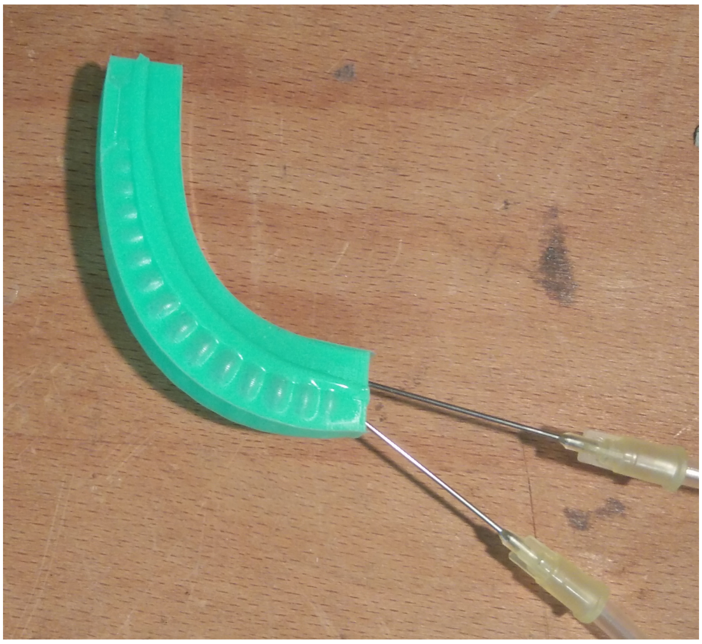

Figure 7.5: Presented actuator bending to the right.

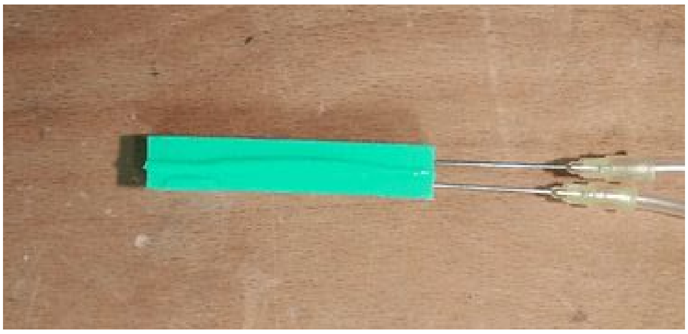

Figure 7.6: Presented actuator in its idle state.

of one air chamber is 8mm. This allows for a small resistance to being deformed without bursting under the applied pressure. The air chambers are periodically placed at intervals of 2mm while the chambers are 1mm thick indicating a trend towards stability. In total, we placed 18 air chambers along the central channel in order to cover the whole component. By doing so, we achieve a smooth deformation of the component when inflating the pneumatic network. Moreover, both components are made from a highly

The evenly distributed pressure leads to a smooth deformation.

