Appendices

A. Different types of SMMs

High temperature memory alloys (HTSMAs)

HTSMAs can operate in high-temperature applications, operating above 100 °C. These alloys have different alloy composition, some including also Ti and Ni. The different variant are categorized in operating temperatures: 100-400C, 400-700 and >700C. See appendix XXX for a table with the different material variants (Ma, 2013). The disadvantage is the difficulty in training them because of poor ductility or poor fatigue resistance at room temperature. This also results in high additional costs. A higher operating temperature makes different characteristics increasingly more difficult to satisfy. This includes acceptable recovery strain and long term stability (Ma, 2013). Despite of intensive recent research, this variant is not yet attractive for commercial use.

Magnetic shape memory alloys (MSMAs) or ferromagnetic shape memory alloys (FSMAs)

MSMAs can actuate on higher frequencies (up to 1 kHz) because the absence of the limited heat transfer but using magnetic field instead. (Tellelin, 2004) This makes it attractive for motor and valve applications needing larger displacements with lower applied force. The disadvantages are the properties of brittle, stiff and only operable at low temperature. This makes it less attractive by using higher temperatures and applied forces. MSMAs are promising candidates for fast and highly accurate positioning systems with potential areas in robotics, medical surgery and pneumatic and hydraulic valves. (MSMnet, 2016)

Shape memory thin film (SMM)

SMMs are mostly applied in microelectromechanical systems (MEMS) serve as mini actuators. (Winzek, 2003) Most powerful alloy is TiNi based which can provide high work output. This NiTi micro actuator can be fabricated in micro dimensions and still produce relatively high force and displacement which ordinary MEMS devices don't have. Interesting industries are biomedical, aerospace, automotive and consumer markets. (Nitin, 2016)

Shape memory polymers (SMPs)

SMPs have lower costs than the SMAs and are more easily manufactured and faster to train. The disadvantages are lower response time and less applicable force to it. At the other hand, they can accurately controlled at a specific transfer temperature. (Voit, 2010)

B. Shape memory effect

Shape Memory Effects

Explaining the steps according to a visual
The explained steps are visualised in **figure 1**.

OWSME:
Step 1: Loading
By deforming a pre-defined twinned martensite under stress, the structure will change to untwinned martensite.

Step 2: Unloading
By unloading the stress, the deformed shape and untwinned martensite structure will remain.

Step 3: Heating
By heating the material to the austenite phase, the material will change to the austenite structure and reform to the pre-defined shape.

Step 4: Cooling down
When cooling down, the material has already it's pre-defined shape because of the applied heat, but will also return to the twinned martensite structure.

TWSME:
The first 3 steps are the same as with the OWSME, but when the material is cooled down step 4 is replaced by step 5.

Step 5: Cooling down
When cooling down, the material changes to a second pre-defined shape in the low temperature martensite phase.

SE:
The superelasticy effect only take place between Af and Md including steps 6 and 7.

Step 6:
Applying a load will make the material change to detwinned martensite and show elastic deformational behaviour.

Step 7:
Unloading will directly result in changing back to the austenite phase and original shape.

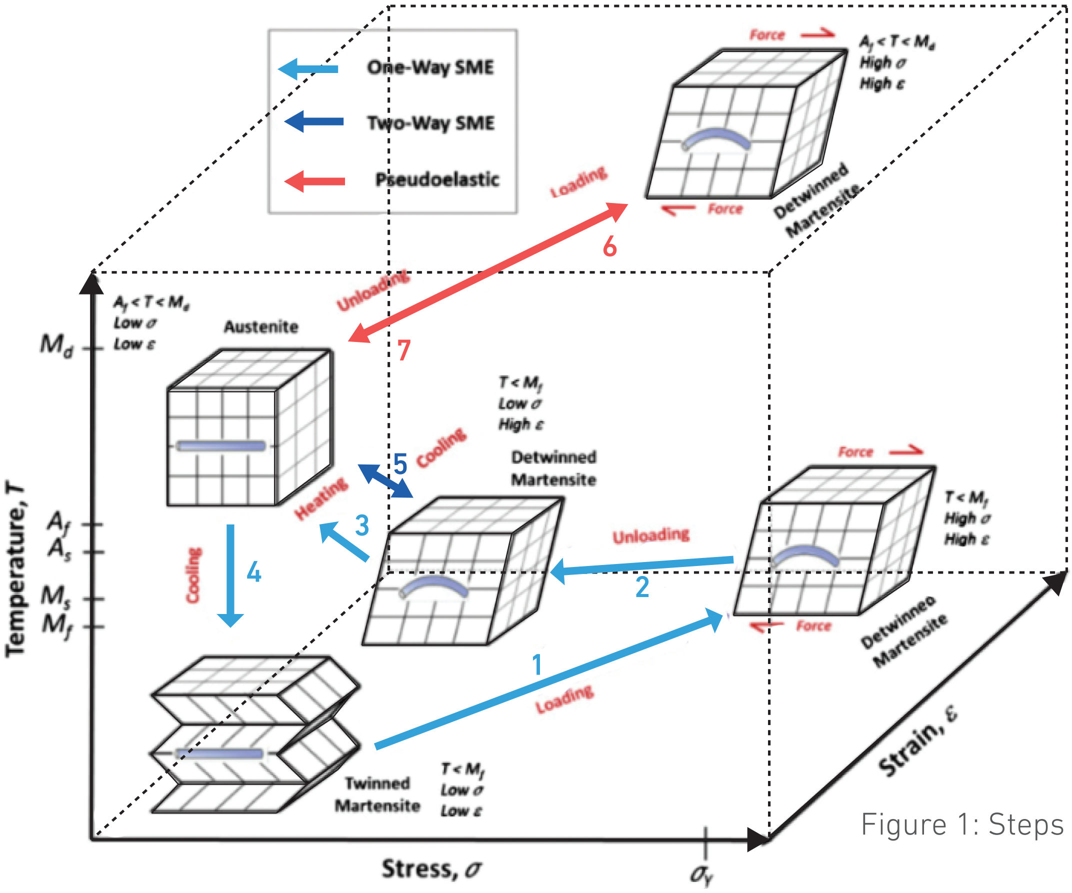
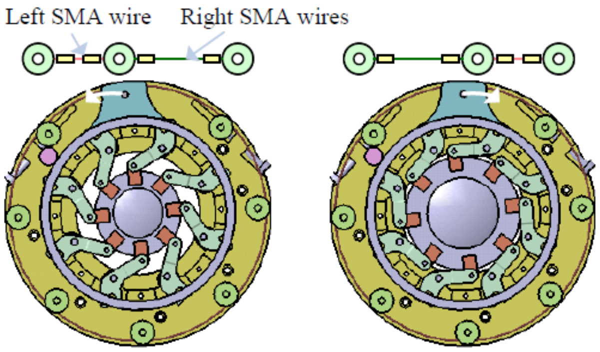


Figure 1: Steps in SME

C. Keep wire contracted

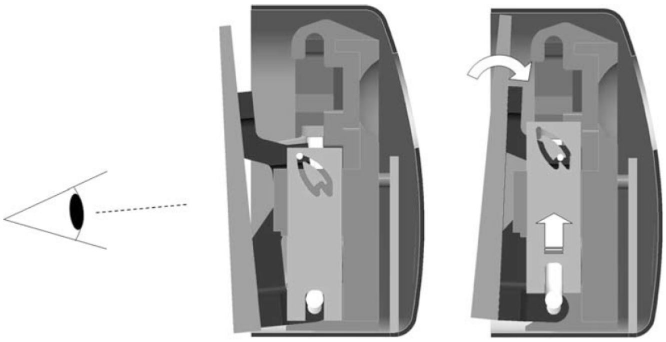
SMA wires can be kept contracted, but it required great care to not overheat the wires. There are also some mechanical solutions to keep the wire contracted. Some interesting examples are shown in **figures 2-6**. The applications are also explained in the main report, **chapter Applications. Figure XX** makes use of a part which is attached to the SMA wire which moves over a grip layer. It only moves when the wire is contracted, or pulled back by the other SMA wires acting in the opposite direction. The latching mechanism in **figure 2** work about the same. Two bowls are pushed towards each other. Only when the SMA wires are heated, the inner bowl rotates. **Figure 3** works a little different. The SMA wires are connected to a pin which moves along a path. The pin can rest in two positions. Every time the wires are heated, the pin slights into the other position, and back. The example is shown in **figure 4**. **Figure 5** makes use of magnets to keep the pins connected to the SMA wires in position. The force of the contracting SMA wires overcomes this force the magnets deliver. **Figure 6** shows a latching mechanism which makes use of a part sliding over a path. When the wire stops moving, it is fixated.



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

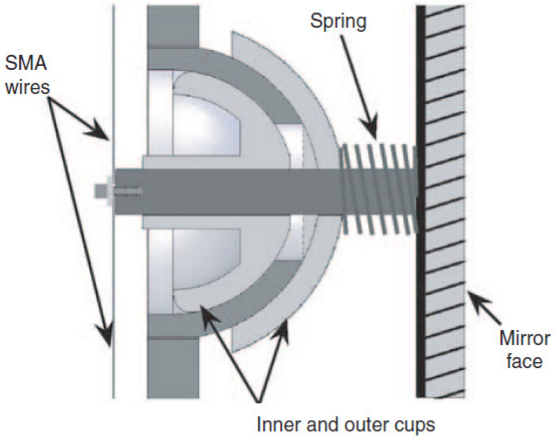
Fig. 7 Operation of KNU eye.

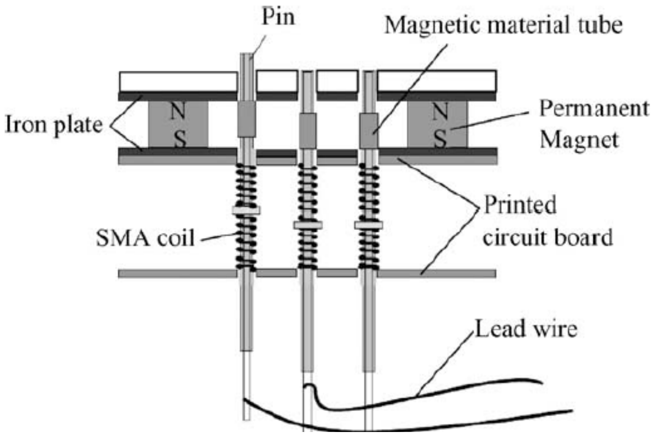
Figure 5. Robot eye

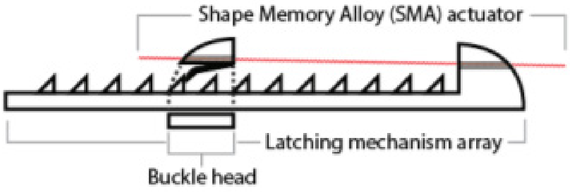


First stabile position

Second stabile position

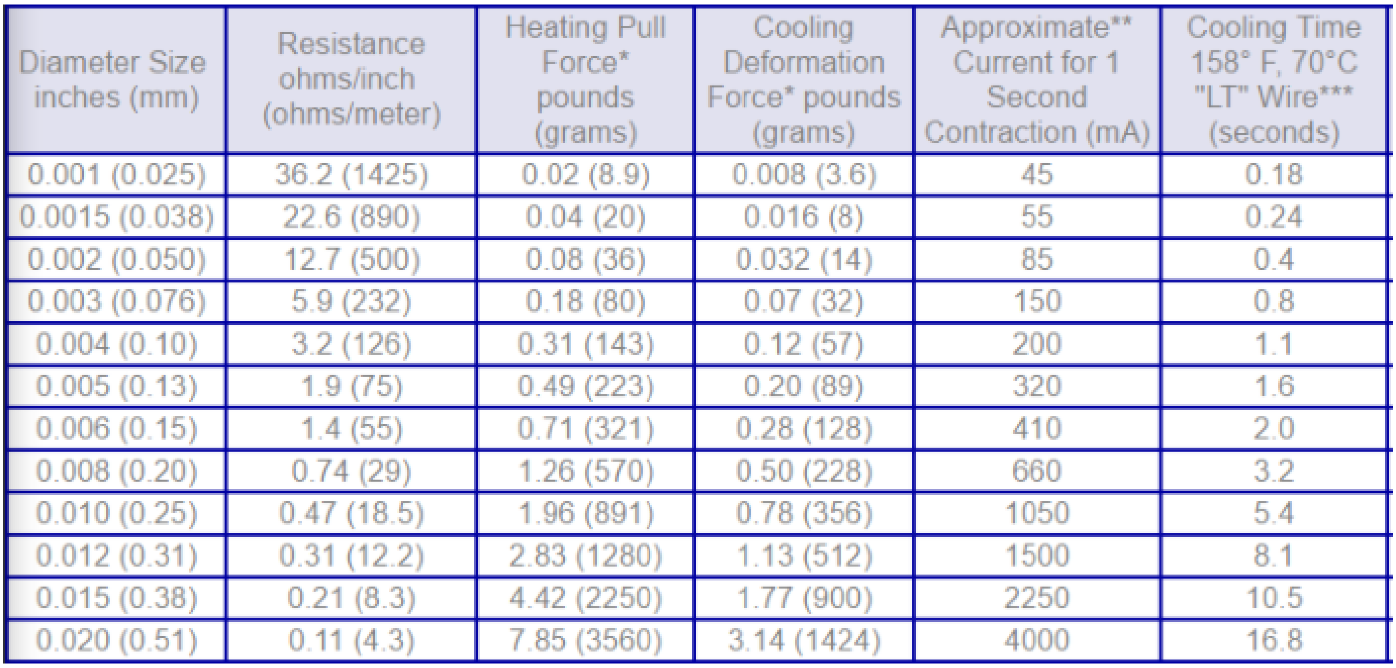






D. Properties of SMA wires

The cooling time depends on the activation temperature and diameter of the wire. The diameter has most influence. The exact properties of the Flexinol wire are shown in **figure 7**.



Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Heating Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158° F, 70°C "LT" Wire*** (seconds)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	0.008 (3.6)	45	0.18
0.0015 (0.038)	22.6 (890)	0.04 (20)	0.016 (8)	55	0.24
0.002 (0.050)	12.7 (500)	0.08 (36)	0.032 (14)	85	0.4
0.003 (0.076)	5.9 (232)	0.18 (80)	0.07 (32)	150	0.8
0.004 (0.10)	3.2 (126)	0.31 (143)	0.12 (57)	200	1.1
0.005 (0.13)	1.9 (75)	0.49 (223)	0.20 (89)	320	1.6
0.006 (0.15)	1.4 (55)	0.71 (321)	0.28 (128)	410	2.0
0.008 (0.20)	0.74 (29)	1.26 (570)	0.50 (228)	660	3.2
0.010 (0.25)	0.47 (18.5)	1.96 (891)	0.78 (356)	1050	5.4
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1.13 (512)	1500	8.1
0.015 (0.38)	0.21 (8.3)	4.42 (2250)	1.77 (900)	2250	10.5
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	3.14 (1424)	4000	16.8

Figure 7: Properties Flexinol wires (Dynalloy Inc)

E. Cooling techniques

There are different cooling techniques to be able to decrease the cooling time of the SMA wire. Figure 8 shows some different solutions. Without any cooling techniques, the cooling time of the wire is 1.6 seconds.

A: Low speed air. A 12V computer fan confining the flow through a 40x89x245 tube. Result 1.1 seconds

B: High speed air. Make use of compressor, SMA wire through 8.9 mm in diameter carbon fiber tube. Result 0.7 seconds

C: Heat Sink. A aluminum tube as heat sink. Only make contact when the wire is cooled. Result 0.7 seconds.

D: FLuid quenching. Water injected into the tube with a velocity of 2.7 m/s. Result 0.4 seconds.

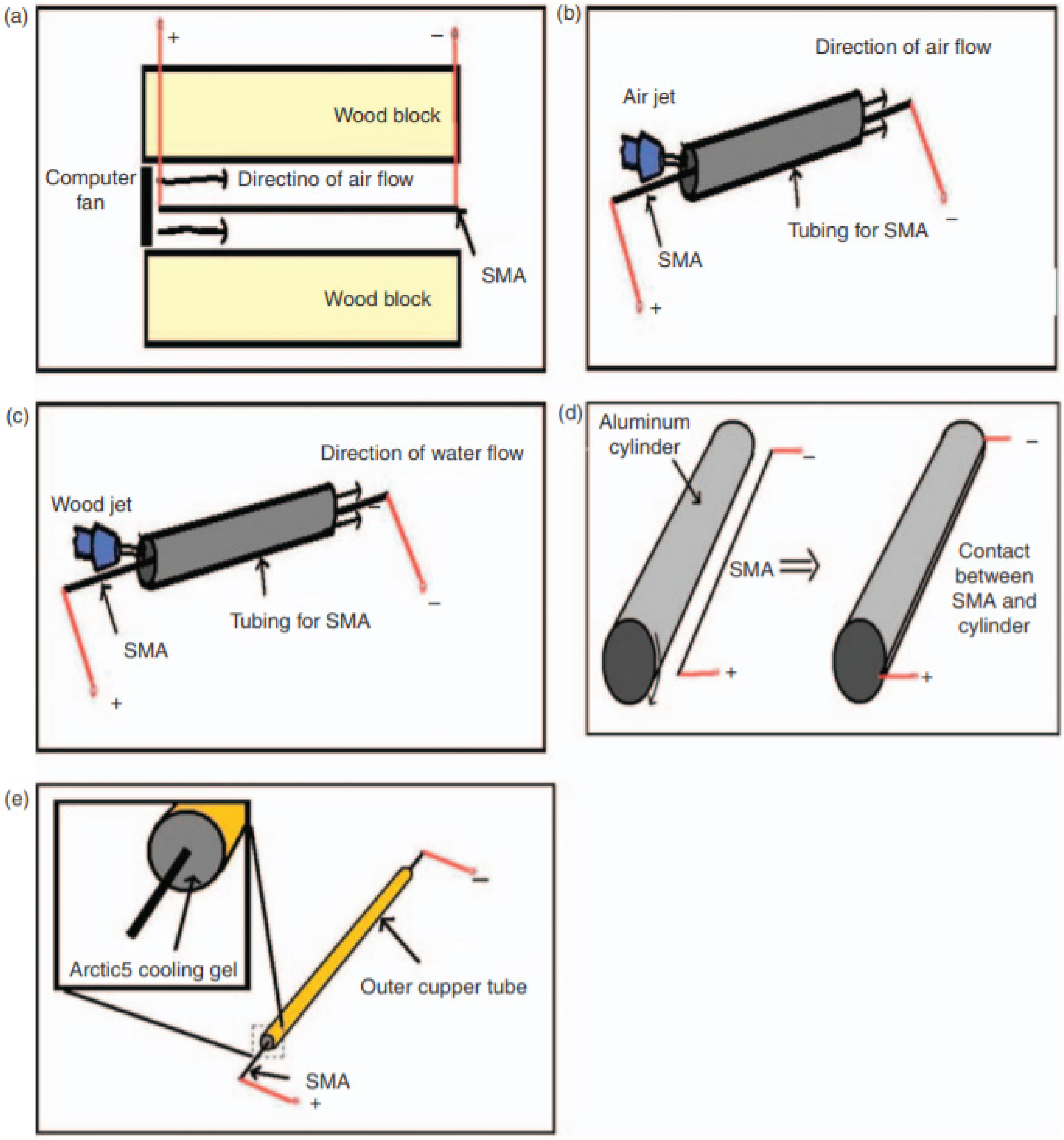


Figure 8: Cooling techniques (Tadesse et al, 2010)

F. Applications SMA wire

This chapter will show and explain applications of some different types of Shape Memory Alloys.

