Control of Pneumatic Soft Robotics

Design of a miniature 3D printed integrated valve, actuated by Shape Memory Alloy Wires.

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Ir. Scharff, R.B.N have been a great mentor during my project. There was always time for a short discussion with positive input form his side. The sessions always gave new insights and a clear direction to work on.

Summery

This master thesis discusses the design of a 3D printed integrated miniature valve to control the air and flow rate in pneumatic soft robotics. the valve is able to control multiple bellows from inside the body of the soft robotic by only using one tube of air supply. The valves are actuated by Shape Memory Alloy actuator wires, named Flexinol. The valves are 3D printed together with the body of the soft robotic including the inflatable bellows.

Soft robotics make use of soft en flexible materials. They are able to perform delicate tasks and adapt to their environment. Soft robotics including multiple inflatable bellows need to be connected to a pneumatic power source. When the bellows need to be controlled individual by the speed of inflation and deflation, a problem occurs. Current valves available on the market are not suited. They are too heavy, large or expensive. In this master theses is worked on the solution.

The analysis phase starts by exploring the world of Shape Memory Alloy wires to determine the advantages the material offers, but also the limitations it brings along.

During the synthesis, the information gathered during the analysis is translated into a problem definition. The choice is made to make use of the SMA wires to actuate 3D printed valves for soft robotic. It makes use of the advantages SMA wires offer and bypasses the limitations of the material.

The concept phase focuses on designing the smallest and at the same time reliable valve to be able to control multiple bellows without any air loss. During this process, a case study is formulated to use as a guideline including a test set-up, amount of pressure and amount of required flow rate. The goal is to create a valve which can be used to control a robotic hand. The result consist out of a single bellow attached by two valves to inflate and deflate the finger.

The detailing phase describes the result of case study 1, but also elaborates on a second case study. This case study focuses on controlling two separate bellows placed in a different orientation than the first case study. This resulted into a different design of the valve.

Result of both case studies are used to set guidelines to be able to eventually create a tool to be able to control any kind of soft robotics.

The last part of this thesis concludes the final outcomes and evaluates on the results. At last, recommendations are listed of how to improve the final result and make the tool as a reality.

Table Of Content

Introduction

This part will explain what this report is about. It will start with an introduction explaining the starting point of the project. It will briefly explain what Shape Memory alloys are, and in what direction is will be used for. The final design goal will be explained and what it will improve to current solutions. The approach of the design process will explain how this final goal is achieved.

Introduction of the project

Many products around us in our daily life make our day easier and more comfortable. Some of these products need to be capable of creating motion to be able to serve the user. There are different solution to create motion from electricity, which are named actuators. Most common actuators are motors, electromagnetic- and piezoelectric actuators. They are used in a wide variety of products like hair dryers, refrigerators, speakers, vehicles but also in valves. Each product requires different requirements to fulfill its function. These requirements have influence on the type of actuator.

Another interesting way to create motion from electricity is by making use of Shape Memory Alloys (SMAs). This material changes its shape when heated while supplying a small current. Special fabricated SMA wires named Flexinol can contract while heated and pull a force while contracting. In this way, it can be used as actuator. When the material cools down, it remembers its pre-defined shape and elongates backs to the original shape. This unique way of actuation has many advantages. It is very lightweight, makes no sound and has a low volume in comparison with other actuators. More details about SMAs and the advantages the material offer will be explained in this report. Besides the advantages of SMAs, the material have some limitations as well. These limitations makes it not attractive to use as actuator in every product. The analysis phase of this report will focus on finding an interesting application making the best use of the properties of SMAs without experiencing the limitations of the material.

The starting point of this graduation project is a concept developed by Roger G. Gilbertson (Gilbertson, 2000), which makes use of Shape Memory Alloys (SMAs). This concept is called the Rubber Tube ''Flexi'' Device. This concept uses SMA wires threaded through a thin and flexible silicone tube to make the tube bend. The SMA wire is in fact being used as actuator. This concept is examined during the analysis and will be further elaborated on during this report. The concept is explained in **chapter SMA Applications.**

At the end of the analysis phase, the choice is made to not work further on the Rubber Tube ''Flexi'' device, but to use the SMA wires to actuate valves used for pneumatic soft robotics. The design goal is explained in the next chapter.

Goal of the project

Problem definition

Soft robotics supplied with air pressure are most often supplied by using a compressor or air-pump. Current solutions to control the air by dividing the supplied air to multiple chambers under different flow rate and air pressure have the opportunity to be improved. Current solutions are heavy, large and/or expensive. Specially for soft robotics, size and weight plays an important role. Besides, the valves available on the market all have their standard design which is not adjustable to specific applications. Hereby, the valves need to be connected which is not space efficient. Therefore, placing valves inside a small soft robotic makes it unsuited.

Design Goal

The design goal is based on the conclusions of the analysis phase. This part of this project focuses on finding an interesting application which benefits from using SMAs as actuator instead of alternative solutions. The outcome of the analysis is translated into a problem definition. The result of this assignment is a first step to solve this problem.

The design goal of this graduation project is to control pneumatic soft robotics consisting of multiple air-chambers. By making use of a valve which is integrated into the 3D printed body of a soft robotic, SMA wires are used to control multiple bellows by supplying the bellows when desired and eventually control the flow rate through the val to be able to control the inflation and deflation speed of the bellows. By supplying the wires with short and small currents the valves will open. By varying the amount of current, the bending speed of a bellow can be controlled.

In the future, the outcomes can be used to create a tool which enables any soft robotic provided by SMA actuated valves to control the airflow.

Chapter: Design Brief will elaborate more on the problem definition and design goal. It will also explain the case studies which are the used to prove the final design goal.

Design approach

Figure 1 shows the different phases of the design process. The analysis phase serves to find the most interesting application opportunities benefit from using SMAs as actuator. A literature study is performed to understand the world of SMAs. At the same time, some first experiments with SMAs are performed to get a better understanding about the Shape Memory Effect. Both will be used to formulate the potentials of SMAs used as actuator. These potentials are compared to the functionalities of various interesting applications. The investigation of potential applications is also part of the literature study. Competitive technologies will be examined to be able to find improvements and determine the role SMA wires can fulfill. Meetings with experts working in the different application fields will help to estimated these potentials.

During the synthesis, a final design goal will be formulated. From the conclusions of the analysis phase, a brainstorm session is held. The function of the brainstorm is to translate all findings into potential design ideas. With all knowledge gained during the analysis phase, a final choice is made in which direction to design for. A more in depth view to this chose direction enables to formulate a design brief. The design brief includes two case studies. A Case study is formulated which serves as guideline during the concept phase to be able to achieve the design goal. A list of requirements is formulated to evaluate the final result at the end of this report.

The concept phase starts by determine a scenario of how to inflate and deflate multiple bellows separately. An extensive prototype overview will explain how the final design of the valve is developed. Before this overview is explained, the choice of selecting the suited spring and Flexinol wires is explained.

The detailing part explains the final concept. It contains two demonstrators. The first demonstrator is the result of case study 1. A seconds demonstrator is designed from case study 2. This case study contains slightly different requirements which leads to a different design.

Both are used as input to be able to create a tool for in the future. This tool will determine the most space efficient way to control any soft pneumatic soft robotic. At the end, the final design will be compared with current solutions and explain the advantages the final design has to offer.

The last part will evaluate on the outcomes and formulates a list of requirements to make the tool a reality.

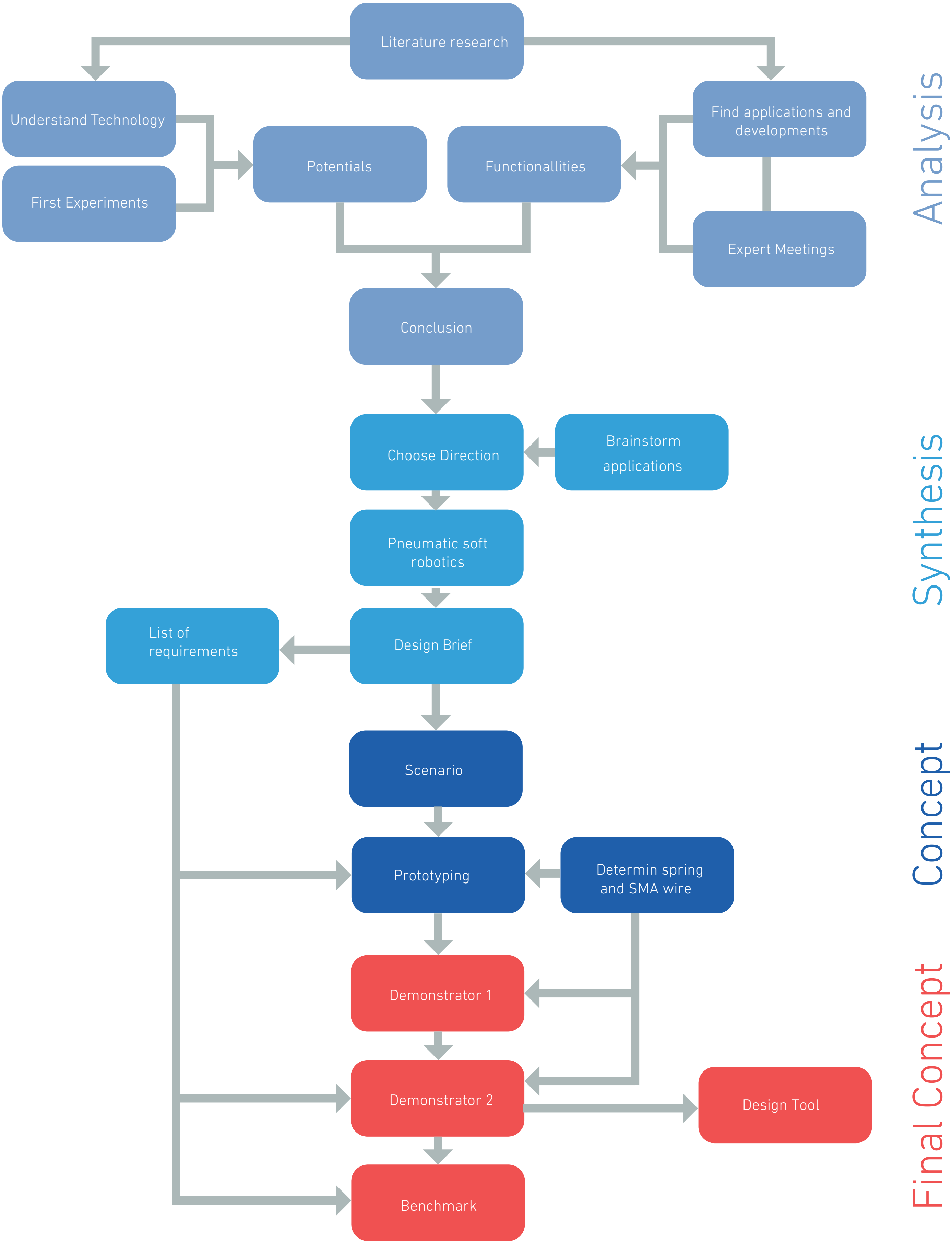


Figure 1: Design Approach

Analysis

This part starts with a literature study to get a better understanding about Shape Memory Alloys. First, the history about SMAs is explained to get an idea which innovation have been made and to get an idea how long it takes for possible new innovations brought onto the market. More details about SMAs will be explained to be able to use SMAs in the most effective way and prevent the material from failure. The manufacturing process will explain how the material is made and how the different functions are realised during the fabrication process. SMAs have different effects. Flexinol is a wire which is used as actuator wire. There will be more elaborated on this type of SMA, because Flexinol is the type of SMA which will be used in the final design. Different applications will be shown clustered per type of movement created with the SMA wire. Most interesting applications will be further investigated. Competitive technologies will be explained and the role of SMA wires will be evaluated for each application. At the end of this chapter, a conclusion will be formulated. This conclusion is used as input for the synthesis.

History

This chapter gives insight in the history of Shape Memory Alloys. It explains the steps being made to the development of SMAs to its current functionalities.

The first step in discovering the shape memory effect was when Adolf Marten in 1890 discovered the martensite in steels. This martensitic transformation was discovered in the Fe-C system. In 1949, the concept of the reversible transformation of martensite was introduced by Kurdjumov and Khandros with CuZn and CuAl alloys (Brezzi, 1991). Later in 1963, the discovery of NiTi was found to possess a shape recovery capability. The term NiTiNOL was given to this discovery of the material together with the Shape Memory Effect (SME) as shape recovery behavior.

In 1965 was found that applying Co or Fe caused a decrease to the transformation temperatures. The first commercial SMA application was the CryoFit. SMAs were used as pipe couplers in 1969 for the F14 jet fighter, but the transfer temperatures were very low which made it hard to prevent it from actuating before assembling it together. In 1989 was found that adding Nb instead made it easier to handle, because of a larger temperature hysteresis. This is the difference between the temperature of the material when it is fully transformed and the temperature which is lower to start the deformation again. The more hysteresis, the easier to work with the alloy regarding to heat applying precision. (Springer, 2008)

High temperature SMAs (HTSMA) with higher transformation temperatures above 100°C were developed around 1970. In 1978 was found that alloying with Cu did not change the transformation temperatures, but do narrow the stress hysteresis.

Regarding the fatigue of the material, Miyazaki showed in 1999 that the presence of Cu in NiTi alloys showed an improvement in fatigue life. This made it suitable for a wide variety of engineering applications. (Springer , 2008)

In 2008, investigations in magnetic SMAs (MSMAs) showed that under the influence of a magnetic field, high actuation frequencies and large strain can be generated. This makes them a candidate for high frequency actuation devices. (Springer, 2008)

During the last decade, research is focusing to enhance the attributes of SMAs by improving the material composition to optimize different transition temperatures, a wider operating range (hysteresis), better material stability, fatigue of the material and the response time (how long it takes before the material heats and cools down). Innovation is not only being made within the composition of the materials, but also how it is manufactured and trained. Besides the SMAs, other smart memory materials (SMM) are being investigated, like ceramics, SMM thin films and shape memory polymers (SMP). The different types of Shape memory materials are further explained in **Appendix A**.

Conclusion

From the history of the SMAs can be concluded that there is still progress being made in optimizing the characteristics of the materials and finding new variants. Despite the progress in innovation, it develops in a slow pace. Most innovations are not further developed than on a concept level and not so many applications have been commercialized yet. This is especially the case for new developed variants like the magnetic- and high temperature SMAs.

Unique properties of SMAs

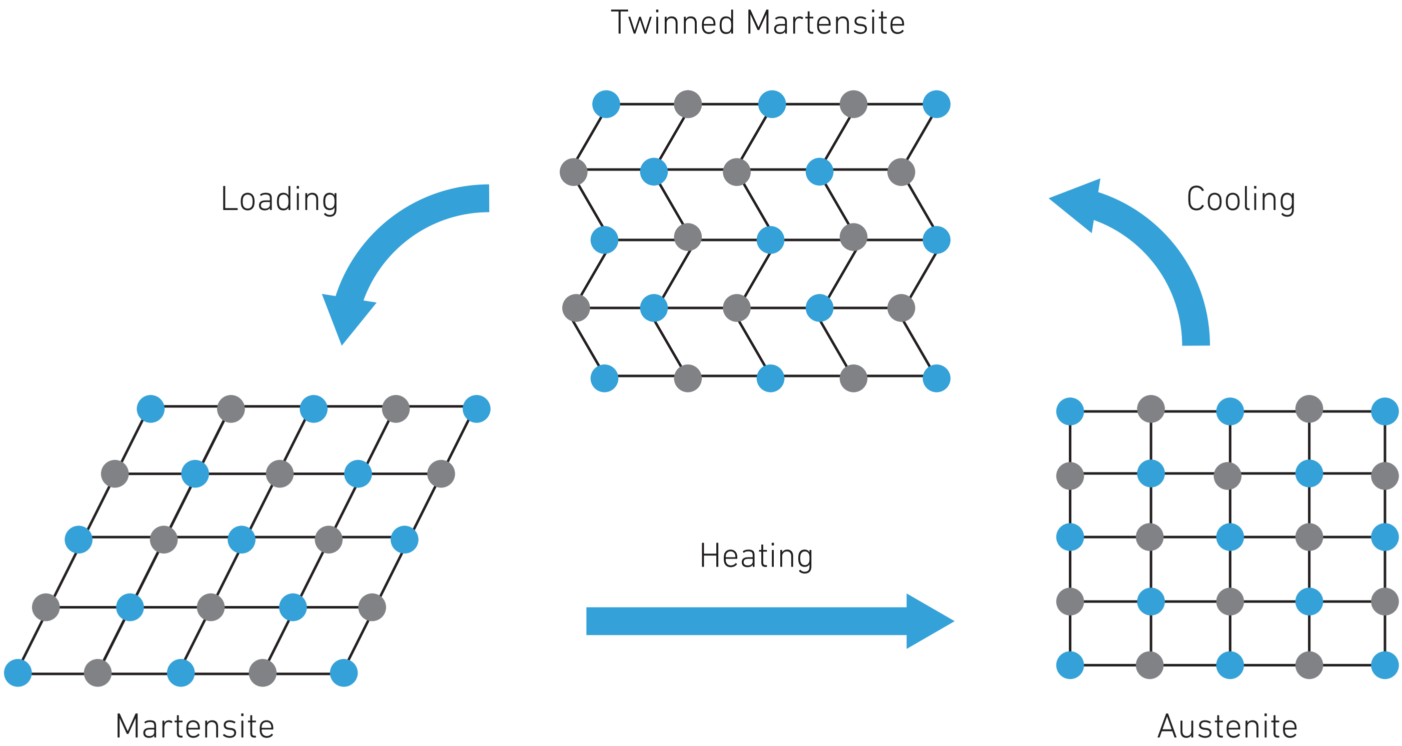
This chapter will explain SMAs in detail, to give the reader a clear understanding about the main topic which will be further elaborated on during this graduation report.

Shape memory materials (SMMs) are so called smart materials with unique properties including the capability to recover their shape after shape deformation initiated when a particular stimulus is applied. This is called the Shape Memory Effect (SME). Despite the first discovery of the shape memory effect in 1932, this phenomenon took a long time to finally be implemented in commercial applications. (Huang, 2010) This is because it took time to optimize the effect and make it possible and finally attractive to work with for commercial purposes. As today, still research is performed to optimize the characteristics of the materials and still new variants are being discovered and optimized.

Phases

SMA's have two different phases under different temperatures, namely martensite and austenite with both a different crystal structures and have therefore different properties, see **figure 2**. The high temperature austenite phase has one crystal structure, but the low temperature martensite phase, consists of a twinned or detwinned martensite structure. The austenite structure is centered cubic parallel, while the martensite structure is parallelogram. This parallelogram structure can be deformed easily and thus, the austenite structure can resist better to external stress. The transformation between the phases occurs by temperature change (or under the influence of magnetic field by MSMAs).

Figure 2: Phase transformations and different crystal structures (Otsuka and wayman, 2002)



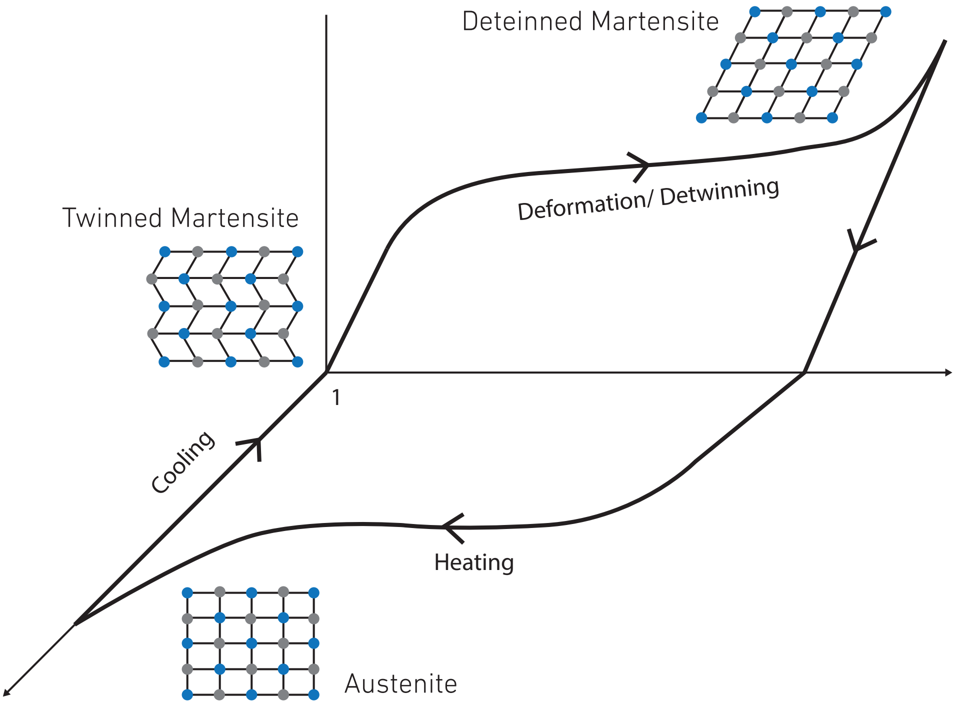


Figure 3: Shape Memory Effect (Springer, 2008)

This transformation is called the martensite transformation. The twinned martensite and detwinned martensite differ in the assembly of martensitic variants (different orientation direction of crystals).

Shape Memory Effect (SME)

The SME can be categorized into the One-Way-SME, Two-Way-SME and the ability to contract which is a related of the other two effects. The different effects will be further explained.

OWSME (one way shape memory effect)

SMAs have the ability to memories their predefined shape after deformation caused by an external load in the martensite phase. Recover to their memorized shape can be realized by applying an external stimulus: heat or a magnetic field upon a certain temperature range. This is called the shape memory effect (Gilbertson, 2005). This effect is realized by the way the SMA is produced and trained. The effect is visualized in figure 3.

Applying a load to twinned martensite results to detwinned martensite, a macroscopic shape change (changed form is retained). Detwinning start stress (σs) is needed to start the detwinning initiation. Reaching the detwinning finish stress (σf) correspondents to the complete detwinning of the material (Springer 2008). The shape of the material is now changed and will remain in this changed shape up until a new force is applied or the material is heated to the austenite phase, see figure 4. The OWSME is showed in steps 1-4.

Heating the martensite will result in the austenite phase, which is called reverse transformation. By heating the SMA in the martensite phase and the starting temperature (As) is reached, it begins to transform into the austenite phase. When the austenite-finish-temperature (Af) is reached, the transformation to the austenite phase is completed. During this transformation, the SMA is recovered to the original form.

Cooling down from the austenite phase will result the structure to change from austenite to twinned martensite. This is called forward transformation. When cooled down to the martensite-start-temperature (Ms), the material will start transforming to the martensite phase. When the martensite-finish-temperature (Mf) is reached, the material is recovered to the martensite twinned structure but the shape stays in its already deformed original shape. These transformations form a cycle which is called the SME. This effect can be repeated multiple times when applied with precision and attentively.

Cooling from the austenite phase with load above σs results not in the twinned, but the detwinned martensite, which does give a sharp shape change. Reheating will result in shape recovery when the load is still applied. (Springer, 2008)

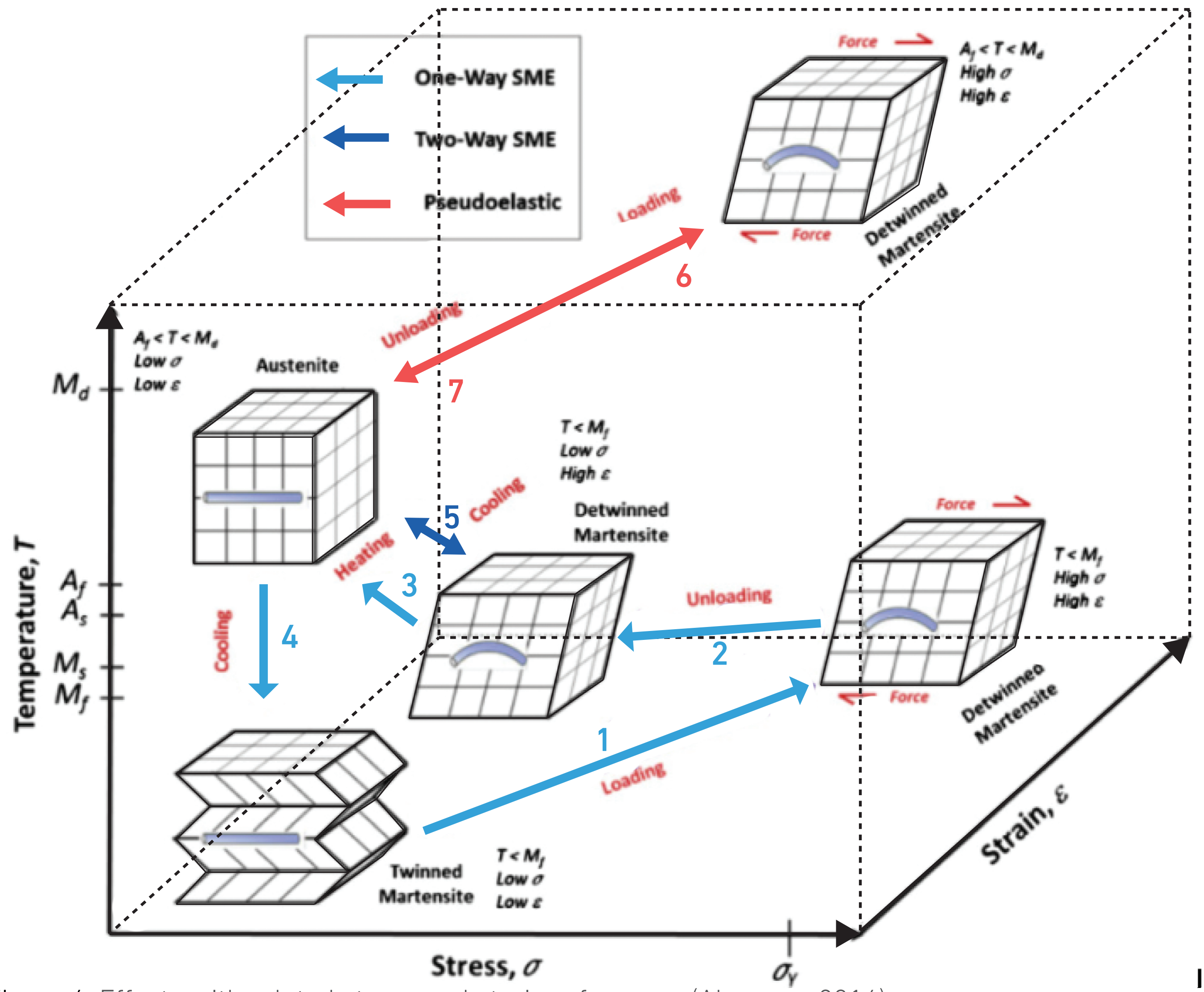


Figure 4: Effects with related stress and strain references (Alaneme, 2016)

SMAs have a difference in transition temperature between heating and cooling. This difference defined by the term hysteresis, which measures this difference (i.e. ΔT = Af – Ms). SMAs differ not only in this hysteresis, but in all phase transition related temperatures. This temperatures can differ very widely and differ because of the composition of the material. The hysteresis with related transition temperatures is shown in figure 5.

The transition in phase changes influences some physical properties and properties including Young's modulus, electrical resistivity, thermal conductivity and thermal expansion. The martensite structure has a lower Young's modulus and Yield Strength, is softer, more malleable and can be deformed more easily. (Hodgon, 1990)

By applying stress to the martensite phase above the Yield strength will result in permanent deformation. The most known and common NiTi alloy will show around 8% strain reaching martensite yield strength. In order to keep the material function constantly over more than 100.000 cycles, a maximum strain of 3-5% is advised. Applying 104 MPa, less than 0.5% of permanent strain occurs over >100.000 cycles. (Mostly and Mavroidis, 2000)

TWSME (two way shape memory effect)

By producing and training a SMA wire with an extra thermo mechanical treatment known as training procedures, the memory effect can memorize not only the first pre-set shape, but also the unloaded deformed detwinned martensite shape. (Huang, 2000) This can be done in various training methods. To supply the SMA with the OWSME, heat treatment is required while fixating the alloy. The TWSMA is obtained by repeating this procedure with a different clamped shape and heat treatment time. (Huang, 2000) TWSMAs can work the same as OWSMAs which is explained before. There is

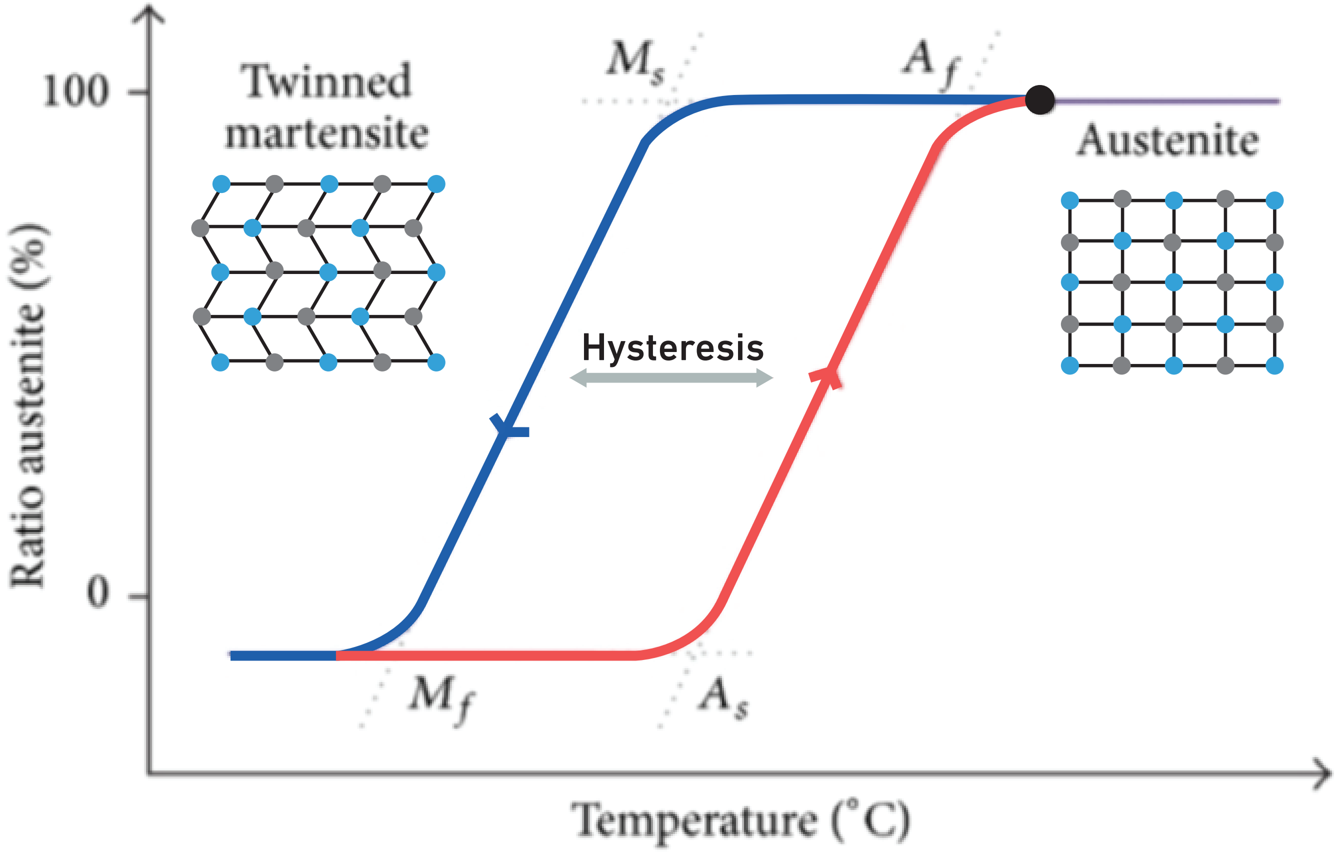


Figure 5: Hysteresis with related transition temperatures (Muller, 2015)

only one difference. The alloy remembers not only a shape when heated, but also when cooled down, the shape changes to a pre-trained shape in the martensite phase. With the OWSME, the pre defined shape will form when heated. When cooled, nothing happens with the shape. But with the TWSMA the shape changes not only to a pre defined shape when heated, but to a second pre defined shape when cooled down. The TWSME is shown in figure 4. The effect is shown in steps 1-3+5.