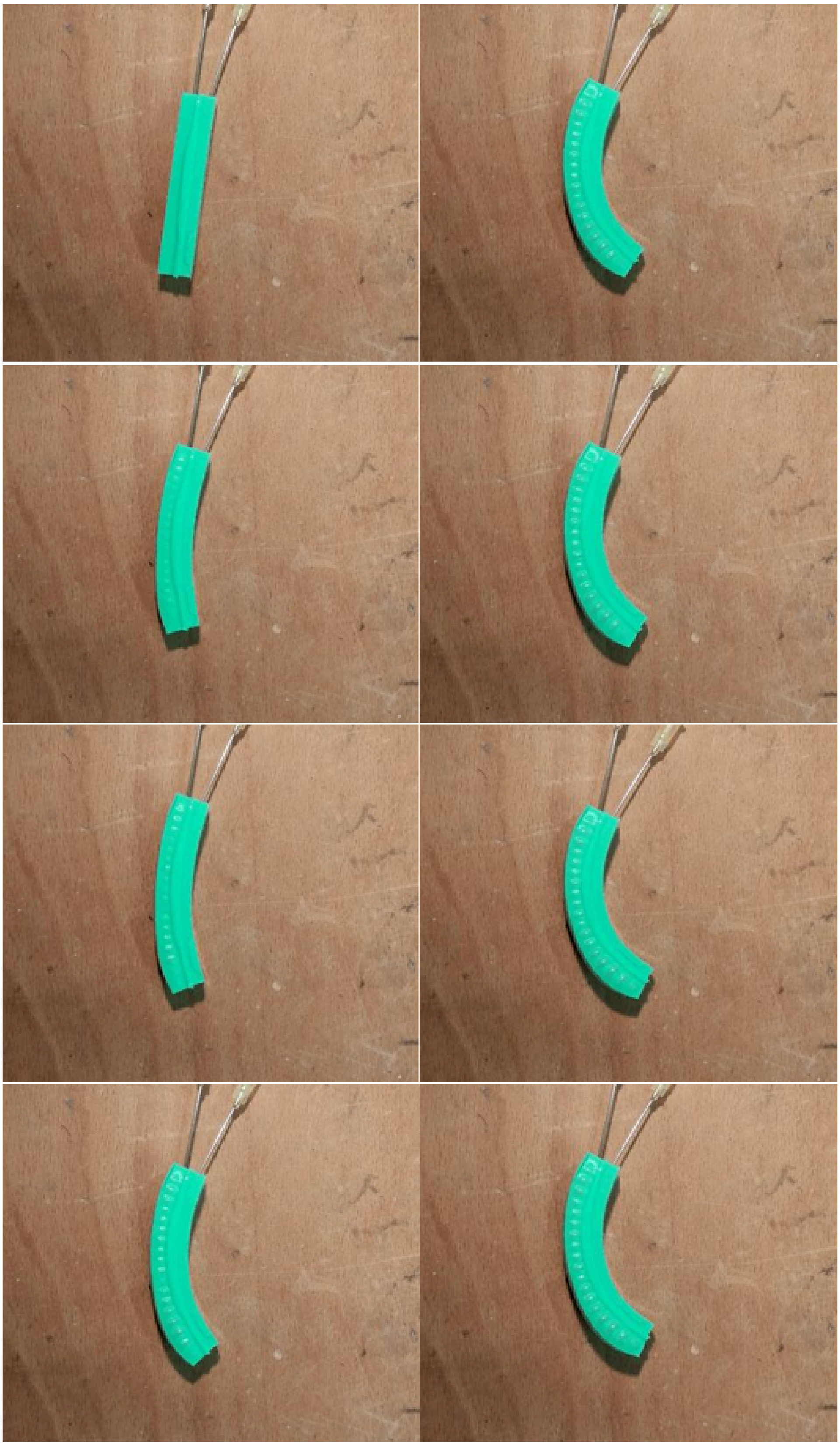

Figure 7.7: The deformation process of bending.