OWSMAs can be set in motion by heat. This can also be done by applying electricity. The first examples don't use electricity to heat the SMA. As mentioned in chapter: History, one of the first applications was CryoFit. SMA as pipe couplers which connected hydraulic tubing in the F14 jet figher. (Springer, 2008) **See figure 9**.

Figure 10 shows a thermostatic valve including a sma spring and bias spring placed in serie to resist each other which neither makes use of electricity. The SMA spring is stronger in high temperature, so when the temperature gets too high, the opening of the warm water becomes smaller.

Another thermal actuator is a greenhouse window opener using a SMA spring. It opens when the temperature gets to high, serving as temperature sensor as well, see **figure 11.**

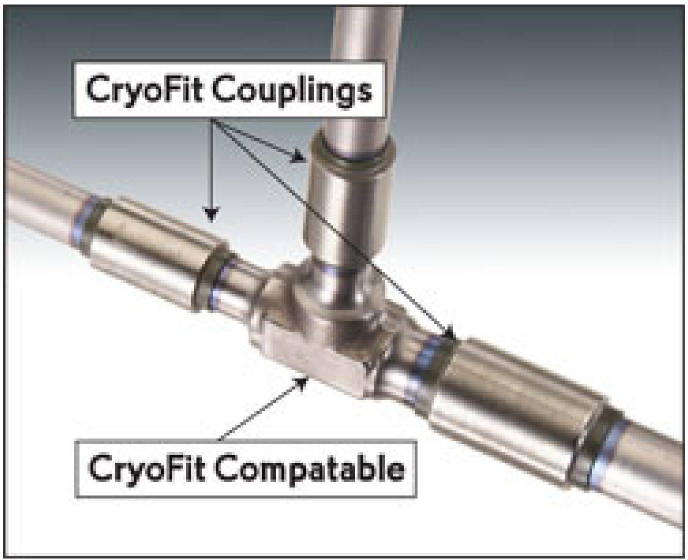
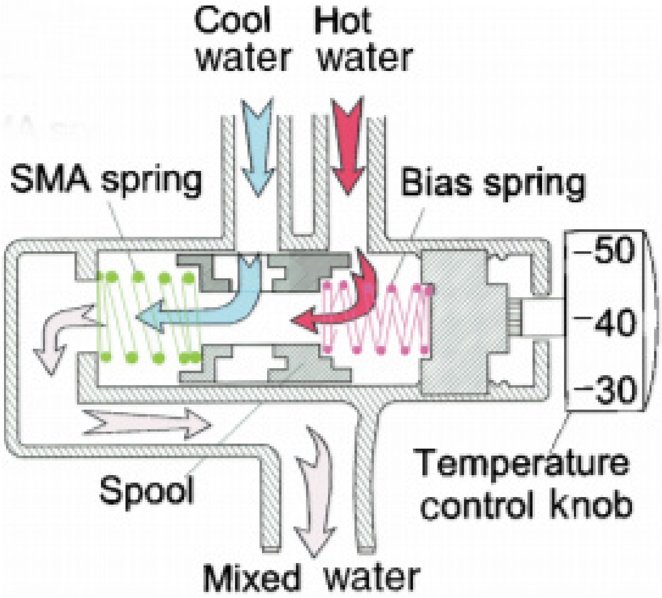


Figure 9: Cryofit Coupler



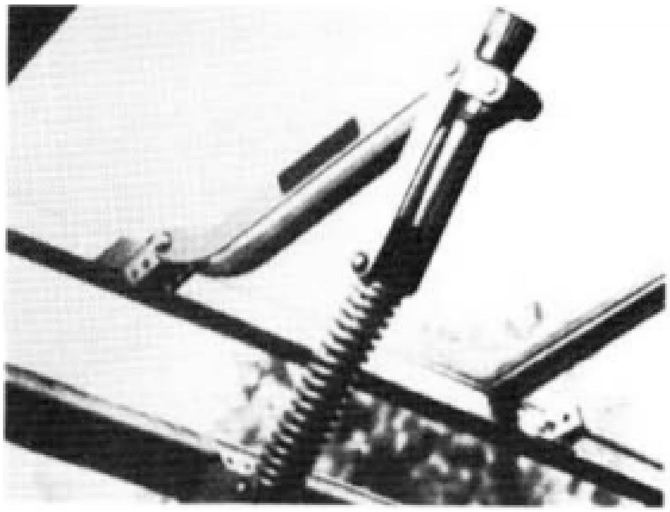


Figure 11: Greenhouse window

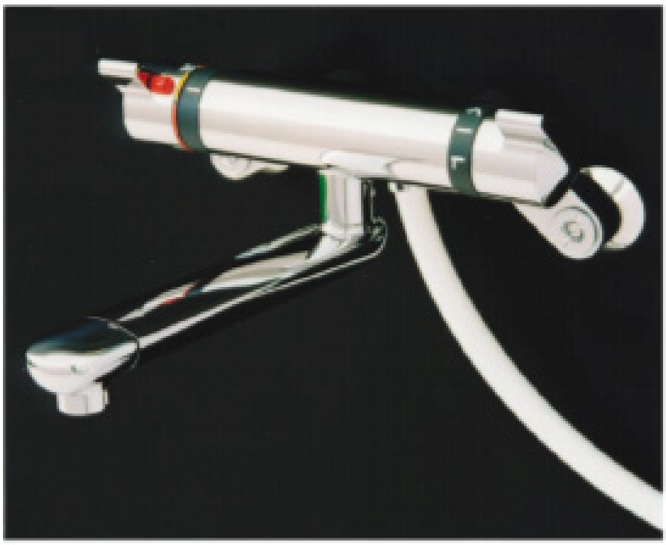


Figure 10: Thermostatic valve

Within the medical domain, some applications make use of OWSME. In figure 12 is an example shown of a SMA self expending stent. It is used to support tubular passage in blood vessels. Because of the heat of the blood, it expands. An example of an orthopedic application is are orthopedic staples. They are used to accelerate the healing process of a bone fracture by making use of the SME, see figure 13.

SE applications are used different domain. Some applications are present in glasses and golf clubs, see figure 14. SMA in a golf club absorbs the impact of the strike. The glasses form to the user's head and reform back to a standard shape when they are taken off. The brassieres offers improved comfort due to a much lower elastic modulus than conventional steel wires and keep their form over time.

Another application within aerospace makes use of SMA beams to bend chevrons onto airplane engines to reduce the noise during take-off, see figure 15. This is an example of HTSMAs.

Within the MSMAs, no product applications are really brought to the market yet. An example of a actuator based on a MSMA which elongates by a magnetic field and contracts using a bias spring, see figure 16.

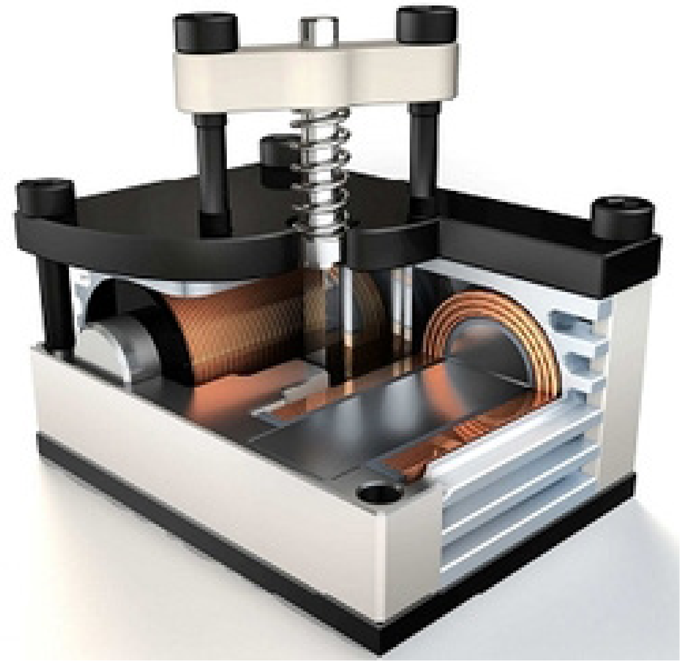


Figure 16: Application of MSMA

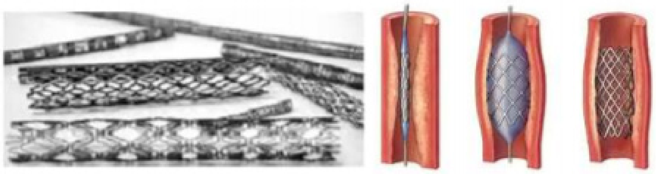


Figure 12: Self extending stent

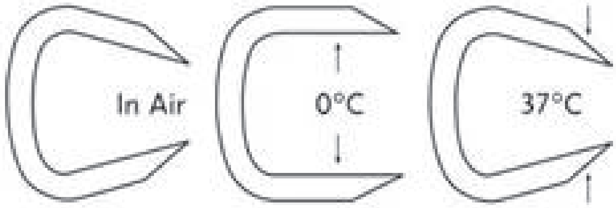


Figure 1: Nitinol staple at various temperatures

Figure 13: Orthopedic staples

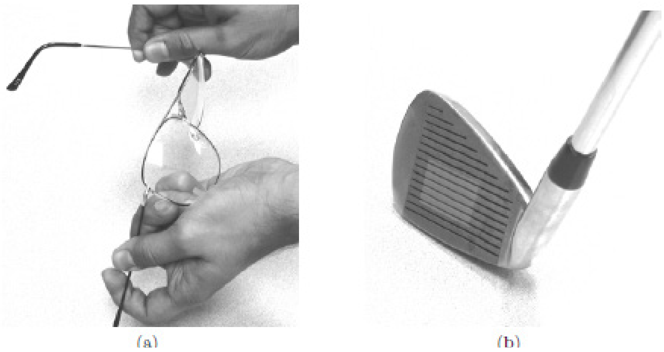


Figure 14: SMA frame of glasses + Golf Club making use of the super elasticity

Fig. 1.22. Boeing variable geometry chevron, flight testing [92].

Figure 15: HTSMAs SMAs used in airplanes

SMA films are mostly applied in Micro-electro-mechanical systems. The thin film can be used for micro valves, micro-pumps, micro grippers and micro sensors. A micro sensor is shown in **figure 17**. The on/off operation works due cooling and heating process.

Within the robotics, SMA wires are used which contract to make movement. An application is a robotic hand with bending fingers actuated with these wires, see **figure 18**.

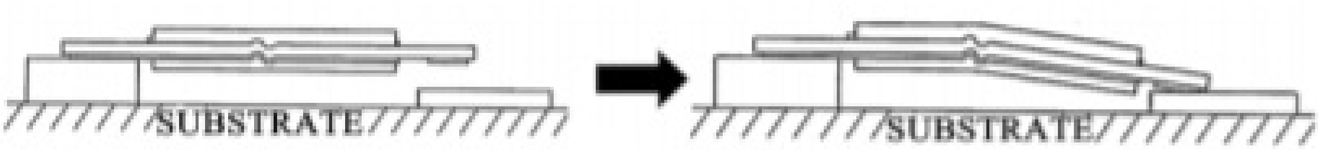


Figure 17: SMA based mictro sensor

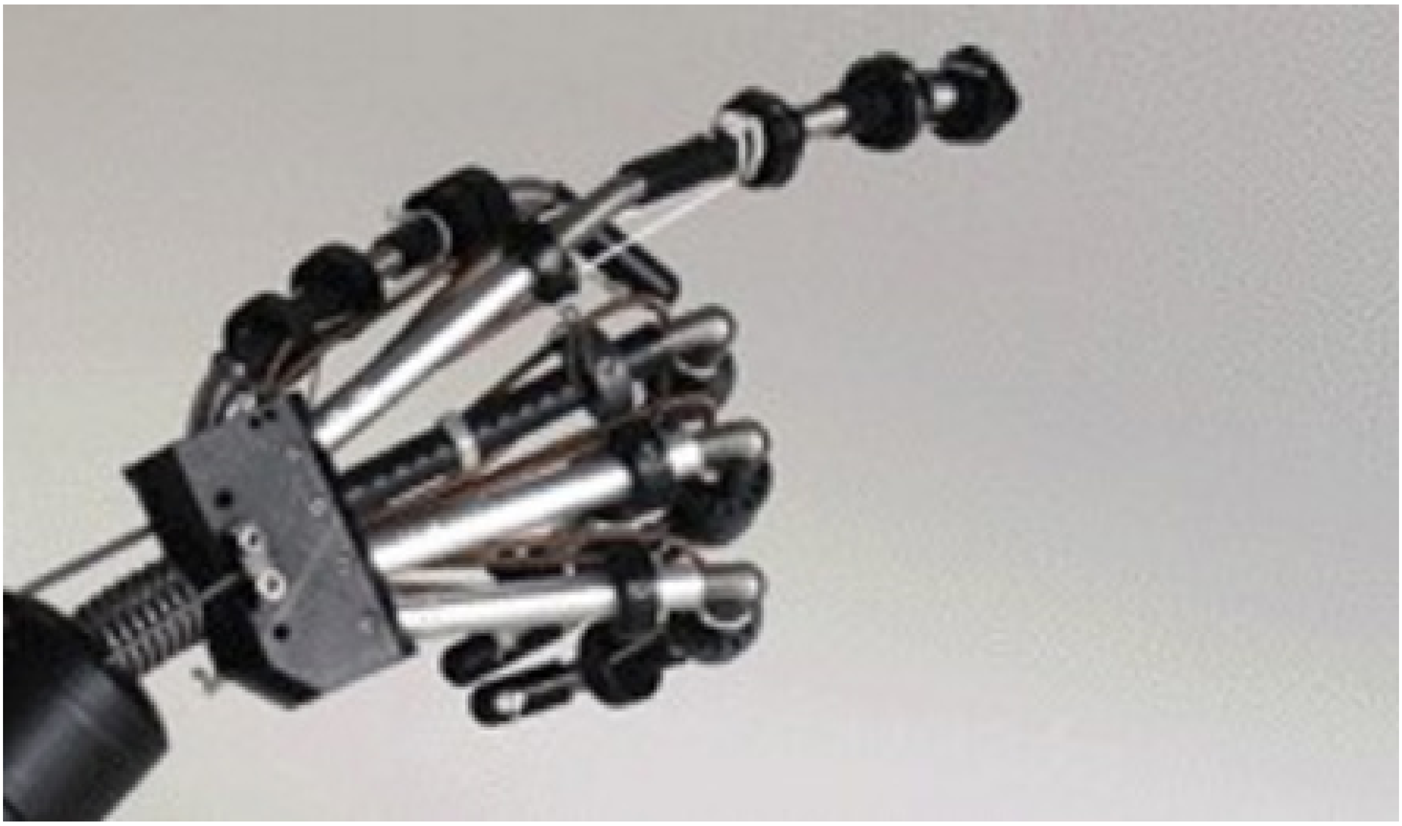


Figure 18: Robotic hand

G. Experiments during the analysis phase

Stretching of the wire

What & How

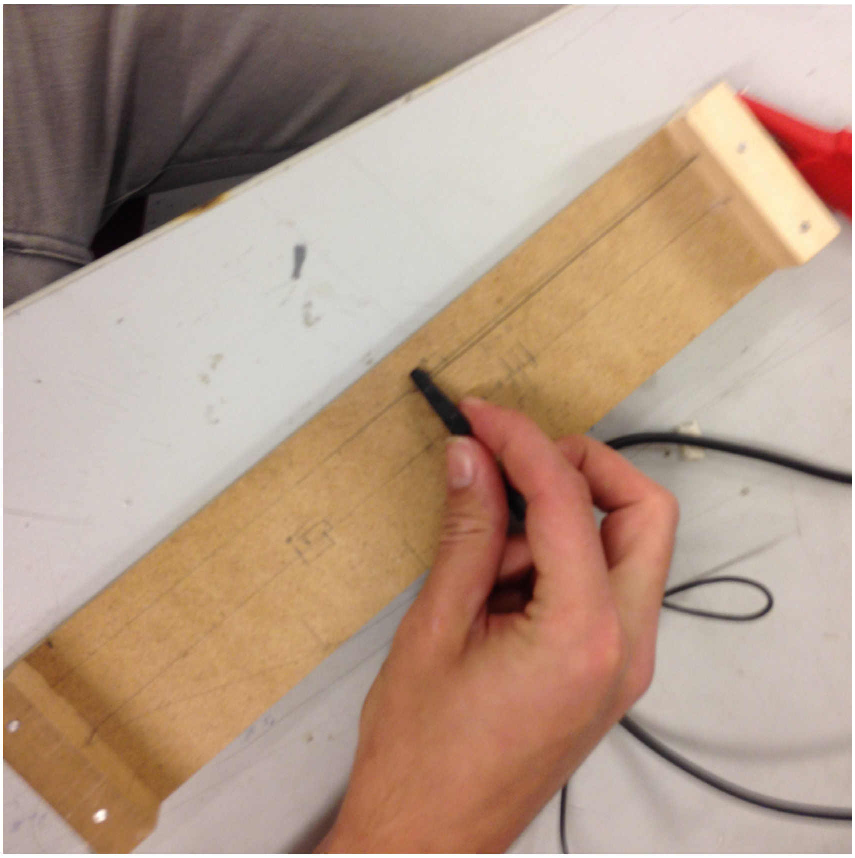
According the literature found, a flexinol wire can contract up to 8% of its length. This test will figure out how to 8% can be realized regarding the applied current and bias force. For this test, a 0.375mm and 0.1mm diameter Flexinol wire is used. Both are fixated as shown in the figure 19. Both ends are connected to the power supply. Different current have been supplied to both SMA wires. Both wires are stretched back after use by pulling the wires by hand with the help of a clamp.