Contraction: Flexinol

Another characteristic which is part of the SME is the ability of contraction when the material is heated. Flexinol is a product which is a SMA wire and specially produced and trained to contract when the wire is heated. This makes it possible to lift a weight during the contraction up to 8% of its length. To keep this function of contraction over multiple cycles, less strain up to 3-5 % is allowed (Mosley and Mavroidis, 2000). A wire with the diameter of 0.15 mm can lift 321 grams (Dynalloy, 2016) without overstraining the wire. When cooling down, the wire elongates back to its original length. Like the other SMA effects, the capability of contraction needs a specific way of training as well. This is done during the fabrication of the wire. Flexinol wires remember only their stretched shape in the martensite phase. But the wire does not elongate back by itself. A bias force is needed to stretch the wire back again. In this way, flexinol is always used as a two way shape memory alloy, but acting in the direction of the length of the wire. The capability to contract will be further explained in **Chapter: SMA as muscle wire.**

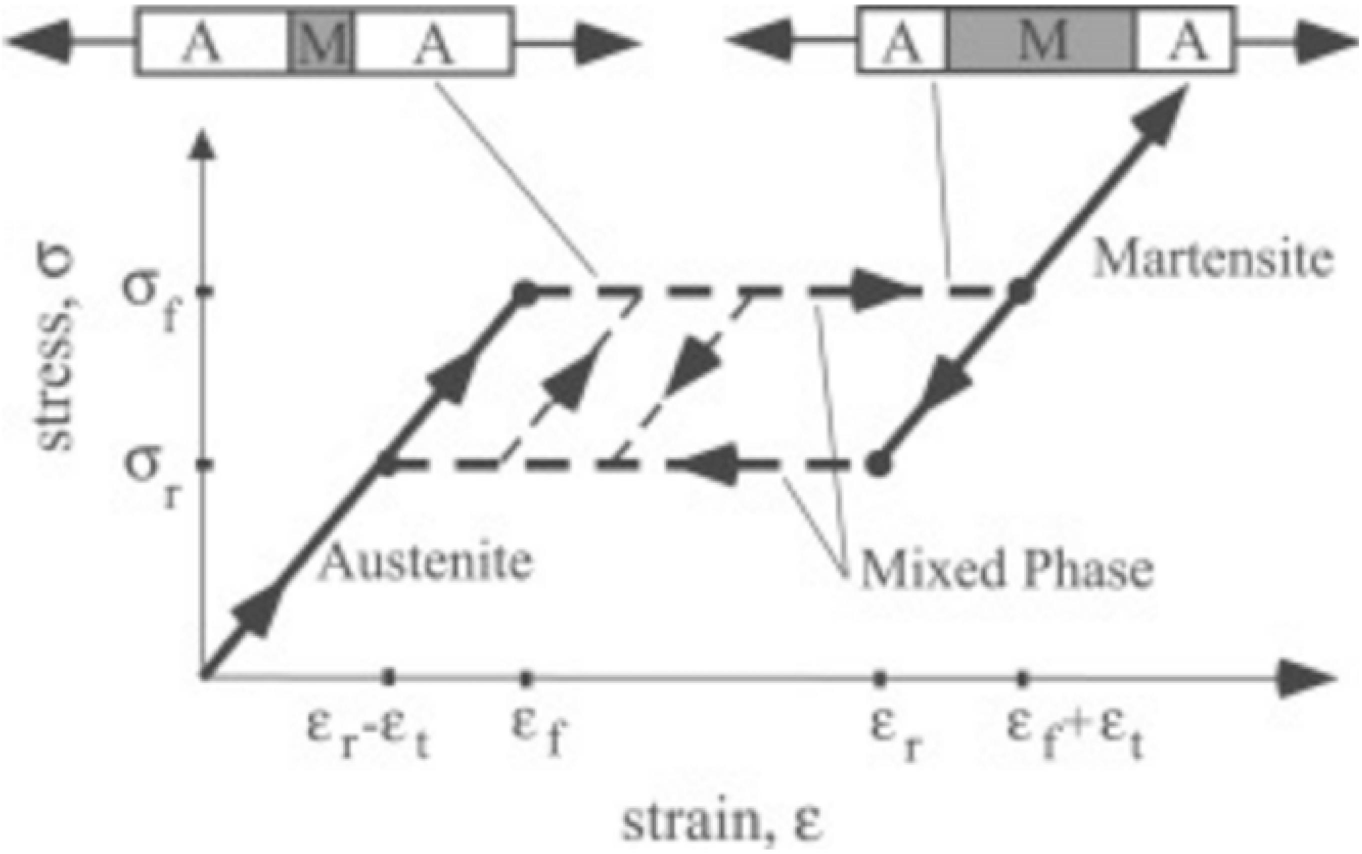


Figure 6: Super elasticity (Springer, 2008)

Super elasticity (SE)

SMAs can also show super elasticity (SE), see figure 6. The SE takes place in steps 6 and 7 in figure 4. This super-elasticity occurs when a load is applied to the wire in a higher temperatures range than which is needed to initiate the SME (Gilbertson, 2005). When unloading the alloy without changing the temperature, it reforms back to its original pre-trained shape.

By applying a high mechanical load to the austenite above the temperature of Af, a fully detwinned martensite is created and the material shows deformational behavior like elastic. Unloading will result in complete austenite and the material reforms to the original shape.

When heating the wire above the temperature to reform the shape (Af), it becomes super elastic while applying a stress above σr. By reaching the σr strain, martensitic transformation starts at parts of the material and will stretch in these parts. The transformation towards the martensite phase starts at strain εf and ends at strain $\varepsilon f+\varepsilon t$. The reverse transformation starts at εr and ends at $\varepsilon r-\varepsilon t$. Super elasticity can be performed between the temperature range of Af<T<Md. Acting in a higher temperature than Md, the material will undergo plastic deformation (Simha, 2016).

In Appendix B is the visual shown of the SMA effects together with an explanation through the phase changes

Conclusion

Still, SMMs are relative unknown to the design world which makes it very interesting to work with. Shape memory alloys (SMAs) are part of SMMs and characterized by the shape memory effect (SME) and superelasticity (SE). These are properties other metals do not have. Flexinol is a SMA which contracts and is therefore able to use a actuator wire. This is used as starting point of this graduation assignment to create a product with.

Manufacturing

This chapter will explain how SMAs are manufactured and how the SME is applied.

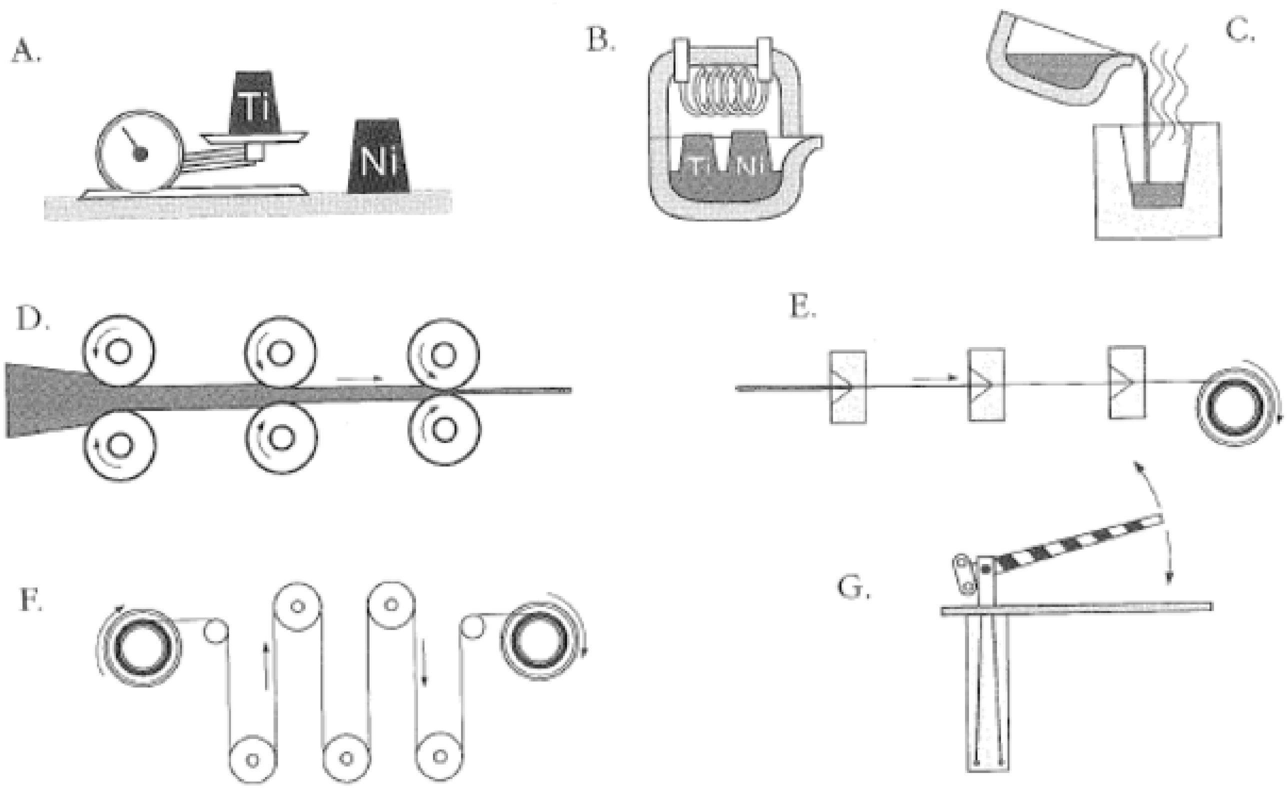
By manufacturing a SMA wire, the composition of the material is of great importance. Most SMA wires are made of Titanium together with Nickle with an equal atomic amount. Small differences in this ratio result in large transformation temperature differences. Some variants have a small amount of Cu or Nb added. The manufacturing steps are shown in **figure 7**. After measuring the materials, it is melted up to 1300°C in a vacuum furnace. After the metals are melted, it is cooled into a solid ingot. Then, it is rolled and formed into bars, rods, sheets or most commonly wires.

The alloy is hard to further process because a handling like drilling for instance, creates too much heat which transforms the material. Because wires are easy to work with, easily electrically powered and to connect, most common shape is the wire. To create the right diameter of the wire, it is drawn through a series of dies.

To apply the alloy with the shape memory effect, it needs an extra action. By clamping the wire solidly into a certain desired shape, it must be prevented from moving. It must be heated far above its transformation temperature up to about 540 °C which is the annealing temperature. When it is cooled down, the alloy has a memory to this clamped desired shape. This action is normally necessary to be done by the buyer of the SMA. When the fabrication and training of the SME effect is carefully performed, it can last for nearly unlimited cycles. Overheating, over-stressing and overstraining needs to be prevented during fabrication, training and use. (Gilbertson, 2005)

To create a TWSMA, more steps are needed. There are a few different methods, but most work with repetition cycles of heating the wire from the

Figure 7: Manufacturing process. (Gilbertson, 2005)



martensite phase to the austenite phase and back (Zaboni, 2007). The different methods are called: Training by over deformation, shape memory cycling, pseudoelastic cycling, combined SME/PE training and by constrained temperature cycling of deformed martensite.

The last is the most common and will be briefly explained. The alloy is deformed below Mf and is constrained and heated above Af. This is repeated for a several times.

There are still some limitations of TWSME: limited stress strain (+-2%) Inherent temperature hysteresis, lower transformation forces while cooling and a limited upper temperature.

Nitinol wires have the capability to bend into all possible directions. The training of this SME effect is therefore always performed after purchase. Flexinol wires on the contrary can only contract in length. This training is performed by the manufacturer of the wire.

Conclusion

SMAs need to be handled with care during their use, but also during the manufacturing. Adding small changes to the composition of the material has influence on different properties of the material, like activation temperature and hysteresis. The effect of SMAs is only achievable with the right training procedure. The TWSME has some limitations which makes is less interesting to work with. Therefore, many applications make use of a bias spring to simulate the same effect by making use of an OWSMAs.

SMA as muscle wire

The two most common ways to create motion from electricity is by making use of motors or solenoids. Another interesting way of creating motion can be done by making use of SMA's. This chapter will explain how Flexinol is used as actuator wire.

By processing SMAs in a special way, like Flexinol, they are able to contract in length when heated. While contracting, the wire is capable of lifting thousands times its own weight. Besides, this motion doesn't create any sound. The NiTi SMA is biocompatible and exhibits high wear resistance. Connecting the wire with other parts like a spring, elastic, lever or rotor, different motions can be realised. By placing the wire into a circuit, heat can be applied to create the motion. (Gilbertson, 2005)

Straight wire actuators: Flexinol as muscle wire

Flexinol is a tradename of SMA actuator wires made of NiTi. This wire is tuned for using as an actuation wire which contracts while heated and can elongate back with a relative small amount of force applied. This is about at least 1/6 of the amount it can lift during its contraction. (Dutta and Chau, 2013). Without using a force to help the wire to stretch back to its original force, the wire will not fully stretch and thus not fully deform again. Therefore in most applications, a bias force is used to keep the wire constantly. Smartflex and Dy90/ Dy70 are SMA wires with comparable functions like Flexinol. (Mertmann, 2008)

The key function of Flexinol is to actuate and lift a weight which is far more heavier than it's own weight. The more heat is applied to the wire, the faster it contracts (Mosley and Mavroidis, 2000). To utilize a memory cycle strain, no more strain of 3-5% is recommended for the Flexinol actuator wire. For an optimal contraction speed and distance, the wire is tightly fixated to both ends to be able to operate directly. (Dynalloy Inc)

To keep a wire contracted for a longer period by keeping it to the right temperature is a challenge. It takes great care to not overheat the wire. To keep the wire contracted can be achieved by constantly changing the applied current. It takes great care, because the wire does not react immediately to the change in heat applied with electricity. While keeping the wire contracted and keep the wire at a constant temperature range, it constantly heats and cools down because of the applied current. The process is influenced on several factors including the diameter of the wire, but also the environment temperature and humidity.

To test if the applied power was too high, is shown by the wire itself which won't elongate back in the same length as it was before. If there can be measured a difference in length, the wire was overheated. Heating the NiTi wire electrically will lead to a lower resistance through the transformation phase. This is in contrary to other metals. (Gilbertson, 2005)

There are also other ways to create a more reliable way of keeping a wire contracted. Some examples will be explained in **Appendix C**.

Actuation frequency

SMAs do not have a high actuation frequency. Because the wire must be actuated by applying heat, it takes some time to heat the wire. The most common way to heat the wire is to apply the wire with a current resulting in a heating time in less than a second (Joule Heating). Applying the wire with a higher current, the wire will be heated faster, but heating the wire too fast can possibly overheat the wire. A recommended heating time is 1 second. Faster heating of the SMA wire can be realized by increasing the applied current, but when the applied current is too high, the material will be damaged. The maximum allowed current is 1A. (Velazquez, 2012). By Applying high currents, a closed loop system is needed to prevent the wire from overheating. The heating time is directly related to the applied current. The amount of current depends on the type and dimensions of the wire. As explained earlier, the environment plays a role as well. The cooling time has even more influence on the total actuation frequency. It takes some time for the material to cool. The diameter of the wire plays the most important role, but the activation temperature makes a difference as well. The cooling time of the most common used diameter of 0.15mm with a recommended pulling force of 321 grams is 2.0/1.7 seconds, depending on the activation temperature. The range in cooling time of wire diameters of 0.025-4.3 mm is in between 0.15-16.8 seconds. This means the wire diameter has a significant influence on the cooling time. A table with more details is shown in **Appendix D.**

In **figure 8**, the actuation energy density of SMA is compared to other active materials. Besides, the actuation frequency, is shown. SMAs have a high actuation energy density, because they are able to recover their shape when the temperature is increased, even with high applied loads (Springer, 2008). This makes it interesting to use as actuator.

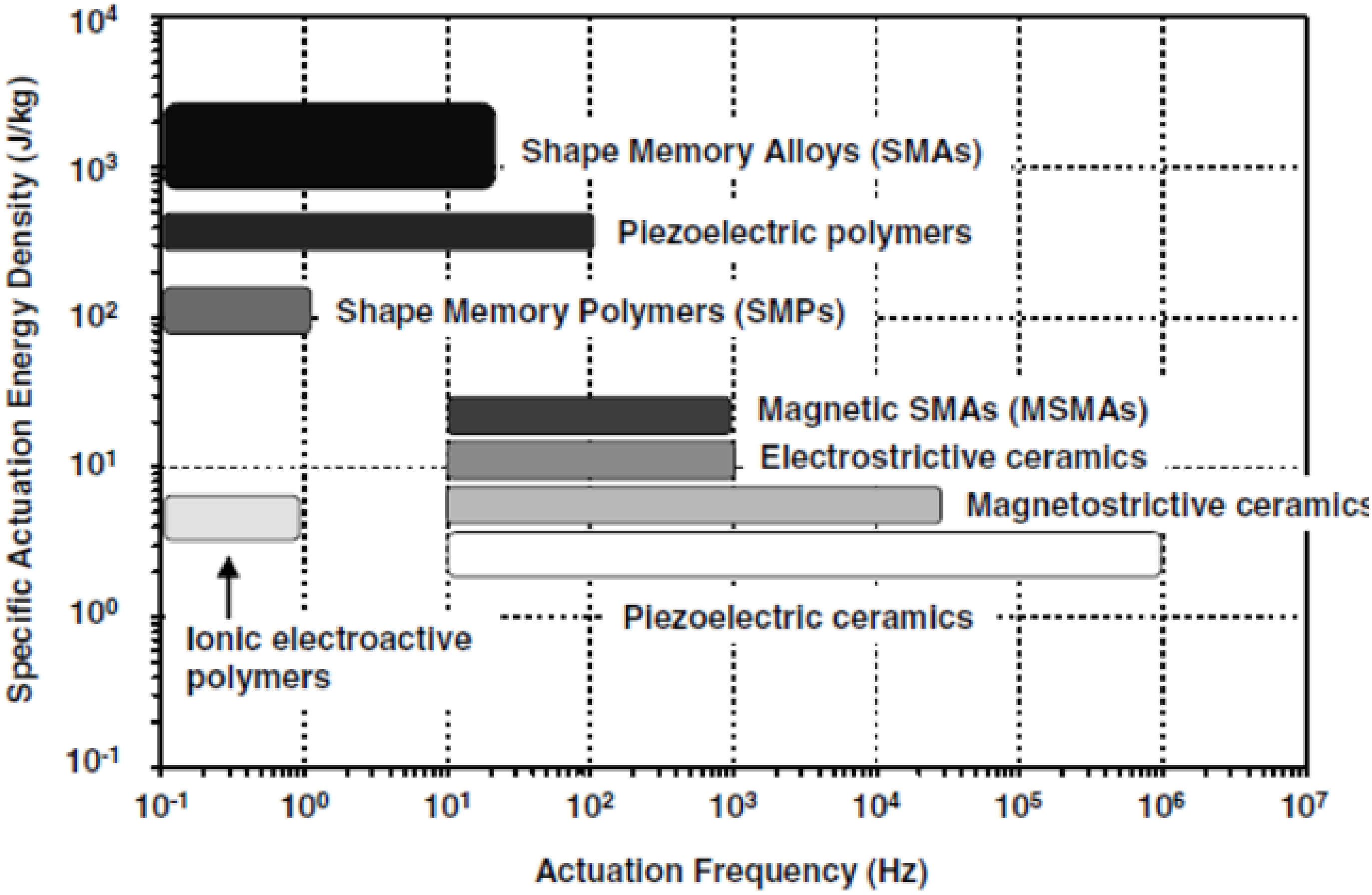
When an SMA wire is used in an application, the required pulling force and cycle time determines the dimensions and is needed the amount of wires. This has influence to the actuation frequency. Because the cooling time can be critical in some situations, many innovations have been made to decrease the cooling time. Besides changing the material composition and wire dimensions, different cooling techniques have been developed.

To achieve the optimal cooling time without making use of alternative techniques is to use thin wires working parallel and to use a wire with a higher activation temperature. Because the transformation temperature is much higher than the environment (room) temperature, the wire will drop below this transformation temperature faster.

By using more thin wires, more surface ratio per volume ratio can be gained which improves the heat transfer. This makes the cooling process faster without sacrificing the bandwidth. The wires must be placed separately with distance in between, so air can flow freely around it. (Mosley and Mavroidis, 2000)

In **figure 9**, results of different cooling techniques are shown. The results shown in the figure are

Figure 8: Actuation frequency/Density (Springer, 2008)



part of an experiment using a SMA wire with the diameter of 0.127mm and activation temperature of 90° C. (Tadesse et al, 2010) Without any cooling techniques, the cooling time of the wire is 1.6 seconds. The best working technique saves 1.2 seconds resulting in 0.4 seconds. The techniques are explained in **Appendix E**.

Fatigue

The fatigue of the material is very important by using the wire as actuator, but with safe precaution over 100.000 of cycles can be performed with neglectable downturn while operating. Important precautions in applied force, applied temperature (prevent overheating) and strain have to be made. (Simha, 2016). Two forms of fatigue can be experienced: mechanical fatigue and shape memory fatigue. Mechanical fatigue is experienced due to dislocations and cracks in the material due to repeated mechanical loading cycles. The shape memory effect occurs also due to thermal loading. This consist of the reduction of recoverable strain. This reduction of strain arises because of formation defects occur during the phase transformation. (Lynch, 2013)

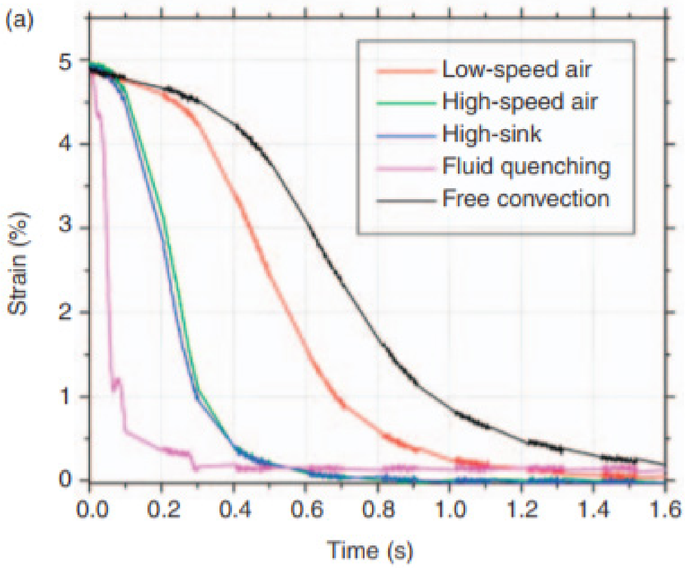


Figure 9: Cooling time of different cooling techniques. (Tadesse et al, 2010)

Conclusion

This chapter shows some differences with the other unique effects of the SMA earlier explained. A flexinol wire has a pre-defined shape when purchased, but only act in one direction, the direction of the length of the wire. No shape has to be trained when the wire is bought. The wire needs to be handled carefully to not overheat or overload the wire. SMA have high energy actuation density, this means it can withstand a high stress per actuation strain percentage of its length. This contributes to the benefit of use SMA wire in small and compact products. To achieve fast cycle frequency, multiple thin wires can be used, or one of the cooling techniques could be integrated into a final design.

SMA Applications

This chapter will explain a selection of different applications making use of SMA actuator wires clustered per type of movement. The examples are used as input to find an interesting product or mechanism to design for during this graduation assignment. This chapter will also refer to more applications explained in the Appendix F.

SMA's are popular to be implemented in sensing, actuating, impact absorption and vibration damping applications. Most common application is as actuator, applied in a wide variety. Within the actuator applications of SMAs, 99% makes use of the Ni-Ti wire (Mertmann, 2008). This is the material composition Flexinol and Nitinol are made out. The key design drivers which can make a material suitable as actuator are the actuation density (available work output per unit volume) and actuation frequency of the material. Having both properties: high actuation density and actuation frequency, would be most ideal. Because SMA don't have a high actuation frequency, applications require very high speed actuation make use of other types of actuations. As explained in **Chapter SMA as muscle wire**, SMA wires do have a high actuation density, which makes it interesting for many applications. Because of all the different unique effects and variants of the SMAs, applications in different product domains have been developed.

Because this graduation assignment focusses on the Flexinol wire which is being used as actuation wire, an overview of applications which make use of the Flexinol wire will be explained. SMA actuator wires are being used in different applications to create movements in sorts of direction. Most interesting applications will be explained.

Bending tubes

Different applications have been developed by making use of SMA wires which pull a tube to a desired direction. In most cases, the application is an active endoscope.

Active endoscope

In **figure 10** shows an example of an active endoscope making use of SMA coils. The coils are placed around the center of the tube along the length. By heating the coils, they contract and pull the tube to a certain direction. The endoscope is able to bend up to 90° C. By applying different amount of currents to the three wires, it is possible to make the endoscope bend to different directions. A plastic coil around makes sure to straighten the endoscope again when the wires cool down.

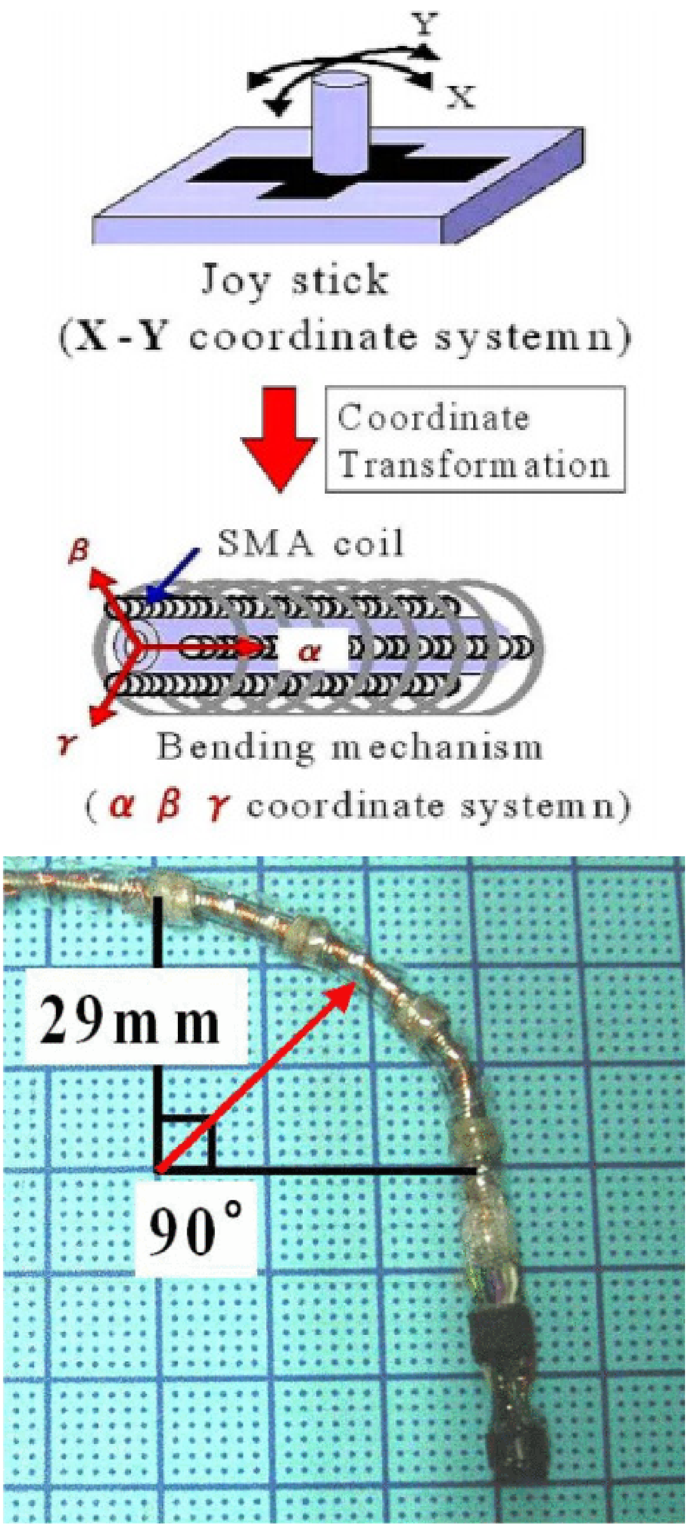


Figure 10: Active endoscope

Rubber tube "Flexi" device

Besides all examples of an active endoscope. A soft gripper can be created using multiple flexible tube wired with SMA wires.

In **figure 10** shows the Rubber tube "Flexi" device. It makes it able to create a bending movement of a flexible tube in different directions. By using more of these tubes, a flexible, simple controllable and lightweight gripper can be created. **Appendix G** shows some first experiments making use of this concept. It also elaborates the other experiments performed during the analysis phase.

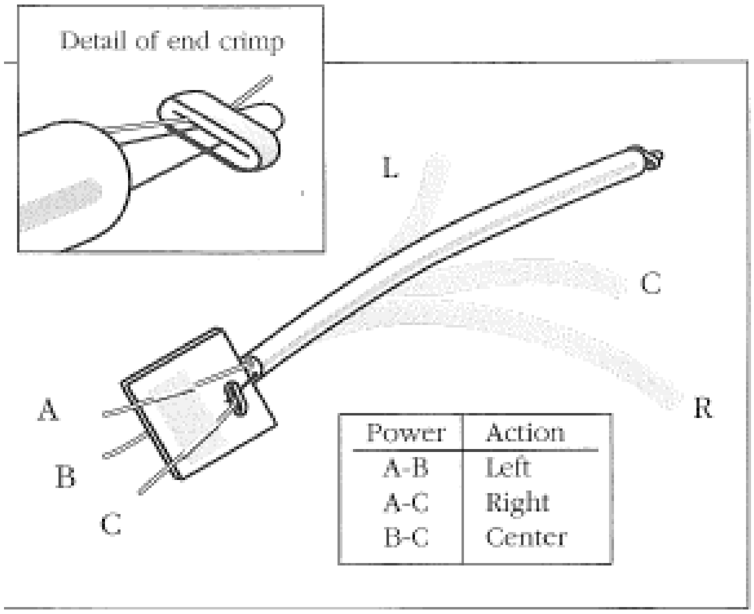
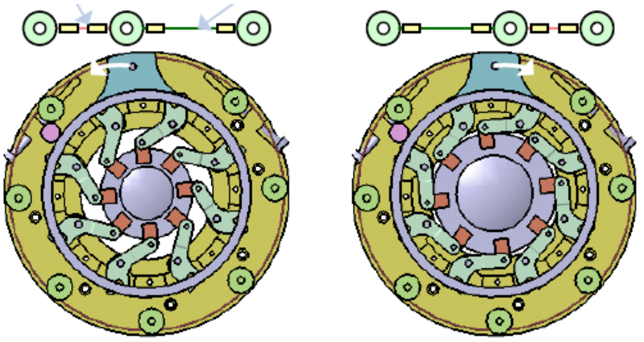


Figure 11: Rubber tube "Flexi"" device (Gilberton, 2005)

Rotational movement

Robot eye

Figure 12 shows a mechanism based on SMA wires to adjust the focal length of an robot eye lens. Two SMA wires around placed along the path of the outer diameter in opposite direction. When the wires are heated, the outer ring starts to rotate, initiating the load arm to make the grippers contract the lens. A friction path is used to keep the ring into position. While the wires cool off, the ring will remain position.



(a) Contraction of lens (b) Elongation of lens

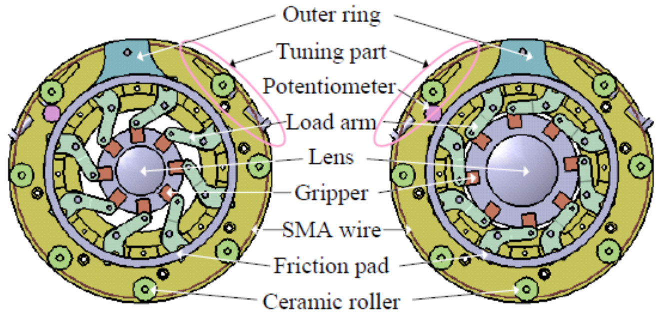


Fig. 3 CAD drawing of KNU eye.

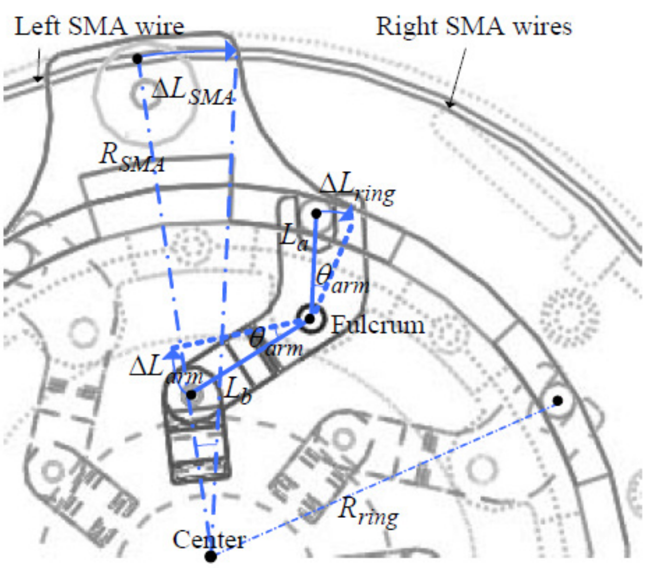
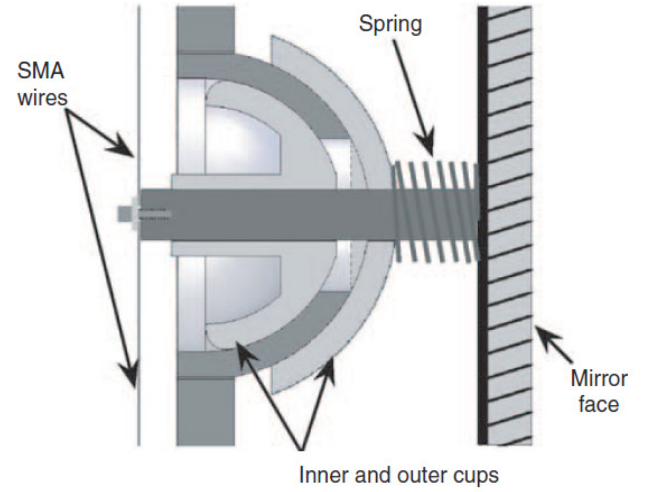


Figure 12: Robot eye (Jong-Moon Choi, 2008)

Car mirror

Figure 13 shows an car mirror actuated by 4 SMA wires in different directions over two axis. By heating the wires, the inner cup will make a rotational movement. A spring which is placed between the mirror and the outer cup of the mechanism will keep the mirror in its place when the wires not heated and the mirror needs to be kept into the desired direction.



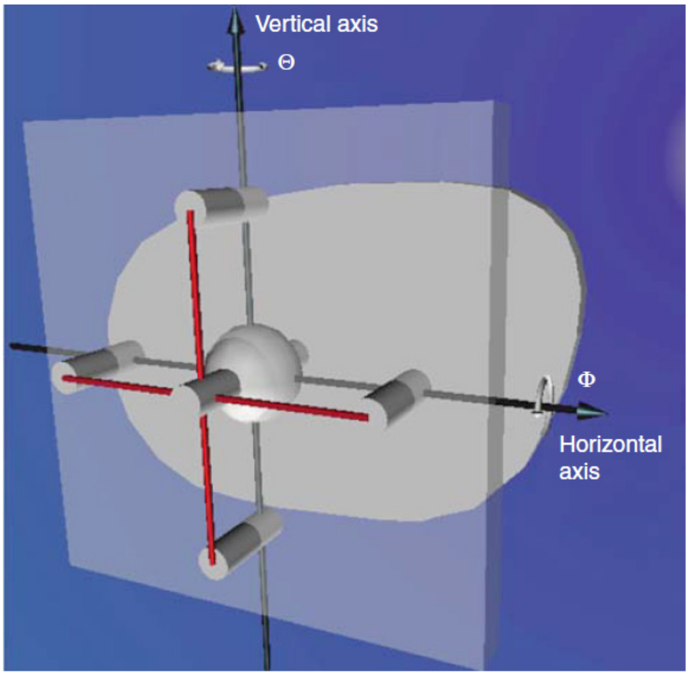


Figure 13: Car mirror actuated by SMA wires (Elahinia, 2008

Anti glare carr mirror

Figure 14 shows a mechanism based on SMA wires to change the angle of a car mirror. This mechanism change the mirror slightly when glare arises in the mirror by another car. It has two stable positions without the use of friction to keep the mirror into position. The mirror can rotate to 8 degrees. A SMA wire pushes a piston vertically. A pin connected to a hinged bracket slides within a slot into the piston. The mirror is attached to the bracket. The bracket can only change its angle and will slide into the two different positions when the SMA wire is heated.