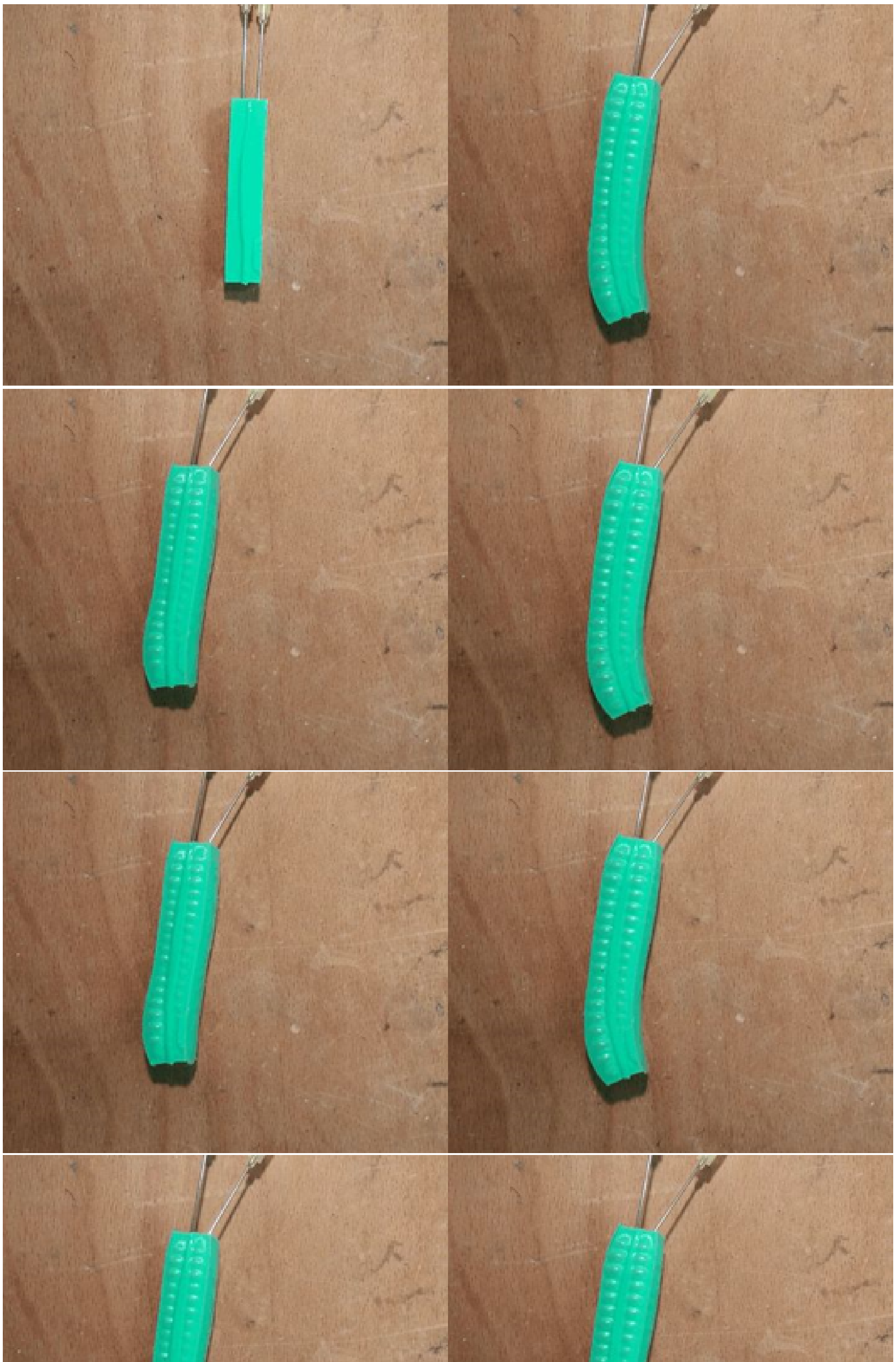

Figure 7.8: The deformation process of extending.

compliant silicone rubber with a shore value of A20. By now, we describe the results for two separate components that expand evenly upon actuation. Since we promise to provide an extending motion as well as a bending motion, we combine these components as described in chapter 5.3. We are now able to actuate each pneumatic network individually or both in concert. When actuating the pneumatic network of just one component, the other component serves as an additional layer of silicone whose thickness is then added to the corresponding base layer of the actuated component. This case is then treated like the usual relation between top surface and base layer from table 7.1 entailing a bending motion towards the idle component. On the other hand, actuating both pneumatic networks simultaneously results in the additional extending motion since both components mutually counteract. The best result that we were able to achieve is a bending of up to 90 degrees in both directions and an elongation from 60mm to 80mm which corresponds to 133.33% of the original size of the actuator. The deformations of the actuator in comparison with its idle state are shown in figure 7.6, figure 7.3, figure 7.5 and figure 7.8 We depict the value assignment and the results in table 7.3. The deformation processes are shown in figure 7.7 and figure 7.8.

The combination of two pneumatic networks offers a bending and an extending motion.

7.4.1 Limitations

Since the process of fabrication relies on hand crafting, it is difficult to build components whose dimensions are accurate to millimeter. Another downside of handcrafting with household goods can be observed, when the actuator is connected to a source of pressure, because the leakage of air tremendously reduces the pressure within the actuator. Furthermore, we experienced the phenomenon where the material gets stiffer over a period of days resulting in an increase of the required pressure.

7.4.2 Discussion

This thesis offers opportunities to HCI applications as well as prototyping.

Our presented actuator is well suited for various application areas where it can have different functions. In virtual reality, for instance, it can be used as input device in order to simulate squeezing actions with pressure-based interaction techniques. On the other hand, it can simultaneously serve as output device that allows for creating multimodal feedback, i.e. visual and haptic feedback. Especially on the small scale level, these actuators can be worn directly on the body in combination with jewellery, e.g. as ear rings or a component of a necklace, in order to express the wearer's mood or to react to her surroundings. The iterative exploration of meaningful parameters and the modeling and fabrication process, that was described in detail, offer valuable opportunities to the HCI community to customize soft robotic actuators on demand. The customization can range from different types of motion to various shapes of the desired objects. These actuators are low-priced and can be easily fabricated without any special skills or technologies in order to create prototypes of new designs.

Table 7.2: Listing of parameters and their effects (2)

Air chamber thickness $\mathrm{w_c}$ and spacing between the air chambers s	
Small $\frac{w_c}{s}$	Increases stability, but decreases flexibility, i.e. the ability to bend or extend. With decreasing $\frac{w_c}{s}$ the pressure that is required for actuation increases.
Big $\frac{w_c}{s}$	Results in smaller resistance to the extension and bending of the actuator. However choosing $\frac{w_c}{s}$ to be too big causes the interior design to tear which eventually leads to a balloon-like structure.

Number of air chambers $\mathrm{n_c}$	
Small n_c	Results in the concentration of pressure. However choosing n_c to be too small results in concentration areas that tend to burst due to the high pressure.
Big n_c	Evenly distributes the pressure resulting in a smooth deformation when periodically positioned.

Shore value of the material, i.e. stiffness	
Small stiffness	Results in a smaller resistance to being deformed. However, materials that are highly flexible lack in strength.
Big stiffness	Requires greater pressure in order to deform the actuator while featuring a greater strength.