Both wires contract up to 5%, no matter the applied current. Only the time it takes differs per current. The lower the current, the longer it takes. Both show a little elongation when cooling down. This varies from 0 to 0.5% of its length. By pulling back the wires, they both change back into their original length.

Conclusions:

The test confirms that a bias force is needed. Then no bias force applied, the wire stays contracted. Theoretically, the wires should be able to show a 8% difference between the two phases. Dynalloy, the fabricator of the wires confirms that in normal use, only 5% contraction is shown by the wires. Probably, the remaining 3% can only be reached by over stretching the wire with a extreme amount of force.

Figure 19: Stretching of the wire



Maximum force of the wire

What & How

Flexinol wires have a advised pulling force. Exceeding the advised force would decrease the lifetime of the wire. This test will show the maximum pulling force of wires with different diameters. The wires will be fixated with a screw on the one side and attached to a newton meter at the other side. The set-up is shown in figure 20 and the results are shown in figure 22.

Conclusion:

The maximum pulling force is almost 4 times the advised pulling force. As expected, using two wires results in twice the amount of force. 4 wires of 0.1 mm have the same cross section area as 1x0.2 mm wire and the advised and maximum pulling force are about the same. But there is a difference between the two options. The cooling and heating time will take shorter by using multiple thinner wires. Besides, 4 wires with a diameter of 0.1 mm is far more flexible than a wire of 0.2 mm. See figure 21.

Figure 22: on top: 4x 0.1 wires, at the bottom: 0.2 wire

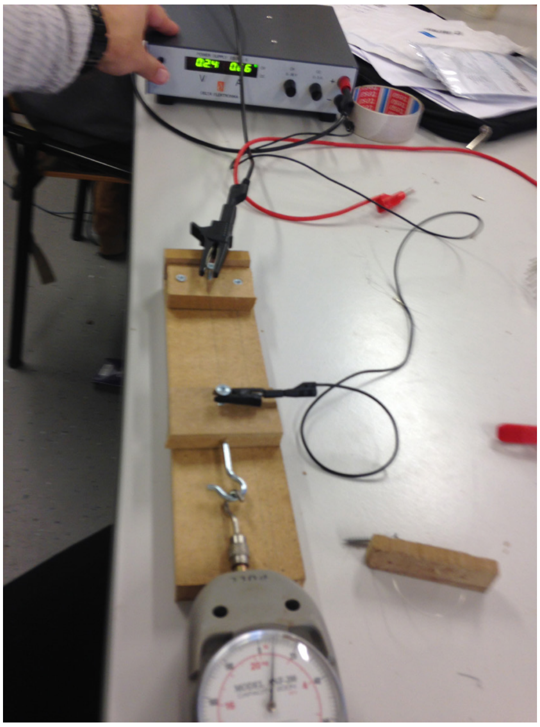


Figure 20: Set-up of test

	4*0.1mm	0.2mm	2x0.2 mm
Advised pulling force (N)	4*1.43= 5.72N	5.7 N	11.4 N
Force (N)	19	22	43
Current (A)	0.61	0.61	0.61

Figure 21: results

Create rotational movement

What & How

Examples found during the literature study show mechanisms making use of rotational movement. A test will be performed to see how well this works in reality. Two SMA wires are attached to a wheel which can rotate around its center. The prototype is shown in **figure 23**.

When heating one of the wire, the wheel will rotate slightly. When the wire cools down, the wheel is partly rotated back. The pre-stressing tension of the wires has influence on how far the wheel will rotate. When both wires are fixated tightly, no rotation will occur. Some kind of friction or latching mechanism is needed to keep the wheel into a rotated position when both wires are cooled down.

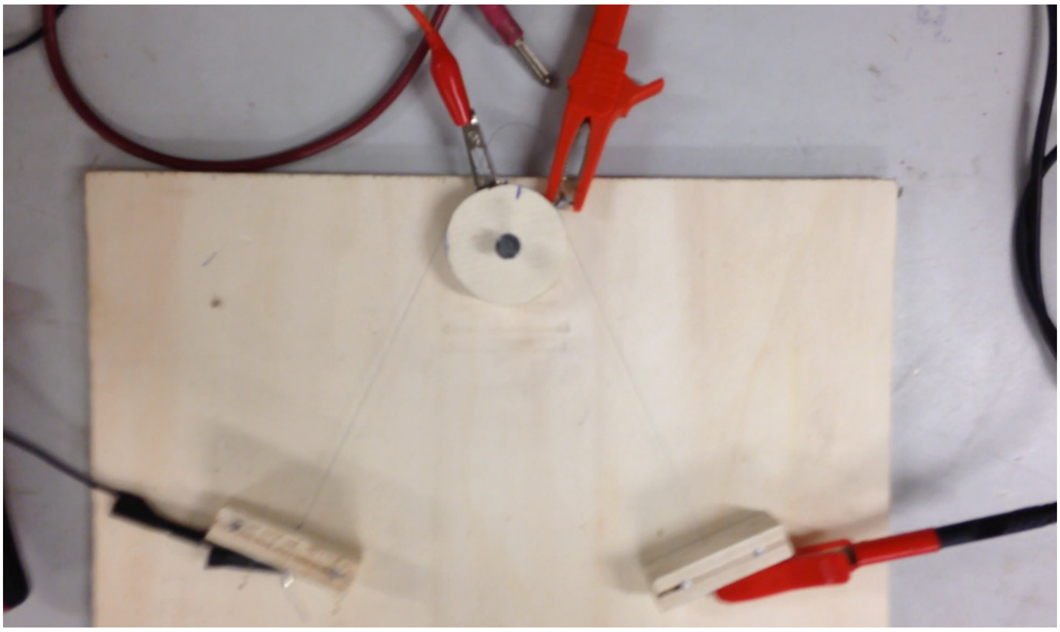


Figure 23: Prototype of rotational movement

Stretching of the tube

What & How

Placing SMA wires inside a silicone flexible tube make it able to bend in different directions. This is shown during some first experiments, an example making use of thee of these tube to realize a gripper is shown in **figure 29**. According found literature, a bias force is needed to elongate the wires back again. During the first test, the flexible tube straightens a little, but not completely. SMA wires will be placed outside the tube and connected with a non conductive wire threaded through the tube, to test how far the flexible tube straightened back. The results will be compared by placing the SMA wire inside the tube, like the original concept. By placing the SMA wires outside the tube might make it possible to add a latching mechanism or friction pad to keep the tube into a bended position when desired. The set-up of the experiment is shown in **figure 25** and **figure 26**. The result are shown in **figure 24**.

Conclusion

By placing the SMA wires outside the tube created the opportunity to place a longer wire to increase the bending angle. A thicker wire with more pulling force does not result in a larger bending angle. The results make it impossible to make a conclusion about straightening of the wire related to wire thickness. But in some situations, the tube stays into a bended position. The wires need to be pulled back to be able to use the wire for a second time.

	0.1 mm	4x 0.1mm	0.15mm	0.2mm	0.375mm
Inside	Yes	No	Yes	Yes	No
Outside	Yes	Semi	Yes	Yes	No

Figure 24: Results

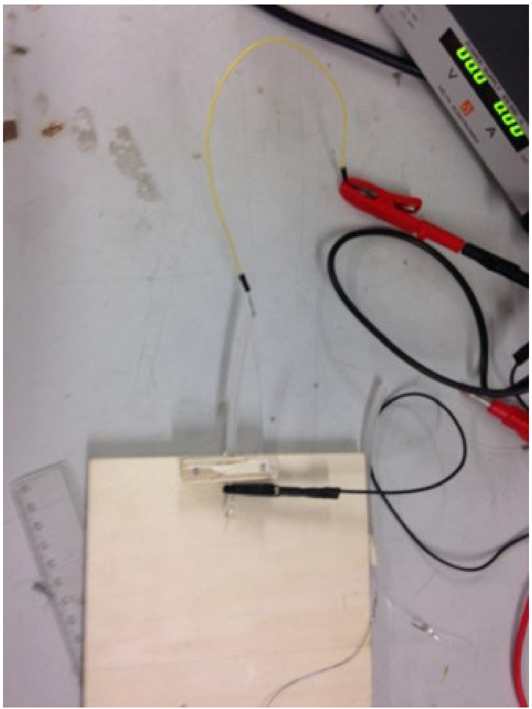


Figure 25: Set-up SMA inside tube

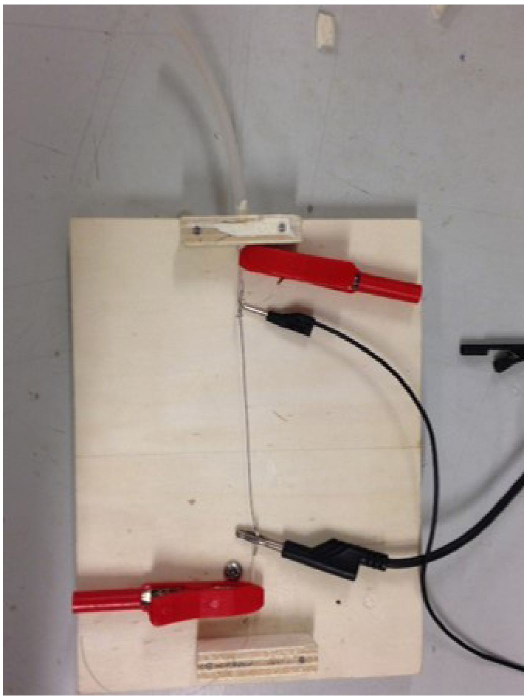


Figure 26: Set-up SMA wire outside tube

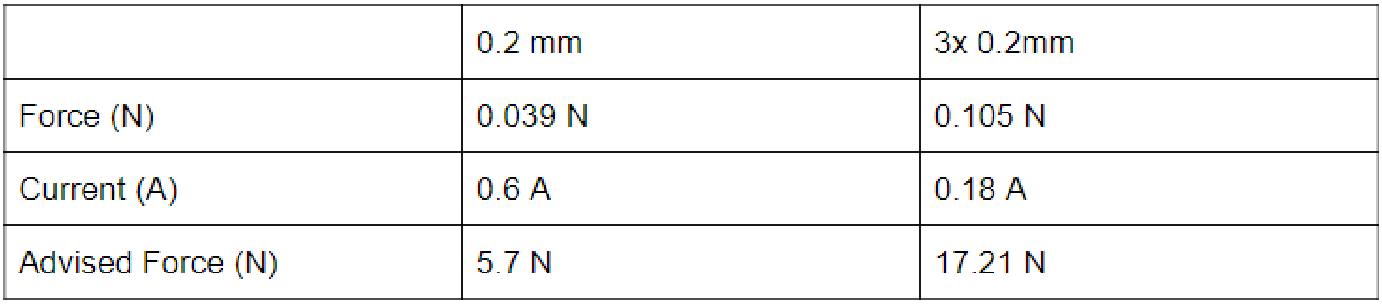
Maximum force of Flexi-Device

What & How

Placing SMA wires into a flexible tube, makes it bend like explained in the concept: Rubber Flexi device. It seems that there is made less effective use of the pulling force of the wires. A test will be be performed to figure out how much force the tube is able to deliver. SMA wires are placed inside a flexible tube, fixated to a scale to measure the force it delivers while heated, see figure 28.

Conclusions

Only a tiny percentage of the advised pulling force of the wires is translated into the force the tube can deliver. This would make it hard to able to pick up an object. The results of different wires are shown in figure 27.



	0.2 mm	3x 0.2mm
Force (N)	0.039 N	0.105 N
Current (A)	0.6 A	0.18 A
Advised Force (N)	5.7 N	17.21 N

Figure 27: results

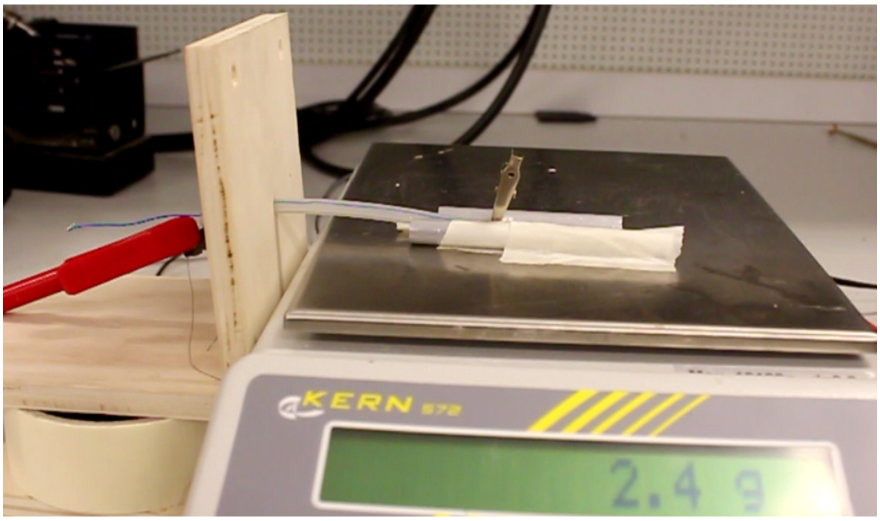


Figure 28: Set-up to test the force delivered by SMA wires placed inside a tube.

Flexi device:Gripper

What & How

Three flexible tube are threaded with SMA wires to form a gripper. The tubes are pointing downwards and bend towards the center point of the three tubes. A lightweight adhesive tape roll is used as object to keep in the air while heating the wires. The prototype is shown in figure 29.

Conclusion

The tubes are not able to lift the lightweight object. Because the tube have a low stiffness, the tubes will bend to the side. A gripper made with this SMAs threaded through the a flexible tube would need a stiffer tube. A different material needs to be chosen, or a certain structure needs to be designed which is only able to bend in one direction. Because of a low force delivered by the threaded SMA wires inside the tube makes it hard to be able to lift objects.

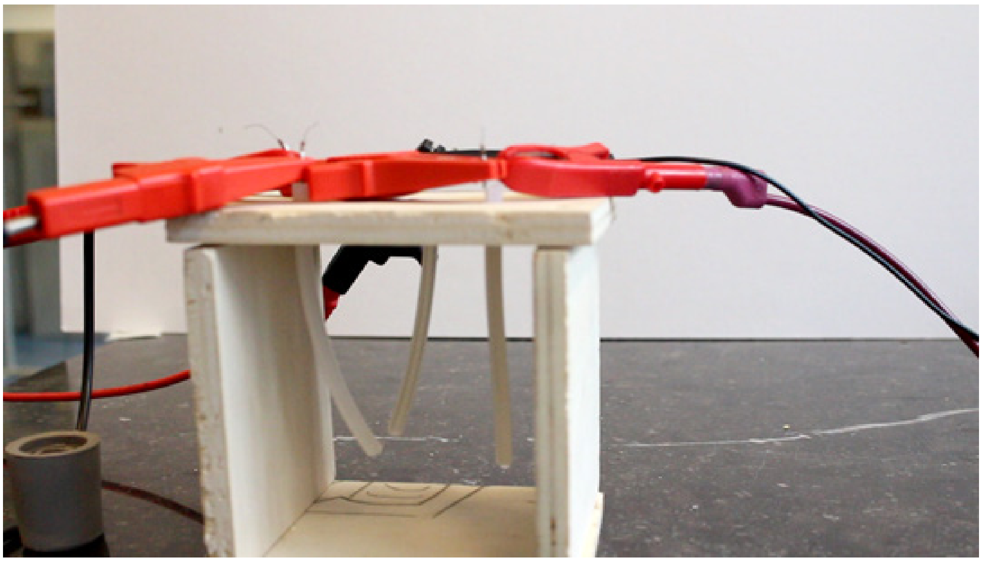


Figure 29: Gripper made with the rubber tube "Flexi" device

H. Basic mechanisms

During Chapter: SMA Applications in the main report, multiple application are shown. All make use of different mechanisms actuated by SMA wires. This chapter shows the basic mechanisms used in the different applications, see **figure 30**.

A: Two SMA wires acting in the opposite directions. It is even possible to use 4 wires cting over two axis. The opposite wire works as bias force of the other SMA wire.

B: A spring used as bias force.

C: A weight placed at the end of the wire can act as bias force.

D: A SMA wire can work together with a lever. In this case it is possible to make a rotational movement and increase the pullin distance, or pulling force.

E: Attaching SMA wires to a cirle shaped object, it can be used to create rotational movement.