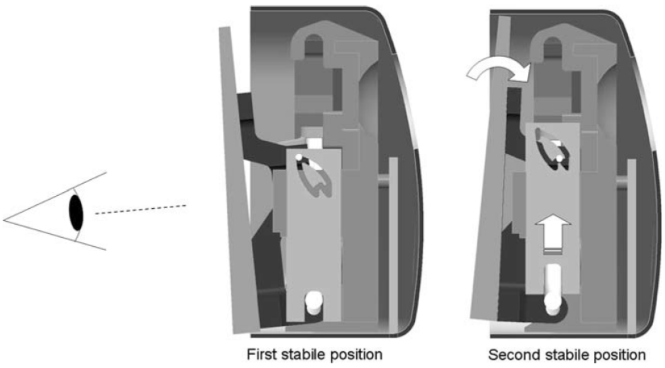


Figure 14: Anti glare car mirror (Luchetti, 2009)

Axial movement

Braille with SMA coils

Figure 15 shows a mechanism to create a braille. The pins are moving in a vertical movement linear to the direction of the SMA coils. In this mechanism, the pins are kept in position by making use of magnets. When the SMA wire is heated, the force created by the SMA wire pulls the pin to the other position.

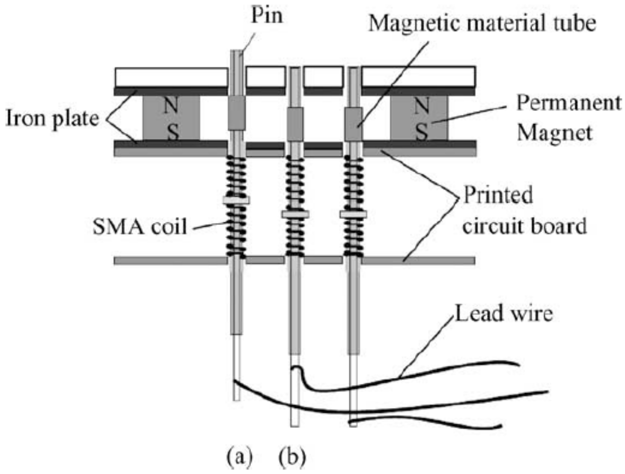


Figure 15: Braille with SMA coils (Haga, 2004)

SMA in bendable tube

Figure 16 shows a tube which can be placed into complex shapes adjusted to a certain environment. The SMA wires providing the pulling force at the end of the tube in axial movement while remain the same outer shape of the tube. The tube includes a few layers which makes it possible for the SMA wire to contract through the whole length of the tube. A spring at the end of the tube pulls the wire back when cooling down.

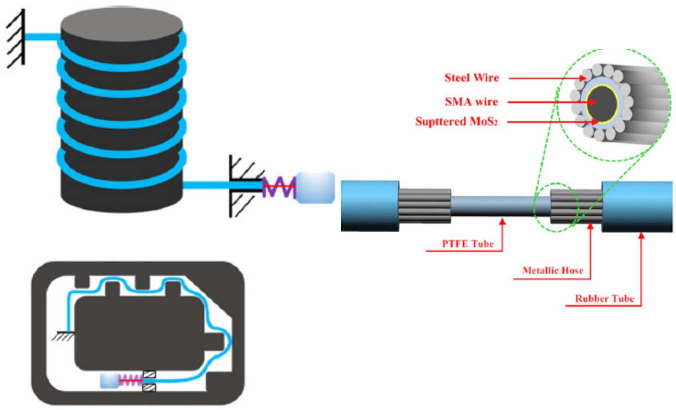


Figure 16: SMA in bendable tube

Linear bending

Many applications make use to create a bending movement by making the SMA wire contract and using a hinge. By using more wires at the same time, a relative high force can be realized. This makes it possible to create a gripper, robot hand, orthosis or prosthesis or a walking robot.

Gripper

The hand shown in figure 17 makes use of multiple SMA wires. In this model, a grip force of 31N is realized using 7 strands of 0.15mm in diameter flexinol wire. The SMA wires are placed before the fingers which bends by making use of a hinge to keep the wire into a straight shape. DIfferent concepts of prosthesis and orthosis are developed by making use of this mechanism with slight differences.

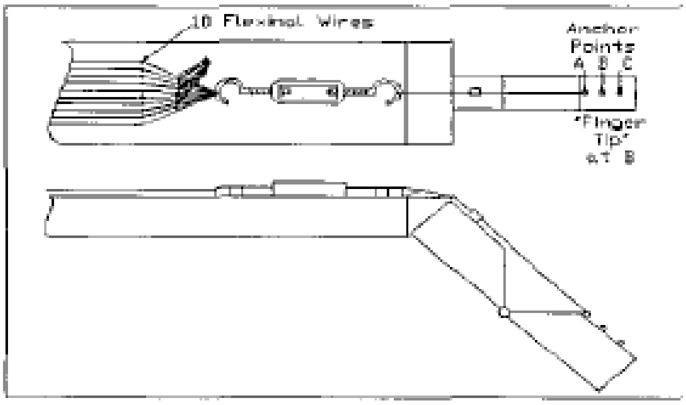


Figure 17: Gripper Dutah and Chua (2003)

Peristaltic movement

By making of SMA wires wrapped around a polymer tube, a soft robotic worm can be created which can move forward. By alternating heating and cooling different areas, it is able to crawl forward. By adding soft component, the worm can withstand high impact forces and able to explore hard to reach places.

Figure 18: Peristaltic movement

Conclusion

Different movements can be created using the same SMA wire. Another interesting thing to see are the different solutions how to keep a mechanism in its placed when the wires cool down. There is performed a lot of research to orthoses, prostheses and active endoscopes. Because of the interest and multiple innovations within these application fields, the potential of the different applications will be examined in the next chapter. The rest of the explained applications will be used as input and inspiration to brainstorm for new ideas. In Appendix H the different found mechanisms are simplified to the basic mechanisms. This gives a clear overview of what the possibilities are.

Search areas

During the search for interesting applications which make use of SMA wires, different examples have been found to create a orthosis, prosthesis and active endoscopes. In this chapter, these different application fields will be further examined including competitive technologies. Each search area will start by an explanation about the functions which need to be fulfilled. Current technologies being used in the search areas will be explained. The role of SMA will be discussed at the end of each search area.

Prosthesis/Orthosis

Because most research is performed to arm prostheses, the focus of this subchapter is an arm prosthesis. The perfect prosthesis needs to be lightweight with a low complexity and a small volume is desired. A prosthesis is used around 130.000 times a yeas. (Luchetti, 2015) A normal hand can open in around ⅛ of a second. Opening a hand in ½ of a second is a experienced as sufficient. (Plettenburg, 2017) The user needs to be able to control the prosthesis against a low effort.

Figure 19:Michelangelo hand

Competitive Technologies

Prosthesis can be divided between active and passive prosthesis. Passive prosthesis needs to be controlled by (the other) hand. Active prosthesis are body or (myo) electrically powered. It is controlled by signals from the brain. Most well known electrical products are the Michelangelo hand and the Bebionic see **Figure 19**. Electrically driven prostheses offer a lot of functionalities. Multiple grip patterns can be chosen. It can make daily dedicated task possible to perform, like cooking and picking of objects. The battery last for about 20 hours. The disadvantages are a high price, relative high weight of around 500-700 grams and a slow cycle time.

Figure 20: Body powered prosthesis

Body powered prosthesis weigh between 400 and 450 grams **figure 20**. The hand or hook can be controlled by moving the shoulders. Users show fatigue symptoms during the day and it requires some practice to control the prosthesis. Besides, straps around the upper body can be visual through the clothes. Another technology linked to prosthesis is air-compression. A number of scientific papers identify possible advantages of using a pneumatic of using a pneumatic limb prosthesis. A pneumatic prosthesis could overcome some limitations of electrical prosthesis, regarding the volume, slow cycle time, volume and weigth.

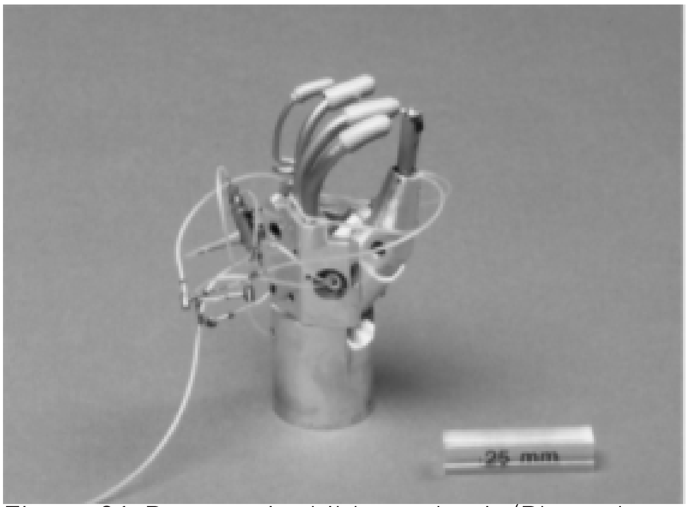


Figure 21: Pneumatic child prosthesis (Plettenburg, 2002)

It can be operated by a small gas container. (Plettenburg, 2002). **Fig 21**

SMA as Prosthesis
Despite all innovation within the market of prosthesis, still many limitations needs to be overcome to create the perfect prosthesis. SMA wires can possibly solve some of the problems. It is lightweight, operates silently, has a extremely low volume, can be deployed with a simple current and can be used against low costs. Unfortunately, it has some serious disadvantages. SMAs have a slow cycle frequency. A concept of a SMA actuated gripper shows a cycle time of 6.28 seconds and very high power supply to be able deliver a force of 21N with the power of 160W (Dutta and Chua, 2003). Because of high required force, many thick SMA wires are required. This would need a large battery with high weight and large volume. The assumption can be made even when optimizing this concept, no realistic hand can be created using SMA wires without the use of a large and heavy battery. The assumption can be made that the limitations will apply to orthosis too. Current alternatives are the better choice

Minimal invasive surgery

Some examples of active endoscopes using SMA wires have been showed. A bending tube actuated by SMA wires can bend in different directions. Active endoscopes are being part of minimal invasive surgery. Minimal invasive surgery is to create less damage to the body than with open surgery. This is in general associated with less pain, shorter hospital stay and fewer complications. (Myo Clinic)

To minimize the size of incision during surgery, the diameter of endoscopic equipment is important. A diameter of 3mm is the optimum. Equipment needs to be reliable, it needs to react fast and a high accuracy is important. Most common minimal invasive equipment make use of a rigid steel thin tube which can be controlled manually from outside the body. A clamp or camera can be attached at the other end, which will enter the body.

Competitive technology
An interesting concept is the HelixFlex. An instrument which can be controlled by hand and is multi steerable. It can bend up to 150° . It has a diameter of 5.8 mm. It is able to create a s-shaped angle. In this way, a surgeon can reach more complex places inside the body form one incision. The top of the HelixFlex which is connected by steel wires bends in a desired direction. The downside of the product at this moment is the high costs. The product can't be use twice because it is to hard to clean. See **figure 22**.

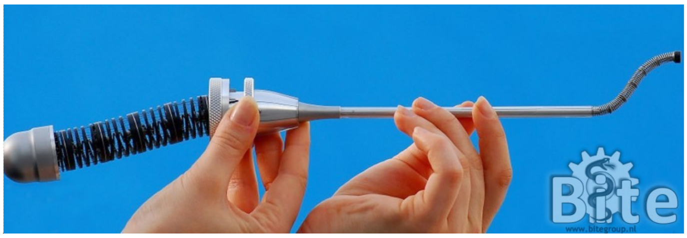


Figure 22: HelixFlex

SMA as minimal invasive surgery
With minimal invasive surgery, the surgeon controls the equipment by hand. High precision is hereby very important. Possibly, robots can (partly) replace the role of the surgeon in the future. But, a high accuracy is required. Using SMA wires to bend the rube with a camera, light or clamp at the end seems not realistic. SMA wires will not be reliable and accurate enough. Environmental factors like temperature and humidity will have too much influence.

Soft robotics

Soft robotics can be seen as robotics containing a soft or flexible body. Because of a soft or flexible body, a soft robotic is better to be able to change to the environment than conventional robotics. A conventional gripper can for instance struggle to handle with varying objects in size, shape and weight. Within the domain of soft robotics, a gripper is the most popular application. Many different types of actuators are identified and explored to use in soft robotics. The rubber flexi device, explained in **Chapter (SMA Applications),** could possibly be offer a better alternative than other actuating technologies. First, an overview of competing technologies will be analyzed.

Competitive technologies

Pneumatics

Pneumatic system use compressible gas/air as medium for actuation. Due to the light weight, small size and relative high payload ratio, makes it interesting to use as soft robotic. A pneumatic soft gripper can actuate in less than a second. A disadvantage is the need of a pump or compressor. Another option would be of using a gas cartridge. The delivered force can be adjusted depending on a varying air pressure. The downside is of changing the air pressure, a heavy and large pressure regulator has to be used. There are different types of actuators working with air pressure.

Materialise gripper:
The inner wall of this gripper is very sensitive and causes the fingers to curve inwards when the pressure is increased, it can also be 3D printed. See **Figure 23.**

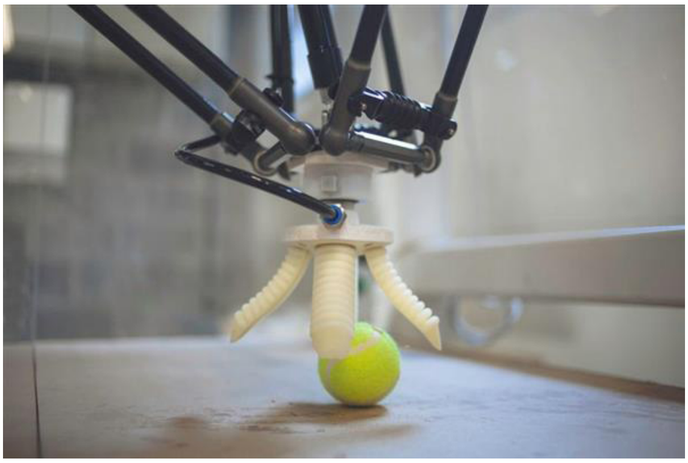


Figure 23: Materialise gripper

PneuNets:
Channels and chambers inside a elastomer. By pressurizing the chambers, they inflate and create motion. The motion is dependent on the geometry of the chambers and material of the walls. Expansion occurs in the least stiff regions. See **figure 24.**

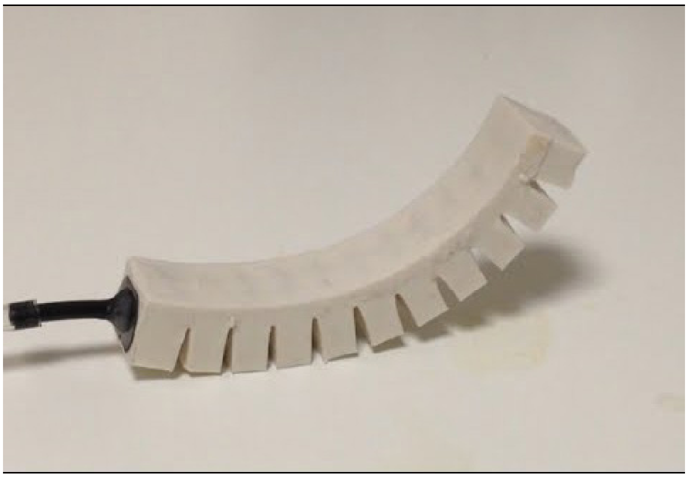


Figure 24: PneuNets

Fiber reinforced actuator:
Elastomer bladder wrapped with in extensive reinforcements. Placing a inextensible fiber on one side make to air expand the balloon to the other side and radial, making the part bend rotational. See **figure 25.**

Figure 25:Fiber reinforced actuator

Pneumatic artificial Muscles (PAM):
Mckibben air muscles are invented in the 1950s. An inflatable inner tube is placed inside a braised mesh, clamped at both ends. The radial expansion results in linear contraction. It can contract up to 75% of its relaxed length. By using two coupled PAMs, a bidirectional movement can be created. See **figure 26.**

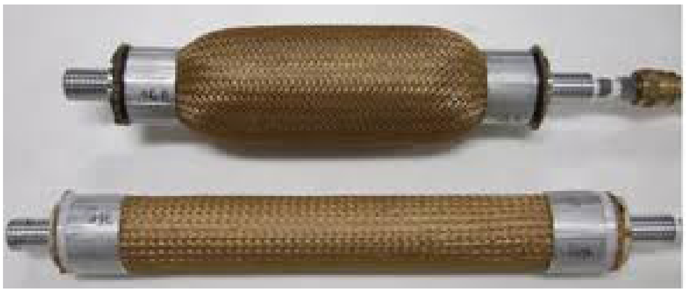


Figure 26: PAM

Electroactive polymers:
EAPs is a large family of polymers which can be used as actuator. It can be categorized into two groups. Ionic and electronic EAPs. Ionic EAPs are driven by the diffusion of ions. Most popular polymer is the Ionic polymer-metal composite (IPMC). Electronic EAPs are driven by an electric field. Dielectric elastomers (DEs) are most popular as Electronic EAP. Both will be more elaborated on.

IPCM actuators consists of a solvent swollen ion-exchange polymer membrane coated with a thin metallic layer. There are some variants of polymer layers, including Nafion® or Flemion® from Dupont™) Driving a voltage of 1-5V make the material swell on one side of the film, and contract on the other side. This results in a bending actuation. (Romansanta et al, 2015) For an example see **figure 28.**

Figure 28: IPCM actuator

IPCM actuators have a strain up to 3%. Together with hydration requirements those are the main drawbacks of the material. Another problem is high costs which makes it at this time difficult to make actual applications with it. IPMCs is seen as most suitable to use as actuator to create biomimetic locomotion and as a microgripper. (Xuan-Lun Wanga et al, 2007). It can last over a million cycles which is high in comparison with the other soft robotic actuators. It can react in less than 0.1 seconds. (Palmer et al, 2014).

DEs can induce several levels of strains, but they do require a large electrical field around 100V/mum. DEs are relative cheap, lightweight, high energy density >8MJ/m3 and a low cycle hysteresis. (Romansanta, 2015) See **figure 29**.

Figure 29: DE actuator

SMA in soft robotics
The rubber tube ''flexi device has a smaller volume than the shown technologies. It makes use of a thin tube which can have advantages in comparison with a film the polymers make use of. Besides, it has a very high energy density. A possible lasting problem could be the slow cycle frequency and high power supply when acting with high forces. By placing the wires inside a tube is not an efficient use of the available pull force. But placing multiple SMA wires inside the tube creates a lot of design freedom.

Conclusion

An important quality of SMA wires is that it is very lightweight but still able to deliver a relative high force. But, using SMA wires in heavy and large applications is not realistic. It requires to much energy consumption and the cycle frequency will drop when using thick wires. Soft robotics make use of small forces and the weight is of great importance. This would make the implementation of SMA wires in soft robotics very interesting.

Conclusion

SMAs have unique properties. It is very lightweight, has a very low volume and can lift a thousand times its own weight by driving a simple current through. It can deliver enough force to actuate a gripper, or rotate a car mirror in less than a second. The low volume, lightweight and simple control makes it very interesting to create a product or mechanism including multiple SMA wires acting as actuators. The wires can work together to create multiple movements in different directions at the same time by controlling the wires separately by driving through a simple current. It can be used as an actuator in a flexible and soft device and makes no sound. It is corrosion resistant and offers a lot of design freedom because of the available variety in material properties. Because of the high actuation density energy, the material can pull high forces with only a small amount of strain, which plays along with the small volume of the SMA used as actuator. But besides all the advantages the material offers, it has some limitations as well. These limitations makes it hard to find a suited application for commercial use. This can be seen by the lack in amount of applications making use of SMA wires brought to the market.

The material has a relative long cycle time because of the cooling time, specially when working with thick wires. The cooling time depends mostly on the thickness of the wire. By selecting a wire with a high activation temperature, the cooling time decreases. Besides, different cooling techniques can be applied. By heating the wire with impulse joule heating, the wire can be heated in a fraction of a second. Because the wire needs to be heated to be able to contract, it is not the most energy efficient actuator. Therefore, using the material to lift a high amount of force, a portable application will need a large battery. This is many cases with for instance a prosthetic not realistic. The material can only contract for about 4% of its length to remain a long lifetime. Flexinol is fabricated and trained to keep its contracted shape when it cools down. A bias force is needed to elongate it back to its original length. To keep the wire contacted for a longer period without using energy, a friction pad or latching mechanism is needed. An overview of the properties of SMA actuator wires is shown in **figure 30.**

The material needs to be handled with care, because over stretching or overheating the wire will drastically decrease the lifetime of the material. Therefore, the biggest challenge of this assignment is to make efficient use of the advantages and find an application which is not eliminated by the limitations of the material. Another interesting challenge is to find a way to overcome limitations by making smart use of other materials or technologies. Possibly, a mechanism actuated by SMA wires can contribute to another technology.

Figure 30: Potentials of SMA and Flexi device

Synthesis

This phase serves to combine and process all knowledge gathered during the analysis phase to be translated into a final design goal. A brainstorm is conducted with input based on the analysis phase. The ideas as outcome are used as inspiration and translated into different design directions. A final design direction is chosen. A more in depth view of the design direction is used to be able to formula a design brief. This explains the problem definition and design goal. The synthesis will end with a list of requirements. This list of requirement will be used to compare the final concept with its competitors and to reflect final outcome.

Brainstorm Session

A brainstorm session is held together with 5 IDE master student active in the three different IDE Masters. The goal of this brainstorm session is to come up with interesting ideas to make use of the advantages SMA wires offer when used as actuator.

Figure 31: Brainstorm session

The advantages SMAs wires offer are used as themes to brainstorm with. The first part of the session is performed without telling the participant in detail what the project is about. The first step was to come up with associations in a group to inspire each other and create a wide view on each theme. Next, the participant were asked to write down products which don't need these properties and product which need or would benefit from it.

After the first part, some prototypes of different mechanism are shown to the participants together with more information about SMAs and what is potentials are.

All ideas from the brainstorm session have been reviewed and used as inspiration to personally add more ideas. A selection of most inspirational and promising ideas have been clustered and are shown in **Appendix I.** Most interesting clusters will be explained in this chapter.

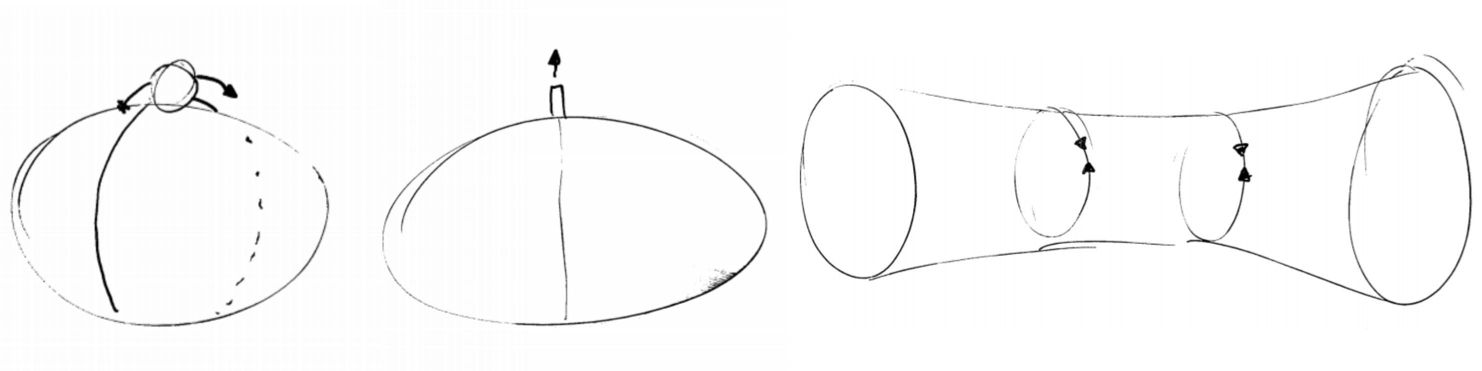


Figure 32: Inflatable objects A,B,C

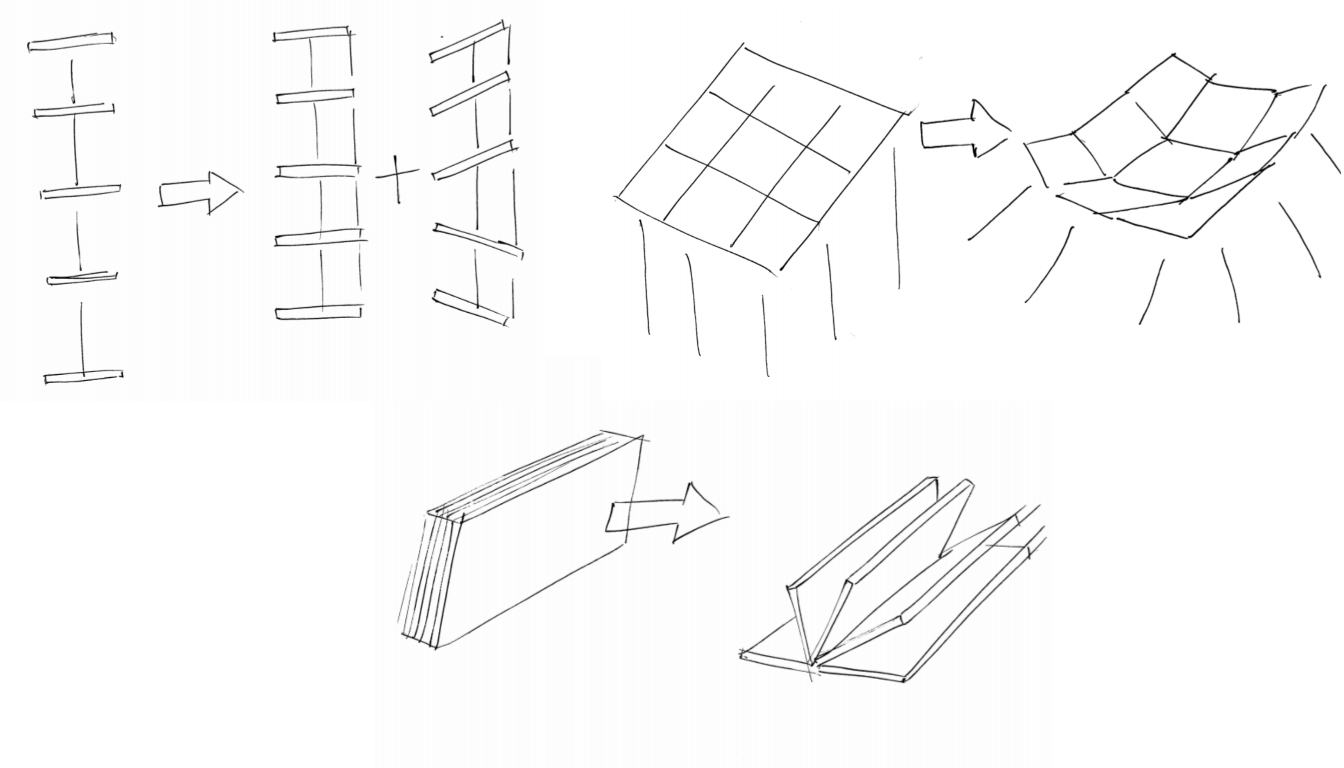


Figure 33: Complex mechanisms A,B,C

Inflatable objects

SMAs can work together with an inflatable object in different ways. The wires can be placed around the object or placed inside the object with different purposes.

By placing an SMA wire around an inflatable object, it can change position of a part placed on the surface, see figure 32A. Instead of placing the wire around it, a SMA wire can also be placed inside the object, see figure 32B. By wrapping multiple circles of SMA wire around an inflatable object, the shape can be changed and even movement can be created. Using a flexible material wrapped around with a SMA wire, only a small contraction of the SMA wire can result in large displacements of the object at another area of the object, see figure 33C

Conclusion

Using SMA wires together with inflatable objects is something completely new. Besides using SMA wires adjusting the shape of an inflated objects. There might be more interesting possibilities in a collaboration between pneumatics and SMA wires.

Complex Mechanisms

By using multiple separately actuated parts, more complex mechanisms can be created. Because the wires can be controlled by a simple current deploy, a lot of space and volume can be saved. Some different ideas will be explained.

By actuating different shelves, a smart luxaflex can be created. The different shelves can make patterns, adjust to the sunlight during the day or season in general. The position between the shelves can be adjusted, or the angle of the shelves. By using SMA wires, not separate expensive, large, heavy and noisy motors need to be used, see figure 33A. Another idea is to create a lamp made out of separate part., see Figure 33B By using multiple separate parts, a product can be created which folds open. In this way, a product can be created which can change shape easily and with light weight, see figure 33C

Conclusion

To create displacement, an actuator is needed. By using a motor, each part which needs to be controlled separately and needs its own motor. Because SMA wires can be supplied by a current very simply, it is possible to create a product with many parts moving separately, even at the same time in different directions. In this way, a unique product can be created.

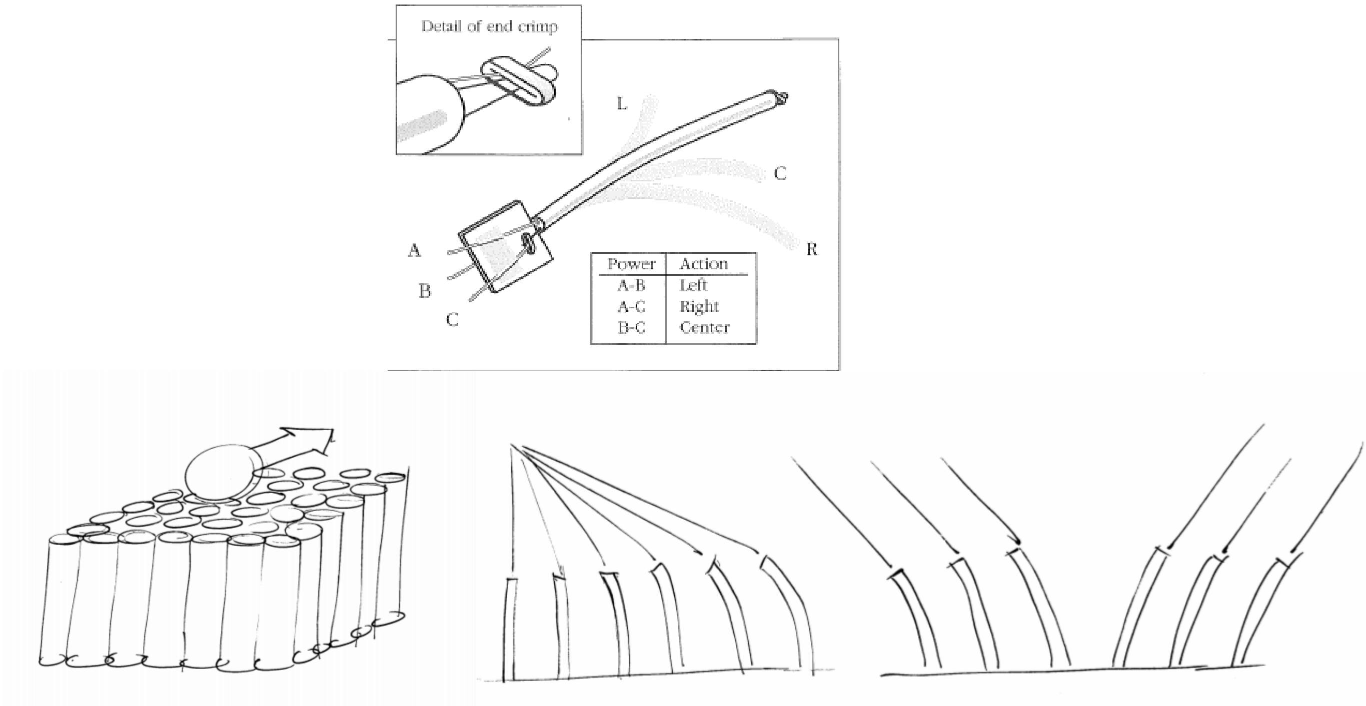


Figure 34: Rubber tube "Flexi" device A,B,C

Rubber tube Flexi Device

A idea which is already explained in this report is a gripper making use of multiple flexible tube actuated by SMA wires. But using multiple flexible tube, other applications can be created. Most interesting found ideas will be explained. Shine light through the tubes in different direction with multiple lights, or all to the same spot. In this way, an interactive wall, or roof can be created by adding sensors, see **figure 34B**. Using multiple tubes acting separately, different light colors and intensities can be created. Sensors can track people walking by or react on sound for instance.

Another option would be to make a lightweight ball move on top of tubes in a certain direction. By drawing a line on a tablet a path of the ball can be determined. Another idea is to make the ball follow your hand, see **figure 34C**.

Conclusion

Because the rubber tube flexi device can be controlled in a simple way it is possible to make a lot of them work together. In this way, large interactive set-ups can be created.

Design direction: Pneumatic Soft Robotics

As explained, a brainstorm session is performed to come up with ideas in different directions. The ideas are clustered and the most promising directions have been compared with each other on different criteria, see **Appendix: J**.

The different directions are evaluated on several criteria. The ideas are eveluated on their potential by making use of the advantages SMAs have. Hereby, the limitations of SMAs are taken into account as well. Also the possibilities in design, role as a IPD student and functionality of the directions are taken into account. At the end, the overall potential is evaluated based on gathered knowledge during the analysis phase together with personal preference as a designer.

From the different clusters as outcome of the brainstorm session, combining SMA wires with inflatable objects seems interesting because the potential and to be able to create something unique. By making use of SMA wires to change the shape of an inflatable object, the wires can adjust the shape to create a displacement or movement. During a discussion with the supervisory team, this direction is developed in something even more interesting:

Make use of SMA wires to create valves for pneumatic soft robotics.

By taking a step back to the analysis phase, pneumatics have been explained as popular and most commercialized soft robotics. It can deliver high performances in comparison with the other technologies. But as explained before, it has some limitations. By creating SMA actuated valves, the limitations can be solved. Pneumatic soft robotics like a pneumatic robot hand for example, is complex to control. It includes multiple bellows which needs to e controlled individually. Most ideal would be to place valves which control the air from inside the hand.

Current solutions make use of solenoid valves which is expensive, has too much volume and is heavy. SMA actuator wires have the potential to regulate the bending speed of the fingers and divide the incoming air and at the same time integrated inside the body of the hand. It can be controlled in a simple way by only driving a current through the wires. By changing the current can determine the bending speed of the fingers. In this way, it makes use of the advantage SMA wires offer to be able to create a more complex mechanism using multiple actuators but keeping the design simple.

The final choice of design direction is based on the ideas developed from the analysis phase together with the conclusions of the analysis phase. The advantages SMAs offer, solve the limitations of a pneumatic actuator. It is a unique combination of two interesting technologies.