Table 7.3: Examined value assignment to the parameters and its results

w_t (mm)	2
w_b (mm)	2
h_c (mm)	3
w_s (mm)	1
l_c (mm)	8
w_c (mm)	1
s (mm)	2
n_c	18
number of pneumatic networks	2
shore value	A20
Extension	From 60mm to 80mm, i.e. 133.33%
Bending	90 degrees in both direction

Chapter 8

Summary and Future Work

The last chapter gives a summary of the thesis and its contributions. To conclude the thesis, we present ideas for future work in the development of soft pneumatic actuators and especially for the design of pneumatic networks that serve to provide a range of different behaviour in order to extend the library of building blocks.

8.1 Summary and Contributions

This thesis describes the development and the design of a pneumatic network's geometry that provides the foundation for a library of building blocks for pneumatic shape changing in soft robotics. The developed geometry is then applied to a soft pneumatic actuator which allows for controlling the change in shape by combining basic motions.

Soft robots offer attractive features to the HCI community.

Soft robots offer attractive features to the Human Computer Interaction community as they are able to provide flexible and adaptive, as well as safe interfaces for user interaction. Advances in smart materials allow for creating such interfaces that are not only flexible but continuously deformable. Furthermore, soft robots can adapt autonomously to different shapes due to various shape-changing mechanisms. We make use of stretchable structures and especially of highly compliant elastomers since they are considered to be part of the most applicable materials to Human Computer Interaction.

Soft pneumatic actuators that are entirely made from a compliant elastomer enable anisotropic behaviour.

Soft pneumatic actuators are responsible for motions that allow for a user interface to change its shape or to provide haptic feedback. These motions result from inflating an internal network of elastomeric channels and depend on the structure and the geometry of the comprised pneumatic network and the material's properties. In contrast to other researchers that employ flexible but not stretchable materials to guide the resulting motion in direction, we eliminate all stiff components and present an actuator that is entirely made of a highly compliant elastomer. This enables a controlled anisotropic behaviour since we are able to provide multiple types of motion, i.e. bending, extending and combinations of both. In addition, we describe the role of soft pneumatic actuators in Human Computer Interaction. They provide dynamic physical affordances and multimodal feedback to expand the communication between the computer and the user. For that purpose, several HCI researchers employ soft pneumatic actuators in a range of application areas such as tangibles, conventional input devices, e.g. buttons, and virtual reality.

Smart materials are used to to create physical affordances.

In order to create physical affordances that unleash the human interactive potential of shape changing interfaces by exploiting material properties, we investigate our material of choice, i.e. silicone rubber. Silicone is a type of elastomer that allow for large-scale deformation and changes in surface areas. Moreover, we decided to use silicone since it is safe in its end form, widely available, easy to manipulate and, most importantly, it offers a low resistance to being deformed. For our purpose of developing a soft pneumatic actuator, silicone has proven to be beneficial due to its durability and compatibility with soft lithography making it very easy to create pneumatic networks.

Soft lithography is used as fabrication method.

Soft lithography is the key idea for creating the described soft pneumatic actuator. Therefore, we describe the modeling of the required molds and the fabrication process in detail.

Last but not least, we describe the development process of forming the geometry of the inner pneumatic network with the aim of achieving a design that evenly expands the actuator. The examined parameters that affect the behaviour of the actuator upon actuation and their effects are then put into a geometry space with the aim of creating a library of building blocks for pneumatic shape changing in soft robotics. The developed geometry and the resulting soft pneumatic actuator provide the foundation for this library. Beyond that, we present the value assignment to the introduced parameters that provides the most promising results.

The presented actuator with its pneumatic network provide the foundation for a library of building blocks.

8.2 Future Work

Further work needs to be done in order to develop various building blocks for pneumatic shape changing in soft robotics that extend our library since there are plenty of types of motions that are not considered in this thesis such as twisting. Soft pneumatic actuators could also provide different types of motion that depend on the applied pressure. For example, the actuator elongates until a given threshold for the applied pressure is reached. Afterwards, the actuator starts to bend. Another challenge that we faced during our study is to maintain a closed connection to a source of pressure. As we employ two pneumatic networks, we also have two inlets that connect the actuator to the source of pressure. Even though we are able to minimize the number of pressure sources, we describe problems concerning the inlets that might lead to failure. Future studies are therefore recommended in order to minimize the number of inlets and to control the air flow within the actuator, for instance with the help of soft membranes that serve as valves. Since the actuator is intended to be employed in the application area of assistive wearable devices and specifically as smart jewellery, further fabrication methods should be investigated in order to be able to create small scale components which is hardly to achieve with the methods presented in this thesis. Further, we suggest the use of water soluble 3D-printed material to create the

The library needs to be extended with building blocks that offer various types of motion.

Further fabrication methods need to be investigated in order to ensure that the actuator and the connections to the source of pressure are closed and to provide small scale building blocks.

molds in order to minimize the steps of casting that are required in the fabrication process. In our approach, it is not possible to create a closed mold while still being able to safely remove the cured silicone from the mold.

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