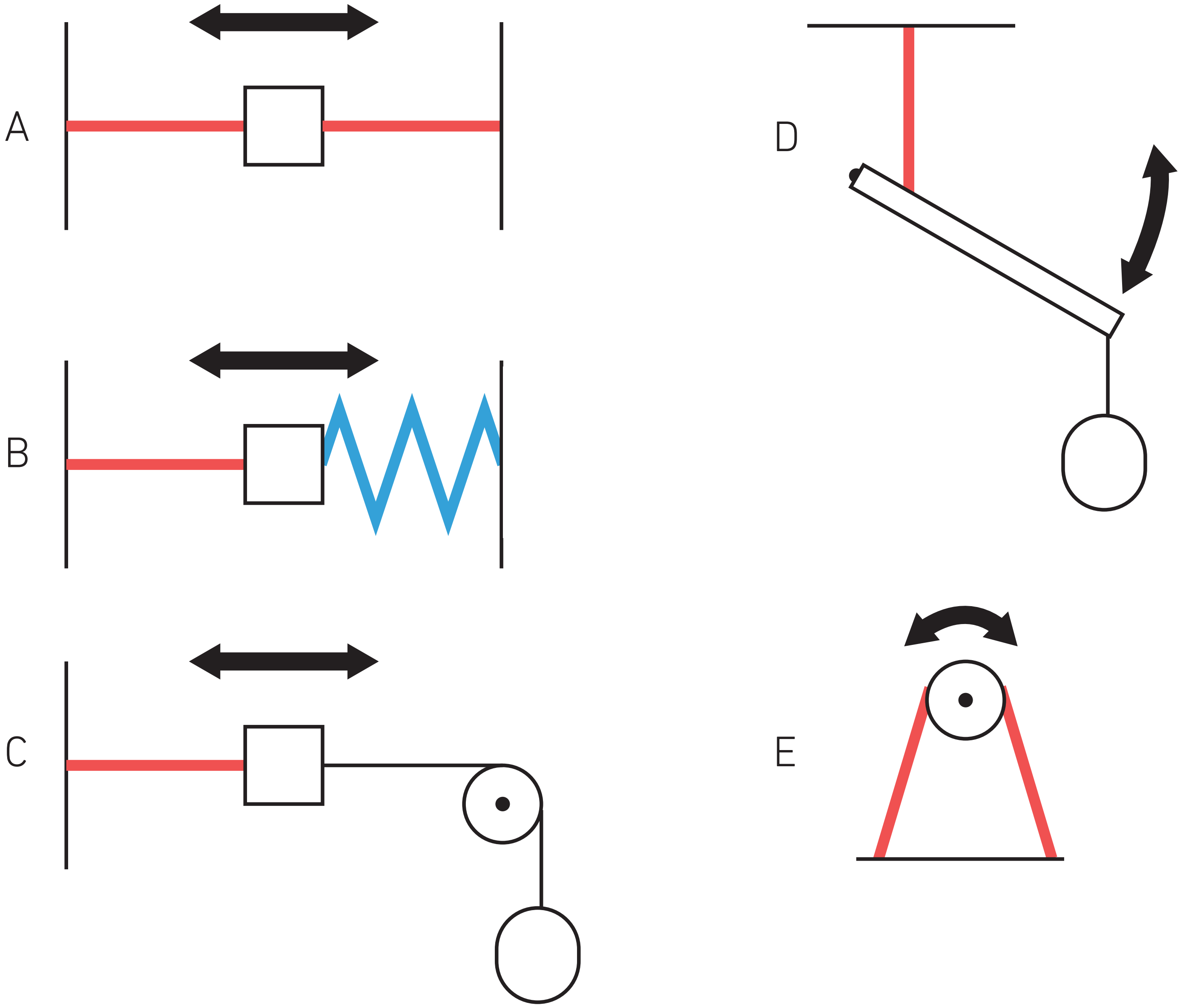


Figure 30: DIfferent basic mechanisms. Red line=SMA, Blue line= Spring

I. Brainstorm

During a first brainstorm session, different ideas came up. Most interesting ideas are clustered and explained in this chapter.

Flexi-Tube

An 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. Using multiple tube acting separately, different light colors and intensity can be used. Sensors can track people walking by or react on sound for instance. See **figure 31**.

Make a lightweight ball move on top of tubes in a certain direction. See **figure 32**.
-React to sensors of movement
-Draw a line on a tablet as path of the ball
-Make the ball follow your hand

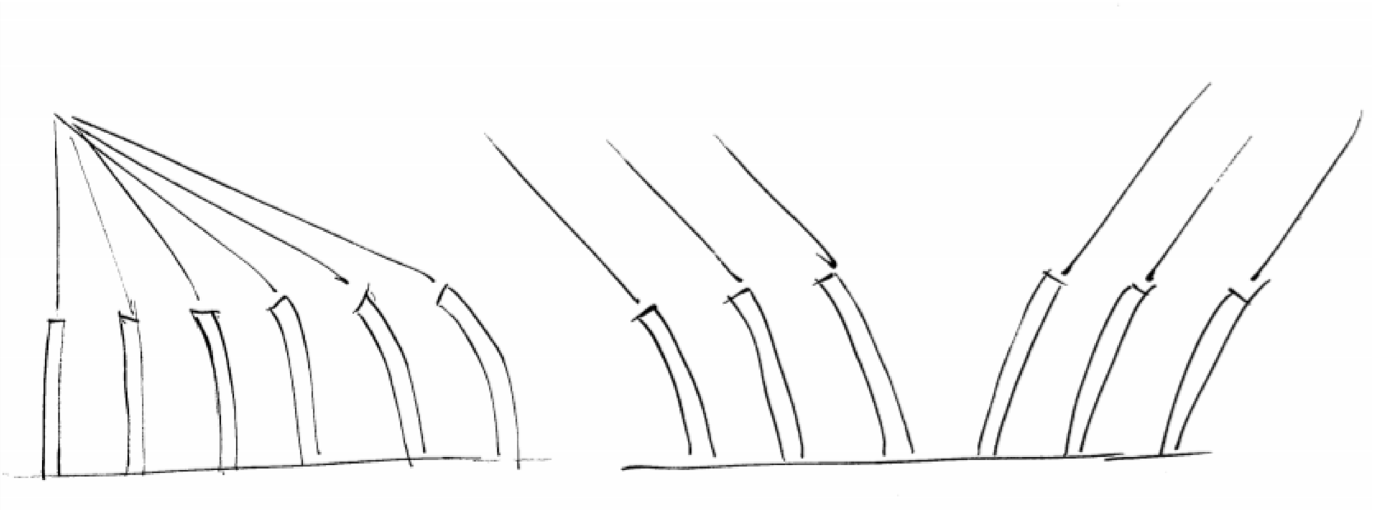


Figure 31: Flexi tube device use to create interactive wall

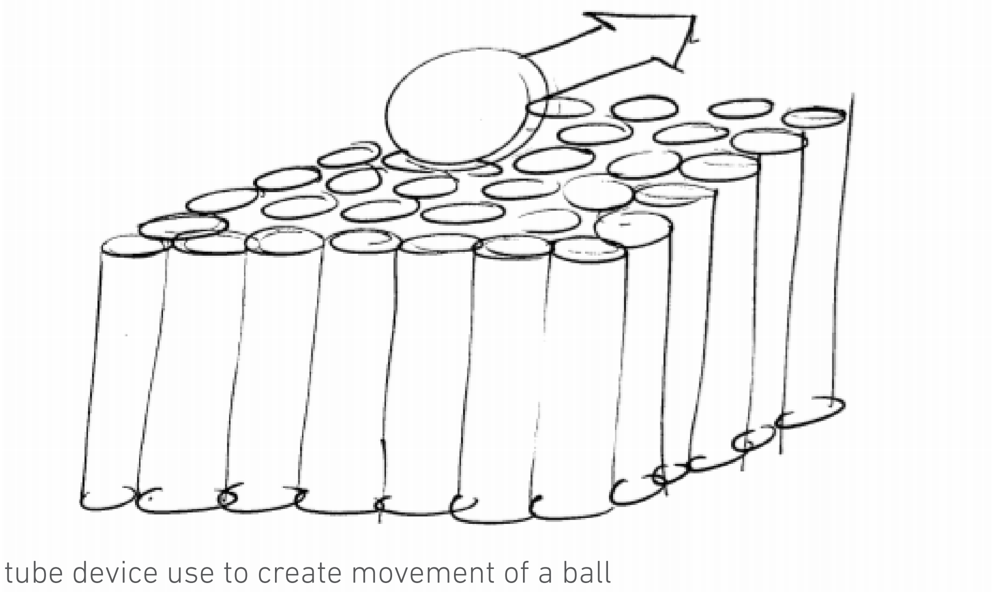


Figure 32: Flexi tube device use to create movement of a ball

Create Movement

SMA wires can be used to create a movement. Not only a part which is fixated to the wire, but also a external part or product. Different examples will be explained how to achieve this.

Make a ball move through a tube by heating different areas of the tube. Possibly make holes to let the ball to exit the tube. It can also be used to make a fluid inside a tube to move into a desired direction. See **figure 33**.

Make use of separate SMA actuated parts. By creating an overlay of the different shelves, a wave-like motion can be created to for instance make a ball placed on top move into a direction. See **figure 34**.

By connecting different shelves in line to the one be before via a fixed point. In this way, the shelves can contract significant more in length working together. The achieve this improvement, a lot more SMA wire is needed. But within the same space, more displacement can be achieved. See **figure 35**.

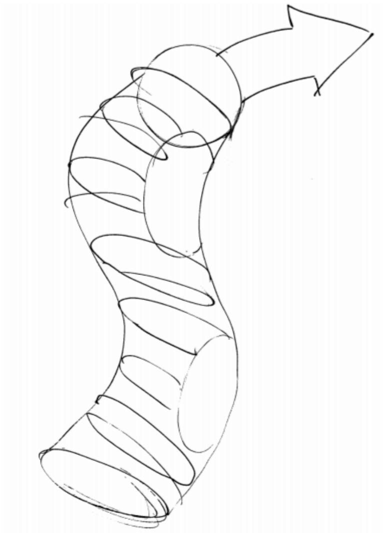


Figure 33: Create movement through a tube

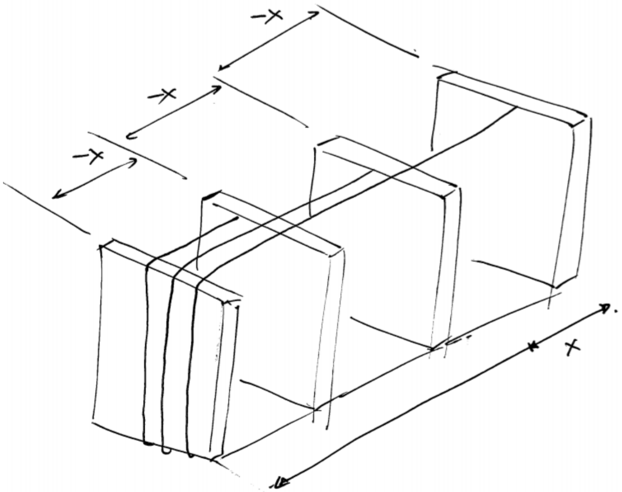


Figure 34: Increase pulling distance

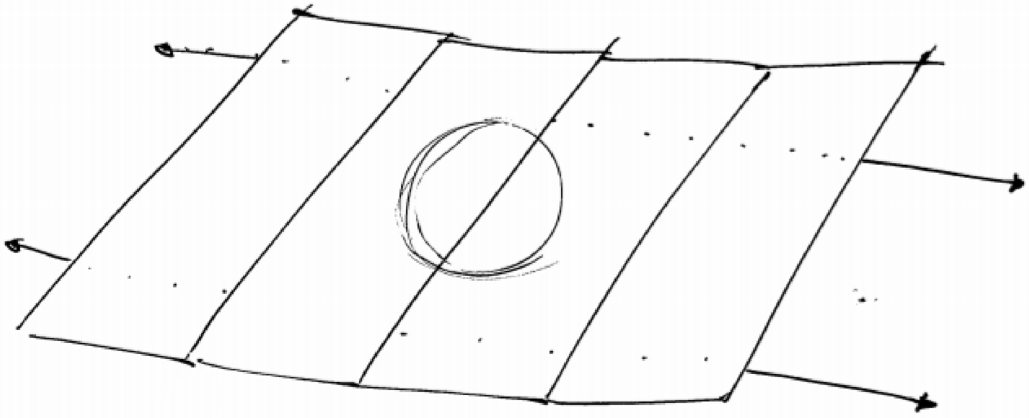


Figure 35: Make shelves move individually to create movement

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 potentials 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 36**.

Another idea is to create a lamp made out of separate part. By changing the angle, the parts can switch from a directional light to a more ambient light. See **figure 37**.

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 38**.

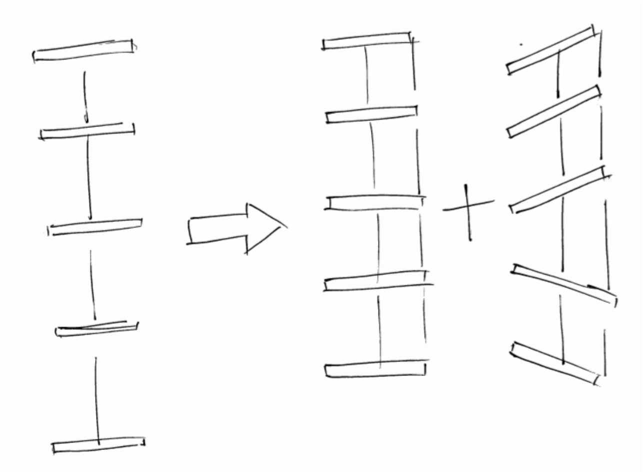


Figure 36: Luxaflex

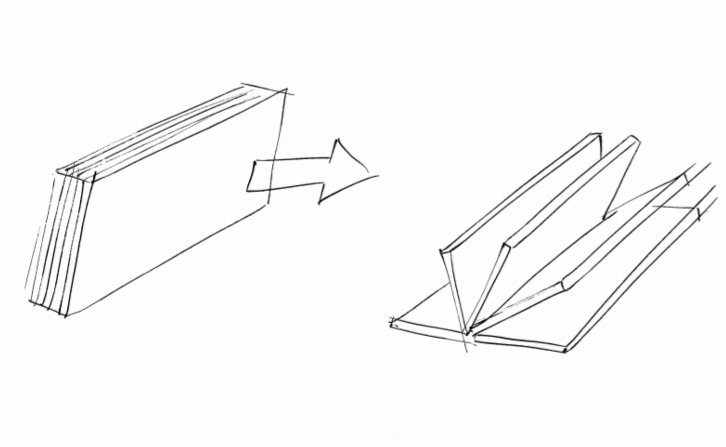


Figure 37: Foldable object

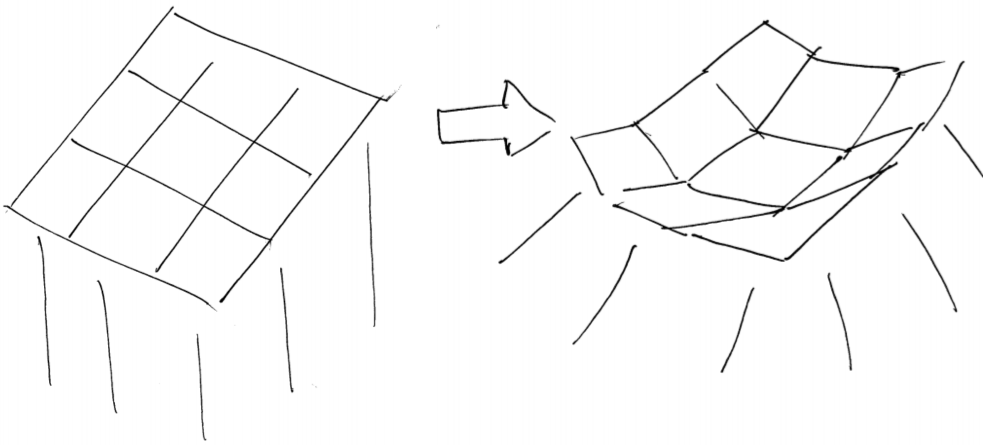


Figure 38: Lamp shine in different directions.

Adjust to environment

While searching for different applications making use of SMA wires, some examples showed mechanism making able to rotate a surface. Different ideas will be shown.

By making of of rotating a surface, a product can be created which tracks a person. Examples could be a mirror, TV or for instance a road sign. See figure 39.

Another option is to create a product which adapts to the changing environment and keep it horizontal automatically. See figure 40

Besides changing position automatically, a person can also interact with a surface to make it adapt to a certain desired position or angle. See figure 41.

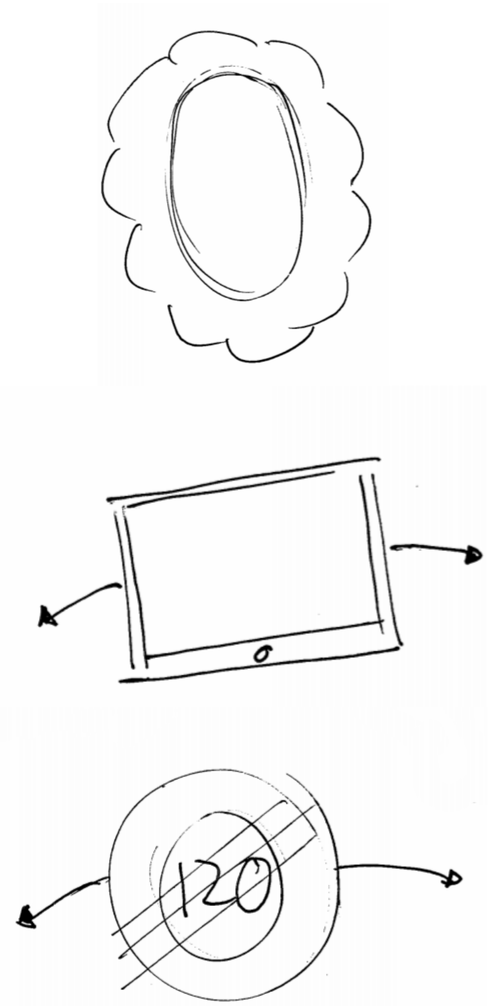


Figure 39: Mirror, TV and Traffic sign

Figure 40: Adapt to environment

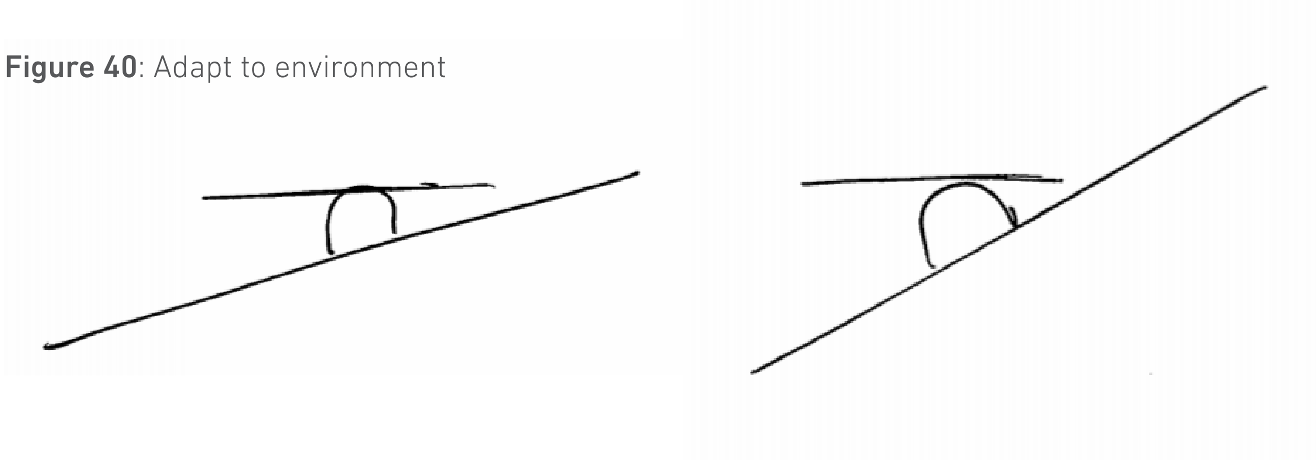
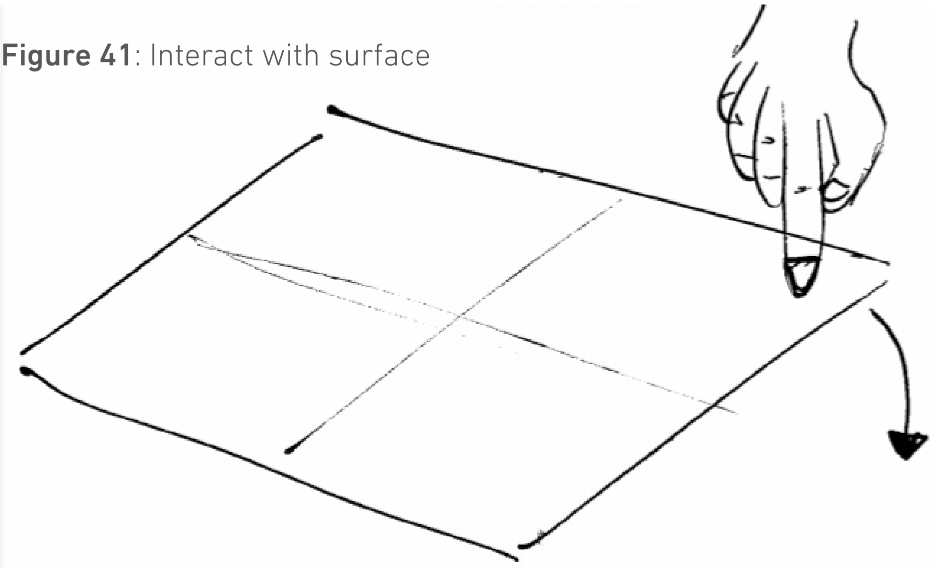


Figure 41: Interact with surface



Integrate in surface

Wires can also be integrated into a surface, like on of the examples shown in the report which makes use of a SMA wire into a tube.