Pneumatic Soft Robotics

This project focuses specially on the control of pneumatic soft robotics by making use of a SMA actuated valve. This chapter will focus on control, types of fabrication, type of actuation and air power supply. This is because these have large influence on the project. From the results, design brief is formulated.

Fabrication

There are different ways to create the body of a soft robotic. Most ideal production process is one which can be realized in a short amount of time and easy integrated with embedded parts, like the SMA wires and a bias-spring. Another important thing is that the body needs to be airtight.

Elastomer casting

An elastomer is poured into a mold. This mold can be made by 3D printing. In this way, air chambers can be created. It is possible to fabricate multiple parts and assemble them together afterwards, and still make it airtight. In this way, making smart use of the mold, different object can be embedded. The air source in form of a tube can be inserted afterwards by first inserting a metal rod and then inserting a tube around it and exerting the metal rod afterwards. By using a mold, it is possible to create a Pneu-net, this type of actuator is explained in **Chapter: Search Areas: soft robotics.**

3D printing

By 3D printing an object, an important thing to take into account is the removal of support material inside the air chambers afterwards. Using Polyjet all support material can be removed by placing it inside a special bath. Most ideal situation would be printing an object integrated with all control parts at the same time. Also, printing two materials including rigid and flexible material at the same time would be possible. 3D printing is a relative new technique which is still being improved. The assumption can be made that material properties will be improved in the nearby future. By using 3D printing a materialse gripper design can be realized. It is explained in **Chapter: Search Areas: soft robotics.**

Pneumatic artificial muscle

Consist of more standard parts. The inflatable part consist of a balloon. This can be off the shelf or self molded. Either, no complex shape is needed. For the mesh around it and connections at both ends, standard parts can be used. A pneumatic artificial muscle is less suited to use inside a robotic hand or gripper, because it needs a relative large volume.

Actuators

There are different options of actuators to create a bending movement using air pressure. In soft robotics, this is done by using inflatable air chambers which translate a shape change into a movement. It is important to use an actuator which can generate enough grip force, have a low volume and create a high bending angle. The different actuators have already been explained in **Chapter Search areas: Soft robotics**. The different actuators are: Materialise gripper, Pneu-nets, Fiber reinforced actuator and PAM.

Air power supply

There are different options to supply a pneumatic soft robotic from air pressure. Each option has its advantages and limitations. The ideal power source would make no sound, can be placed inside a soft robotic and can create a high grip force.

Compressor

Not able to place inside the soft robotic because of weight, size, noise and power supply. But connecting it externally by tubes is possible. It is relative cheap and can deliver a strong actuation from a distance to a lightweight product. It gives a constant pressure.

Micropump

A micro-pump can be placed inside a soft robot, but it has some weight and volume. It works with small voltage and can deliver enough air pressure to supply most of the soft robotics. But, It is noisy and expensive.

Pressurized gas cartridge

By using a pressurized gas cartridge, there is no need for electronics. It is silent and small enough to place inside a robot. But, it's a finite power supply. How higher the needed pressure, the bigger the cartridge. Pressurized gas cartridges work with a high air pressure. A pressure regulator has to be used to make it suited to work with low air pressure supplied pneumatic soft robotics.

Control

The flow speed of the air determines the bending speed of the bellows This can be realized by using a solenoid valve. At the same time, it can split the air into two ways. In this way it can also serve as supplying multiple chambers with air. These valves can be placed close or attached to a soft robotic body, but it has some weight and volume which make it hard to integrate inside a body.

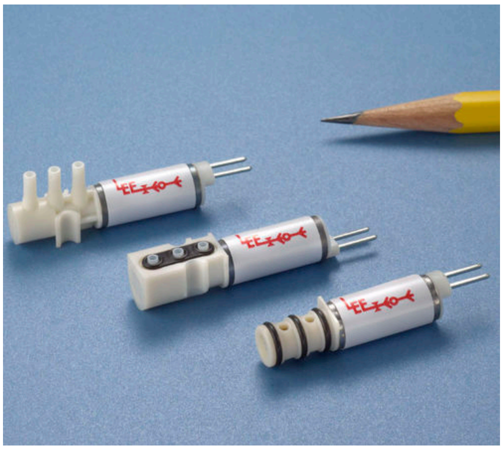
During this project, a visit to Festo took place. This company is amongst other things specialized in pneumatic control systems. According Jan Koudijzer, manager customer solutions at Festo BV, the requirements of these solenoid valves are mainly focusing on the reliability, cycle time and durability. This is because current valves are used in factories which is mass production . The valves are placed inside large and heavy robots, with therefore less importance to the total weight and volume. Therefore, not many lightweight and low volume valves are available on the market. However, soft robotics is a relative new field with the need for lightweight and low volume valves. It is expected to grow in the future, and an interesting example is collaborative robots.

Despite Fest have no miniature valves, some interesting miniature valves have been found. The different valves are explained on the next page.

The valves are evaluated on multiple functions:
Weight, volume, integration, control flow rate, pressure, flow rate, power supply and price. The functions are explained together with the relevance to the design goal of this assignment which values are desired. More details about functionalities of the valves are explained in **Appendix K**.

Weight:	47 grams
Volume:	46*17.5*17.5mm
Integration:	no
Control flow rate:	No
Pressure:	7 bar
Flow rate:	19l/m
Power	2W
Price:	44$

Figure 35: Asco: Miniature solenoid valve (Asco)

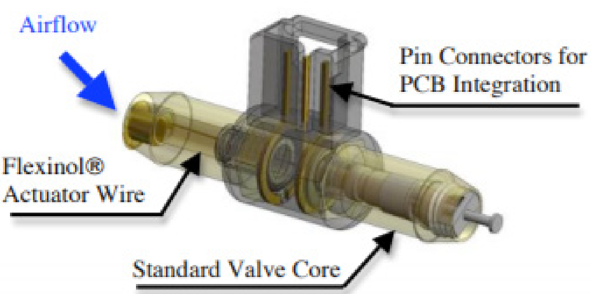


Weight:	4.5 grams
Volume:	7.5*7.5*34 mm
Integration:	no
Control flow rate:	No
Pressure:	2 bar
Flow rate:	6 l/m
Power	0.5 W
Price:	12$

Figure 36: Lee: Miniature solenoid valve (Lee Company)

Weight:	63 grams
Volume:	16.5*17*45.3 mm
Integration:	no
Control flow rate:	Yes
Pressure:	8 bar
Flow rate:	20 l/m
Power	2 W
Price:	12-150$

Figure 37: VSO Max HP proportional valve (Parker)



Weight:	4.5 grams
Volume:	7.5*7.5*34 mm
Integration:	no
Control flow rate:	Yes
Pressure:	7 bar
Flow rate:	20 l/m
Power	0.5 W
Price:	30$

Figure 38: Dynalloy SMA proportional valve (Dynalloy Inc)

Figure 35 shows a miniature valve with relative high weight. Supplying a whole hand would result in 235 grams. it has an acceptable volume, but because each valves needs to be connected with tubes, the total volume will increase which makes it also hard to integrate into the body of a soft robotic. The flow rate can not be controlled. Being able to supply 7 bar makes it an expensive valve.

Figure 36 shows a miniature valve with very low weight. Supplying a whole hand would result in 22.5 grams. It has an very small, but because each valves needs to be connected with tubes, the total volume will increase which makes it also hard to integrate into the body of a soft robotic. The flow rate can not be controlled. The small size makes it able to supply up to 2 bar which is very acceptable but the flow rate is slow. It is also quit cheap.

Figure 37 shows a miniature valve with high weight. Supplying a whole hand would result in 630 grams. This is because it only available in a two-way variant. To control a bellow, the two are needed. The volume of a single valve is acceptable, but because each valves needs to be connected (twice) with tubes, the total volume will increase which makes it also hard to integrate into the body of a soft robotic. Together with the high weight integration into a soft robotic is not realistic. This valve is able to change the flow rate by changing the current. It can supply a high air-pressure. Because of the good functionalities is might be an expensive valve.

Figure 38 shows a miniature valve making use of flexinol wires. This makes it very lightweight and a low volume. It is a two-way valves which requires 2 valves to control one bellow. Connecting all the valve will increase the total volume. By using flexinol wires, a high pressure can be supplied and the flow rate can be controlled. The flow rate is high and requires not a large current. This makes it an interesting valve.

Because all parts are separate part, they need to be connected to a bellow. Not only the tubes but the connections take space. This take place and can make it a challenge to place multiple valve into a certain shape of a soft robotic.

Conclusion

By 3D printing the body of a pneumatic soft robotic, a valve could be integrated into the design. This makes it interesting to make use of 3D printing. It appears there are actually already some examples of miniature valves. But the valve being able to regulate the flow rate have larger dimensions and a significant higher weight. Besides, only 2-way proportional miniature valves a are available. Therefore, two valves would be needed control a bellow. All valves have a standard design and the valves need to be connected to each other and the bellow require extra space. These conclusions show great opportunities in creating a integrated 3D printed valve making use of SMA wires.

Design Brief

"Create a fully integrated control system in 3D printed pneumatic soft robotics, adaptable to any desired design parameter."

Problem Definition

Pneumatic soft robotics supplied by air pressure are most often actuated by a compressor or air-pump. To control multiple air-chambers at the same time, expensive, heavy and parts with large volume like solenoid valves and air pressure regulators are used. Solenoid valves are used to divide the air supply to the different air chambers to make it able to use only one compressor or air-pump. Solenoid valves can divide the air, but can also influence the flow rate through the valve. Solenoid valves making use of only dividing the air can have a small volume and low weight, but solenoid valves to regulate the flow rate (proportional solenoid valves) have a significant larger volume and weight.

Placing proportional solenoid valves near or attached to the body is undesirable because of the weight, volume and complexity. Not only the volume of the valve itself takes space, but also connecting the valves takes place. Another option would be to supply each chamber with a separate tube.

Air pressure regulators can control the air pressure which can be used to for instance to determine the bending angle on a pneumatic finger.

The control of pneumatic soft robotics has opportunities to be improved. Specially products with the need of low weight and volume, the ability to change the flow rate at any time and to create more simplicity by using less devices and parts. By integrating the control system into the body of the pneumatic soft robotics can significantly decrease the total volume, complexity and costs. Another important advantage is the opportunity to adjust the control system to any desired shape integrated within the body on an pneumatic soft robotic. Besides, connections between parts increase the chance of air-leakage.

Goal of the project

The design goal of this graduation project is to control pneumatic soft robotics consisting of multiple air bellows. By making use of a valve which is integrated into the 3D printed body of a soft robotic, SMA wires are used to control multiple chambers by supplying the chambers when desired and eventually control the flow rate through the valve. By supplying the wires with short and small currents the valves will open. By varying the amount of current, the bending speed of a bellow can be controlled. The intention is to create the foundation of a tool to be able to control any kind of pneumatic soft robotic with different demands regarding the total volume air pressure, required flow rates and orientation of the different bellows.

By making use of SMA based valves, the weight, total volume, costs and complexity of soft robotic can be drastically decreased compared to current solutions. The future control system will not only divide the air to the different bellows, but is able to regulate the time it takes to bend the bellows.

Two case studies are formulated to work towards the design goal. The case studies have different orientation of the bellows resulting in a different design. Both outcomes can be evaluated and compared at the end.

Case study1

Soft robotics come in various shapes and bellows. An interesting example making use of multiple bellows is a pneumatic robotic hand. It requires to control 5 separate fingers. By controlling the hand by only one air-tube while controlling all fingers is a challenging but interesting goal. The final demonstrator will consist out of a finger attached to a valve controlling the inflation and deflation of the finger. Hereby, the placement, direction and size of the valve will be taken under consideration. The demonstrator will include only one finger because the assumption can be made by multiplying the design of the demonstrator aligned parallel next to each other will work to control a whole hand. Thereby, this is only the first step in designing a miniature integrated valve actuated by SMA wires. Besides, 3D printing a whole hand is not cheap.

Case study 2

When a working prototype of Case study 1 is proven, a second demonstrator will be designed. This case study is focusing on controlling two bellows separately. A walking robot is chosen to design. The design of the walking robot is based on the multigait (Shepherd et al, 2011) . Because the walking robot has its bellows opposite orientated, instead of parallel aligned next to each other, this would probably have impact on the final design of the valve.

Set-up demonstrator of both case studies

The valves will be supplied by a compressor attached via a tube to the design of the valve. The control will be done manually to be able to test both demonstrators an being able to simply adjust the amount and time of the applied current.

The bellow used for the final demonstrator is able to withstand 0.5-1 bar. Both demonstrators are required to withstand this amount of air pressure. The bellow is shown in **figure 39**. During the prototype phase, the bar is set more optimistically up to 4 bar. The bellow which is able to withstand this amount of air pressure is shown in **figure 40**,

The demonstartors are 3D printed using PolyJet: Rigid material Vero and flexible material Agilus30.

Figure 39: Bellow used in both demonstrators

Figure 40: Bellow used by starting the prototyping

List of requirements

A list of requirements and desires is listed on this page. Both are categorized in different themes: Control, Integration, body, strength and SMA wire

Control

Requirements

- Control mechanism needs to be able to control multiple bellows separately at the same time
- Control mechanism is controlled with only one compressor
- The value of air pressure should be enough to make a bellow bend 180 degrees
- The control mechanism is able to pressurize the fingers up to 1 bar
- Control mechanism is able to regulate both inflation and deflation speed of each bellow separately
-The control mechanism needs to be ale to make the attached bellow bend in less than 0.5 seconds.
- The bellow can be re-inflated 1 second after the bellow is deflated

Desires

- Control mechanism needs to be able to start inflating an air chamber, even before the other air chambers are fully deflated
- Control mechanism needs to be able to close the inlet of air flow when a desired finger position is reached
- The control mechanism is able to pressurize the finger up to 4 bar.
- The control mechanism is able to adjust the inflation speed of the bellow
- As low as possible separately controlled SMA wires are used to control the flow rate to minimize the amount of electric wires and the complexity of the soft robotic

Integration

Requirements

- Tubes, connections and air chambers need to be airtight.
- SMA wires are fixated at both ends in the body of the hand
- Electrical wires are placed inside the hand

Desires

- Mechanism can be reopened/reassembled and remain air-tight when closed again.
- As less as possible extra parts needs to be placed inside the hand
- As less as possible connections to remain air-tight mechanism

Body

Requirements

- The entire control mechanism is placed inside the body of a pneumatic soft robotic
- The weight of the control mechanism needs to be less then the smallest proportional valve available on the market. This is 63 grams.
- The volume of a single valves needs to be smaller than the smallest proportional valve available on the market. This is 16.5*17*45.3 mm (Excluding connections to air-tubes)

Desires

- The weight of the entire valve needs to be as small as possible
- The volume of the control mechanism needs to be as small as possible

Strength
Requirements
- Valve is able to withstand forces which arise due to the air pressure needed to make a finger bend up to 180 degrees
- Control mechanism needs to be able to close the inlet of air flow when the maximum air pressure is reached

Flexinol
Requirements
-Flexinol wires should not exceed its advised contraction length of 4%.
-The activation finish temperature of the Flexinol wires will not be exceeded
-The applied current should not be over 1A to prevent the wire from failure
-The maximum advised pull force of the SMA wire will not be exceeded.

Conceptualization

This phase elaborates on the process of designing the SMA actuated valve. First, a scenario is set to be able to control multiple bellows according case study 1. During the prototyping, the suited spring design and type of SMA are chosen. A prototype overview shows the road towards the final design in a quick overview including the performed tests and important design decisions. The next parts explains this process in more details.

Set-up Scenario

The goal of this project is to control the air supply of a pneumatic soft robotics by using SMA actuated valves. Each bellow will be controlled individually by inflating and deflating the bellows at any desires moment. The result of various valve set-ups will be investigated during the chapter. The final result is shown in figure 41 and is based on case study 1 containing a pneumatic robot hand.

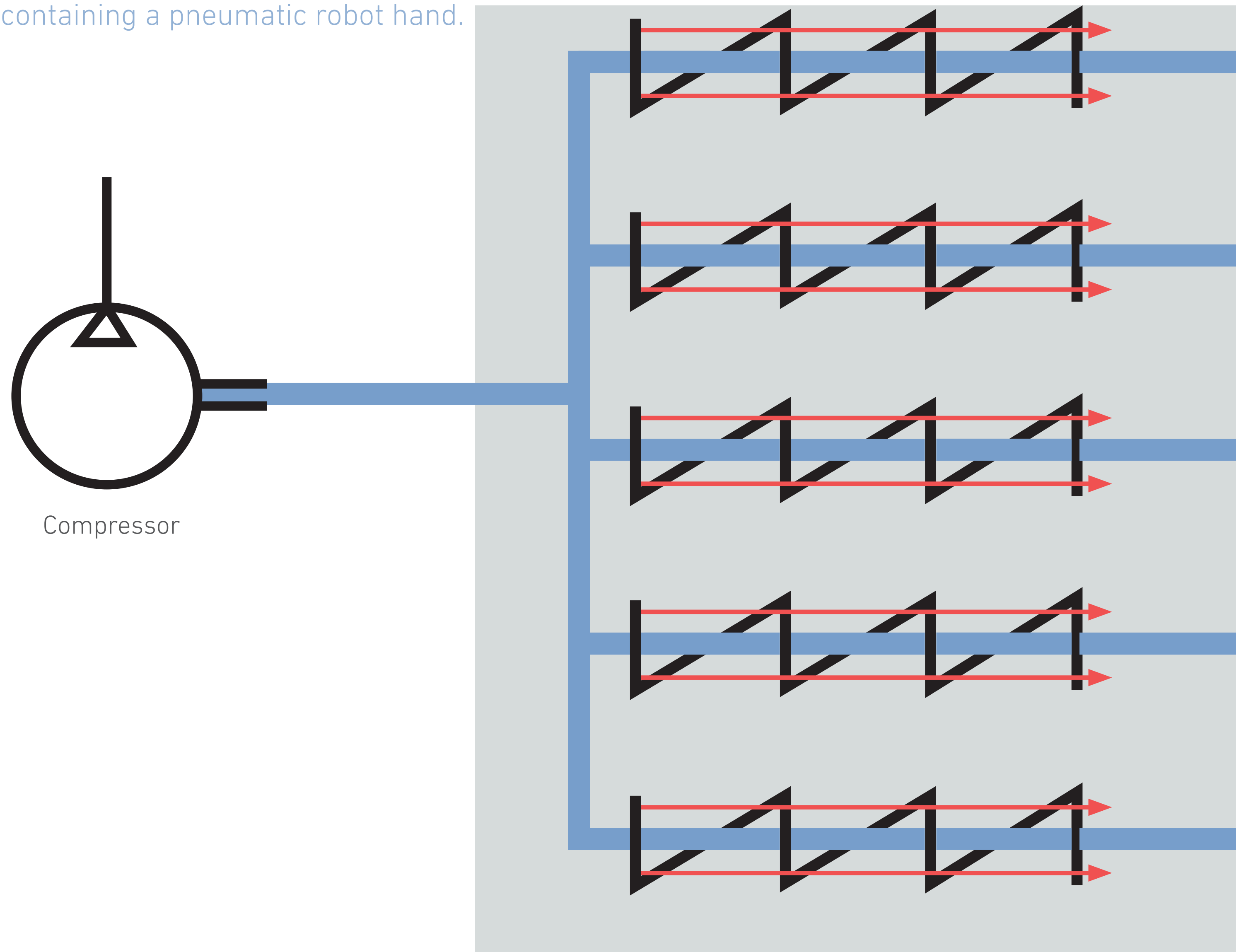
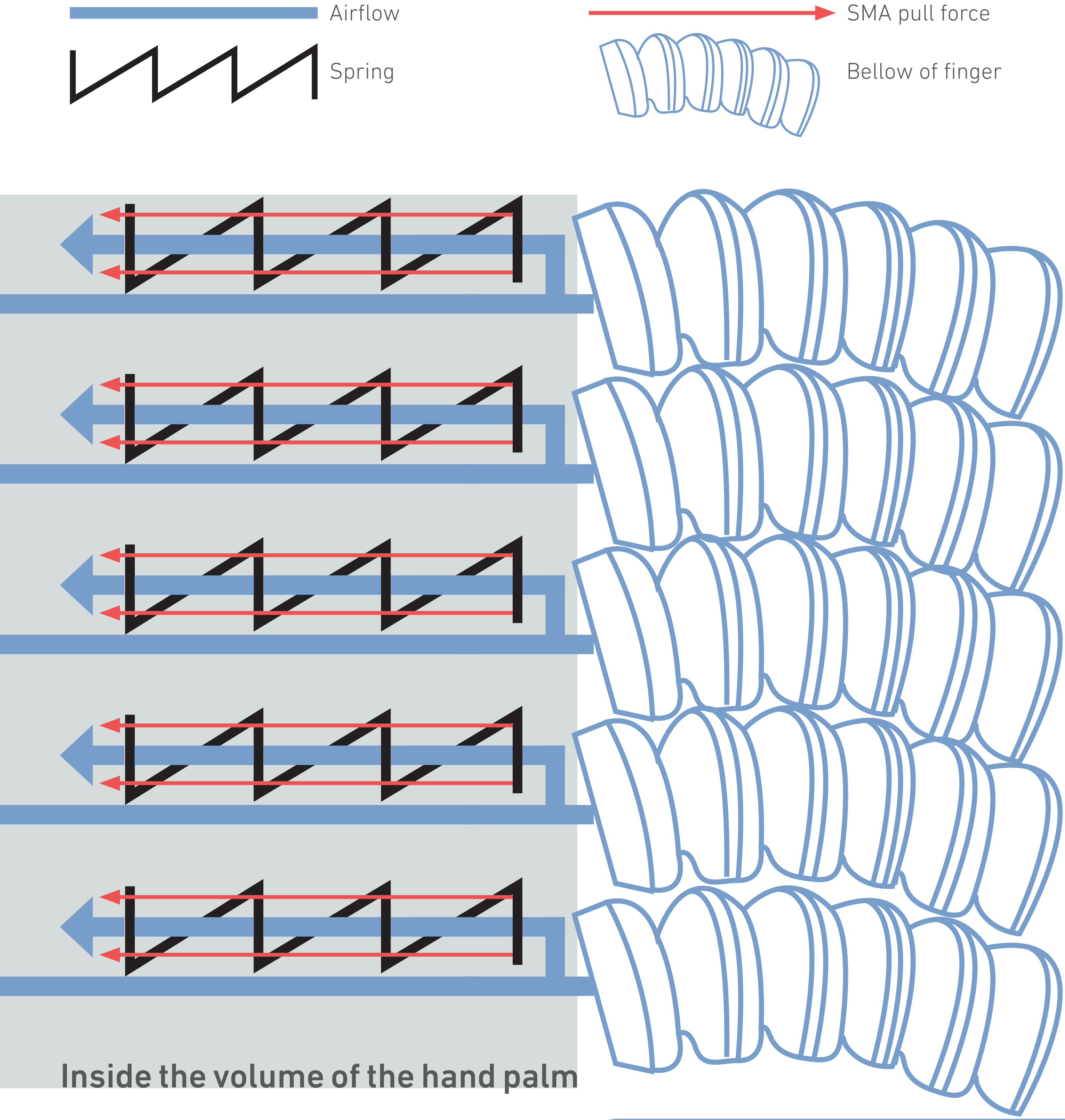


Figure 41: Set-up scenario

Explanation of Set-up

The valves will be integrated inside the 3D printed hand, resulting in different opportunities. First of all, the air will be divided inside the hand by making use of the valves. The flow rate can be adjusted very simple by changing the current to heat the wires. The final set-ups used as input to start the prototyping with is shown in **figure 41**. A compressor will supply the hand with a certain amount of air-pressure. Inside the hand palm, the air is divided. Each finger will contain one valve which is used to inflate the finger and one valve to deflate the finger. Each finger can be controlled completely individual. Even during the short period of a finger being inflated or deflated, another finger can be controlled at any desired moment. At the end, both valves per finger will be integrated into one part.

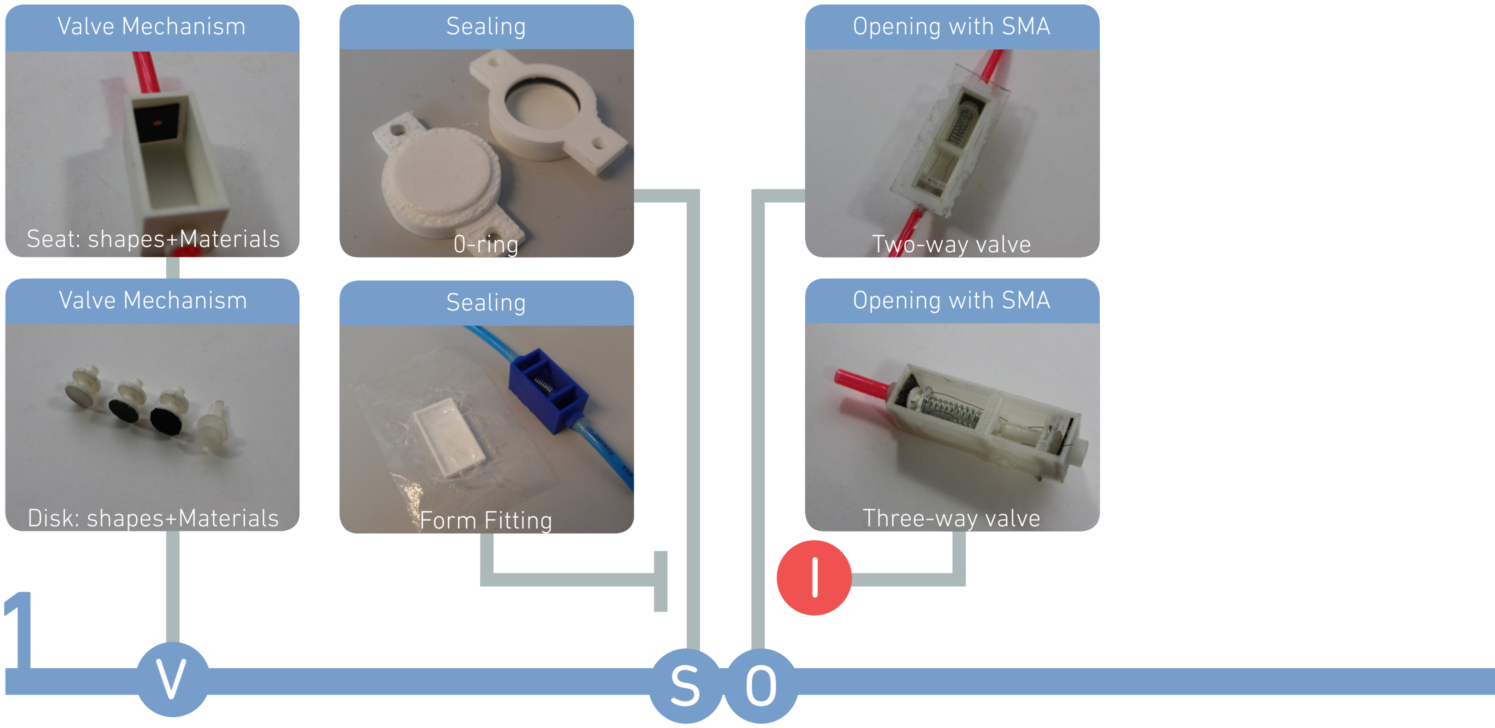


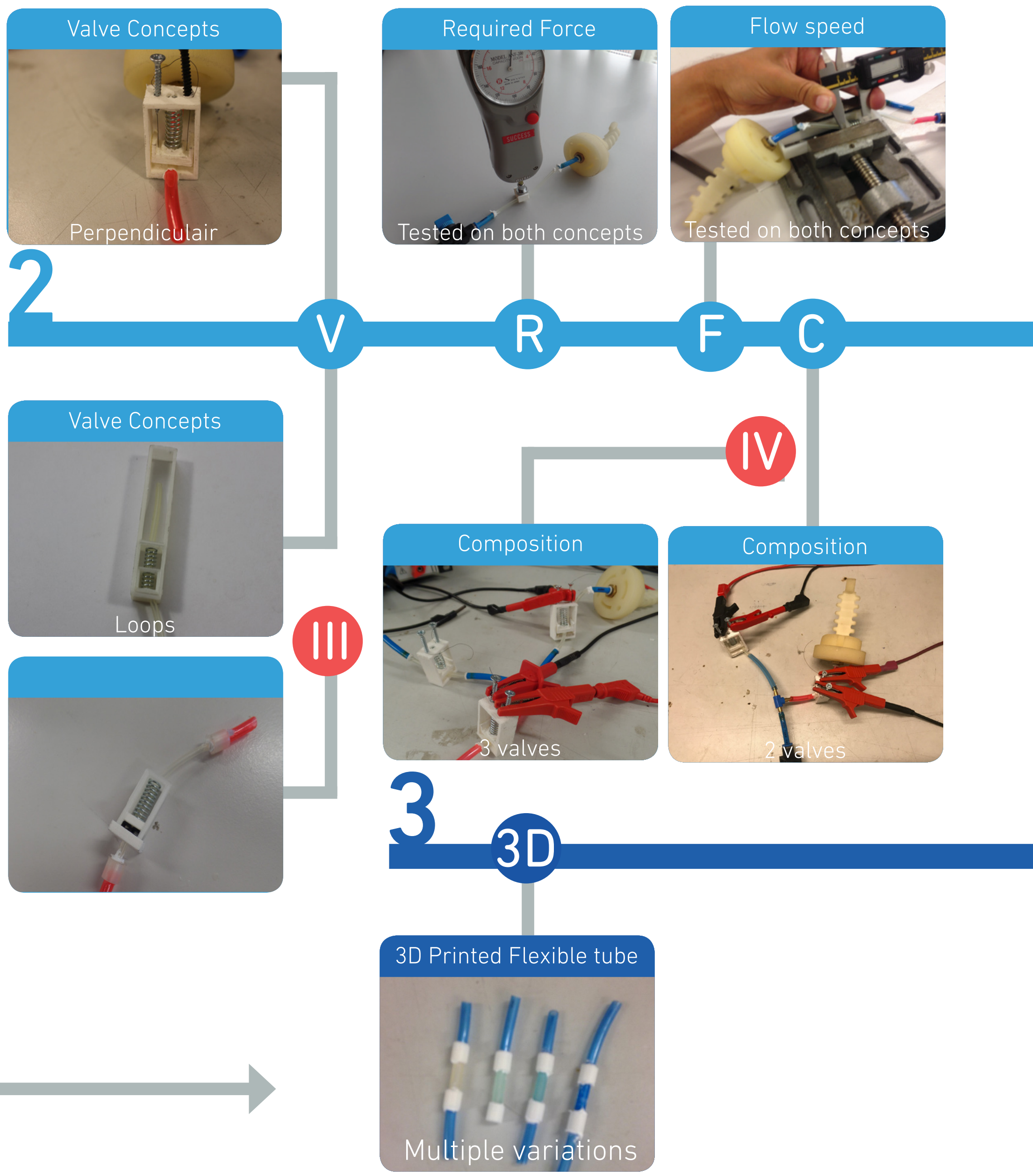
Other set-ups

Appendix L will show the other scenario's which are not chosen to be used. It explains how combination of valves affect the function of the fingers. In particular, how to control the fingers separately and which kind of valves are required.

Conclusion

By using two SMA actuated valves per finger, each finger can be controlled completely separately. All fingers can be controlled by inflation and deflation speed of the fingers. Creating a three-way valve by making use of SMA wires is not realistic This is concluded from the prototype phase. By making use of only SMA wires enables the control system to be placed entirely inside the hand. Only a compressor is needed to supply the air.





- **I** Decision to make use of 2-way valves
- **II** Decision to only continue with External Disk Valve. It shows more potential
- **III** Decision to use only 2 concepts to test various functions
- **IV** Decision to use two valve to control each bellow
- **V** Decision to adjust the design and work with a 3D printed flexible tube
- **VI** Parallel valve does not work with a 3D printed flexible tube
- **VII** Final design of the valve is chosen.

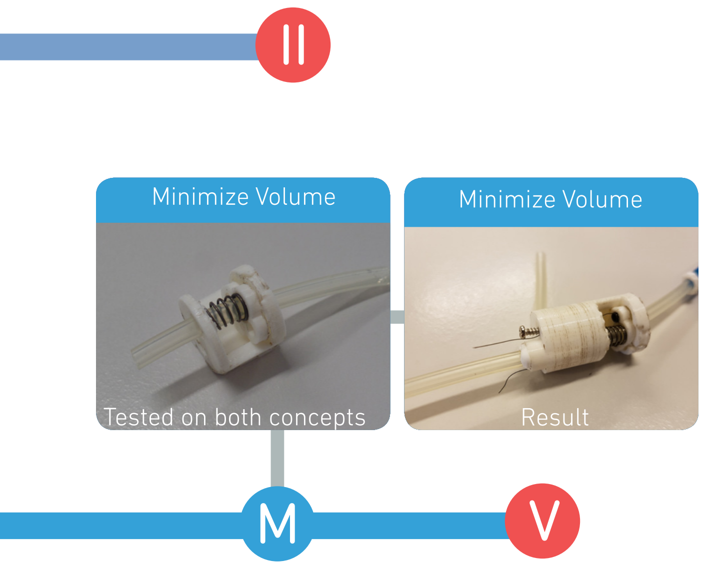
Time →

Prototype Overview

The prototype overview is a chronological road-map of all prototypes towards the final concept. It contains three different phases: internal DIsk Valve, External Disk Valve and Integration of 3D printed Flexible tube. As visualized, the phases have overlap in time. Each symbol at the time line is further explained in detail during the next chapters.

V Explains what is tested at the point in the time line. Letter represents the firs letter of what is tested.

I Important design decisions which have influence on the final design of the valve.



1 Internal Disk Valve

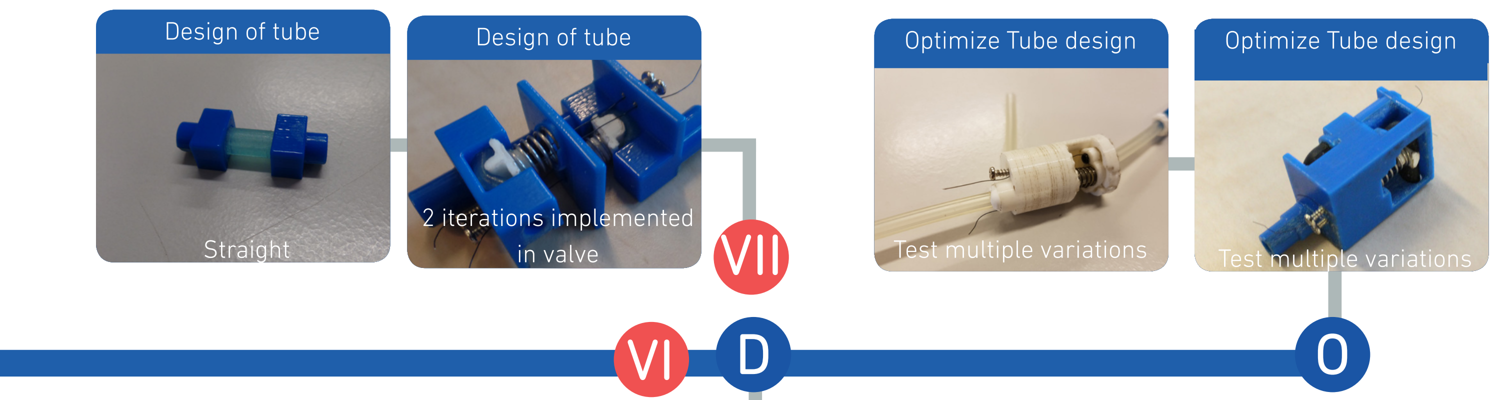
A concept based on existing valve examples During this phase, a valve mechanism, sealing and function of the SMA wires are tested.

2 External Disk Valve

A concept making use of a silicone tube which is compressed. The concept is tested on required force to compress the tube, flow speed through the valve, minimization of the volume of the valve ad composition of the valves to control multiple fingers.

3 Integration of 3D Printed Tube

A continuation of the External dIsk valve. The silicone tube is replaced by a 3D printed tube to improve the integration of the valve, but has significant influence on the design of the valve.



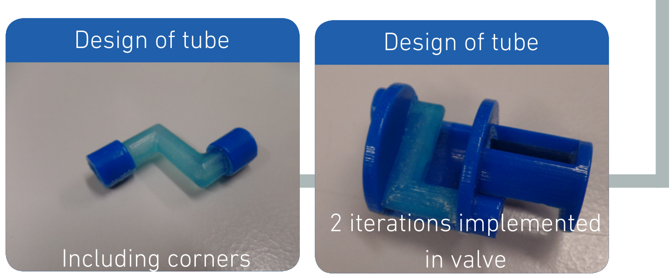


Figure 42: Prototype overview

Internal Disk Valve

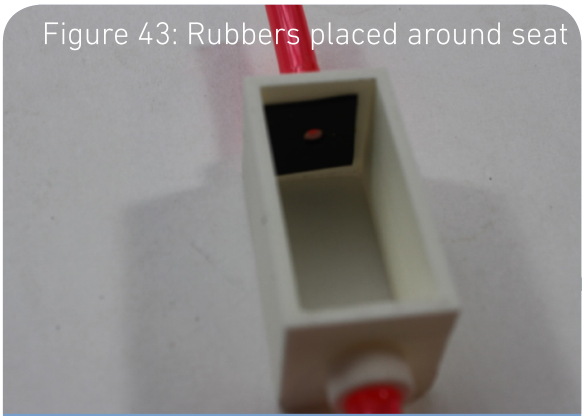
Examples of existing valves consists of a solid closing mechanism. The disk is placed inside the pressurized chamber, or enters it when closing off the air supply. The body around it contains a rigid seat. This chapter will elaborate on a concept based on the existing pneumatic valves, explained in Appendix: M. By 3D printing a valve with an internal disk, the disk, attached SMA wire and spring are placed inside the pressurized chamber. This requires a sealing which is air tight. Therefore, this chapter, the valve mechanism, function of the SMA wires and sealing will be tested.

V **Valve Mechanism Test**
Variations in material and shapes of the disk and seat are tested.

Next Steps

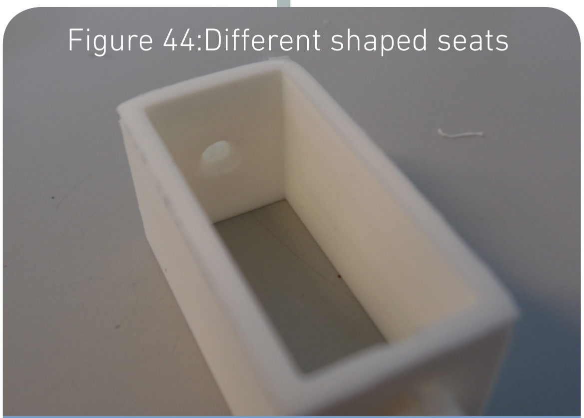
V

Figure 43: Rubbers placed around seat



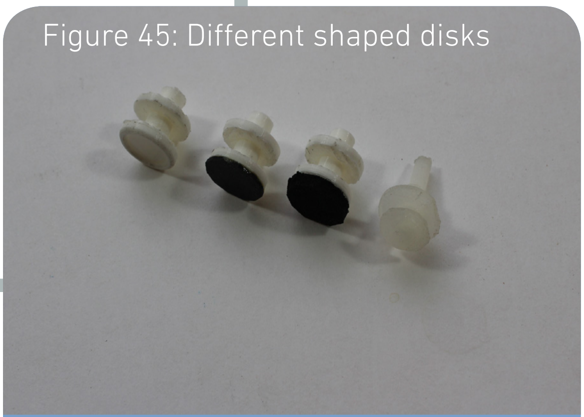
Rubber against the seat works best

Figure 44:Different shaped seats



Ridge or edge against seat has no influence

Figure 45: Different shaped disks



Dome shaped disk works best

Valve Mechanism Result

Combination of domes shaped disk compressed to the seat which is covered by a rubber foil works best. It is able to block up to 6 bar.

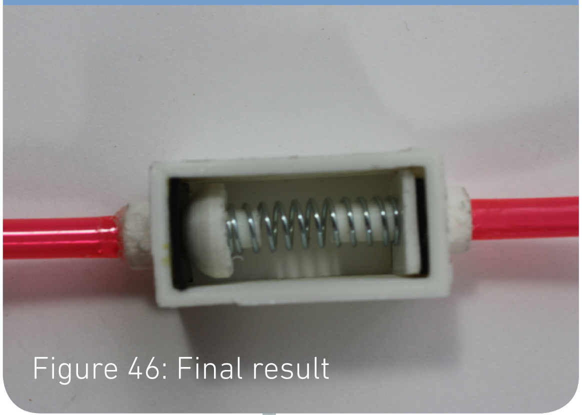


Figure 46: Final result

Next Steps

The final valve design is shown in figure XXX. It is able to block 6 bar which satisfies the desired 4 bar, thus will be implemented in the following prototypes.

V

What & how

Different closing mechanisms have been tested to keep the air supply closed when desired. Variations in the following parameters have been made: Shape of the disk, shape of the seat and the materials of both parts. During the tests, a spring is used to clamp the two parts together. Different amounts of air pressure have been used as input. More details about the setup-up, all variations and results can be found in **Appendix N**.

Results

Clamping together two surfaces both 3D printed is not able to keep the valve closed at any pressure amount. Placing a rubber foil over the disk works better, but still starts releasing air around 1.5 bar. Placing rubber foil around the seat clamped by a dome as blocking parts works by far the best, see **Figure 46**. It is able to block at least 6 bar. The only remark is about the fixation of the rubber foil to the 3D printed part. Gluing both parts together results in an extra assembly step. An option would be to print a flexible surface of against the seat. The final result is shown in **figure 46**.

Conclusion

To reduce the amount of assembly steps, the surface to the seat should be printed with a flexible material. By decreasing the amount of separate parts the change of air loss is decreased. This makes the valve more reliable. The spring used in this test performs approximately 15 N to block at least 6 bar, which seems hopeful.

0 Opening the valve

A pneumatic finger is supplied with 4 bar. The valves are opened by 1 mm by heating the SMA wires

01 **Two-way valve**

To control a finger, two two-way valves are needed to inflate and deflate the finger separately while supplying the finger with one air supply

02 **Three-way valve**

To control a finger, one three-way valve is needed to inflate and deflate the finger while supplying the finger with one air supply

! **Design decision**

01

Able to open and close with SMA supplied with 4-6 bar

Figure 47: Two way valve

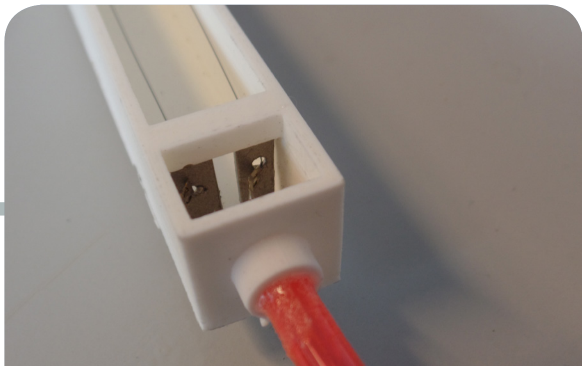


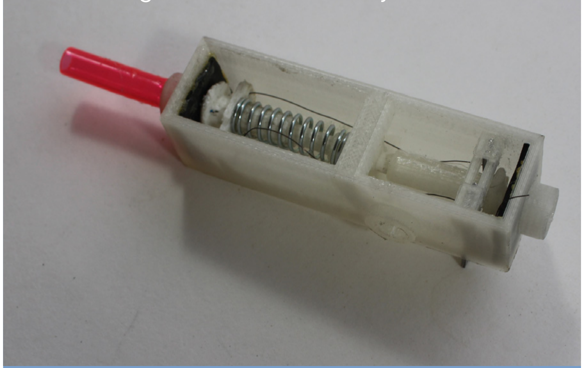
Figure 48: Fixation SMA wires

What & How

During the process to create an air chamber together with a suited sealing, prototypes have been tested to open the valve using SMA wires. The valve needs to be opened by heating the SMA wires. The wires contract and the disk is pulled back against the direction of the spring force. When the wires are cooled down, the spring will return the disk to close the valve again. More details about the prototypes are explained in **Appendix: Experiments: N.**

Besides the two-way valve, **figure 47+48+50**, a three-way valve is tested **figure 49**. The three way valve makes also use of only one SMA wire, like the two way valve. When the SMA wires are heated, the valve opens and an attached finger will be pressurized. The third opening including the extra disk will be shut off. When the wire cools down, the supply will be blocked and the attached finger will be deflated.

Figure 49:Three-way valve



Not able to block 2nd opening

02

Design Decision

For further prototypes, only the two-way valve will be tested, because the three way valve does not work. But by using two two-way valves, a finger can be controlled completely individual.

I

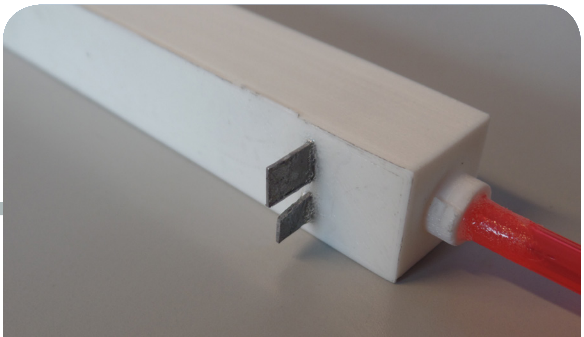


Figure 50: Conductive connection parts SMA wires

Results

Using SMA wires contracting by 1 mm to open the valve, works successfully. Supplying the chamber with 4 bar keeps the air out. When the wires are heating, the valve opens. When attaching the valve to a pneumatic finger, it bends. But, the chamber is still not airtight. The dimensions of the spring do also play an important role. It is concluded that more force is needed to close the valve when the chamber is supplied with pressure than keeping the air outside the chamber. Unfortunately, the three way valve does not work.

Conclusion

Making a pneumatic finger bend by using a valve inside a chamber works, but is not fully successful yet. Still, several aspects need to be optimized. The valve is not fully airtight. The closing mechanism makes use of a rubber layer which needs to be assembled or printed in one model. A three way valve using only one SMA wire seems not to realistic.

S Sealing

A pneumatic finger is supplied up to 4 bar. The valves are tested at which air pressure any air loss occurs.

S1 Form Fitting

By printing two separate parts, a form-fit sealing is tested to create an air-tight sealing.

S2 O-ring

By printing two separate parts, a o-ring sealing is tested to create an air-tight connection.

Design Decision

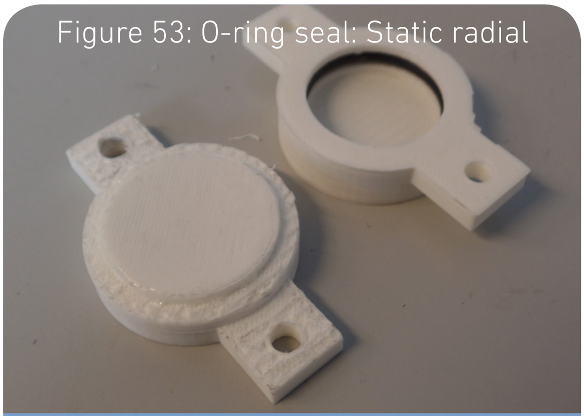


Figure 53: O-ring seal: Static radial

Static radial sealing can block up to 2 bar with only a little air loss

S2

S1

Many air loss at any air pressure

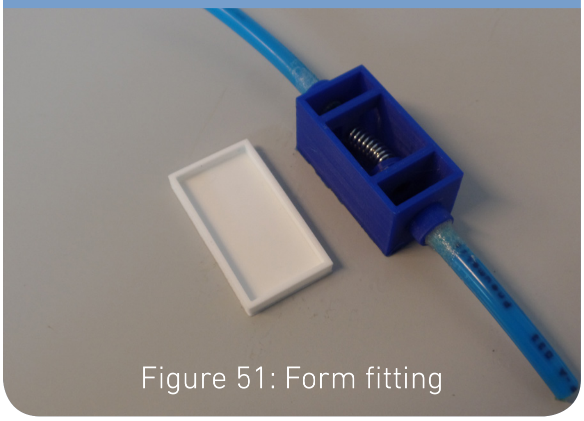


Figure 51: Form fitting

S1

Foil helps, but stil many air loss occurs, even when clamped with external force

Figure 52:Form fitting with foil in between

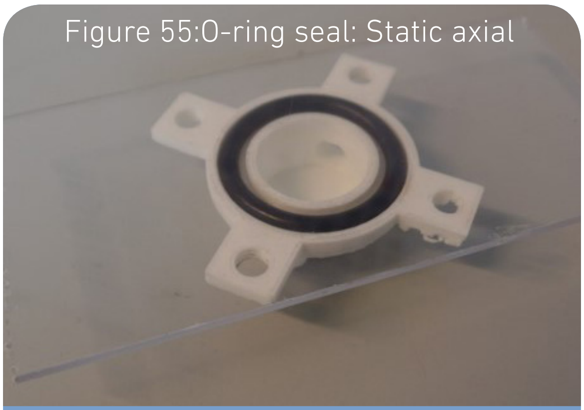
What & How

A valve actuating inside an airtight chamber requires extra attention to make the chamber airtight to prevent any air loss. The SMA wires need to be placed inside the chamber because the wires can not act through a 3D printed surface without any air loss. Therefore, different options are tested to create an airtight connection which can also be disassembled for maintenance purposes. Besides, little adjustments can be made inside the chamber while testing when using a mechanism which can be reassembled.

Results

Creating an airtight box while using 3D printed parts is complicated. Specially if it needs to be reassembled too. None of the prototypes have been tested completely successful, even when parts have been clamped together with external force. Using glue to seal two form fitting parts creates only a little amount of air loss **Figure 54** By adding a transparent lid makes it able to see what's happening inside the chamber. But, glue is not able to be reassembled. The best solution is using a static radial connection **Figure 53**. With

Figure 55:O-ring seal: Static axial



Many air loss occurs, even when clamped with external force

S2

Design Decision

At this point of the prototype phase, three most important parts of the internal disk valve are tested. The valve mechanism, the function of the SMA wire and the sealing of the air chamber. Because the sealing keeps causing leakage problems, the choice is made to choose the external valve to work further on. This external valve will be explained extensively in the next part of the chapter. The internal disk valve ends here.

II

S1

Using glue works best for now, but has no potential.

Figure 54:Form fitting together with glue

different attempts by changing the dimensions of the sealing, the final prototype only creates a little air loss. Air loss is probably caused partly by the quality of the 3D print. Because the print is made of of layers, a little air can possibly pass through the parts at the place the parts meet. How bigger the two separate parts are, the more chance any air loss arises because of the deflection in both parts. The different prototypes will be explained in more detail at **Appendix N**.

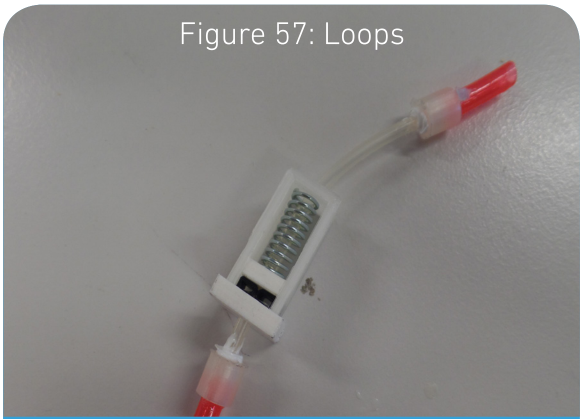
Conclusion

Creating an airtight chamber using 3D printed parts is a complex problem. It will require a lot of experiments to find the perfect sealing. Not only the printing technique, but also the printer quality of the printer has influence on the dimensions. To be able to place all parts inside the pressurized chamber, a large surface as sealing is required. By applying a high level of air pressure and using 3D printed parts,it will be a complex problem to solve.

External Disk Valve

An external valve consist of a closing mechanism which is placed around a flexible tube which is pressed by a spring to close it. It can be opened by heating a SMA wire to be able to bend a pneumatic finger. No air tight chamber has to be designed which will results in no air loss at all. The challenge is to create a valve which takes as less amount of volume as possible. Most desirable would be a valve with the spring and SMA wires in working along the direction of the flexible tube to create an efficient use of space.

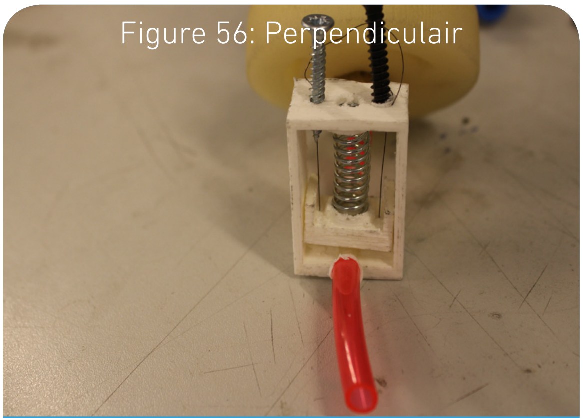
Figure 57: Loops



Many assembly steps, only able to block 2 bar with only a little air loss

V1

Figure 56: Perpendiculair



Able to block up to 4 bar.

V2

V Valve Mechanism

Three concepts have been tested. A silicone tube is used which is able to withstand 4 bar

V1 Loops
This concept makes use of two rubber loops compressed by the spring the block the air supplied tube.

V2 Perpendicular
This concept makes use of a disk placed perpendicular to the air supplied tube.

V3 Parallel
This concept makes use of two parts both with containing a hole with a distance in between in with the tube is clamped.

III Design Decision

What & How
Squeezing a flexible tube to stop the incoming air to flow through can be realized in different ways. Three different mechanisms are tested. In all three solutions, a flexible tube is pressed by making use of a spring which pressed the tube. By attaching SMA wires, the valve can be opened by heating the wires.

Concept Loops: A valve which contains two rubber loops. The flexible tube is placed in between the two loops. By placing a spring above, the loops will press the flexible tube to stop the incoming air to pass through, see **figure 57**.

Parallel Pinch: A mechanism which makes use of two separate parts both including a hole with the flexible tube passing through. The two holes are placed against each other, but with a distance from each other in the perpendicular direction of the

Figure 58: Parallel

Able to block up to 4 bar

Design Decision

Parallel and perpendicular valves works best. Be applying 15 N, both valves block up to 6 bar. Concept Loops blocks only 2 bar with the same spring force. Therefore Concept Parallel and Perpendicular will be fu ther examined. Concept Loops ends here.

V3

III

tube. By placing a spring on top makes the valve press the flexible tube to prevent the tube from air flowing through, see **figure 56**.

Concept Perpendicular: A mechanism which presses the flexible tube to a closed position by placing a part perpendicular to the direction of the tube. A spring is placed on top to press the part against the flexible tube, see **figure 58**. More details about the valves are explained in **Appendix O.**

Results

To test the different mechanisms, the both springs are used with the same deflection in compressed condition resulting in 6 and 15 N. The less powerful spring was not able to withstand a high pressure in all three concepts. Therefore, for the final results, the stronger spring is used. The mechanism with the loops is able to block incoming air up to 2 bar.

The other two concepts are able to block incoming air pressure up to 6 bar. The dimensions and compression of the spring play an important role to the final outcomes. Compared to the internal valve explained in **sub-chapter Prototyping: Internal valve,** the other two valves seem to need about the same amount of force to be able to keep the valve closed when supplied with a high amount of air pressure. This will be further tested.

Conclusion:

Closing the valve externally works well. The last two mechanisms works best, and there is no air loss when the valve is opened to supply an attached pneumatic finger to the valve. The two valves will be further tested to determine the length of SMA wires needed to open the valves and amount of force delivered by the spring is needed to be able to block to incoming air.

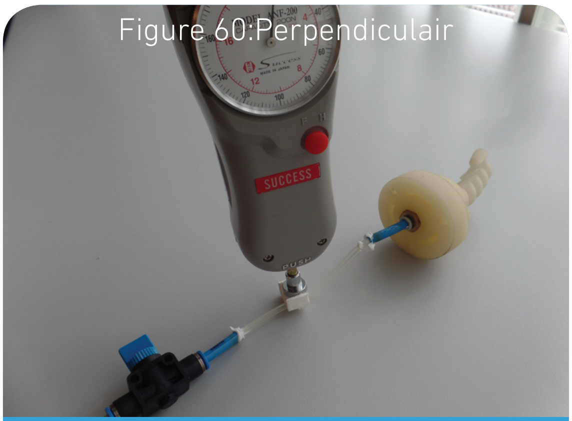


Figure 60:Perpendiculair

Require 9.1N to block 4 bar

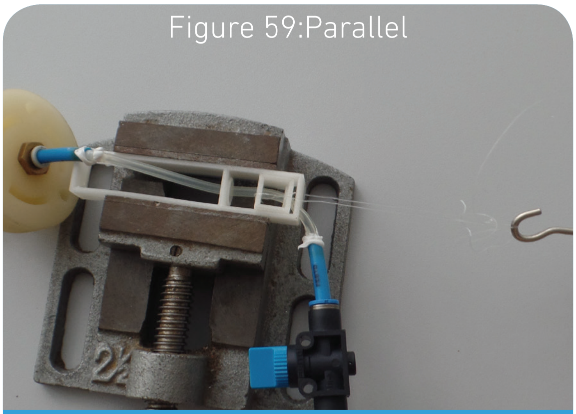


Figure 59:Parallel

Require 6.1N to block 4 bar

R1 R2

R Required Force

Both concepts are tested how much force is required to block incoming air .

R1 Perpendicular valve

The newton meter is placed on top of the disk compressing the silicone tube.

R2 Parallel valve

A Newton meter is attached to the valve using a cord. The newton meter shows the force needed to block the incoming air.

Next Steps

Next Steps

Both valves have potential, because only a little force is required. Closing a valve with a compressed chamber behind required about 3 times the force compared to a valve which has environmental pressure behind the valve. The final concept will make use of the advantage.

What & How

The two concepts are tested on the amount of force is needed to keep the valve closed when supplied with air pressure. In the final valve, the SMA wires will open the valve acting in the opposite direction of the spring force. The less force is needed, the smaller the dimensions of the spring are needed. The dimensions of the spring has large influence on the final dimensions of the valve. More details about the tests are explained in **Appendix: O.**

Concept: Perpendicular valve (**figure 60**), is tested by measuring the force needed to close a flexible tube supplied at different air pressures. There is 29.7N needed to be able to close the tube supplied with 4 bar. Measuring the force needed to close the tube with only air flowing through and an open end with 4 bar result in only 9.1N. Both scenarios are explained in **Appendix O**.

Concept: Parallel valve (**figure 59**), is compared to the first concept by the amount of force needed to keep the tube closed after supplied with 4 bar. This results in 6.1 N.

The needed force close the valve with air flowing through is about ⅓ of the required force to close a tube which is already supplied with an air pressure. Concept parallel valve only needs ⅔ of the amount of force of concept perpendicular valve. This could possibly be because of the friction inside the valve of the parallel valve.

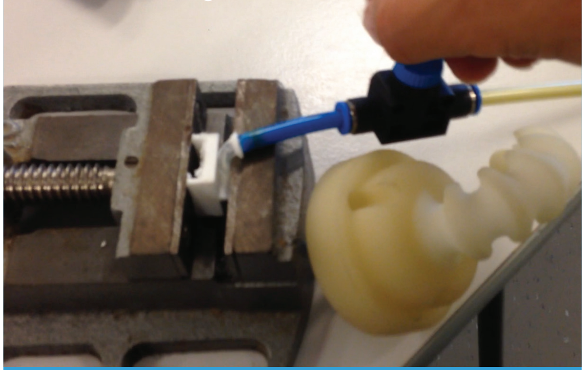
Conclusion

A scenario which has an separate valve acting as ventil is desirable to be able to use a low amount of spring force. This is taken into account to determine the final valve set-up to control the different fingers.

Figure 62:Perpendiculair

Opening the valve 1mm result in a 0.3 s bending speed of the finger.

Figure 61:Parallel



Opening the valve 1mm result in a 0.3 s bending speed ogf the finger.

F1

F2

Flow Speed Potential

F

A pneumatic finger is supplied with 4 bar. The valves are opened at different distances.

F1 **Perpendicular valve**

The Valve is opened by 0.5 and 1 mm to test the flow speed of the valve.

F1 **Parallel valve**

The Valve is opened by 0.5 and 1 mm to test the flow speed of the valve.

Next Steps

Next Steps

The relation between bending speed of the finger with the opening distance of the valves seems to be equal at both valves. Opening the valve by 1 mm results in 25 mm of SMA wire. This is tested next.

What & How

Both concepts have been tested on the inflation speed. The inflation speed depends on the amount of current supplied on the SMA wire, length of the wire and the mechanism itself. The less distance is needed to open the valve, the shorter length of SMA wire is needed which is beneficial to the total volume of the valve. More information is explained in **Appendix O**.

Results

First, both concepts have been tested by opening the valves at 0.5 mm and 1 mm. The inflation speed of the finger is in both experiments is about 0.3 and 0.1 seconds at both concepts

Conclusion

Opening the valve for only 1mm creates fast bending speed of the attached finger when pressurized with 4 bar.

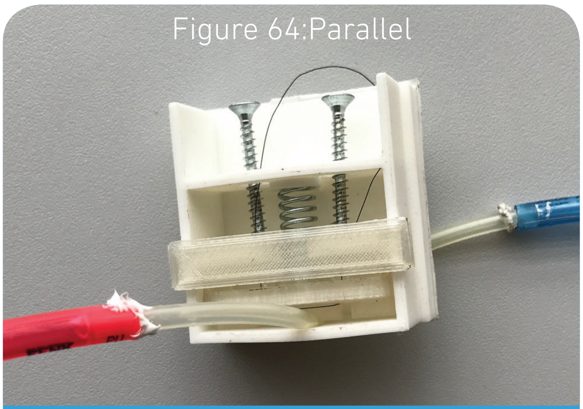


Figure 64:Parallel

Someting about inflations speed

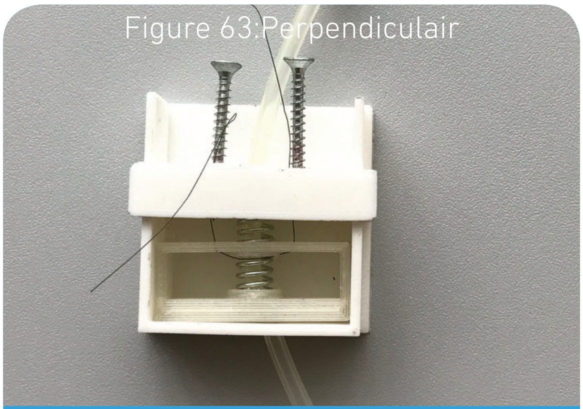


Figure 63:Perpendicular

Someting about inflations speed

F3 F4

F Flow Speed Actuated By SMA

Inflation speed actuated by SMA wires. A pneumatic finger is supplied with 4 bar. The valves are opened by SMA wires.

F3 Perpendicular valve
This prototype is able to adjust the length of the SMA wires to variate the opening of the valve while heating the wires.

F4 Perpendicular valve
This prototype is able to adjust the length of the SMA wires to variate the opening of the valve while heating the wires.

Next Steps
At this point, both valves are tested on required force and flow speed through the valves. Both valves work well. Both valves will be used to find the best valve composition which takes the less space.

What & How

Both concepts have also been tested by opening the valves with SMA wires. A length of the SMA wires is chosen to open the valve at 0.5 and 1mm taken the maximum contraction length of the SMA wires into account.

Results

Both concepts have a slower inflation speed in comparison with a constant opening. Using a contraction length of 0.5 mm, the finger attached to the perpendicular valve bends 0.55 seconds. The finger attached to the parallel valve bends in 0.6 seconds.

Using SMA wires with a contraction length of 1mm makes the finger bends in 0.3 seconds with both concepts. The deflation of the finger takes 0.45 seconds.

The results of 25mm to pull the valve open by 1 mm SMA wire using different currents are shown below: For more information, see **Appendix 0**.

1.7V, 0.76A= 0.3 seconds
1.4V, 0.49A= 0.60 seconds
1.2V, 0.55A = 0.7 seconds
1.0V, 0.44A = 1.0 seconds

Conclusion

The length of the SMA and applied current have large influence on the bending speed of the finger. The results show great potential.

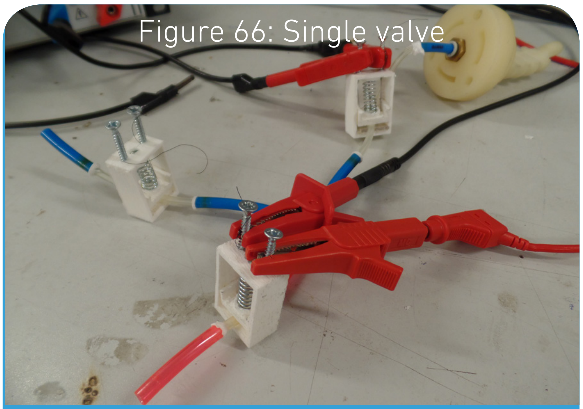


Figure 66: Single valve

7 valves to control 5 fingers

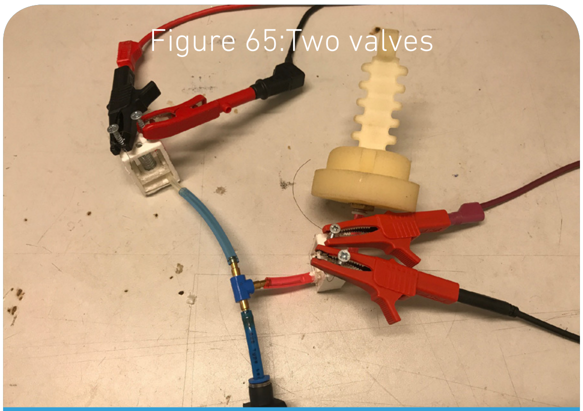


Figure 65:Two valves

10 valves to control 5 fingers

C1

C2

C Composition of valves

Two setups are tested considering to control a whole hand. Only one two-way valve can not control a finger.

C1 Single valve
Each finger has one valve. Two valves are connected to each finger. Total amount of 7 valves

C2 Perpendicular valve
Each finger has two valves. Total amount of valves is 10.

IV Design Decision

What & How

Before starting the prototyping different set-ups have been defined to control different finger on one hand, see **chapter Scenario set-up**. The two different valves set-ups have been tested to find out how many valves are needed.

Results

By opening the first valve when the air pressure is supplied, the finger stars to bend directly. By blocking the air pressure from the compressor, after a while the finger starts to straighten again slowly. This is because of air loss inside the finger itself. When the supply of air pressure is maintained, the finger remains into a bended position. This is because it takes more force of the spring is not high enough. This phenomenon is explained in **Appendix O: Required force**. Apparently, the spring which is used can not deliver enough force to press the flexible tube fully into a closed position after the SMA wires are cooled down. By opening the valve which acts a ventil, the air flows out and the finger straightens again. This takes place while the air pressure is maintained by the compressor. This means the air pressure drop of the valve acting as ventil enables to first valve to fully close again and keep the incoming air pressure out.

Design Decision
Using two valves per finger gives more opportunities in control possibilities. Besides, it is slightly faster, requires less energy consumption and time in between action takes less time.

Conclusion

The different set-ups seems to have no influence on the bending speed of the finger. The difference is by using the two valves per finger, each finger can be inflated and deflated completely individual. By making use of only one valve per finger plus two valves connected to all fingers, the each action has to happen one after each other. This decreases the actuation frequency of the valve.

Because the bellows will be controlled by two separate valves, the first valve can cool down during the period the 2nd valve opens to deflate the finger. This increases the actuation frequency.

M Minimize total volume

A spring is used with the minimal compression length to block 4 bar. The SMA wires can be placed inside or outside of the spring.

M1 Parallel valve

With the suited spring to be able to block 4 bar, an as small as possible design is created resulting in two variants.