Integrating the wires into flexible surface, it can be folded around a part or product and clamp it to fixate it around it. See **figure 42**.

It can also be used to create a surface to unroll or roll something up. See **figure 43**.

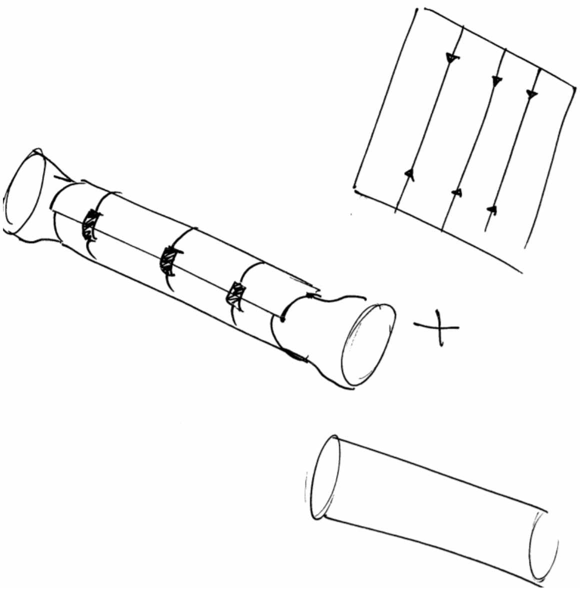


Figure 42: Fold SMA wires around a surface

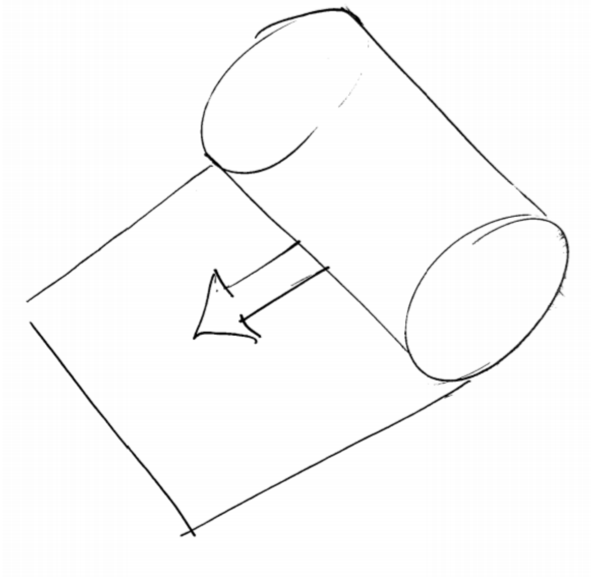


Figure 43: Use SMA wires to unroll something Integrate in surface

Inflatable

SMAs can work together with 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 a part on top change from position. See **figure 44**.

By placing the wire inside the inflatable object, something at the end of the wire can be pulled inside or outside the surface. See **figure 45**.

By wrapping multiple circles or SMA wire around an inflatable object, the shape can be changed and even movement can be created. Using a flexible material, only a small contraction can result in large displacements of the object at another area of the object. See **figure 46**.

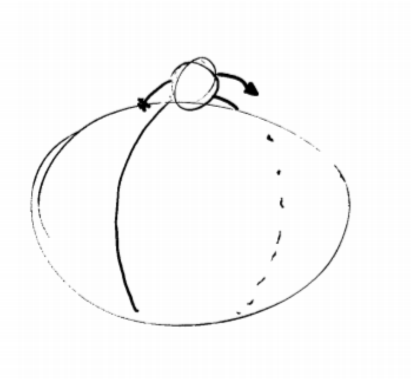


Figure 44: Change position by wrapping it around an inflatable object.

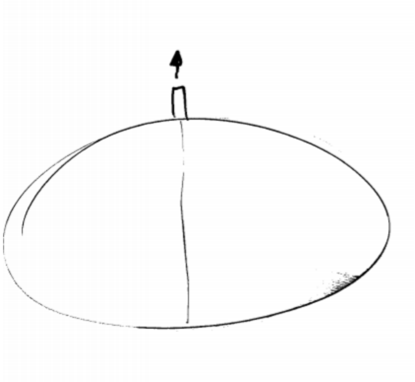


Figure 45: place wires inside an inflatable object

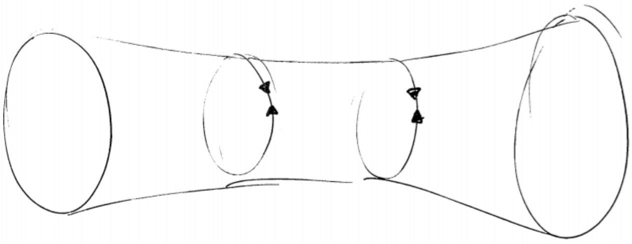


Figure 46: Adjust shape of inflatable objects

J. Choose direction

Figure 47 compares the different design directions. The table evaluates the directions on the most important values of SMAs. It also evaluates on the possibilities, role as IPD student, functionality of a potential product and overall potential.

Make use of advantages material	Inflatable objects	Complex mechanisms	Flexi tube device: Interactive set-up	Flexi tube Device: Gripper
Lightweight	Lightweight construction	Save on weight of motors.	Makes it possible to create a larger set-up	Is very lightweight
Thin volume	Easy to integrate around or inside the object	Save volume of motors, can create thin parts which actuate in different directions.	Save volume of motors, can create thin parts which actuate in different directions.	Thin tube with no parts in/around/on top of the tube
Simple deploy	Can be simple, possibility to make a more complex shape	Simple deploy of current, able to make a complex mechanism/ product/movement, but can also create something simple with parts moving along the same axis	Simple deploy of current, able to make a complex mechanism/ product/movement, but can also create something simple with parts moving along the same axis	Very Simple deploy of current with only a bending movement. Creating more functions (Keep in position, different directions) can make it more complex.
Flexible	Make use of flexibility of the wires, possibly able to squeeze in the air object	Placing in a tube or on foil can make it flexible	Tubes are flexible which makes it possible to create patterns	Tube is flexible
Portable	Able to make a portable object, how will it be inflated (Automatically)	2 Using more parts to actuate will make it hard to make something portable	No, but also not necessary	Able to make portable product, but then it needs to be kept not too complex
Silent operation	Operation of wires can be silent, to inflate the object can make sound	Operation of wires is silent, depends on function if it's needed	Operation or wires is silent, depends on function if it's needed	Operation or wires is silent, depends on function if it's needed
Possibilities	Unique properties: adjustable settings of inflation shape/volume,different shape per inflation, change during inflation and possibility create movement	Make a complex and unique mechanism/movement with different parts and combined actuation. Create actuation with multiple simple parts	Able to create a unique interactive set-up which makes it easier to realize relating the electronics	Make interactive system with multiple tubes performing desired tasks.
Role as IPD Student	1 How to create more than 5% of outline. (create collaboration of wires in a certain mechanism) 2 Interaction between wires and material of inflatable object 3 Create a lock/release mechanism to create different volumes/shapes 4 Find an interesting product 5 Is it realistic? What is the amount of pressure on the wires	1 A possible direction is interactive design, but this is not a IPD direction, and does not have my preference 2 Spend time on creating a locking/release mechanism to make different positions 3 Combine different actuation movements together 4 More difficult mechanism will require possible complex programming	1 An interactive design, but this is not a IPD direction, and does not have my preference	1 Work on re-stretching of the tube. 2 Add different function 3 Find interesting products 4 Create feedback when a gripper misses its object
Functional Product	Potential to create a functional product	Seems hard to find a product with high functionality	Not a functional product	Seems a little difficult to find a functional product.
Overall Potential	Able to make use of the different advantages of the product. Also depends a little on what kind of application will be made. Plenty of possibilities, potential and fits in role as a IPD student. Also a unique and new application.	Challenge is to make optimal use of material potential.	Can make something unique, is not the perfect fit personally and role as IPD student.	Can make something which does something unique with low volume, rotate, bend, keep in position. But it seems that's it. After a first few experiments doesn't seem to work very accurately.

Figure 47: Choose direction

K. Functionalities of current valves

Functionalities

To be able to control soft robotics, some different functions are important.

Weight, volume, integration, control flow rate, pressure, flow rate, power supply and price.

Weight: Pneumatic soft robotics can not deliver a very high force. This is because most soft robotic are supplied with only 0.5 to 4 bar.

Volume: Pneumatic soft robotics are small and can not effort large valve placed on top of the body. Therefore, the total volume needs to be as small as possible.

Integration: Being able to place the valves inside the body would be ideal. The less components are needed, the easier it is. Connections between the parts take extra space which is undesirable.

Flow rate: From the test in performed during the prototype phase, a tube with an inside diameter of 1 mm can make a bellow bend in about 0.3 seconds which seems fast enough. A tube/orifice with a diameter of 1 mm has the flow rate of 15 l/m.
(TLV flow rate calculator)

Control flow rate: Being able to control the flow rate can make the bellow inflate and deflate in different speeds. This something interesting which opens many opportunities.

Air Power supply: the more air pressure, the more force the bellow can deliver. The higher the force, the more opportunities it enable to lift up an object or make a walking robot lift its own weight while walking in a certain direction.

Price: A high price of a valve makes it less interesting, specially when using multiple valves.

L. Set-up scenario's

The case study of this project is to control the air supply of a pneumatic robotic hand by using SMA actuated valves. Each finger will be controlled individually by inflating and deflating the finger at any desires moment. The result of various valve set-ups will be investigated during the chapter. The final result is shown in the main report.

Solenoid Valves

The option to use solenoid valves to control multiple fingers is an option. The problem is that all the solenoid valves including the connection parts and tube will not fit inside the hand. Therefore the valves can be placed around the hand, or near the compressor. There are no solenoid valve in the 3-way variant available on the market.

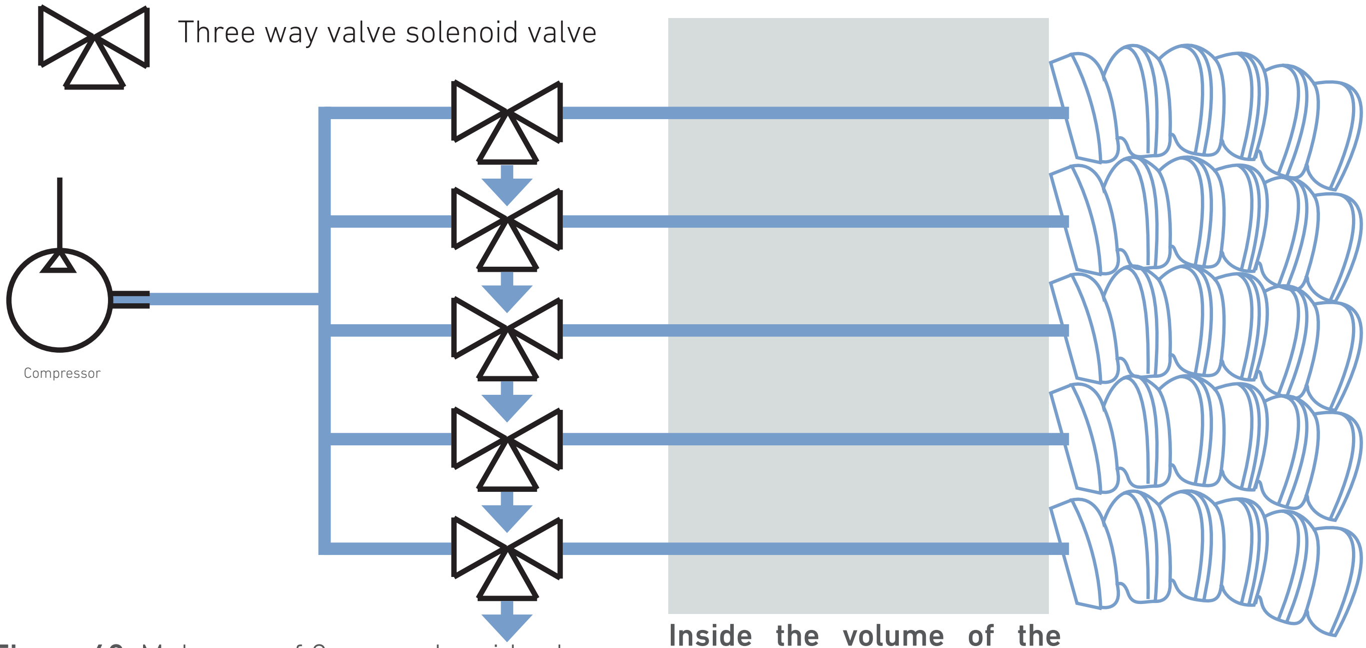


Figure 48: Make use of 3-way solenoid valves

Timing
Each finger can be controlled completely individual. Requires much power to keep a finger into a bending position.

Flow speed
Neither the inflation speed as the deflation speed can be controlled.

Bending position
When power of the solenoid valve is off, finger start to deflate, or a special latching solenoid valve is required.

Solenoid Valve + two-way SMA valve per finger

By placing a solenoid valve outside of the hand near the compressor, only one SMA actuated valve per finger is required to control the fingers individually.

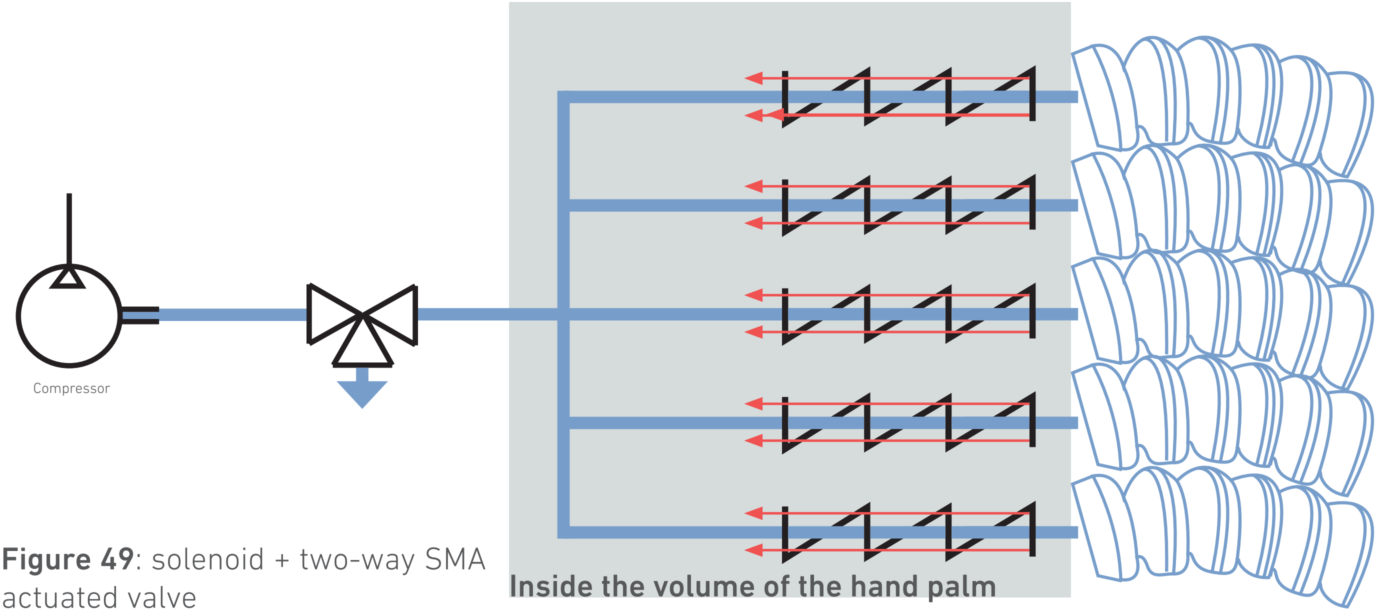


Figure 49: solenoid + two-way SMA actuated valve

Timing
Each finger can be controlled individually, but when one of the fingers in deflating, the others can not be inflated at the same time.

Flow speed
Two-way SMA wires can determine the flow rate through the valve in both directions. In this way, both bending speed and deflation can be changed.

Bending position
Has the potential to roughly determine a bending position of the finger.

Three-way SMA valve per finger

Most ideal situation would be to only use one valve including one SMA wire per finger. The prototype phase this valve does not work.