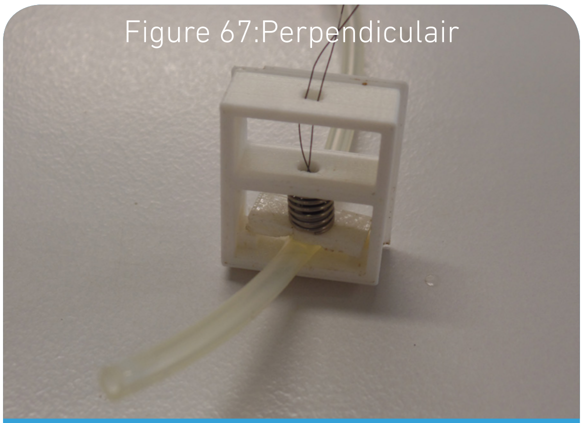


Figure 67:Perpendiculair

Able to block 4 bar

M1 M2

Able to bloack 4 bar, but needs extra part

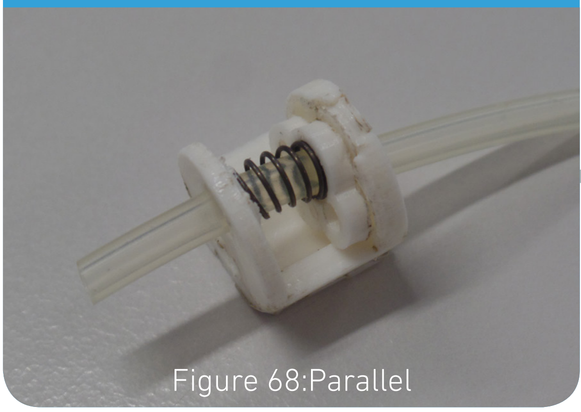


Figure 68:Parallel

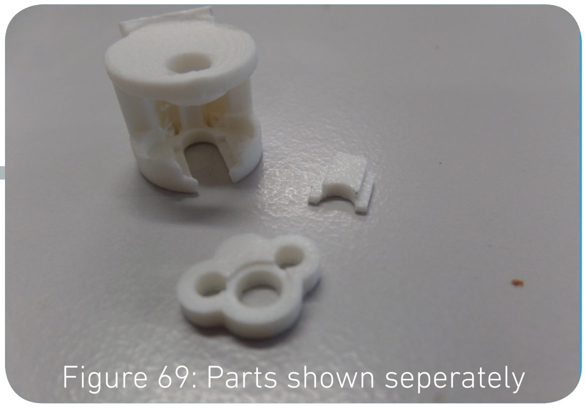


Figure 69: Parts shown seperately

What & How

As explained, both the parallel and perpendicular valve work to control the incoming air. But the next step is to minimize the volume of the valves. A mathematical model is created to determine the suited dimensions of the spring which will be used, see **chapter: determine spring dimensions and SMA wire**.

Results

There are two options of placing the SMA wires at both concepts. The SMA wires can be placed inside or outside of the spring. With the parallel concept, the silicone tube can be placed inside the spring when the SMA wires are placed around the spring to save space. The parallel valve needs an extra part to assemble the parts. The silicon tube placed inside the valve makes it impossible to place the spring in compressed state inside the valve.

The result is shown in **figure 68+69**. The perpendicular valve does not have this problem. The model is shown in **figure 67**.

The two options is placing the flexinol wires could increase the possibilities in a final design to make both valves compact integrated along the same axis to save space. Both concepts are able to block 4 bar of incoming air. For more details, **see Appendix O.**

Conclusion

There are two options of how to use both valves. This increases the opportunities for a final design. By determine the final design by combining the required valves the best suited solution can be chosen.

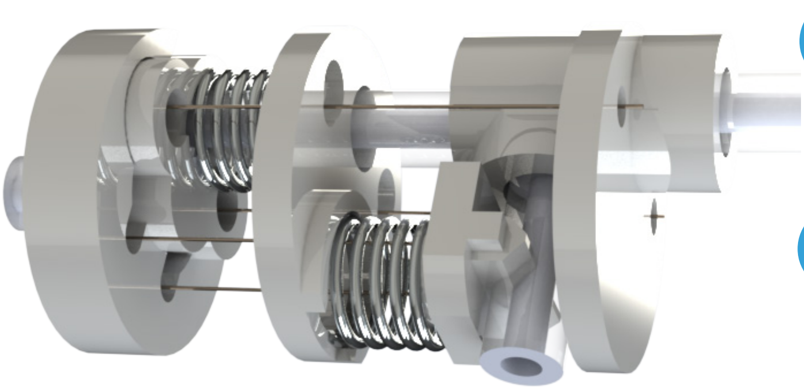


Figure 71: Solid works model of the final valve making use of the silicone tubes

M1 **Parallel valve**
With the suited spring to be able to block 4 bar, an as small as possible design is created resulting in two variants.

M3 **Perpendicular valve**
For the final valve making use of a silicone tube makes use of both the perpendicular and the parallel valve to minimize the total volume.

V **Design Decision**

M3

V

Connections of silicone tube fail

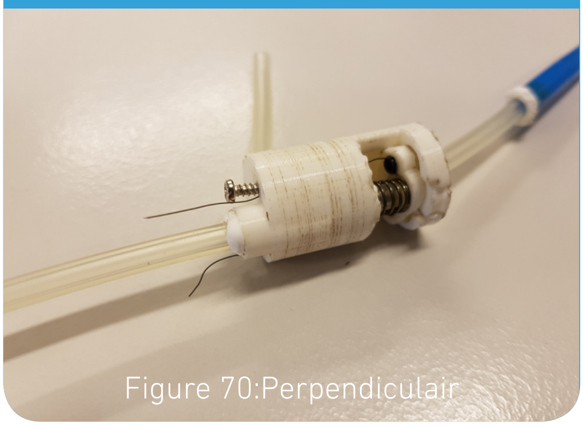


Figure 70:Perpendiculair

Design Decision
The use of silicone tubing makes it hard to connect all separate parts while designing for a small volume. The more connections, the more chance of air loss. 3D printed tubes integrated in the model could be the solution. During the next chapter is explained that using 3D printed tubes have a better potential and will be used in the final design of the valve. Because the internal disk valve has the problem which the external valve does not have, the external valve will be used for further prototyping

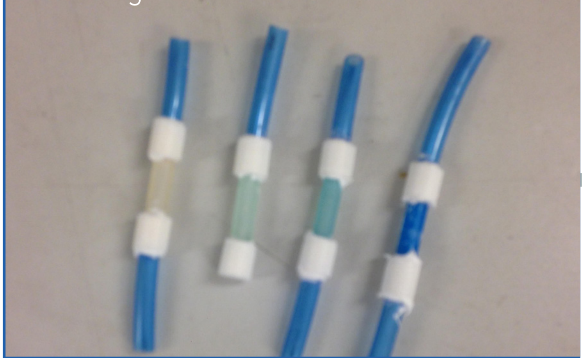
Final Design
Figure 70+71 shows the design of a entire valve of a finger. The concept makes use of both prototyped valves. The parallel valve is used to regulate the incoming air. The perpendicular valve is used as ventil. In this way, the valve can be placed below the finger inside the hand palm. The valve has a diameter of 15 mm and a length of 30 mm. But, unfortunately the valve does not work properly. Because several silicone tubes needs to be connected to the 3D printed model, applying air pressure results in too much air loss due to failing connections. For more details see Appendix O.

At the end, the goal is to create the valve with 3D printed flexible tubes with the advantages earlier explained. The choice was made to first use a silicone tube to test the valve, but due to the failure of connecting the silicone tubes, the choice is made to continue the process using the 3D printed flexible tubes instead of improving this design. Besides, replacing the silicone tube by an integrated 3D printed tube can have influence on the final design.

Integration 3D printed tube

As explained in the previous two chapters, the external disk valves has to best potential. Therefore, the choice is made to choose this type of valve. A concept is designed making use of a silicone tube which is compressed be the force of a compression spring. To make the valve completely integrated to the body of various soft robotics, the whole valve will be 3D printed as one part. By 3D printing the flexible tube, no connections inside the valve will occur, with minimizing the chance of air leakage. This chapter will focus on the function and the integrability of the 3D printed flexible tube.

Figure 72: Variation in tubes



15% FLX tubes can withstand up to 4 bar

3D printed flexible tube 6mm in diameter				
Wall thickness	1.25		1.5	
%FLX	50	15	50	15
Max Pressure (bar)	X	2.5	1.5	4
Force oto keep tube closed (N)		1.5 bar = 8N	1.5 bar= 4.5N	2 bar= 12N

Higher RGD%+wall thickness results in more allowable

Table 1

E1

E Exploration

Tubes with variation in wall thickness and FLX% (flexibility) are printed with the goal to replace the silicon tube which is used in the previous prototypes.

E1 Test strength of the tubes

All tubes are tested on amount of air pressure they can withstand, including the related force to close it off.

E2 Tube as parallel valve

A 3D printed tube is placed in both concepts to test if it works without failure.

Design Decision

E2

Flexible tube breaks

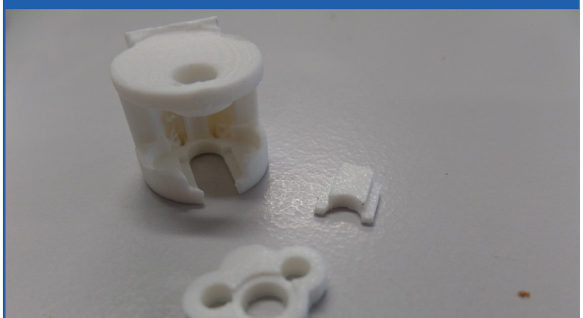


Figure 73: 3D printed tube placed inside prallel valve fails (shows only the valve)

1.75		2	
50	15	50	15
2	>4	2.5	>4
1.5 bar= 5N	x	2 bar= 7N	x

pressure, but increases the force block the pressure

Design Decision

To be able to control a bellow with 4 bar, a flexible tube with a Flexibility percentage of 15% is required to withstand the air pressure. But, first results show failure of the tubes when compressed by the force to close the tube, when much air pressure is applied. Therefore, provisional experiments will focus on supplying only 2 bar. The 3D printed tube is not suited to use as the parallel valve. Therefore, only the perpendicular valve is used for the upcoming prototypes. This has a large impact on the final design of the valve.

VI

What & How

By using the flexible tube which is used during the experiments as part of the closing mechanism, it needs to be assembled to the body of the valve which is 3D printed. By printing this tube together with a rigid closing mechanism, an assembly step can be reduced. Another interesting advantage is the reduction of a connection between two separate parts which has to possibility to create air loss. Therefore, different flexible tubes are 3D printed to find out what the opportunities are.

Figure 72 shows the tubes with different flexibility percentages. More details are explained in Appendix P.

The 3D printed tube is also place inside both concept valves to see if any problems occur regarding the strength of the tube, see figure73.

Results

Table 1 shows the results in the maximum supply of pressure and associated spring force to block this amount of pressure. Only the tubes with 50% and 15% of flexibility are shown because more flexibility results in less air pressure far below the desired 4 bar. Placing the 3D printed tube inside the parallel valve makes the tube break into two pieces. Besides, the parallel valve can not be printed into one model.

Conclusion

More flexibility results in less force to keep the valve closed which is beneficial, but only the low FLX% can withstand high air pressure. A tube with flexibility of only 15% starting with a wall thickness of 1.5 mm has the potential to withstand 4 bar without failure. But more fore is required to close the tube. Because the flexible tube breaks while placing in inside the parallel valve and the model can not be printed as one part, this concept ends here.

Figure 74: Straight tube: FLX 50%

Max 2 bar, 7N to keep closed

Figure 75: 3rd iteration: FLX 50%

Tubes fail at connection

Max 2 bar, 7N to keep closed

Figure 76: Tube with corners: 50% FLX

Fails during assembly

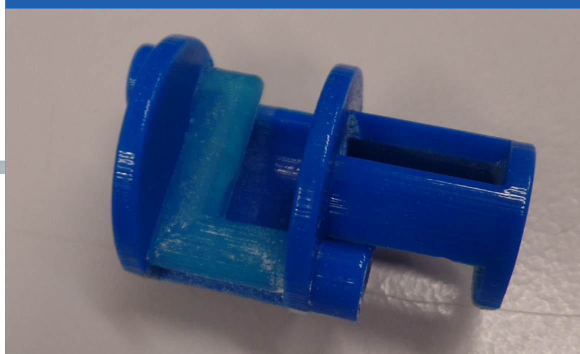


Figure 77: 1st iteration: FLX 30%

What & How

Two designs of tubes are tested which will be compressed by a spring to close the valve. The tubes are printed with a flexibility of 50%. The wall thickness is set to 1.75mm with an outer diameter of 5.5mm. The flexible tube in **figure 74** transfers from flexible to rigid material around the corners. This decreases the surface of flexible material to expand. This could probably increase the maximum air pressure, because less surface surface is able to expand. Besides, the corners are less vulnerable. The critical part of the tube is the connection between the two materials. The flexible tube in **figure 76** shows corners made with flexible material. Both tubes will be used as valve with both the iterations shown in **figures 75+77-79**.
More details about the designs, set-up of the models and results are explained in **Appedix P**.

Results

Both prototypes are able to withstand 2 bar without failure. Both tubes need about 7N to keep the tube closed while pressurized.

Figure 77 makes use of 30% flexibility. (30 %FLX) This prototype tears at the middle after a few attempts of placing the spring inside the prototype. The disk cuts the tube.

Figure 79 shows a single valve making use of 15% FLX. The tube is too brittle, it tears at the middle where the disk touches the tube, and at the inside corner of the tube. The failure happens when the spring is placed for a little while on the tube.

D Design of Flexible tube

Two tubes with a different design are tested which have influence on the final design.

D1 Straight Flexible Tube
Two iterations of double two-way valves are designed with minimal dimensions.

D2 Flexible Tube with corners
Two iterations of single two-way valves are designed with minimal dimensions.

VII Design Decision

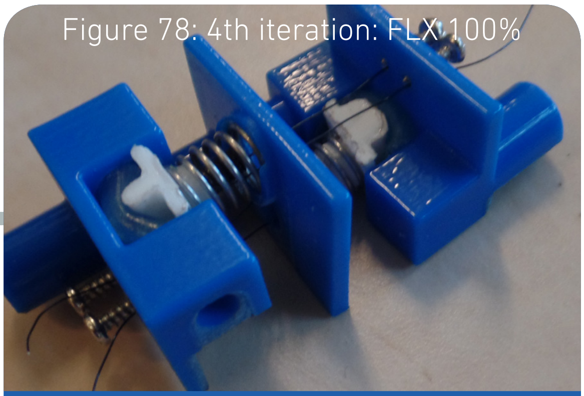


Figure 78: 4th iteration: FLX 100%

Tubes fail at connection

D1

D2

VII

Tube is too brittle

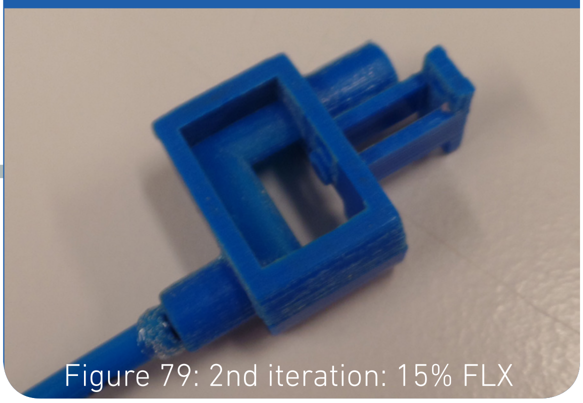


Figure 79: 2nd iteration: 15% FLX

Design Decision
The next step is to find a way to prevent the tube from failure. Variations in flexibility, cross section and wall thickness will be made. Despite the failures, the design with flexible corners seems to have most potential, thus will be used. The maximum allowable pressure is decreased to 1 bar. The amount of pressure of the demonstrator of both case studies. Thus, the choice is made to not focus on higher pressures which enables more soft robotics to be supplied with air. In the recommendations will be explained how to be able to realize this in the future.

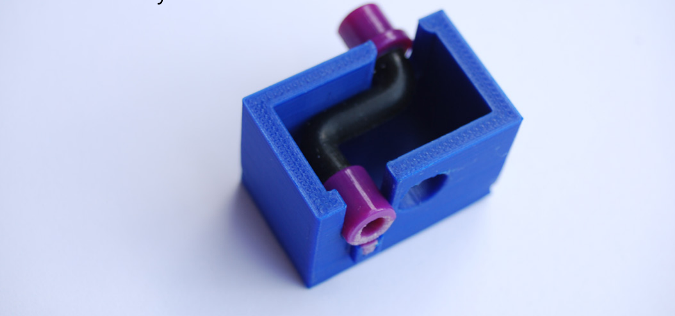
Figure 75shows two a doubled valve including two straight tubes used which are compressed. The tubes have 50% FLX. The tube fails at the connection point of the flexible material to the rigid part of the model.

Figure 78 shows the model making use of 100% FLX and the tubes floating0.3 mm above the surface. Both support in enabling the tube of more freedom to deflect when compressed. Unfortunately, this prototype fails at the corners as well.

Conclusion:
Somehow, the first two tubes shown in figure 74+76 work fine, but implementing these tubes inside a valve causes problems. This is probably caused because these tubes are not fixated to a rigid model which enables the tube to deform.

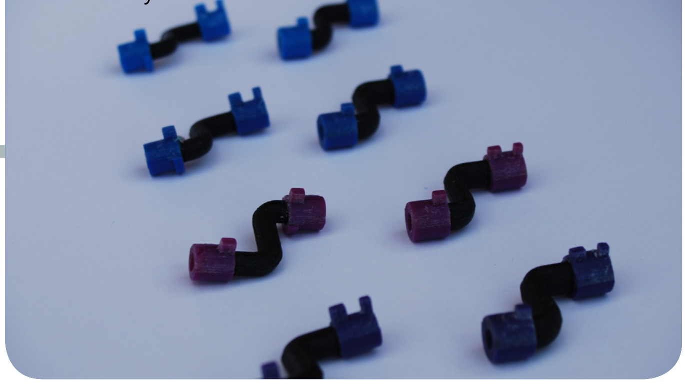
Besides, tubes with less flexibility can deflect less which makes them fail faster. On the other hand, more flexibility causes faster expansion of the tube results in a less supply of air pressure. Taken the results of this chapter into account, the tube seems to be able to need more length to have more space to deform when compressed by the spring. The straight tube has now a length of 10mm, which results in failure at the material transfer. Therefore, the choice is made to continue with the design making use of corners with the flexible tube. The corner will have a larger radius to reduce the chance of failure of the tube.

Figure 80: Setup of the a tube placed inside the body



Best variation: Oval design and 100%FLX

Figure 83: Variations in wall thickness, flexibility and cross section.



01 02

Model works, but bending speed of finger is still a little slow.

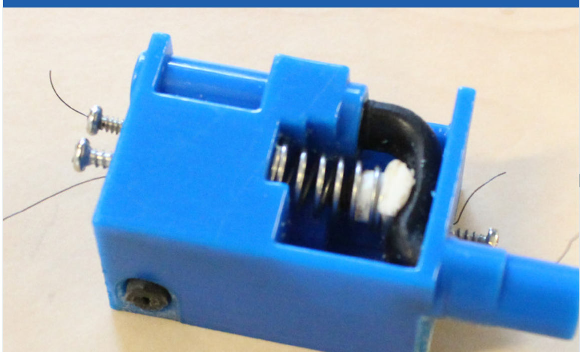


Figure 81: frontsde, tube inlet of air

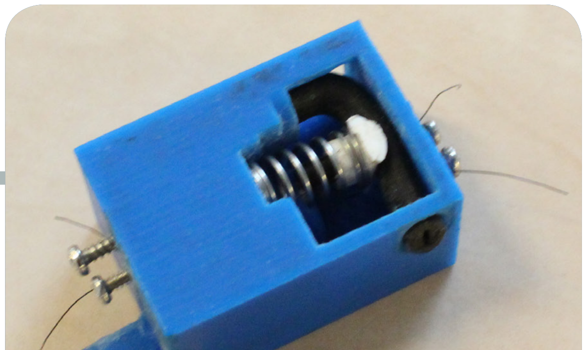


Figure 82: backside, tube as ventil

0 Optimize Tube Design

flexible tube designs are tested and integrated into a final working valve including an integrated bellow acting as pneumatic finger.

01 Variation in tube design

Variations are tested on cross section, wall thickness and FLX%.

02 Integration of tube in valve

The best tube design is integrated into a final valve to control a pneumatic finger

03 Final prototype

The final valve is printed together with a pneumatic finger. This has impact on the design of the valve.

Final design

Figure 84: Final Design

Final design is supplied with 0.5 bar

Final Design
The final design is shown in figure XXX, but will be explained in more details in Chapter XXX. Using a tube with a cetain amount of RGD% instead of fully flexible, the tube shows permanent deformation when supplied with air and the compressed spring for a longer period. This makes it impossible to use for multiple cycles and a 100% FLX tube is used.

03

What & How
The final prototype will consist of a valve attached to a finger. The design of the finger used which can be printed with the same printer requires in between 0.5-1 bar of air pressure. Because failure of the previous prototypes, the maximum required air pressure will be set to 1 bar. A set of tubes will are printed with variations in cross section, flexibility and wall thickness. According the results in **table 1**, the FLX% and wall thicknesses are linked to be able to withstand 1 bar. Besides round profiles, also an oval shaped tube is used. By using an oval tube, the tubes will be compress less in height resulting in less deflection of the tube. All inside diameters of the round tube are set to 1.5mm which should keep the flow speed fast enough the be able to bend a finger within 0.5 seconds. The inside space of the oval tubes have about the same surface to keep the flow speed of the air also fast enough. The tubes are shown in **figure 83**. More details about the tubes and setups s explained in **Appendix P.**

Results
The results of maximum air pressure together with the required force to close the tube are shown in **Appendix P.** A remarkable result is that tubes containing a RGD%, the tube shows failure over a couple amount of cycles. Only when the air supply is remained together with the spring compressing the tube. Tubes containing 100% FLX show no failure. Besides, the oval shaped tubes require less force to fully compress the tube.

Figures 81+82 show a first model including the conclusion to the outcomes of testing results. The model works, but the flow speed of the valve is not fast enough. When deflating the finger, it take up to over a second. The flexible tube of the final prototype shown in **figure 84** has a slightly larger cross section. This enables the valve to inflate and deflate the finger faster. The valve is printed into one model together with the pneumatic finger design. More details about the final prototype are explained in **Chapter: Demonstrator Case Study 1: Pneumatic finger**.

Conclusion
The results show the oval tube with 100% FLX works best and wall thickness of 1.75mm. Only a small amount of force is needed to close the tube when pressurized with 1 bar. The final design works, but there are still some improvements. These will discussed in **Chapter: Demonstrator Case Study 1: Pneumatic finger**.

Determine Spring Dimensions and SMA wire

To be able to create an integrated miniature valve, a spring with the minimal dimensions will be used. At the same time it needs to be able to deliver the required force to be able to close the valve by compressing the flexible tube. This chapter will translate the required force into the suited dimensions of the spring, but also the required dimensions of the SMA wire. First is explained how to determine the dimensions of both the spring and the SMA wire. Afterwards, the dimensions are calculated by using the air pressure used during this project.

During the concept phase, different valve concepts have been tested. By trial and error, first decisions about the design of the valve are made. But, to minimize the total volume of the valve, concrete values are of interest, including the SMA wires and the spring. This chapter translates the required force to be able to block the incoming air to the suited SMA wire and spring properties to be able to create a miniature valve with high actuation frequency.

The steps are as following:
- Start with the required force to block an amount of air pressure.
- Determine the Spring dimensions
- Determine the length and type of SMA wire.

Prototyping: 4bar

To be able to supply nearly all soft robotics, 4 bar of air pressure is set to first begin the prototype phase with. It appeared, the flexible tube was not able to withstand this amount of air pressure. Therefore the final design is set to withstand only 1 bar. The amount of pressure is used to actuate the bellows used in both case studies.

Demonstrators: Pneumatic finger and Walking robot

The bellow used as demonstrator is can be supplied with 0.5 to 1 bar. To much pressure will result in failure of the flexible material of the bellow which expands during inflation. Some first experiments with the bellow show some air leakage sometime. When no air-leakage inside the whole design including the valve is achieved, only 0.5 bar is required to inflate the bellow. Only a little air-leakage requires a up to 1 bar to make the bellow bend. Therefore, the valves implemented in both demonstrators are required to withstand 1 bar.

Required Force

The required force depends on the air pressure which is supplied to the soft robotic. But besides that, many factors have influence, like the material of the tube and dimensions of the tube (length, thickness, diameter). The best option is to test this value during an experiment.

Determine Spring Dimensions

To keep the bending speed of the attached bellow below 0.5 seconds, a flexinol wire with the length of 25 mm should be enough to open the valve by 1mm. This is based on tests during the prototype phase. But to create a small as possible valve, the exact dimensions of the spring are required. These dimensions are mostly based on the required force to keep the valve closed.

Formulas to calculate spring dimensions are used to create a mathematical model which shows all properties of the spring with the input of a required compression force. The values are also shown in graphs to create an overview and creates an image of what the influence of the different parameter are and of what value. It makes it able to pick the best suited spring dimensions in any desired situation.

Input:
- Compression Force (F)
- Material: ASTM A228 Music wire (See Appendix

P for choice)
- G= Shear modules of spring material
- Tensile strength of spring material (Depends on wire thickness and material of the spring

Output with which have no influence on the design:
N= Amount of active windings
Nt= Amount of total windings
Lf= Free length of the springs
- C = Spring index
- Ks= Wahl factor (Ratio mean diameter of spring to wire diameter.
- d= Wire thickness

Important Output which has influence on the design:
- k= Spring constant
- D= Spring diameter
- Ls= Length of spring in solid state (compressed)
- Fmax= Force of the spring when opened.

Fmax is the force of the spring in compressed state when the valve is opened by 1 mm, thus compressed 1 mm more than the start position (Fsolid).

The main formula used in the mathematical model is

Shear stress = 0.45 * Tensile strength

Shear stress = (8F/pi* d2)*C*Ks
The tensile strength depends only on the wire material of the spring, but variates per sketchiness of the wire. This relation is implemented into the model.

From this formula, different formulas are used to calculate the windings, spring constant, deflection and spring length. These will be explained in **Appendix Q**.

Determine the SMA wire
By selecting the right SMA wire, a choice is made in activation temperature, diameter and length.

The higher the activation temperature, the faster the cooling time.

The diameter of the wire depends on the required force the wire has to pull.

The length of the wire is related to the contraction length and determines the distance of the valve to open. The spring will be compressed further by this distance. This results in increase of compression force of the spring. The increase in compression force plus the safety factor needs to be provided by the SMA wire. The increase in compression force is related to the spring constant. Therefore, the spring constant needs to be as small as possible.

Prototyping 4 bar

Required force

In **Chapter External Disk Valve**, the required force is determined to be able to block 4 bar of incoming air, resulting in 9N. A safety value of 0.5N is added which results in a required compression force of 9.5N.

Determine Spring Dimensions

In **figures 85+86**, the output of the four important variables of the spring design are shown. Because the spring diameter is set to 6mm to be able to thread and fixate two SMA through the spring, a choice have is made in Ls= Spring of solid state (mm) and k= Spring constant (N/m)

A small as possible spring constant is desirable, but this increases the length of Ls. Selecting a spring with Ls= 7 mm, the spring enables the two separate valves to be place close to each other because the disk won't interfere with body around the spring of the valve places next to it.

Selecting a small wire diameter will result in a lower spring constant.

Result:
d= 0.55 mm
D= 6.1 mm
k= 0.4 N/m
Ls= 6.6 mm
Material: Music wire

This result is for now only theoretically, because selecting the exact calculated spring is not an easy task. At the time of prototyping a spring is bought with quit comparable properties:

d=0.63 mm
D= 6.3 mm, (outer diameter 6.9mm)
k= 0.97 N/m
Ls= 6.2 mm
Material: RVS

All exact dimensions are shown in **Appendix P**.

SMA wire

The SMA wire need to be able to lift the disk to open the valve and compress the spring 1 mm further. The pull force requires in 0.97+0.5= 1.5N. Theoretically a wire of 0.1 mm in diameter is able to pull the valve open.

To be able to make sure the wires won't fail during the experiments, a double 0.15 mm wire is used.

Case studies: 0.5 bar

The choice is made to use the same spring and SMA wire for both demonstrators.

Because the 3D printed tube has a width of 6.5 mm, the maximum spring diameter is set to this valve because the tubes and thus the spring are placed next to each other. The maximum length of solid state is still the same. This means the spring constant can be minimized in theory. This result in less required pulling force of the SMA wire. The SMA wire used for both demonstrators is kept the same for practical reasons. This makes it easy to work with.

The final design of the spring and type of SMA wire will be explained in the next sub-chapter.

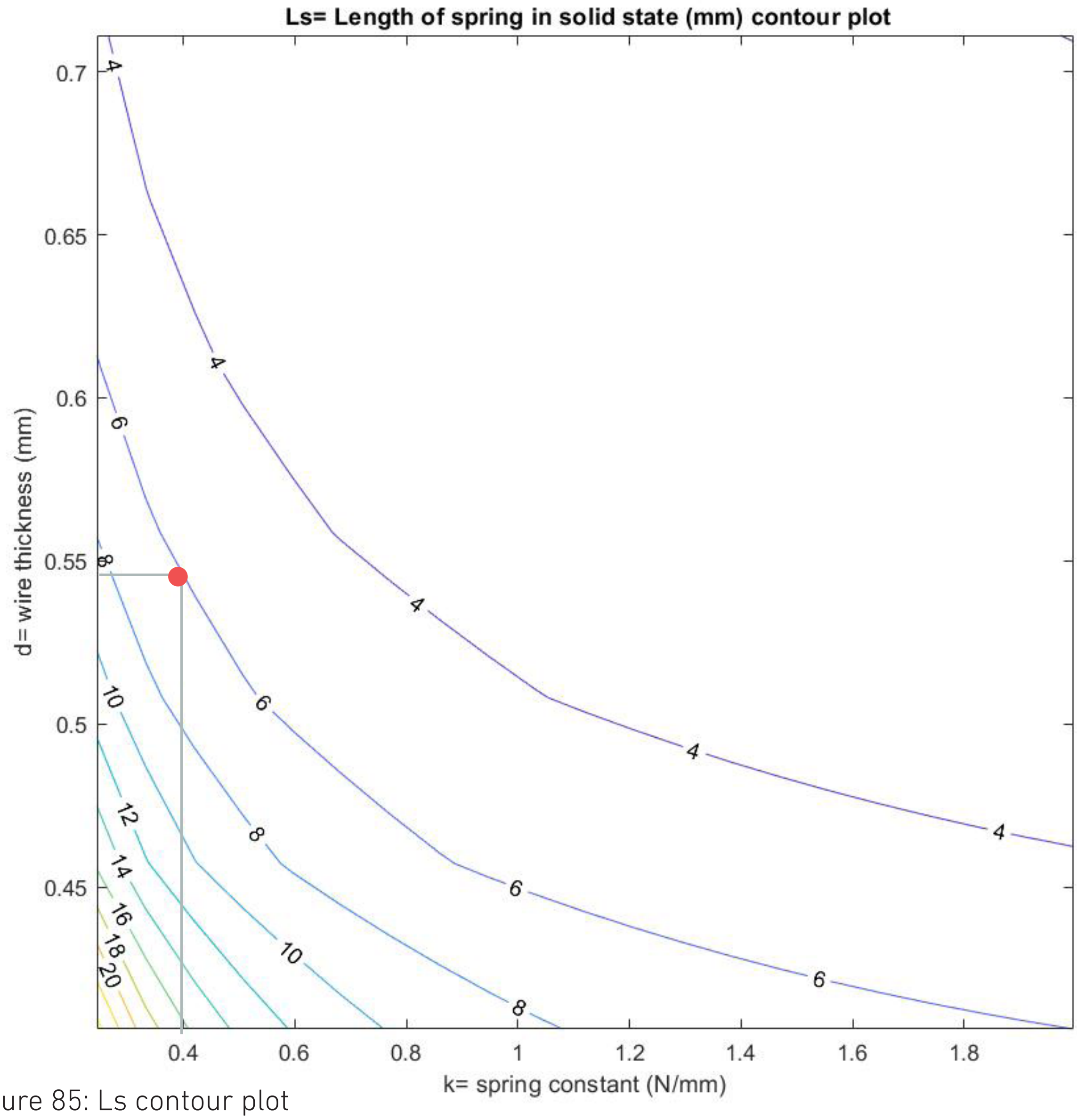


Figure 85: Ls contour plot

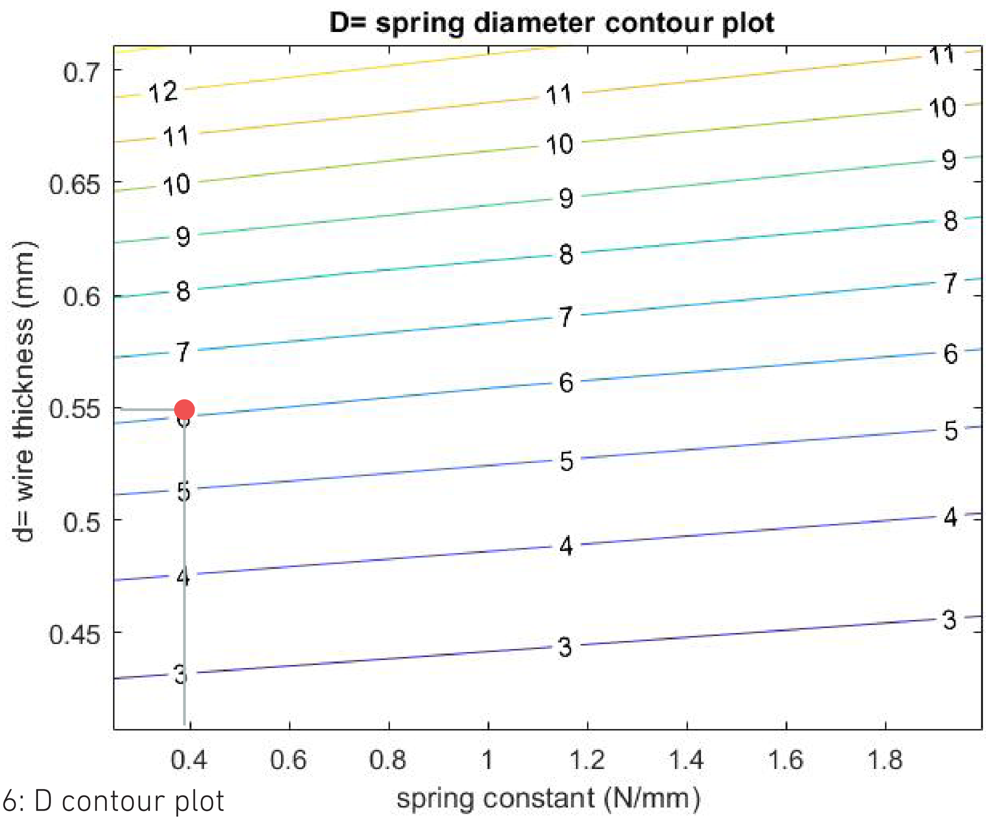


Figure 86: D contour plot

Optimizing spring and SMA wire for design of both Case studies

Required force
The required force is determined to be able to block 1 bar of incoming air, resulting in 4 N. A safety value of 0.5 N is added which results in a required compression force of 4.5N.

Determine Spring Dimensions
In figures 87+88, the output of the four important variables of the spring design are shown. Because the spring diameter is set to 6mm, to be able to thread and fixate two SMA through the spring, a choice have is made in Ls= Spring of solid state (mm) and k= Spring constant (N/m)

A small as possible spring constant is desirable, but this increases the length of Ls. Selecting a spring with Ls= 7 mm, the spring enables the two separate valves to be place close to each other because the disk won't interfere with body around the spring where it rests on.

Selecting a small wire diameter will result in a lower spring constant.