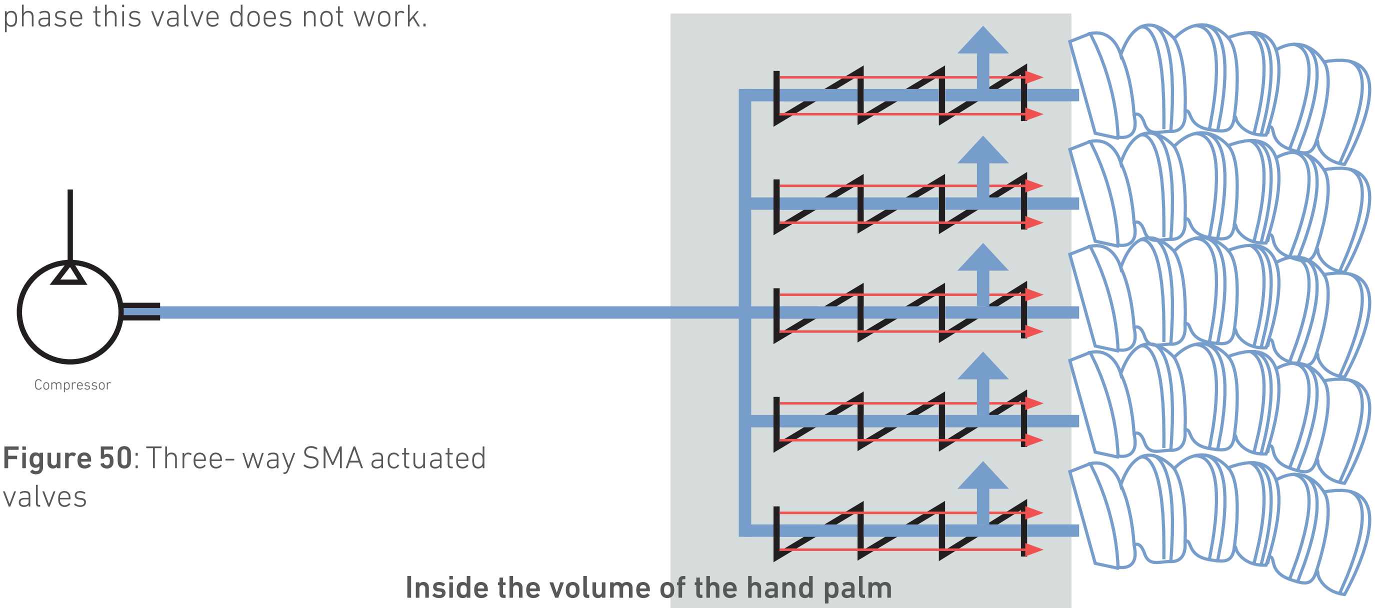


Figure 50: Three- way SMA actuated valves

Timing
Each finger can be controlled completely individual. Finge

Flow speed
Bending speed of the finger can be changed, deflation speed not.

Bending position
When power is off, finger start to deflate, thus not able to create a bending position.

Three-way SMA valve per finger

Each finger has it's own valve to inflate the finger, but one common deflation valve. For every inflation, the first valve is heated together with valve with also inflated the finger. By deflating a finger, both the valve acting as common ventil together with the valve of the finger which is deflated are both heated. This makes it possible to only use 7 valves to control a whole hand.

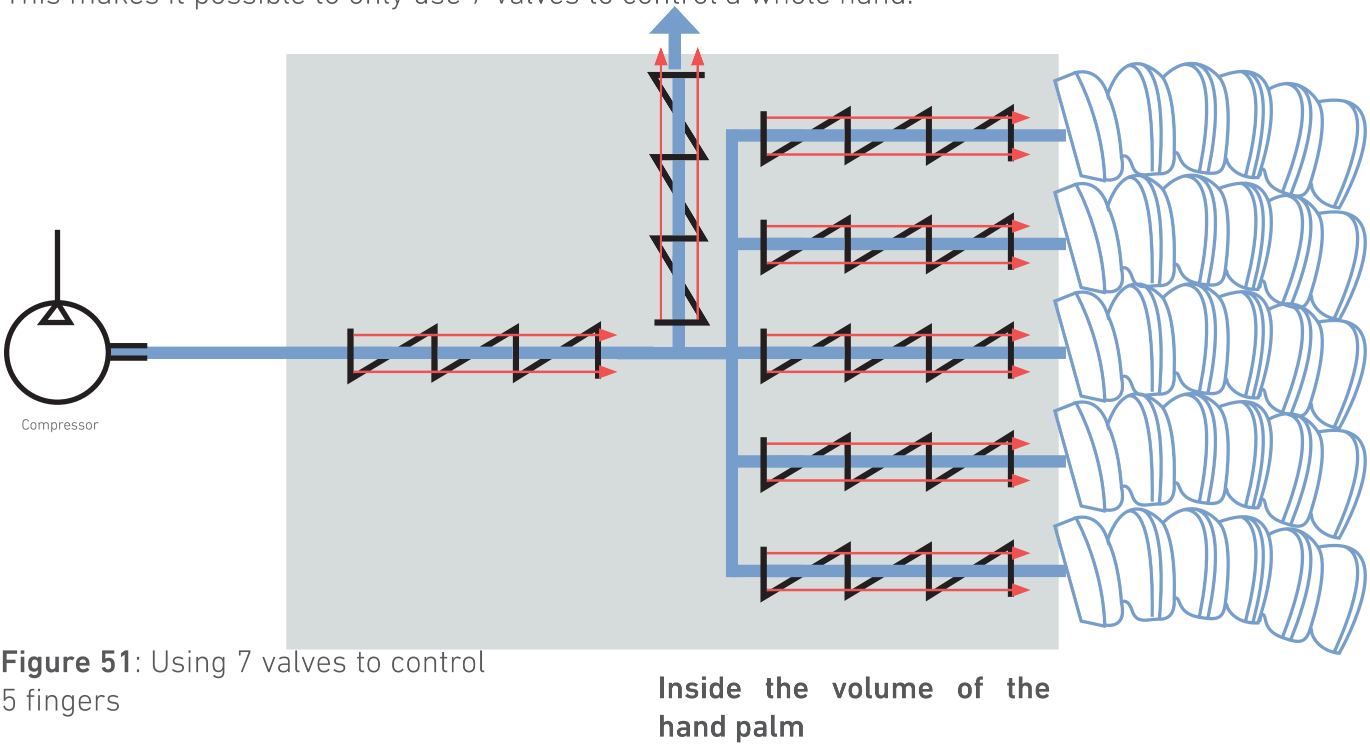


Figure 51: Using 7 valves to control 5 fingers

Timing
Each finger can be controlled individually, but when deflating a finger, no other finger can be inflated.

Flow speed
Bending and deflating speed of the finger can be changed,

Bending position
Has the potential to roughly determine a bending position of the finger.

M. Examples of valves

One way valves allow a fluid/gas to travel only through the valve in one direction and automatically prevents back (reverse) flow. They need no (electrical) help and are therefore self-automated. The valves are able to keep the air outside. By using a one-way valve as basis, the SMA wires can be added to open the valve to inflate the fingers. In this way, a two way valve is created. Some examples are shown in figures 52-56.

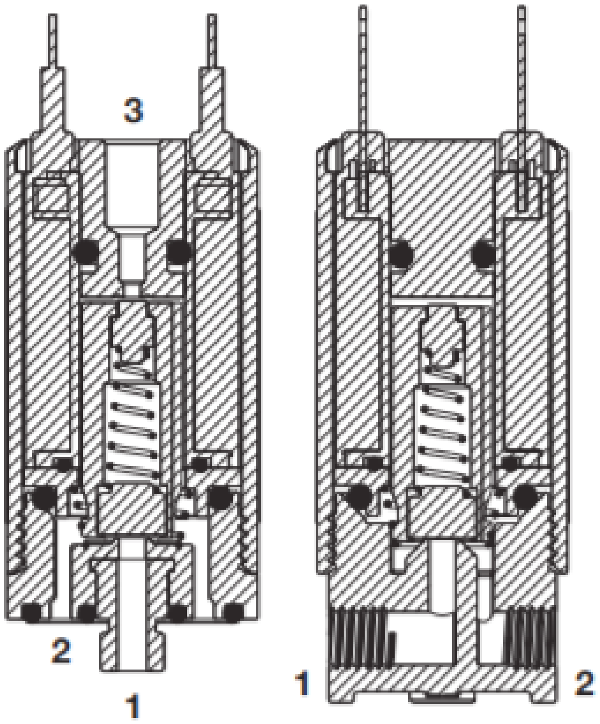


Figure 52: Valve used in miniature solenoid valves

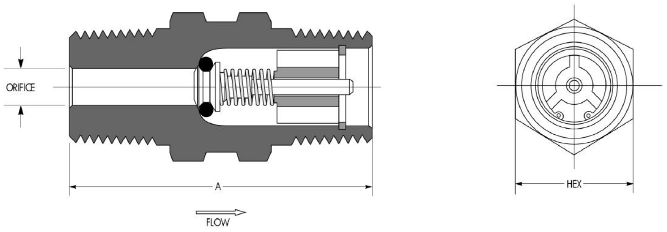


Figure 53: Inline check valve

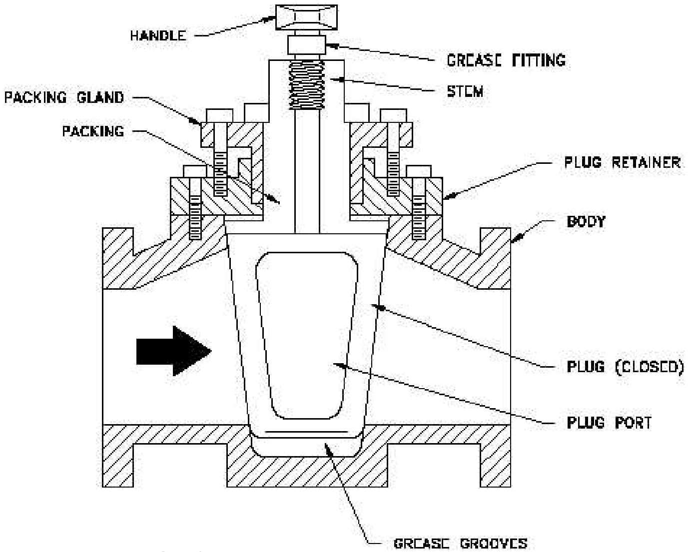


Figure 54: On/ off plug valve

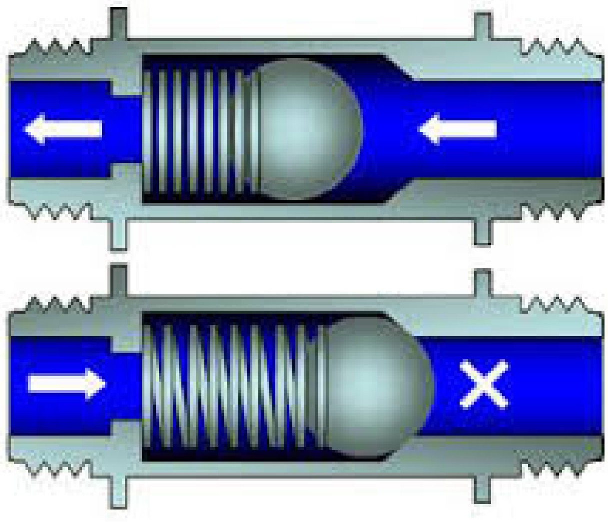


Figure 55: Inline check valve

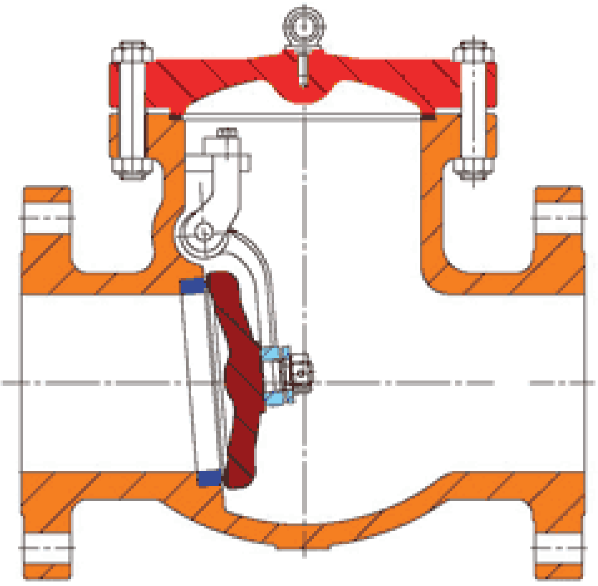


Figure 56: Swing chack valve

N. Internal disk valve

Valve mechanism

What & How

Test different shapes of the valve to be able to block the incoming by closing the valve. This test makes not use of any SMA wires, because the valve will not be opened during this test. A compressor will be connected to the valve. The pressure will be increased up until air starts to flow through the valve. By putting the valve in a cup of water, air loss will be visible. For this test the following spring is used: Spring length: 1*7.7*30. The spring is compressed by 6.5mm. This means the force of the compressed spring is 15N.

Prototypes

By clamping two part together, the materials and shape of both parts can have influence on the result.

1 Different disks have been printed. A dome, an upstanding ridge and a flat surface. Two flat part have been supplied with both rubber materials. The rubber foil has a thickness of 1mm, the rubber foam has a thickness of 3 mm. The diameter of the disks are 14mm. The upstanding ridge is 1 mm in depth, and the dome has a depth of 5 mm. See figure 57.

2 Different variations of the seat have been 3D printed inside the body of the valve. One round hole with a 90 degrees corner, one with a chamfer inside the body and one with an upstanding ridge. See figure 58.

3 The seat of the body is also covered by the two types of rubber. See figures 59 shows the a compact rubber foil around the seat another variant with the 3mm foam is used like the disk in figure 57.

Results

A first simple prototype is made to be able to test quickly if used rubber foil and foam can stop the airflow. Both materials are pressed to the opening of a tube supplied with air pressure. A part with a flat end is attached around to the air tube, to mimic the upcoming test situations. This part is glued to the tube with an opening at the end. Both materials succeed in blocking the airflow up to 4 bar.

The results of all combinations are shown in figure 60.

Figure 57: Different shaped disks

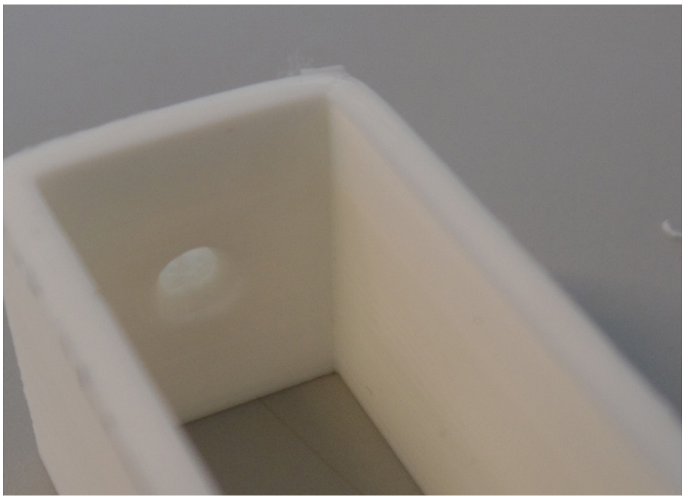


Figure 58: Picture of seat with chamfer inside body

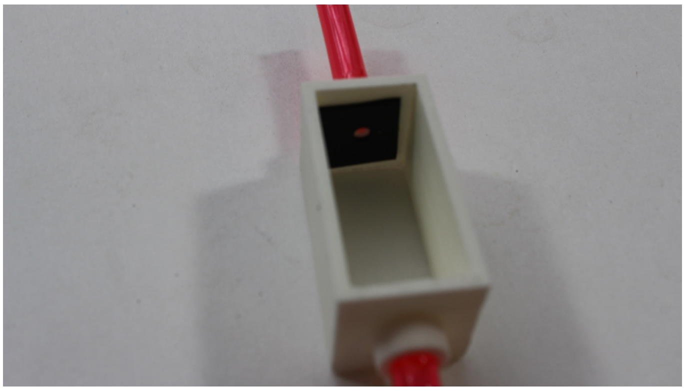


Figure 59: Rubber foil around the seat of the valve

Opening the valve

What & How

Different boxes are 3D printed which contain a valve mechanism. SMA wires are connected to a power supply which heat the SMA wires over a short period of time which is about 1 second.

Prototypes

1. First, a prototype is created using a form-fit sealing with a foil in between. Both parts are clamped together externally, see figure 61.

This prototype is tested to block the air-inflow and open the valve by heating the sma wires. At this early stage some problems occur. Using a foil and clamp the parts together make no airtight model. Besides, the length of the box is too long which make both parts bend a little and create air loss. The valve is not airtight and the spring has not enough compressed force to close the air inlet.

2 The next prototype has some improvements. The box has smaller dimensions and the outcomes of the previous sub-chapter are implemented. The sma wires work really well. While heating the wires, the blocking part is pulled back. When cooling down, the spring brings back the disk. The sma wires are connected by a metal parts through the body and sealed with glue. It has to be assures the wires make good contact with the wires. See figure62

3 A three way valve is tested. A extra disk is attached to the same spring and SMA wire, see figure 63

Figure 63 shows a three way valve. When the SMA wires are heated, the valve should open and close the back opening. Unfortunately, the force of the SMA wires is not enough to close the back passageway.