Result:
d= 0.42 mm
D= 6.1 mm
k= 0.09 N/m
Ls= 6.9 mm
Material: Music wire

All exact dimensions are shown in Appendix P.

SMA wire
The SMA wire need to be able to lift the disk to open the valve and compress the spring 1 mm further. The pull force requires in 0.09+0.5= 0.6N. Theoretically a wire of 0.076 mm in diameter is able to pull the valve open.

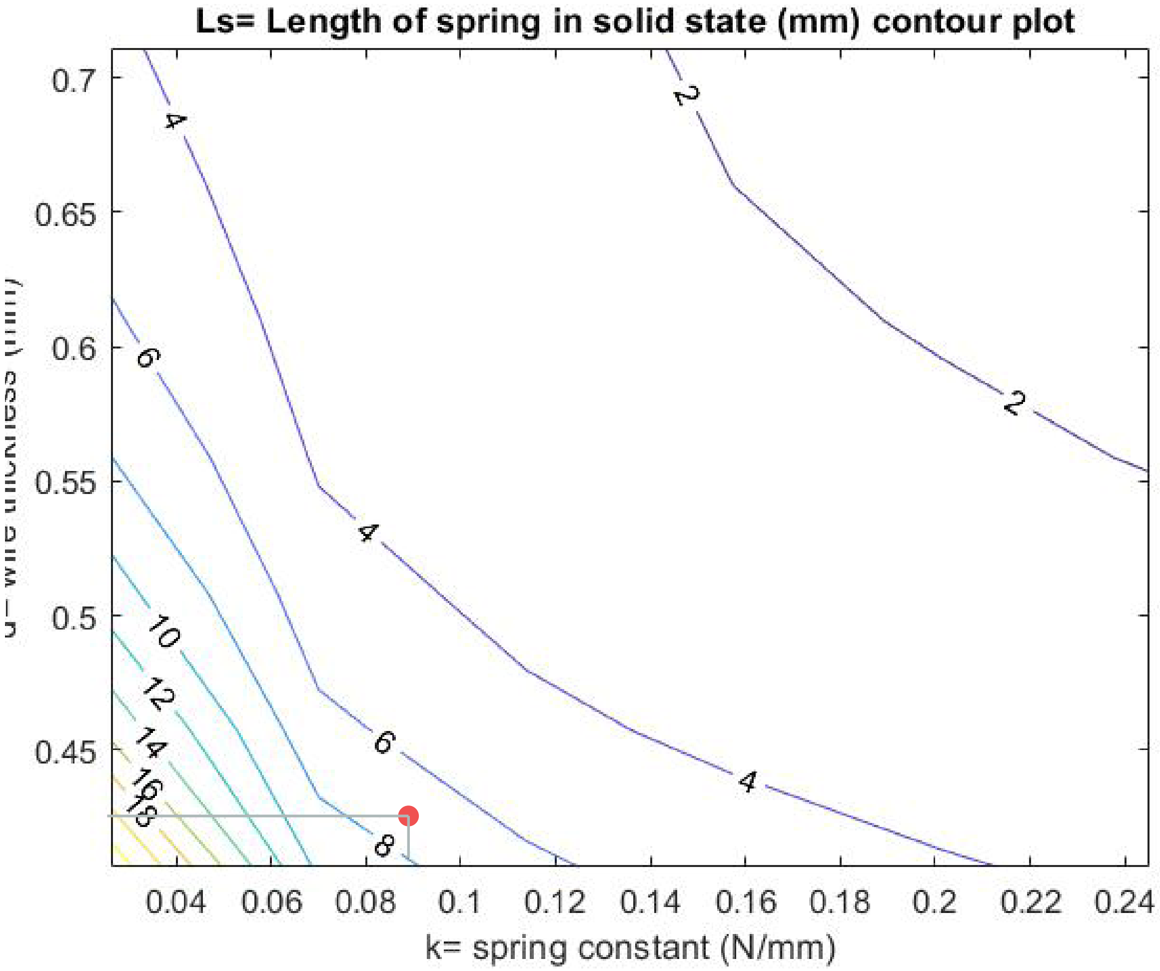
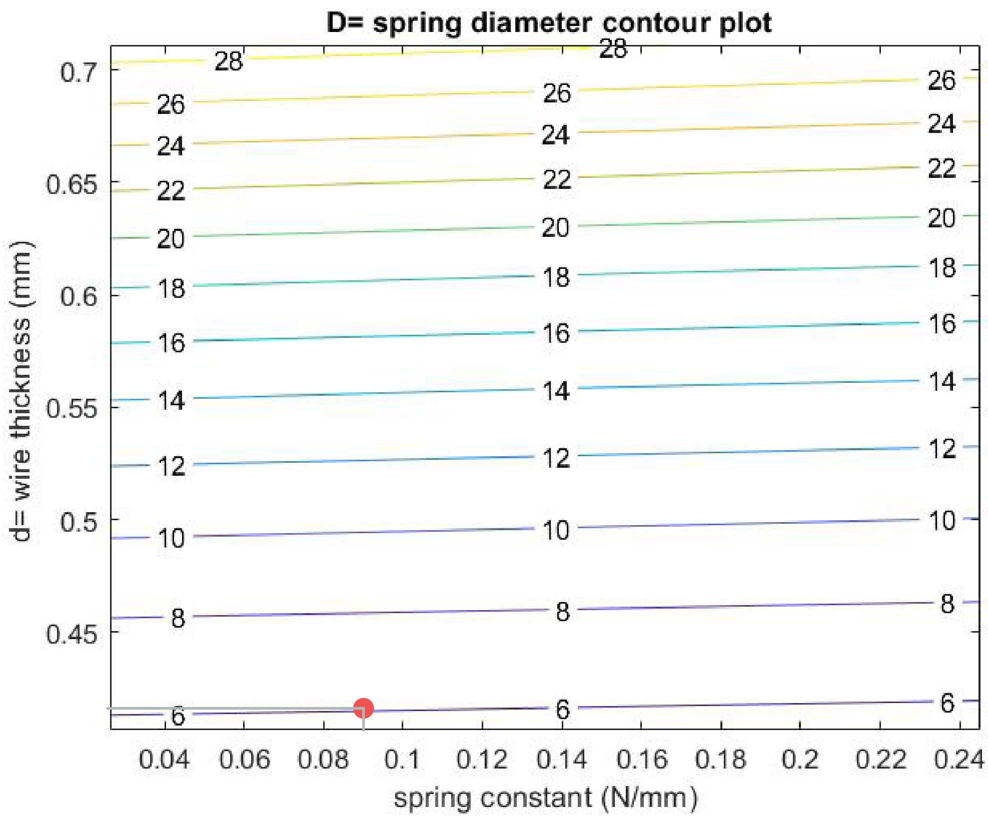


Figure 87: Ls contour plot



Figure

Detailing

This part will elaborate on the result of both case studies. First, the result of case study 1 is explained. It explains how it work, how it is build and how it looks. The second case study is explained together with the differences in design is brings along. A benchmark together with competitors is explained to show the value of the valves created during this graduation assignment. This part ends with an explanation how to develop a tool to be able to support any kind of soft robotic regarding different flow rates, air pressure and volume.

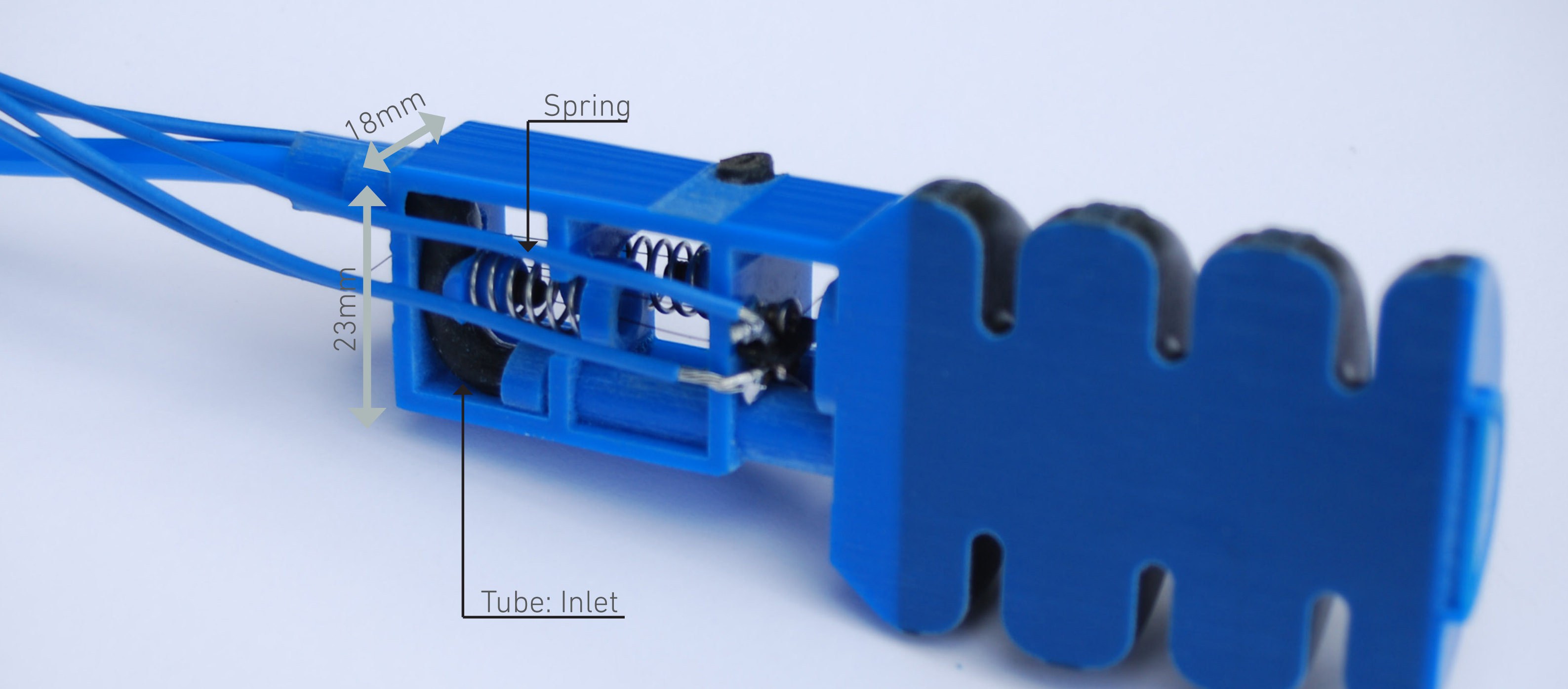


Figure 89: Valve: bottom side

Demonstrator case study 1: Pneumatic finger

The final concept is briefly explained at the end of the last chapter. During the prototyping phase, multiple conclusions have lead to a final demonstrator of a valve integrated to the bellow. This chapter will explain in more details how it works.

Result

Figures 89-92 show the demonstrator of the valve attached to a bellow. The valve is designed in the way it acts along the length of the finger. In this way, it can be integrated inside a hand palm of a pneumatic robotic hand. The demonstrator includes two valves both directly attached to the bellow. Both make use of a compressed spring which make the disk to close the flexible tube. Both valves are opened by heating the SMA wire which is placed in between the disk and the frame of the valve. Both valves make use of a double threaded SMA wire to be able to use a thin SMA wire. This enables to reopen the valve quickly because of a short cooling time of the wires. The valve works well en no air-leakage is experienced. More details with be shown in **Appendix Q**.

The bellow has two plugs to be able to remove the support material after printing. To be able to fixate the SMA wires on the side of the bellow, a distance of 10mm is created to be able to place the screws and plug of the bellow. The SMA wires have a length of 25 mm to be able to open the valve far enough to make the bellow bend in 0.4 seconds.

Figure 91 shows the inflated bellow. It is able to bend in 0.4 seconds. It starts to bend directly when the current is applied to the SMA wires. The bellow deflates in 0.6 seconds.

The demonstrator makes use of a manual control box to be able to experiment with the time to heat the wires, see **figure 92**. Integrating the valve in an application, this can be done automatically by connecting the wires to a control board.

All four ends of the SMA wires are connected to an electrical wire. In this demonstrator, all four wires are connected to the control box, but ideally half of the amount of the wires can combined into one wire inside the valve to reduct the amount of wires threaded along the air-tube. This will be taken into consideration at the demonstrator of the walking

Figure 90: Valve: Upper side

Figure 91: Inflated bellow

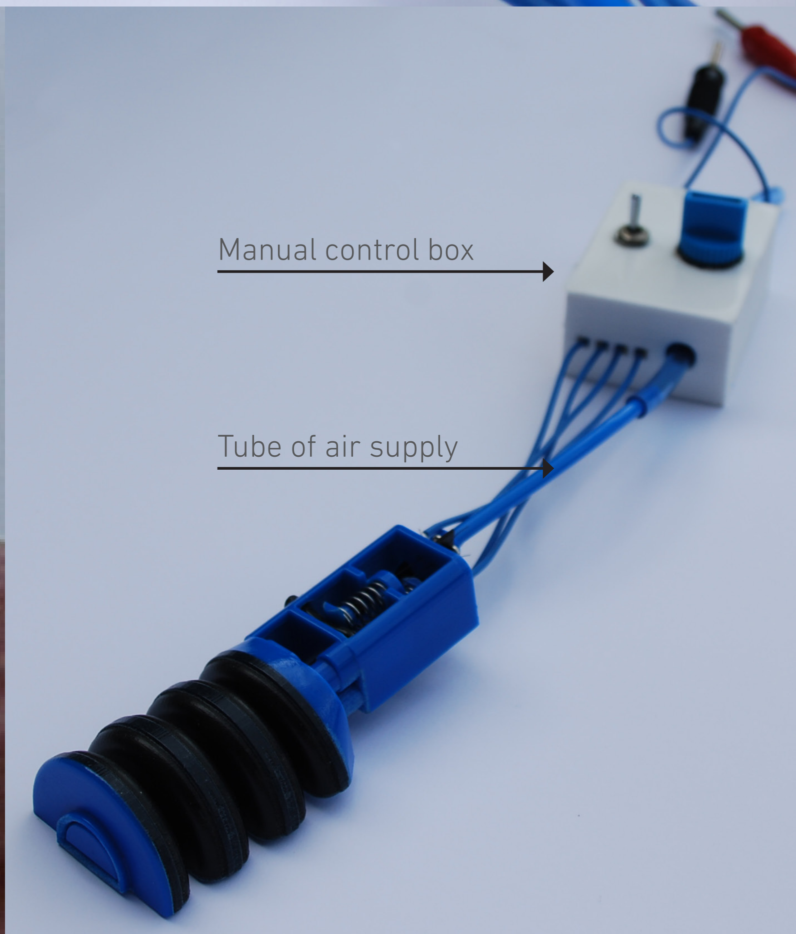


Figure 92: Set-up

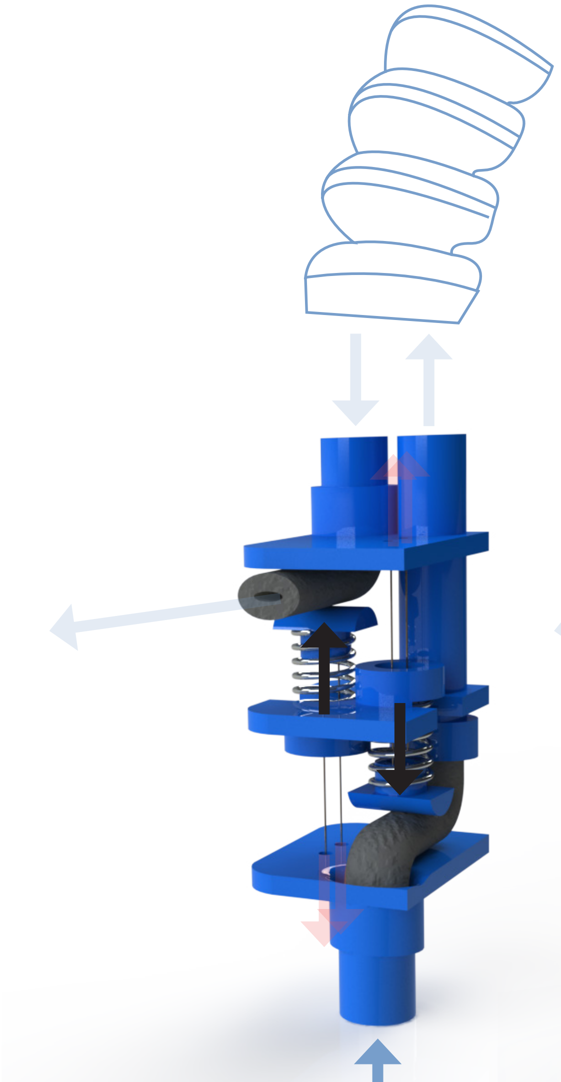


Figure 93: closed

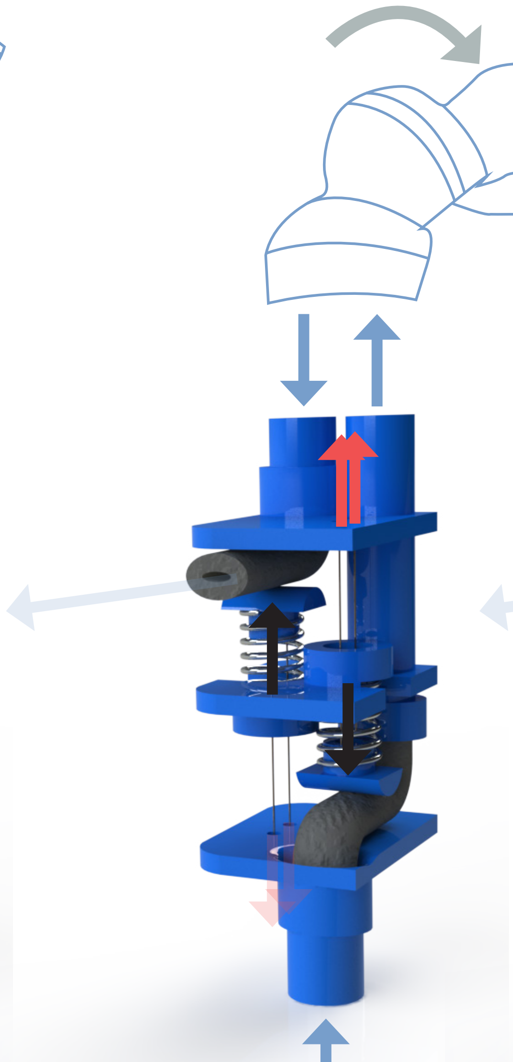


Figure 94: opening

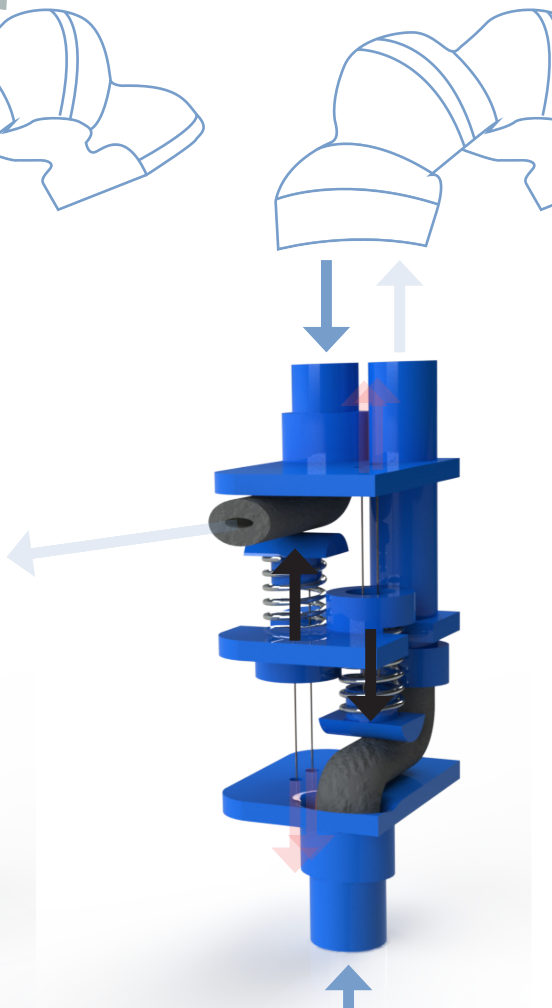


Figure 95: opened

Keep valve closed

Compressor pressurizes the model, but is blocked by the compression force of the spring. Therefore, the attached bellow stays deflated.

Open valve

SMA wires are heated, and pull back the sprig to open the first valve. Finger starts to inflate.

Keep pressurized

When the SMA wires cool down, almost no air flows through the valve. Eventual small leakage in the bellow will be redress.

robot. More details about the demonstrator are explained and visualized at **Appendix Q.**

Control of the valve

In **figures 93-97** is shown how the concept works. A compressor is attached to the valve. It contains two separate valves. The first valve has the function to make the attached finger inflate to make it bend. The 2nd valve has the function the deflate the finger to straighten it again to it's original shape. Both valves are directly connected to the bellow. **Figures 93-97** show the valve detached from the bellow and walls to strengthen the valve, to enable a better view of how the valve works. By applying different amounts of current, the bending speed of the bellow can be determined.

Implement to a hand

Figure 98 shows an example of implementing 4 valves controlling the fingers of a hand excluding the thumb. The design of the demonstrator is multiplied by 4 times as aligned parallel next to each other. The valves can be actually placed even more compact making use of the same space in width. This result in a total width of 72mm instead of 86mm. The air supplied tube can be divided in the bottom to the four different air-inlets of the design. At the top of the model, 4 bellows can be placed by connecting each bellow to both the enter and exit valve.

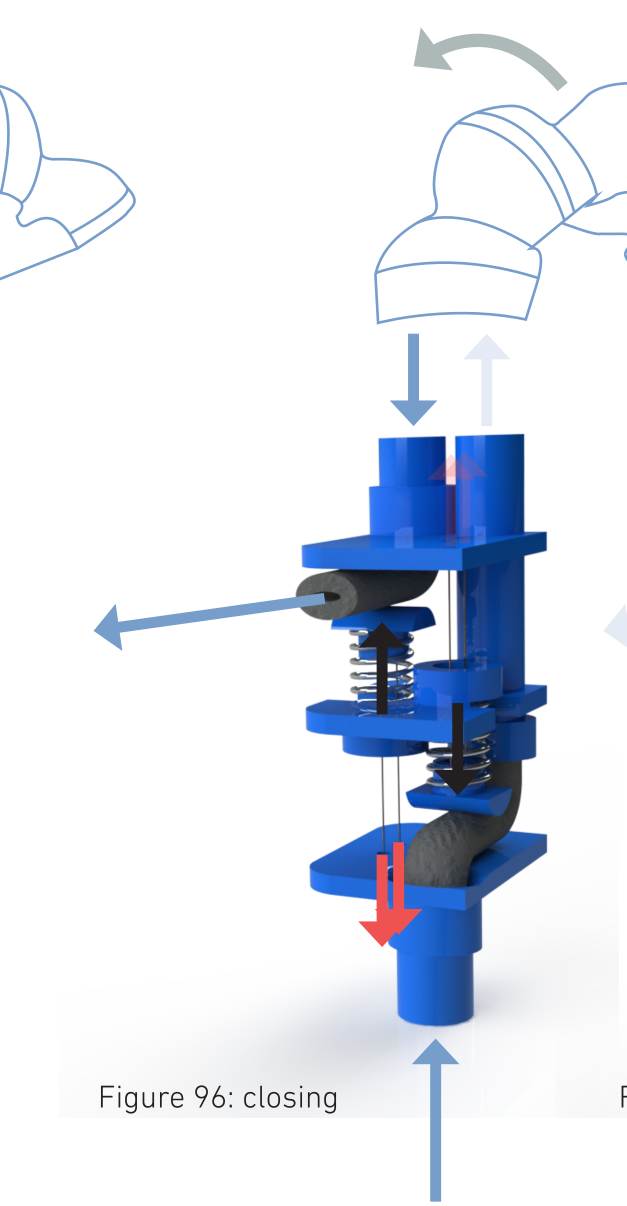


Figure 96: closing

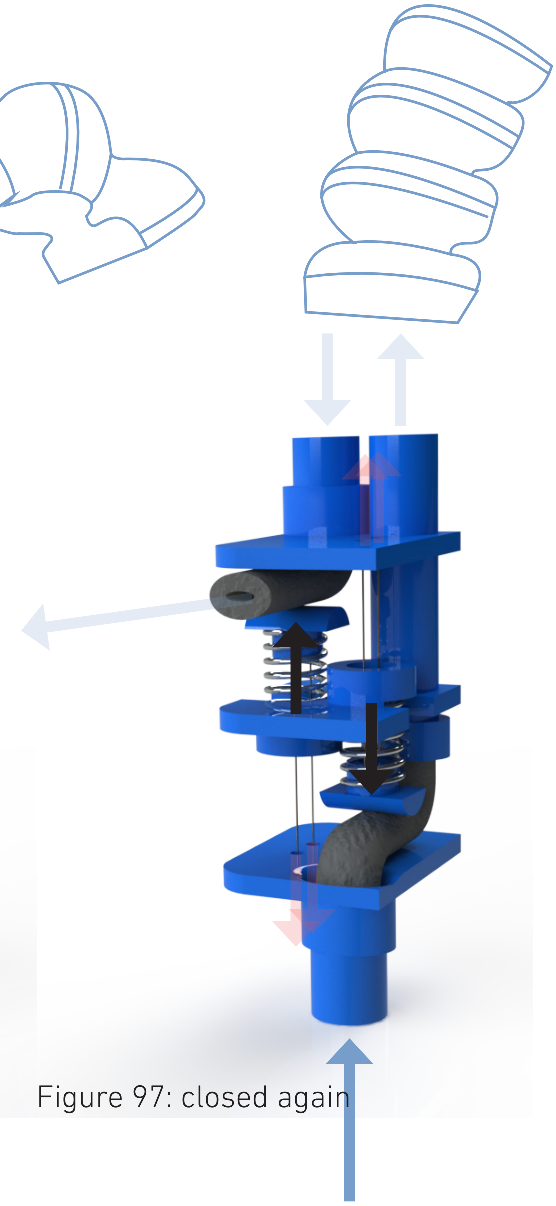
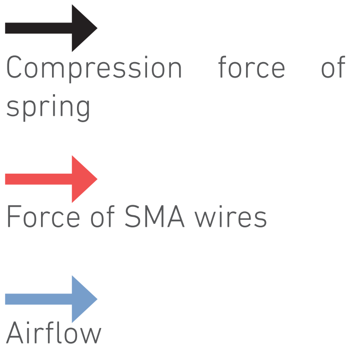


Figure 97: closed again



Deflate

Heating the second pair of SMA wires, the air starts flow through the second valve and the finger deflates. When the finger is deflated, the first valve fully closes.

Keep valve closed

When the SMA wires are cooled, the finger stays deflated.

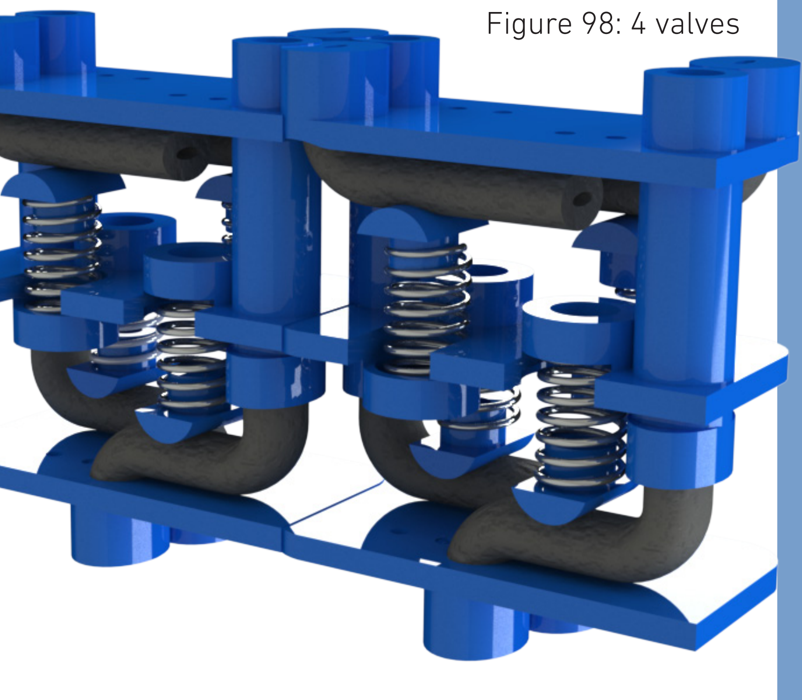


Figure 98: 4 valves

Conclusion Case study 1

By designing this valve, the placement of the valve inside the hand-palm is taken in consideration. The cross section and length of the valve is kept as minimum as possible (18x23x34-44). Hereby both width and depth of the tube are both of equal importance. The two separate valves including both a flexible tube, spring and SMA wire. They are are placed next to each other acting in opposite direction. This is to be able to save space in width of the valve (18mm). By placing both Disks next to each other would take more space. The orientation of the valves enable to save space in the width controlling multiple bellows. Applying different amounts of current enable the bellow to bend in different speeds.

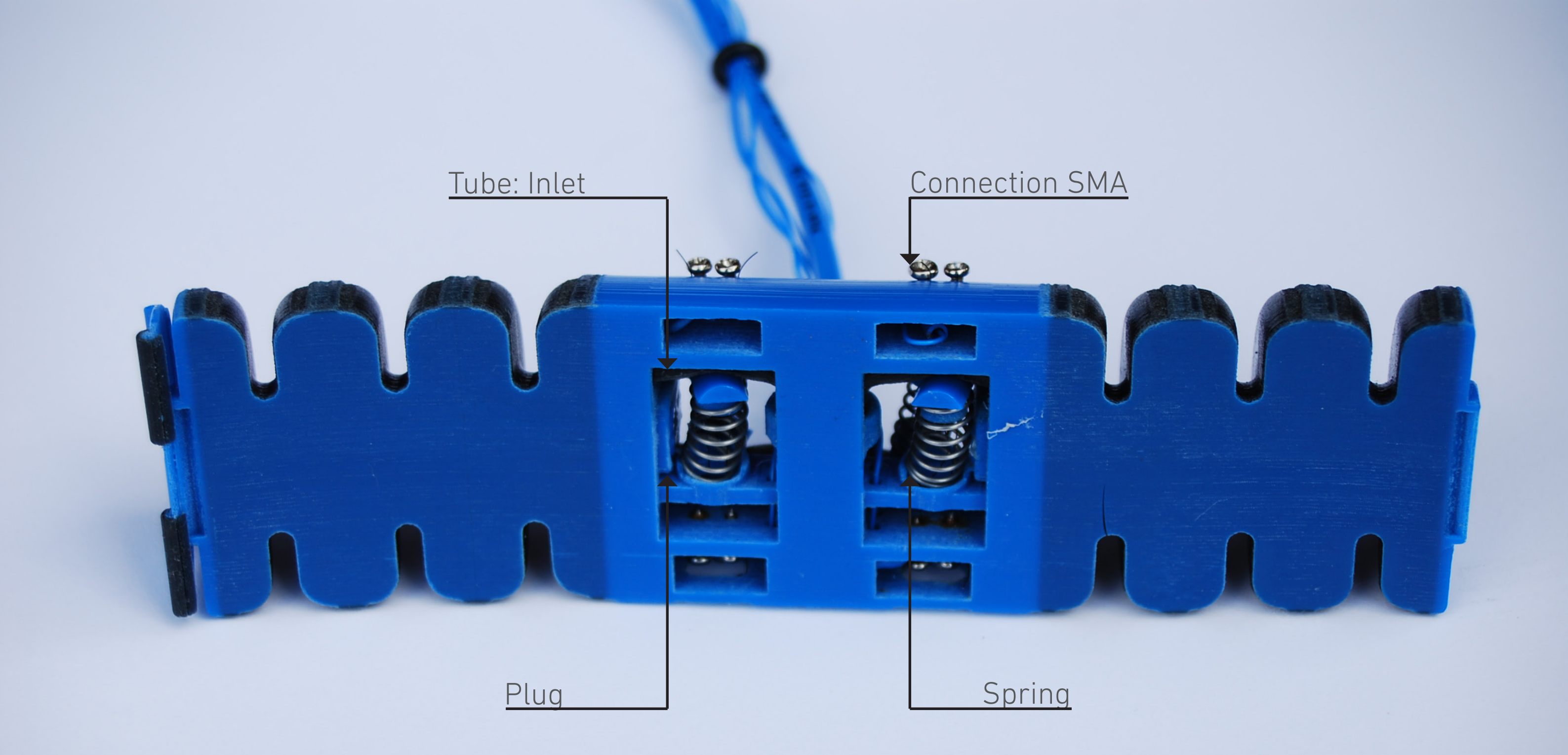


Figure 99: Bottom view

Demonstrator case study 2: Walking robot

The previous chapter has explained the well working valve attached to a single bellow. An important advantage of the miniature integrated valve is that it enables to control multiple bellows with a single tube or air supply. A demonstrator is designed including two bellows which can be controlled completely individual. This demonstrator consist of a walking robot. To make most efficient use of the occupied space of the double valve, the design is slightly adjusted.

Result

Figures 99-101 show the demonstrator of the valve attached to both bellows. The valve is designed in between both bellows in kept inside the outer shape of the cross section of both bellows. The SMA wires and springs are now placed perpendicular to the direction of the length both bellows. This choice is made to be able to remove the support material inside the bellows. It enables to supply the valves from one point in the middle with air. It takes at the same time an interesting turn in making most efficient use of the occupied space of both valves. This result in the total volume of both valves of only 40*41*18mm.

The SMA wires are made a little shorter resulting in 21 mm instead of 25 mm. Both bellows are supplied with only one tube or air supply and 5 electrical wires. All four valves air connected by 2 electrical wires. One of all four valves are combined into one electrical wire inside the model.