	3mm hole	rubber foil	rubber foam
Flat	x	1 bar	x
Edge	x	1 bar	x
Dome	x	6 bar	2 bar
1mm R	4 bar, but a little air loss	1 bar	x
3mm R	1.5 bar	1 bar	x

Figure 60: Results of tests seats and disks

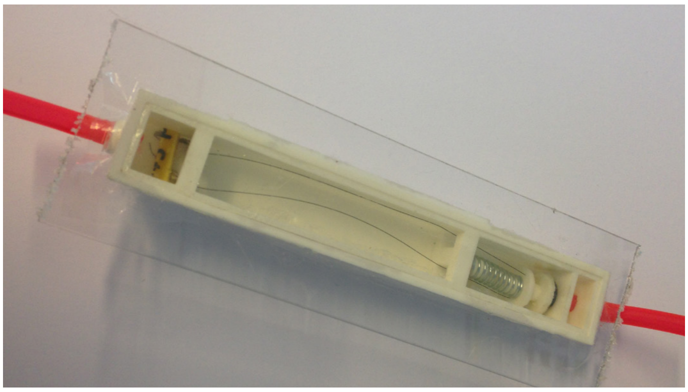


Figure 61: 1st prototype opened by SMA wires

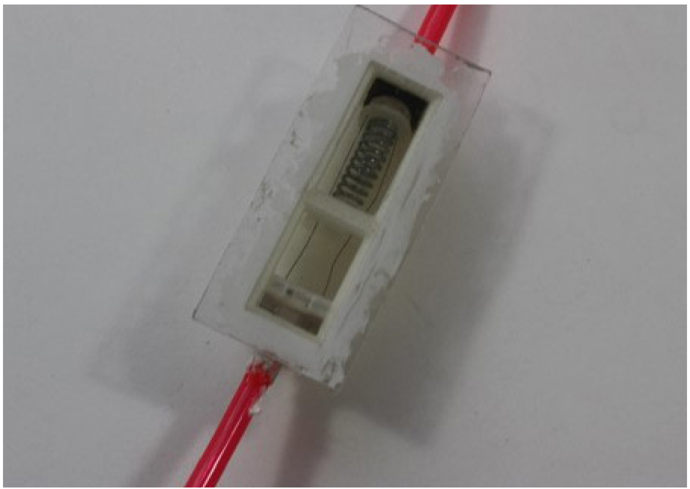


Figure 62: Well working two-way valve

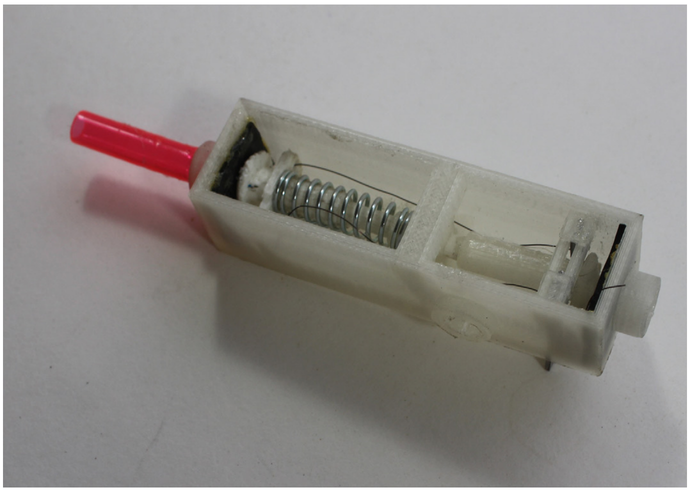


Figure 63: Not working three-way valve

Sealing

What & How

The boxed are connected to a pneumatic finger on end, a compressor at the other end. The parts are connected by tubes which transfer the supplied air. The tubes are glued to the parts to prevent any air loss. Two types of sealing are tested. A form fit and an O ring connection

Prototypes: Form fitting

1 A box is printed with a separate lid. The inner perimeter of the lid has the same dimensions of the over perimeter of the box. When the lid is attached and the tubes are connected to the compressor and finger, the connection is far from air-tight. See figure 64.

2 Another solution is to place a plastic foil in between the two parts. The connection is still not airtight, but less air is lost while connecting the box to the finger and a compressor. The more air pressure is supplied to the box, the two parts need to be clamped together. Otherwise, at a certain air pressure, the parts will stay together. See figure 65.

3 Plexiglas is now glued to the lid. This replaces only the top of the lid. Again a foil is placed in between. In this case, there can be seen what is happening inside the box. The connection is not experienced as less airtight, but still far from completely air-tight. See figure 66.

Prototypes: O-ring static radial

1 A static radial sealing is the first solution tested to seal two separate parts. The suited dimensions of the body around the o-ring have been looked up. For these prototypes, an O-ring is used. The belonging dimensions of the body of the o-ring sealing are used.

Making use of a rubber O-ring can possibly be giving a better air-tight connection. By making an airtight connection using an o-ring, the printing quality is important. A few printing attempts have been made, See figures 67+68. From both the inside shape as the outside shape. The printing speed and line thickness are of importance. Besides, the wall-thickness should be 2mm minimal while using the Ultimaker 3: PLA. Besides the connection, critical parts are at the connection to the tube, but in one

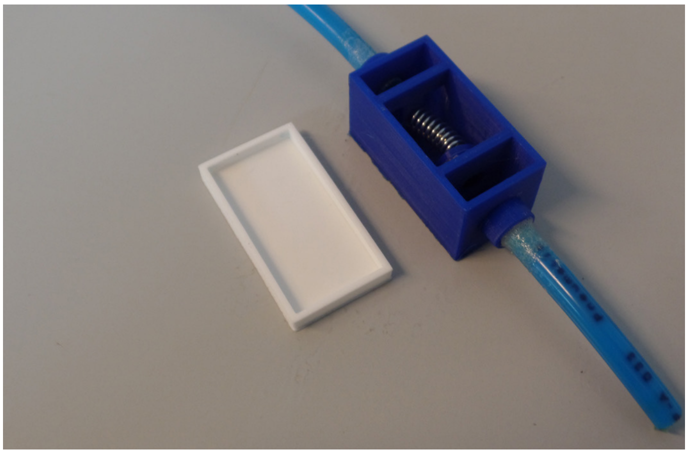


Figure 64: Form fit

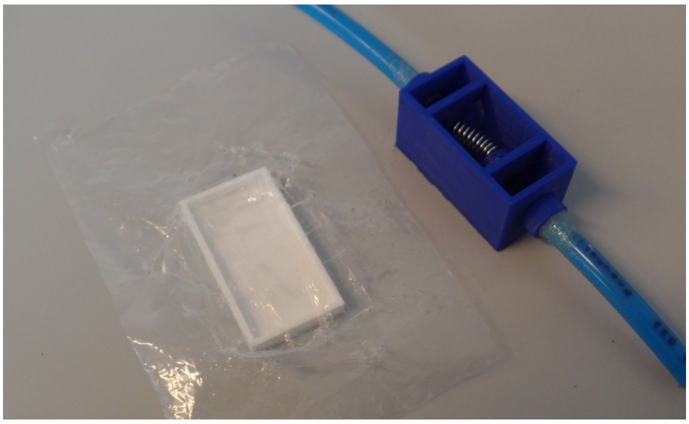


Figure 65: Form fit with plastic foil in between

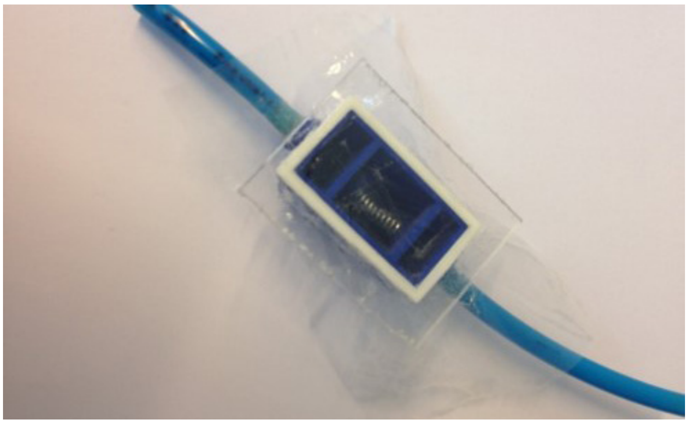


Figure 66: Use glue between form fit connection

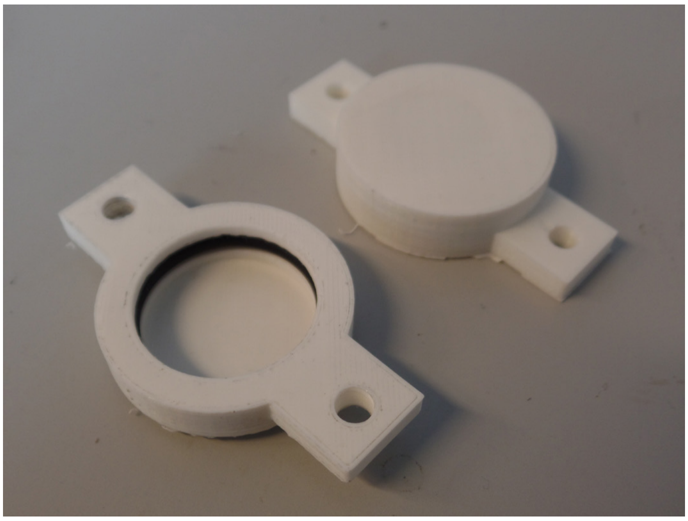


Figure 67: Static radial connection

print also the wall thickness on the top. A 2 mm wall thickness is required to be able to make an airtight model.

The two parts can be connected using threaded wire, or clamped together. By using a high force to clamp both parts, the connection is not airtight, but close. By pressurize the box with 2 bar, a little air flows out. Exceeding the 2 bar, a lot of air is lost.

Prototypes: O-ring axial

This solution does not work at all. The two parts are hard to clamp together because both parts have too much flexibility. When both parts are clamped together, the amount of force which is needed compress the rubber ring result in deflection in both parts. This means the print is not rigid enough. See figure 69.

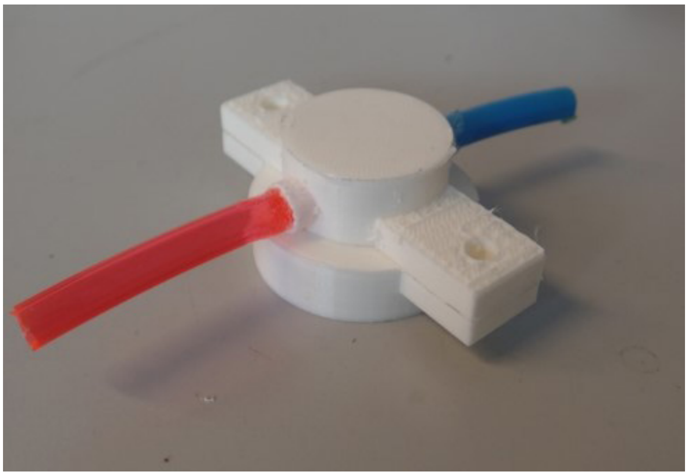


Figure 68: Static radial connection assembled

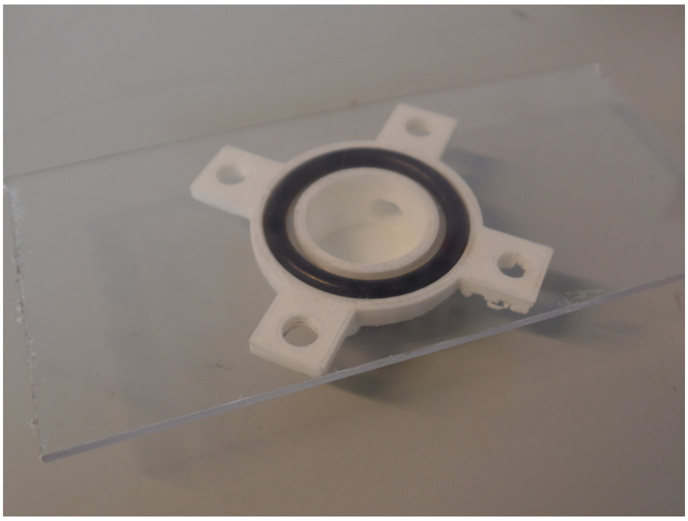


Figure 69: Static axial connection

O. External disk valve

Valve mechanism

What & How

Test different mechanisms to block the incoming air by pressing a flexible tube to a closed position. A compressor will be connected to the valve. The pressure will be increased up until air starts to flow through the valve. By putting the valve in a cup of water, air loss will be visible. At the end, SMA wires are implemented to open the valves.

The prototypes are tested by using two different flexible tubes. The thinnest tube explodes by supplying it with 4 bar. It starts to expand around 1-2 bar. The thicker tube able to withstand 4 bar without too large expansion of the tube. Therefore, only the thicker silicone tube is used for further experiments.

For the prototypes, two different springs are tested. They compress the tube by 6 and 15 N. Both springs are used in each prototype.

Concept Loops

Figure 70+71 shows the prototype of a mechanism making use of rubber loops. The flexible tube is placed in between the two loops. By placing a spring above, the loops will press the flexible tube. This concept enable to keep the total volume compact. The mechanism act in the direction of the wire.

A spring force of 15N is used to press the flexible tube. At around 2 bar, the valve starts to pass through some air.

Concept Parallel

Figures 72+73 show a mechanism which makes use of two separate parts both 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 tube. By placing a spring on top makes valve press the flexible tube by making a sharp angle which blocks the incoming air.

The valve is tested with the two different flexible tubes. By using the thin tube, the holes have a diameter of 4mm with a distance of 2mm in

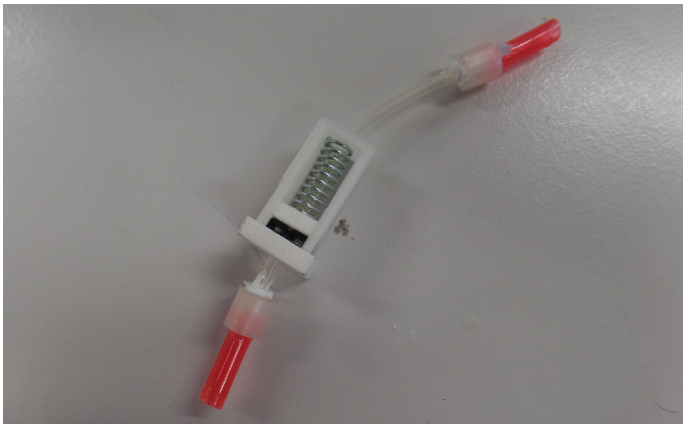


Figure 70: Concept Loops assembled

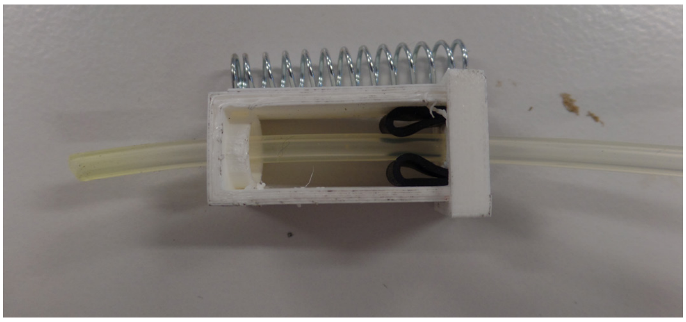


Figure 71: Concept Loops

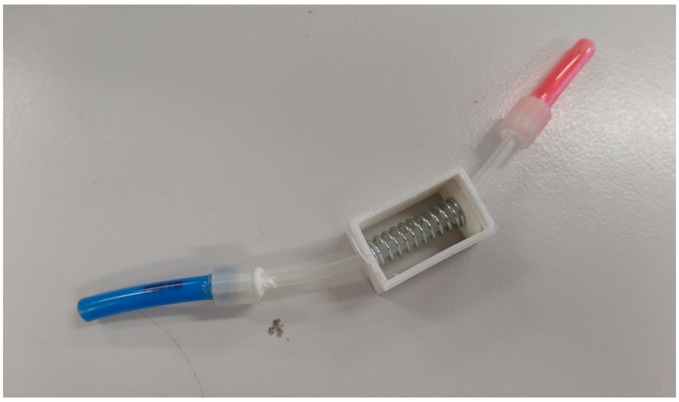


Figure 72: Concept parallel thick silicone tube

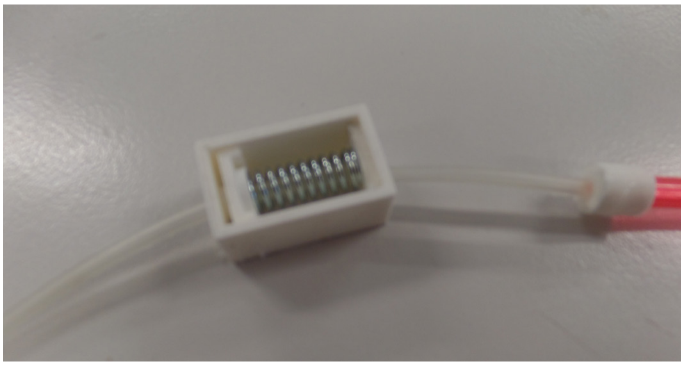


Figure 73: Concept parallel thin silicone tube

between.

The different distances between the two holes by making use of the thicker flexible tube is 4.5 mm and the holes have a diameter of 5mm.

Figures 74 show ta prototype making use of SMA wires to open the valve. It appears that there is more force needed to close the valve when supplied with air than remain to keep the valve closed. Therefore, a prototype is made to close the valve again by placing an SMA wire acting in the opposite direction, see **figure 75**. Unfortunately, the force of the SMA wires will not keep the valve closed. This is because the force of the wires will disappear when the wires cool down again. It appears, the air in between the valve and the finger need to be released to close the valve again without having to use a stronger spring.

Concept Perpendiculair

Figure 76 shows 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.

The valve is able to stop the incoming air up to 4 bar by a spring force of 15 N without any air slipping through the valve. The wires are fixated by screws placed in the body of the box.