Figure 101 shows the inflated bellow. It is able to bend in 0.7 seconds and straighten back in 0.8 seconds, which is significant more than the 0.4 and 0.6 second of the first demonstrator. Possible reasons and solutions will be discussed at **Chapter Conclusion and evaluation.**

The demonstrator makes use of a manual control box to be able to experiment with the time to heat

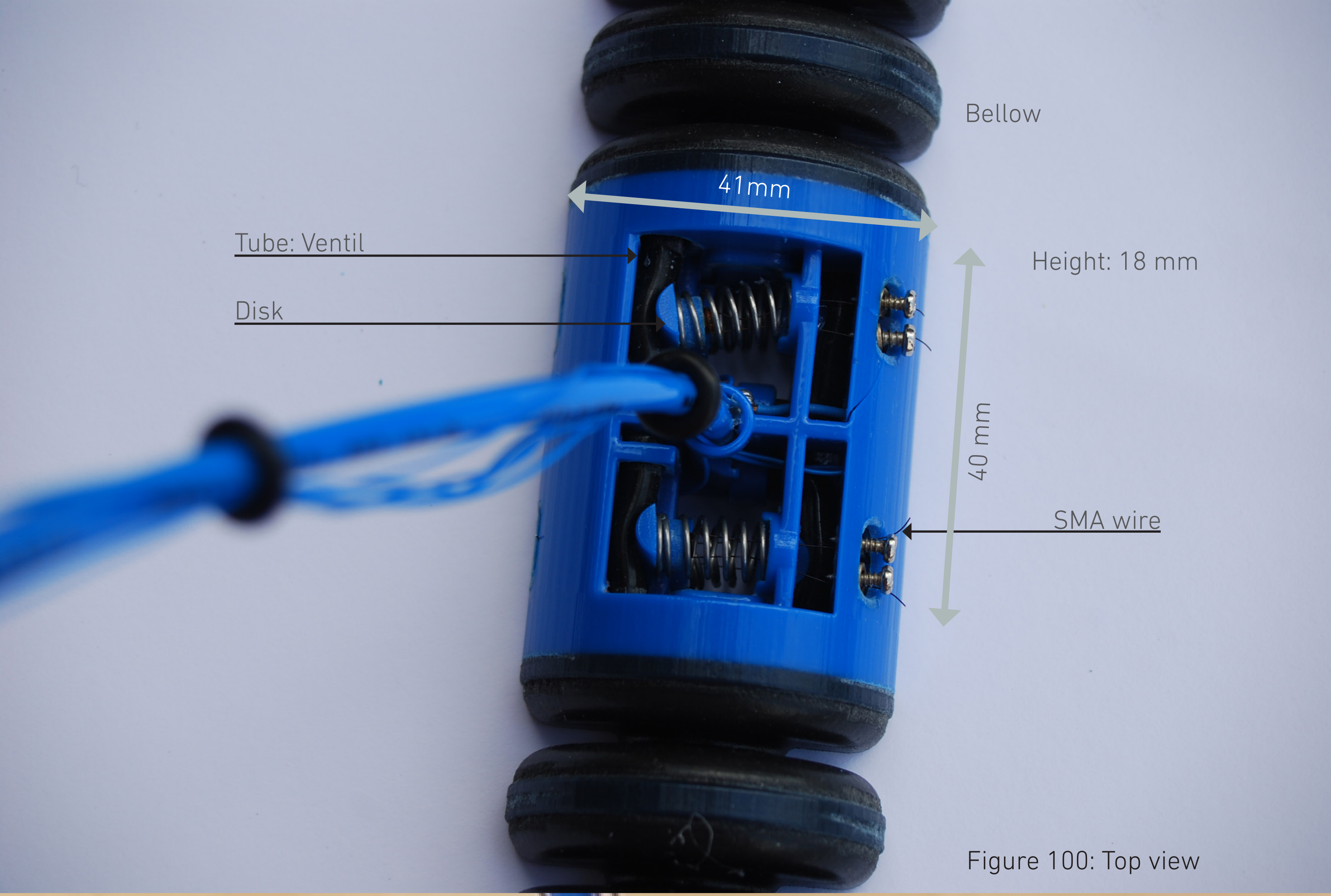


Figure 100: Top view

Figure 101: Both bellows inflated

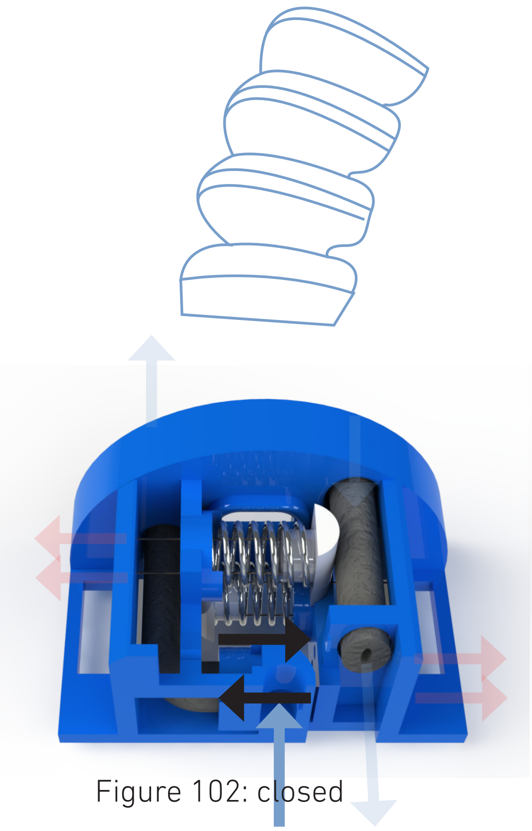


Figure 102: closed

Keep valve closed

Compressor pressurizes the model, but is blocked by the compression force of the spring. Therefore, the attached bellow stays deflated.

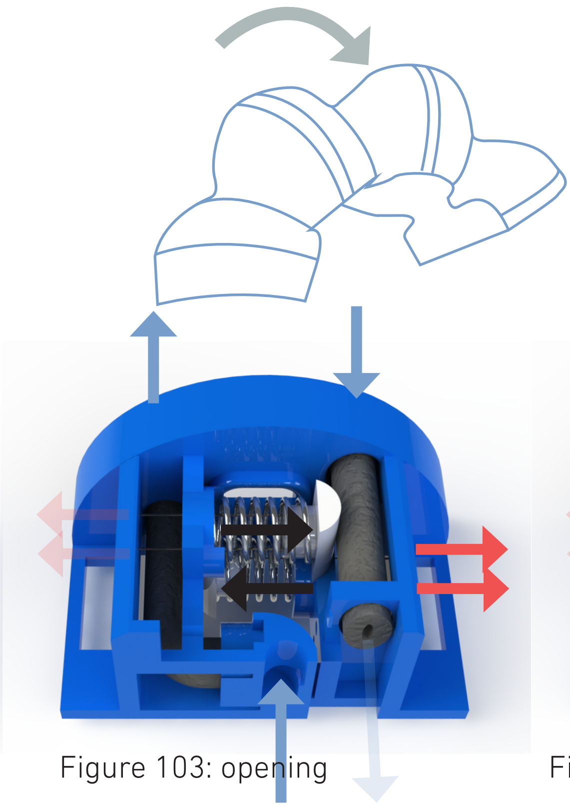


Figure 103: opening

Open valve

SMA wires are heated, and pull back the sprig to open the first valve. Finger starts to inflate.

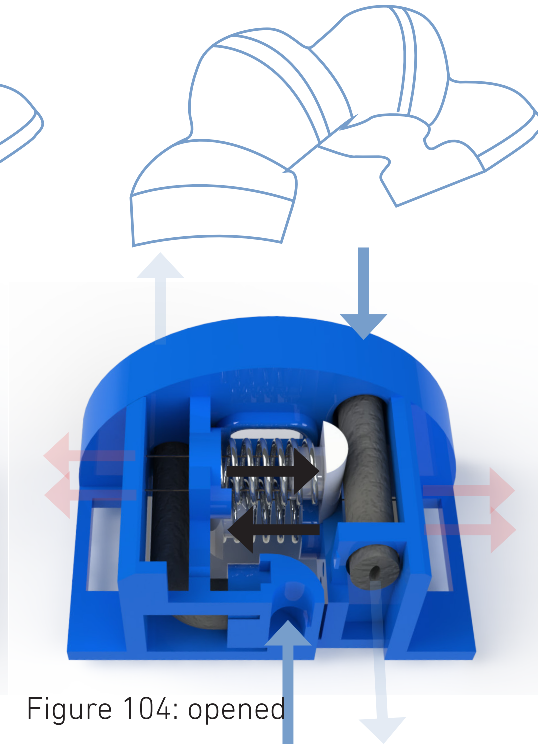


Figure 104: opened

Keep pressurized

When the SMA wires cool down, almost no air flows through the valve. Eventual small leakage in the bellow will be redress.

the wires. Different variations of plugs at the end of both bellows are 3 printed. The different designs have a grip layer to enables the robot to walk. The plugs with the results are explained in **Appendix R**.

More details about the demonstrator are explained and visualized at **Appendix R.**

Control of the valve

In **figures 102-106** is shown how the walking robot works. A compressor is attached to the both bellows via the valve. The figures only show one half of the valve and again, some walls to strengthen the valve are missing in these images to improve the visibility. The other side looks exactly the same and is supplied by the same inlet. Both bellows can be controlled completely individual.

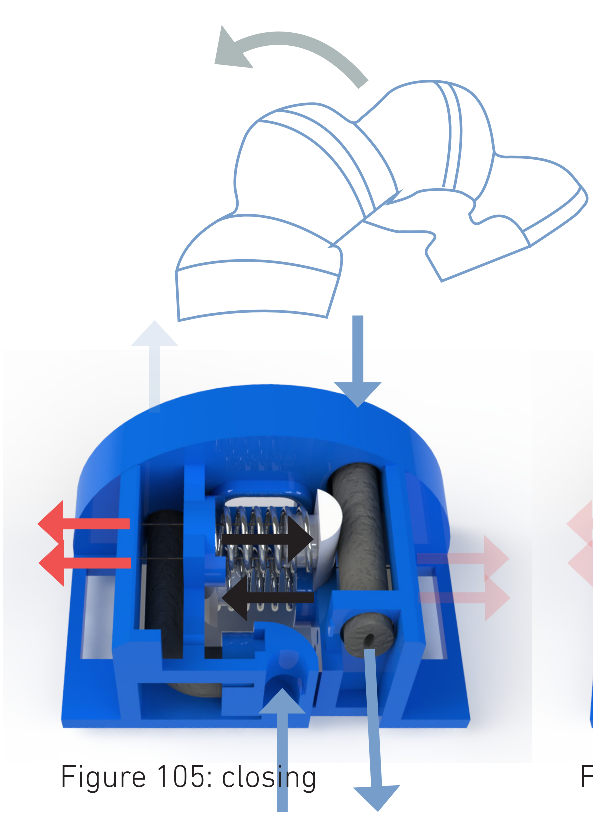


Figure 105: closing

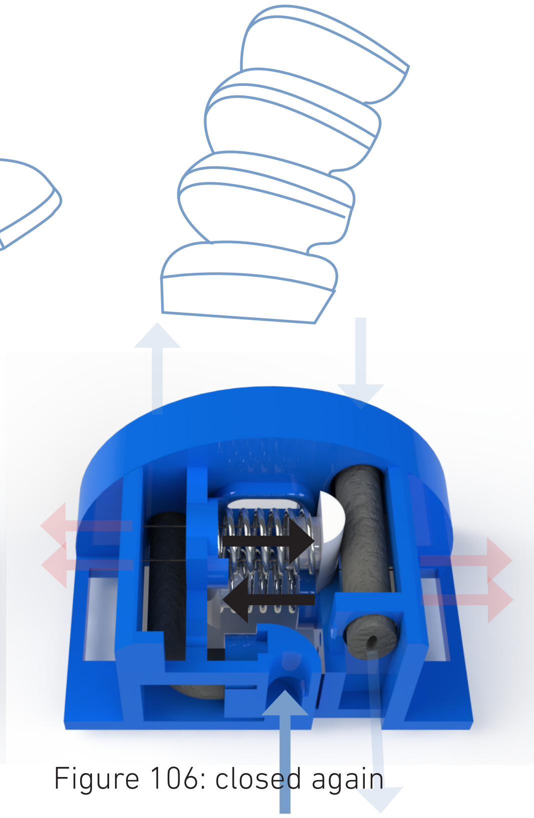


Figure 106: closed again

Deflate

Heating the second pair of SMA wires, the air starts flow through the second valve and the finger deflates. When the finger is deflated, the first valve fully closes.

Keep valve closed

When the SMA wires are cooled, the finger stays deflated.

Conclusion Case study 2

By designing this valve, the placement of the valve between the two bellows is taken in consideration. Beside both bellows will be supplied by a tube in between the two doubled valves, to keep the path to both valves equal. The goal was to keep the valve inside the cross section of the bellow and minimize the total length. Because the width is limited to a dimension of 44mm, instead of as small as possible, the working direction of the valve is changed by 90 degrees compared to Case study 1. This makes it able to keep the length between the two bellows not too long. Using twice the design of case study 1 would result in a length of 88mm. It is now only 40mm.

Benchmark

This chapter will compare the final result with current solutions to control the airflow for soft robotics. With knowledge gained during this assignment, an estimation of potential valve will be included in the comparison between the valves.

Figure 107: Asco: Miniature solenoid valve

Weight:	47 grams
Volume:	46*17.5*17.5mm
Integration:	no
Control flow rate:	no
Pressure:	7 bar
Flow rate:	19l/m
Power	2W
Price:	44$

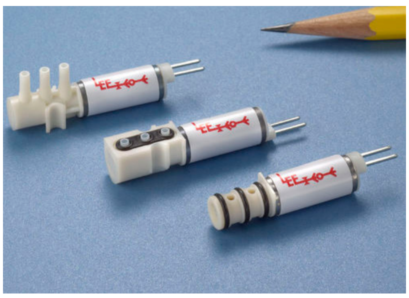


Figure 108: Lee: Miniature solenoid valve

Weight:	4.5 grams
Volume:	7.5*7.5*34 mm
Integration:	no
Control flow rate:	No
Pressure:	2 bar
Flow rate:	6 l/m
Power	0.5 W
Price:	12$

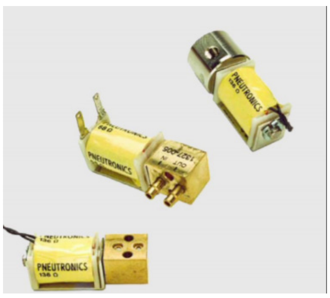


Figure 109: Parker: proportional valve

Weight:	63 grams
Volume:	16.5*17*45.3 mm
Integration:	no
Control flow rate:	Yes
Pressure:	8 bar
Flow rate:	20 l/m
Power	2 W
Price:	12-150$

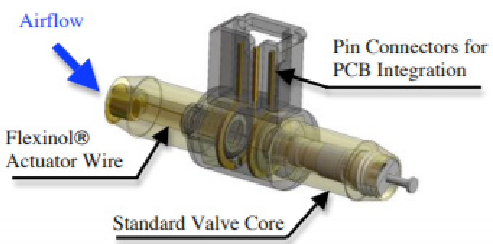


Figure 110: Dynalloy SMA proportional valve

Weight:	4.5 grams
Volume:	7.5*7.5*34 mm
Integration:	no
Control flow rate:	Yes
Pressure:	7 bar
Flow rate:	20 l/m
Power	0.5 W
Price:	30$

Current Design

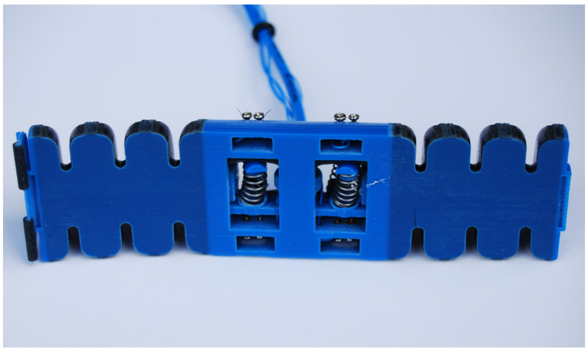


Figure 112: Miniature SMA valve

Weight:	6.6 grams
Volume:	41*18*20mm
Integration:	Yes
Control flow rate:	Yes
Pressure:	1 bar
Flow rate:	20 l/m
Power	1.2 W
Price:	18$

Expectation

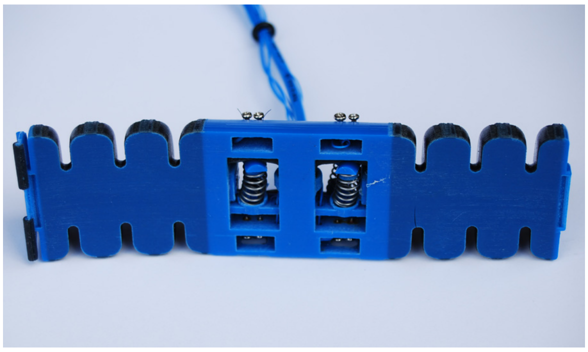


Figure 111: Potential miniature SMA valve

Weight:	5 grams
Volume:	<41*18*20mm
Integration:	Yes
Control flow rate:	Yes
Pressure:	4-8 bar
Flow rate:	20-40 l/m
Power	0.25 W
Price:	18$

As explained in **Chapter Peumatic soft robotics**, controlling a soft robotic by placing multiple valves inside the body requires a low volume and weight. All current solution consist of separate valves which need to be connected. This takes extra space and can also cause air-leakage. The design of the assignment fills this gap. It is 3D printed which makes it lightweight. It is not as small as the smallest valve on the market, but because the shape can be adapted to any desired volume and printed together with the same model makes it much easier to ingrate. This makes it at the end to smallest solution to control multiple bellows integrated inside a soft robotic. It is actually smaller en much more lightweight than a proportional solenoid valve which is also able to control the flow rate. The current print quality enables it to only apply 1 bar, but the assumption can be made that this will improve in the future. In this case, it is able to withstand up to 4-8 bar, as proved during the prototype phase making use of a silicone tube.

Tool to control any pneumatic soft robotics

This report has explained how to control the air together with the potential to control the flow rate for soft robotics. The eventual goal is to create a tool to automatically model the composition of valves to control a single or multiple bellows in the available volume inside the body of the soft robotics. The required air pressure, flow rate, volume, amount of bellows and the orientation of the bellows will be taken into account. This will result in selecting the suited spring dimensions, SMA wire and composition of the valves. This chapter will explain which steps are required to achieve this tool and which parameters have influence on the design.

During this graduation assignment, a valve is designed based on the implementation inside a robotic hand, named case study 1. The required air pressure of 1 bar, volume in dimensions of all three axis, orientation of the valve and flow rate are taken in consideration. During case study 2, the requirements in volume and orientation of the bellows was different. This resulted into a different design. In the future, even more variations in parameters are possible. Besides, changes in required air pressure and flow rate will have influence to the final design of the valve. The steps of the tool are visualized in **figure 113**.

How will the tool work?

1. Flexible tube

The required air pressure will determine the properties of the tube. The tube needs to be tested if it can withstand the pressure and the related force of the spring. The available volume can also have impact on the design of the tube. This is because the diameter and length of the tube has influence on the volume of the valve. The required flow rate determines the inside minimal diameter of the inside of the tube.

2. Spring design

The design of the tube has influence on the required force to be able to block the flexible tube which has influence to the design of the spring. The available space has also influence on the length and diameter of the spring.

3. SMA wire

The pressure inside the tube together with the properties of the tube have influence on the type of SMA. Hereby, the required flow rate determines how far the tube needs to be opened. This Affects the length of the SMA wire.

Design of single valve

At this point, the properties of a single valve are determined. But, each bellow needs two separate valves. Using multiple valves require even more valves.

4. Placement of the valves

The flexible tube together with the spring and SMA must be doubled to be able to control the inflation and deflation of a bellow. This creates multiple possibilities. The valves can be placed next to each other, behind each other or on top of each other. They can face to the same direction or the opposite direction. This choice is based on the requirements from the available volume, orientation of the bellows and amount of bellows.

Next steps

To be able to supply soft robotics by more than 1 bar, a better quality of the tube is required. The assumption can be made that in the near future a better quality of flexible material will be available. This could also have positive influence on the current valve by using smaller tubes resulting in a smaller valve. The valves will be controlled automatically. This will require electronics including a control board and program to control the valves. The flow rate can be adjusted by changing the applied current. More testes will figure out what current will result in which inflation/defltion speed.

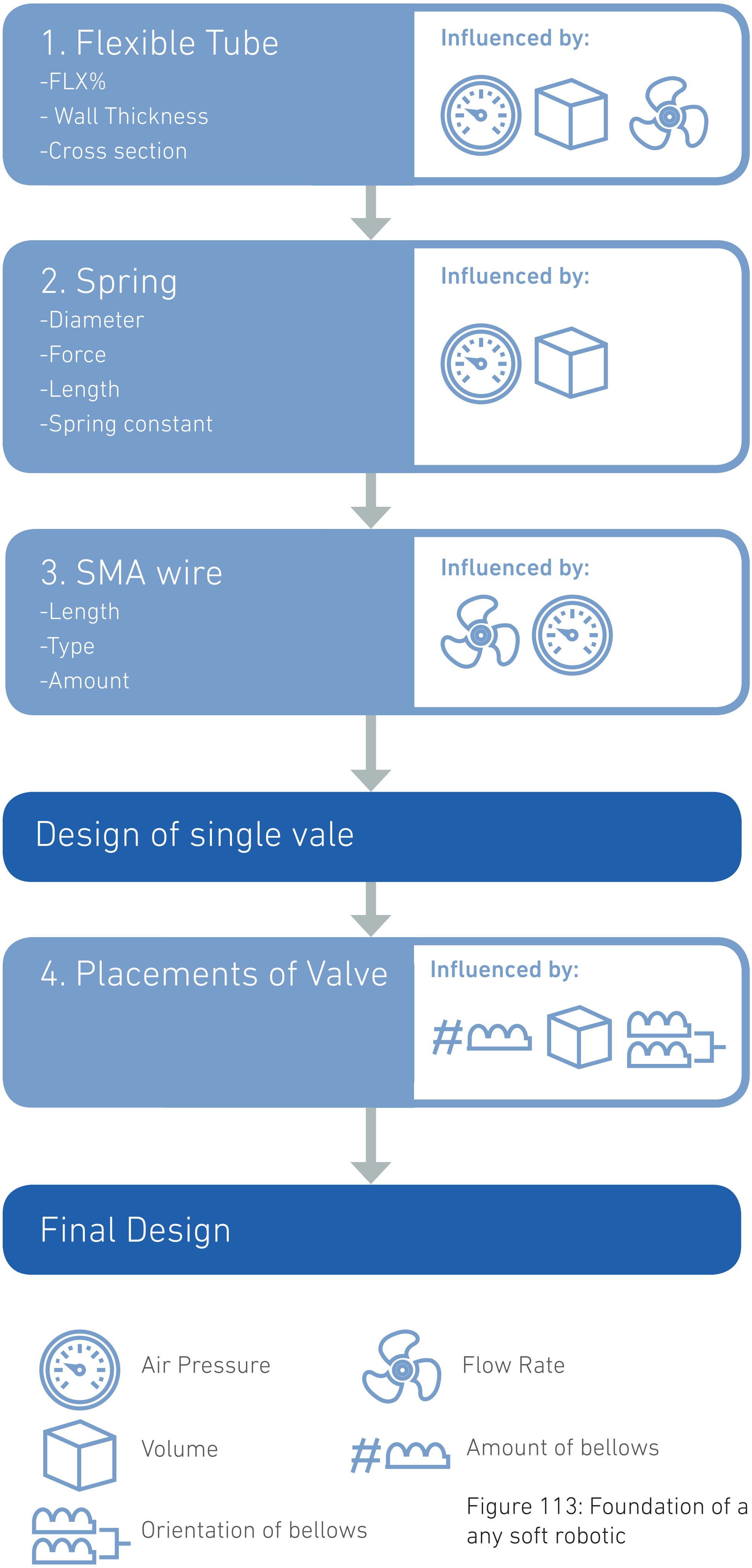


Figure 113: Foundation of a tool to control any soft robotic

Evaluation

This part elaborates on the conclusions about the final results gathered during the this graduation assignment. It evaluates on the results and design decisions. A list of recommendations explains the steps to improve the current design of the valve.

Conclusion and evaluation

The goal of this assignment was to create a product or mechanism making use of the unique properties of Shape Memory Alloy actuator wires. By exploring the world of SMA an interesting collaboration with pneumatic soft robotics is found. Pneumatic soft robotics is something relative new and is quickly evolving. Being able to 3D print soft bodies brings many new opportunities in creating complex and integrated soft and flexible products.

During the analysis was found that current soft robotic products including multiple air chambers are supplied by multiple air supply tubes connected between the air source and body of the product. Current valves to control and divide the incoming air have a large volume, are heavy and expensive and all have a standard design which is not adaptable to the diversity in shapes and volumes of the current portfolio of soft robotics.

SMA actuator wires can play in important and interesting role in fulfilling the need of the gap of integrated miniature valves. The design goal of this graduation assignment is therefore formulated as following:

Design a 3D printed miniature integrated valve which controls pneumatic soft robotics including multiple air chambers. Make use of SMA actuator wires to actuate the valve to divide the air and control the actuation of the bellows including the bending speed.

To prove the functionalities of the design, a case study is formulated which is based on controlling a pneumatic robotic hand by integrating the valves inside the hand-palm. The demonstrator included one valve attached to a bellow to control the inflation and deflation of the bellow.

A second demonstrator is build to show a single tube supplied with air to divide the air inside a small body of a walking robot. The choice is made to design a pneumatic walking robot including two bellows which are controlled separately to make it move forward.

In the future, a tool can be created to be able to create a design for any desired soft robotic with various air-pressure, flow speed and amount and orientation of the bellows inside an available amount of space.

Flexible tube

Both demonstrators make use of flexible tubes which is opened and closed. Because the flexible tubes are attached to the body of the bellow, no connections are required to control multiple bellows. This minimizes the change of any air leakage and simplifies the total design by not needing multiple separate electronic driven valves.

By starting the prototype phase, a silicone tube is used. It was able to withstand 4 bar, but most soft robotics use only 0.5-2 bar. A first concept of a valve was tested successfully, but replacing the silicone tube to the 3D printed flexible tube had many consequences. The quality of the 3D printed tube is not able to withstand up to 4 bar. It appeared to withstand only about 1 bar while compressing it while supplied with air. At the end, it has not been a deal breaker because the bellow used in the demonstrator can only withstand 0.5 to 1 bar. It is found that the tube needs to be printed with a 100% flexibility and by making use of an oval shaped tube, the valves has to be opened less in height which is beneficial to the flow speed and at the same time failure of the tube. This is because the tube is faced with a smaller acting force and deflection when compressed while supplied with air pressure. Because the lack in quality of the tube, the tube shows creep when supplied with air for a long period. Therefore, the prototypes show some decrease in functionality over time. The decrease in functionality is experienced in a slower response in opening the valve and reaching less fast bending speed of the bellow. Therefore, both demonstrators are only supplied with air pressure when controlled and shut from the compressor right after usage.

Spring

During the prototype phase, the required force is tested to be able to close the valve when supplied with 4 bar. A spring is used with minimal dimension in length and diameter. Both demonstrators only makes use of 0.5-1 bar. This results in less force to be able to close the valve while supplied with air pressure. It requires 4.2 N to keep the valve closed. Because the tube has a width of 6.5 mm, the diameter of the spring does not have to be decreased. Therefore, the same spring is used for the demonstrators.

In future applications making use of multiple bellows, the spring length and diameter could have more importance. Selecting the minimal dimensions creates more design freedom to be able to create a miniature valve. Specially when a future application is supplied by a higher amount of air pressure. The spring constant on the other hand is of great importance to the choice of SMA wire which determines the actuation frequency of the valve.

Another interesting conclusion is about the required force the valve to close. There is a significant larger force required to close the valve when the bellow is fully inflated and pressurized. In fact, the first valve does not fully close when the wires cool down. The first valve closes at the moment the seconds valve opens. The pressure inside the bellow drops which makes the first valve to close. In this way, any small amount of air leakage is supplemented during the inflation of the bellow and a less amount of spring force is required which has beneficial influence on the total volume of the valve.

SMA wire as valve actuator
The SMA wires used in the first demonstrator have a length of 25 mm. It enables the valve to make the finger bend in 0.4 seconds and deflate in 0.6 seconds. The demonstrator of the walking robot has SMA wires with a length of 21mm and enables the bellows to bend in 0.7 seconds and deflate in 0.8 seconds. This is an significant increase. It is most likely not only due to the length of the SMA wires, but also because the disks are not placed completely properly because of a small design mistake.

The SMA wires used for both demonstrators have a diameter of 0.15 mm. It results in a cooling time of 1.7 seconds. This means the valve can re-open after 1.7 seconds. Actually, a thinner SMA wire can be used which results in faster cooling times. This means the actuation frequency can be further improved. When the first valve is opened, it cools down directly. During the deflation of the bellow which takes another 0.6 seconds, the SMA wires of the first valve already cool down. This increases the actuation frequency of the valve. Using 0.1mm SMA wires which in theory can be used to open the valve acting with 1 bar, the cooling time is only 0.9 seconds. By deflating the finger directly, only 0.9-0.6= 0.3 seconds have to be waited to bend the bellow again after direct deflation.

The inflation time is faster than the deflation time because the valve acting the make the bellow bend is supplied with a constant overpressure of 1 bar. By deflating the bellow, the chamber drops in air pressure while deflating. Therefore, it takes a little more time to deflate.
Applying a smaller current can make the bellows to inflate and deflate slower. Prototypes have shown to supplying the wires with 0.2-0.7 A, the bending speed of the bellow increase from 0.3-1 seconds. Supplying 0.7A, the bellow starts to bend directly when the current is applied. The bellows show a little increase in bending speed during this movement. Using a feedback control system, the wires can be controlled in temperature by adjusting the applied current during the inflation. This can enables the valve to control the flow rate, thus bending speed of the bellow accurately.

Total volume of the valve
A compressed spring is placed on top of the tube with a disk in between to close the tube properly without causing any failure of the tube. To open the valve, SMA wires are supplied by a small current. Both the spring and SMA wire act perpendicular to the direction of the flexible tube. Because each bellow need two separate valves to control the inflation and deflation separately. A set of valves are working together to control multiple bellows. The valves can be placed next to each other, on top of each other or even make use of the same space. This creates a lot of design freedom to adapt the shape of the entire control mechanism to any desired or required volume.

Both demonstrator show already two different solutions of placing the separate valves to make efficient use of the available volume.

Both demonstrators show the result of a small miniature valve which are both able to control the incoming air. The lack of quality in quality of the tubes results in relative large wall thickness of the tubes and a large radius of the angle in the path of the tube. It shows room for improvement.

The demonstrator of the walking robot is designed by placing the two springs a little too close to each other. This result in the disks to not remain fully horizontal. This is because the body which the spring of the other valve rests on interferes with the disk. This could be solve by placing the two valves a few mm more from each other, use a shorter spring or longer SMA wires. The demonstrator shows the simplicity of dividing the air to two bellows with each two separate valves. placing the valves to control two bellows takes also twice the amount or less of volume. This is an interesting result which is not realistic by making use of standard designed solenoid actuated valves.

Fixation of SMA wires
In both demonstrators, the SMA wires are fixated by pulling the wires through a hole inserted by a small screw. This solution works, but is not quite smooth. Besides, inserting the screw makes the SMA wire wound around the screw which influences the strained length of the SMA wire. It sometimes take a few attempts to create the right amount in length of the SMA wire placed in the valve. When the length is to much, the wire is not fully straighten. When the length is not long enough, the SMA wire pulls the valve a little open before actuating the valve.

Walking robot
Case study 2 focuses on controlling a walking robot including two bellows. They can be controlled separately by using only one air-tube which supplied the robot of air pressure. This was the main goal of this case study. A additional goal was to make the robot actually to move forward. Unfortunately, this is not realized yet.

More time is required to make the robot actually walk forward. Possibly a few iterations are required.

Choice of Design direction
The analyses explained the following findings about the advantages SMAs offer:

Lightweight
Silent operation
Deploy simple current
Small volume
High actuation density
Able to keep in contracted position

But some limitations:

Relative slow cycle frequency
Bad energy efficiency

The choice is made to create valves actuated by making use of SMA wires. It is concluded that this application makes efficient use of both advantages and disadvantages.

Pneumatic soft robotics require a lightweight design and small volume. By applying a simple current, multiple valves can be controlled easily. Because only a relative small force is required, thin (0.1mm in diameter) SMA can be used. They have a cooling time of only 0.9 seconds. Because two valves are not heated at the same time to inflate and deflate the bellow, a fast actuation cycle can be realized. Only 0.25W is required to open the valve.

Using SMAs to actuate soft robotics without making use of air-pressure, much more force is required which has large influence on the actuation frequency and power supply. Therefore, the collaboration together with pneumatics is an interesting choice making smart use of the limitations of SMAs.

Recommendations

Flexible tube
During this project was founds that the 3d printed flexible tube was only able to withstand 1 bar and can't be faced with air pressure for a long period without decrease in functionality.

- The assumption can be made that the printing quality of flexible materials will be evolved which solve this problem.

- More research can be performed in finding the best thickness and cross section of the tube to be able to make the tube withstand more air pressure but at the same time allow a fast flow rate.

- By attaching the bottom of the tube to the to surface its floating above and by attaching the top of the tube to the disk, the decrease in response time over time could possibly be prevented. In this way, the tube would possibly opened easier and won't stick together.

Spring
For both demonstrators, the dimensions of the springs have no leading role in the design of the valve. When working with higher pressures, this could have more influence on the design. For the demonstrators a 0.15 mm in diameter SMA wire is used. By optimizing the spring, faster actuation frequency can be realized.

- The mathematical model which is created making use of the formulas to determine the spring dimensions, a suited spring design can be chosen for any desired scenario.

SMA as valve actuator
The SMA wires work well to open the valves enable the bellow to bend in 0.4 seconds. This could possibly be increased even further by:

- Making use of PWM signals
- Increase the SMA wire length a little further

Some experiments regarding the flow rate have been performed. It showed different bending speed of the pneumatic finger. To be able to determine a certain flow rate, more research is required between the relation of applied current to the inflation speed.

Besides the current, the type of actuator, diameter of the tube and pressure have influence to the result.

Using a feedback control system sensing the temperature of the wires, the temperature of the wires can be controlled more precisely which enable to control the flow rate better to being able to determine the (constant) bending speed of the bellow.

Total volume of the valve
The valve used with the demonstrator of the walking robot has the volume of 40x41x18. Because it contains the valves to control 2 bellows, a single bellow would only need 20x41x18 mm.

- A better printing quality can lead to smaller flexible tubes which have impact on the total volume of the valve.

- Analyzing the current design can eventually lead to new ideas to place the valves differently to make even more efficient use of the total volume.

Fixation of SMA wire
The current solution works but can be improved.

- Find a way to clamp the wire which takes as less as possible of space.

Control
The valve is now controlled manually, but the idea is that the valve is controlled automatically by using a control board and a battery supplying the SMA wires of a current.

Opportunity: Autonomous walking robot
A miniature valve leads to new opportunities. Because the valve can be integrated into a lightweight body, no connection tubes needs to be used. Using a small sized control board together with a small micro-pump, an autonomous small and lightweight robot can be designed. More research is required to make the robot actually to move forward.

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