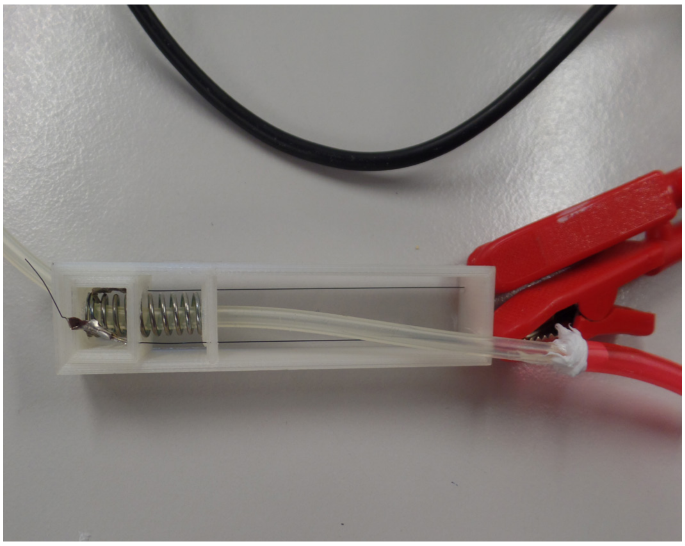


Figure 74: Parellel valve actuatd by SMA wires

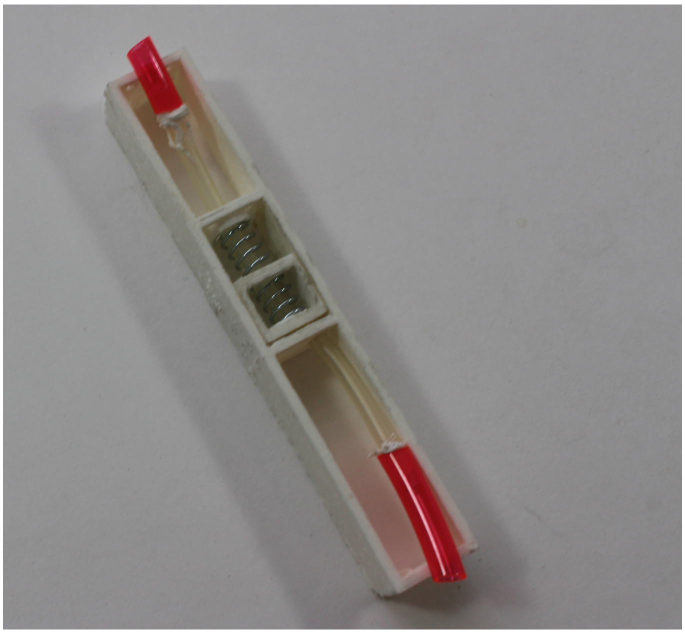


Figure 75: Concept parallel opend with two pair of sma wires in opposite direction. (SMA wires are missing in this photo)

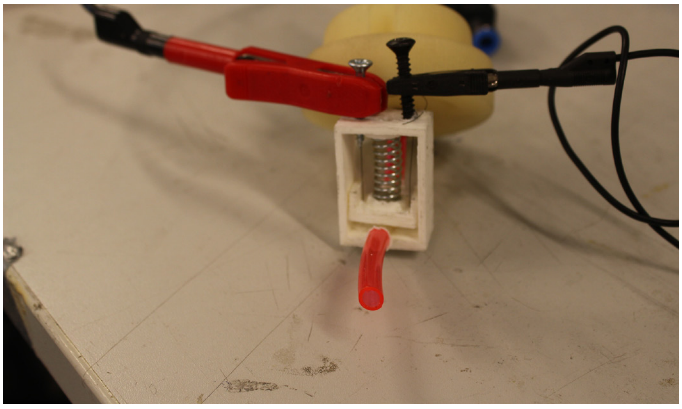


Figure 76: Concept perpendicular valve opened by using SMA wires.

Required Force

What & How

Both concepts have been tested on the amount of force is needed to keep the valve closed, see **figure 77 A**. Only one of the two concept is tested to close with only air flowing through the valve, see **figure 77 B**.

A: in this situation, the air flows in both direction thorugh the same valve. The tube is pressurized when the air has to deflate.

B: in this situation, the air flows through the tube, and a second valve has an open end which leads to the surrounding air. When the valve acting as ventil open, the bellow is de pressurized, and the first valve closes. In this way, a less strong spring is required.

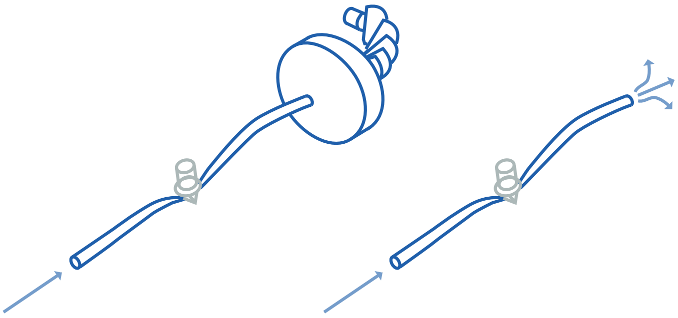


Figure 77: A compres tube which is pressurized V compress tube which is not pressurized

Perpendicular pinch valve

4 Different amounts of air pressure is supplied. All test have been performed 3 times. The results of scenario A is shown in **figure 78**. Scenario B is shown in **figure79**.

Parallel pinch valve

The parallel valve is only tested in situation B, this is because this will be the function the vale will need to fulfill taken the final valve setup in mind. The test is repeated 3 times. Supplying the valve with 4 bar. Only 6N is required.

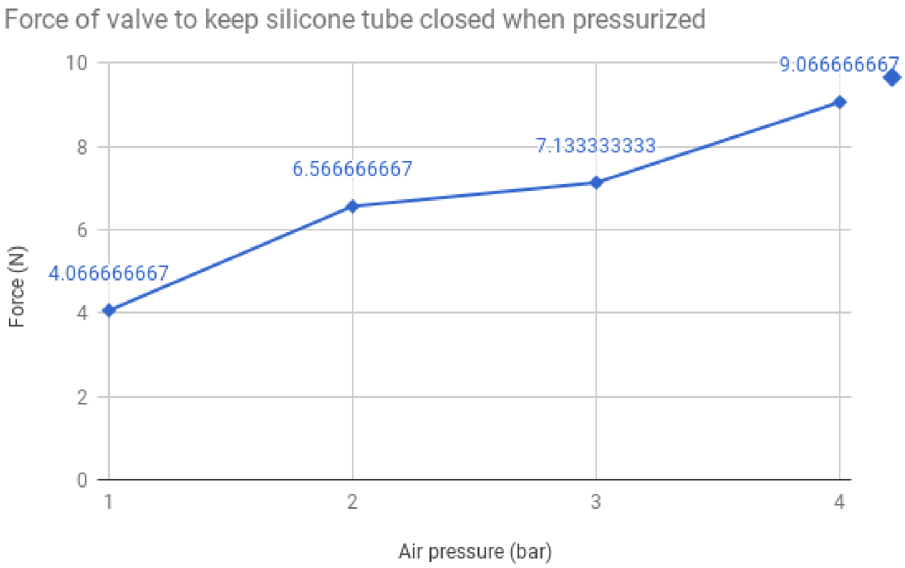


Figure 78: scenario A

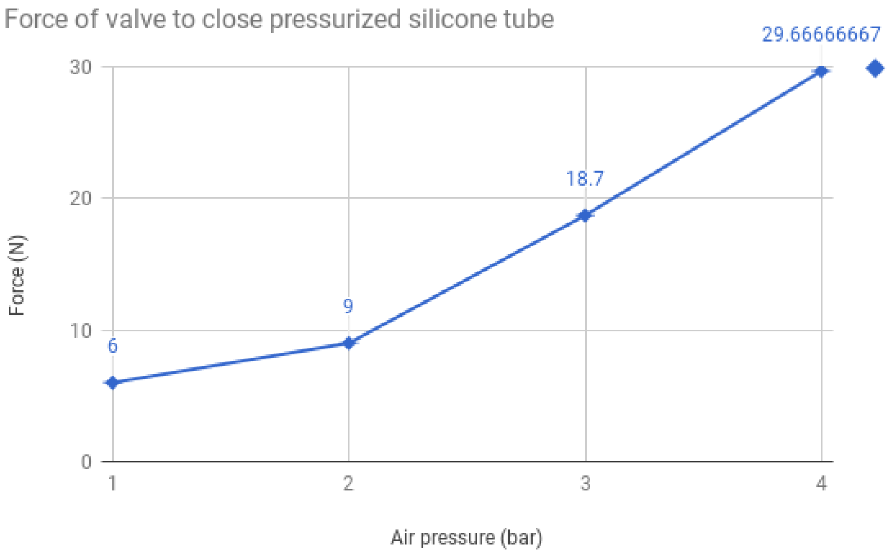


Figure 79: Scenario B

Inflation Speed

What & How

Both concepts are tested on the inflation speed. How further the valve has to be opened, the more SMA wire is needed, which is not desirable. Both concepts have been prototyped with the possibility to adjust the length of the SMA wires. The part which fixates the SMA wires is adjustable in distance from the tube and can be clamped to the body of the valve. Both concepts are shown in the figures 80+81.

A 2mm diameter SMA wire is used. The advised current is 0.66A to heat the wires for 1 second. For the experiments with adjustable SMA lenght, 0.8A is used. Therefore, the applied current has not be applied a little less than a second.

The inflation speed is tested by making use of 12.5 and 25 mm of SMA wire resulting in respectively 0.5 and 1mm contraction length.

By supplying different amounts of currents, the attached finger bends in different speeds. SMA wires contract up to 5% over a period of time. This time depends on the amount of current. It is expected that the finger will open not only in shorter amount of time while supplied with a higher current, but also a increase in speed. According the analyzes recordings, the tube shows almost a constant bending speed. Although the beginning of the bending movement seems to start is little slower the end of the bending movement of the finger. In the future, a feedback control system can be used to precisely determine a constant bending speed of a finger by keeping the wire in a constant temperature related to a certain contracting length. This length is related to the opening of the valve which determined the flow rate trough the valve.

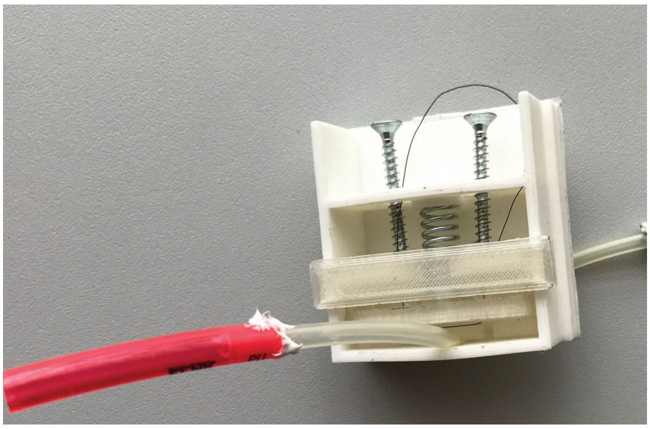


Figure 80: Perpendicular valve

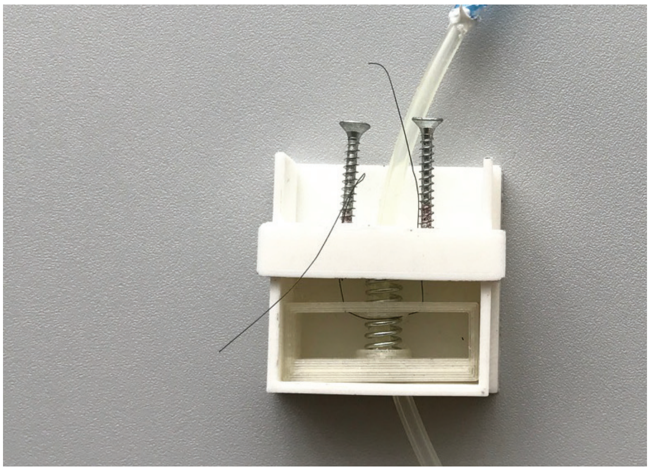


Figure 81: Parallel valve

Minimize the volume

What & How

Two springs are used for the next prototypes: D21510 and D11265.

D21510 has an outside diameter of 6.93 mm, a wire thickness of 0.63 mm, a free length of 17mm, a compressed length of 6.2 mm at a maximum force of 10.37N with a spring constant of 0.7. This spring can be used to place the flexinol wires inside or a tube supplied with air.

D11265 has an outside diameter of 5.5 mm, a wire thickness of 0.5 mm, a free length of 16.d mm, a compressed length of 4.44 mm at a maximum force of 11.08 and a spring constant of 0.93. This spring has the smallest outside diameter to deliver the required force the press the silicone tube supplied with 4 bar.

The D21510 makes it possible to place the flexinol wires inside the spring. The D11265 has the minimal diameter to be able to block 4 bar and can be while placing the SMA wires around it.

Prototypes: Parallel

In the first prototype, the silicone tube is threaded through the spring. When the spring is placed inside the valve between the body and the part which closes the tube, it is impossible to place the flexible tube through the spring and 3D printed parts. This is because the body around the spring makes it impossible to bend the compressed spring and place it inside the valve while the tube is threaded trough the spring.

The next two prototypes have an extra part. After the tube and spring are placed, the spring is compressed a bit further to implement the extra parts which is then pushed by the spring to the body of the valve. **Figure 82** shows a model with the SMA wires placed inside the spring. **Figure 83** shows a model with the silicone tube placed inside the spring. Both prototypes are able to block 4 bar while applying 8N.

Prototypes: Perpendiculair

In this prototype, the SMA wires are placed inside the spring. The valve is able to withstand 4 bar. Supplying more pressure results in air slipping through the valve. **See figure 84**.

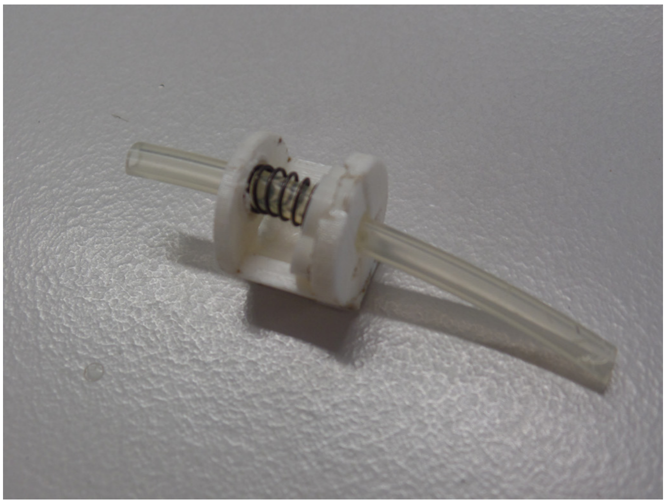


Figure 82: Parallel valve, silicone tube threaded though the spring

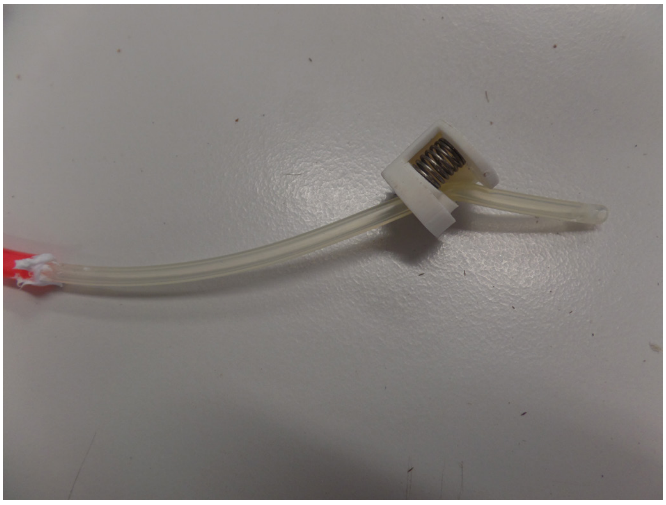


Figure 83: Parallel valve, silicone tube next to the spring. This enable the flexinol wires to thread through the spring.

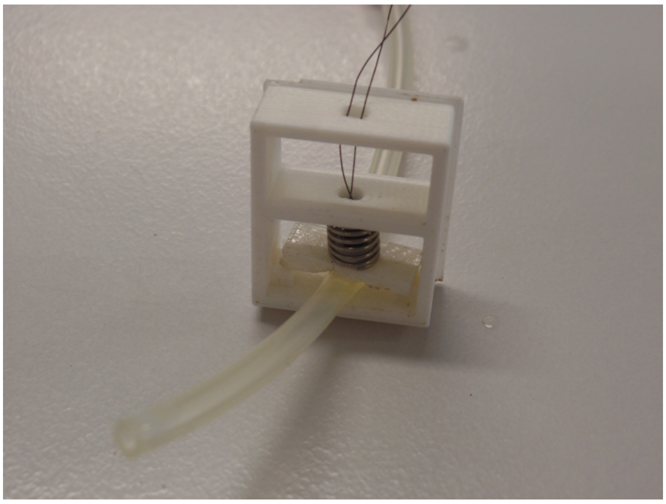


Figure 84: Perpendicular valve: flexinol wires threaded through the valve.

Final result

This prototype is to test the complete valve using a silicone tube. To keep the valve in the same direction of the length of the finger, both tested valves are used. The parallel valve is used to inflate the finger. The perpendicular valve is used as ventil and deflate the finger. The design of the valve takes the placement of all parts in consideration. Because the spring only need about 6-8 mm in compressed state, two valves can be placed in the length of the flexinol wires of only one valve. This reduces a lot of space.

The valve has a diameter of 15mm and 30mm in length. The downside of the prototype is the amount of steps are required to assemble the whole valve. The silicone tubes are attached with glue, the SMA wires are fixated using screws, the springs are placed, and the extra part of the parallel valve is inserted. Unfortunately, the valve does not work properly. This is because the glue connection of the silicone tubes fail when applied with pressure. Because of the small dimensions of the valve, it is a complex work to place all the tubes properly. Replacing the silicone tube by a 3D printed and integrated flexible tube, this problem could be solved. For the final result see figures 85-86.

Conclusion

Both the parallel and perpendicular valve have been tested separately and worked well. Integrating the two valves inside the same space, some problems occur, mostly because the connection of the silicone tubes cause problems. Therefore, the next step is to design the valve using 3D printed tubes. By using 3D printed tubes, less connections will be needed which decrease the change of air loss. But important to notice, by finding a solution to fixate the tubes properly, this valve should work considering the results from previous prototypes. This prototype shows the assembly of all separate parts is possible and the springs can be placed inside the valve.

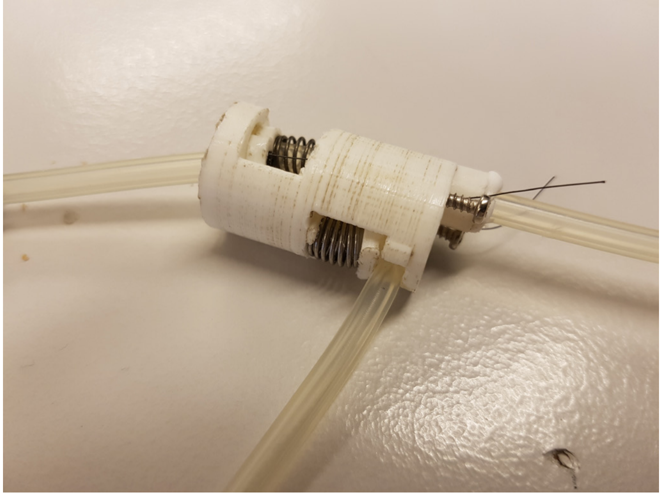


Figure 85: Final result valve with silicone tube

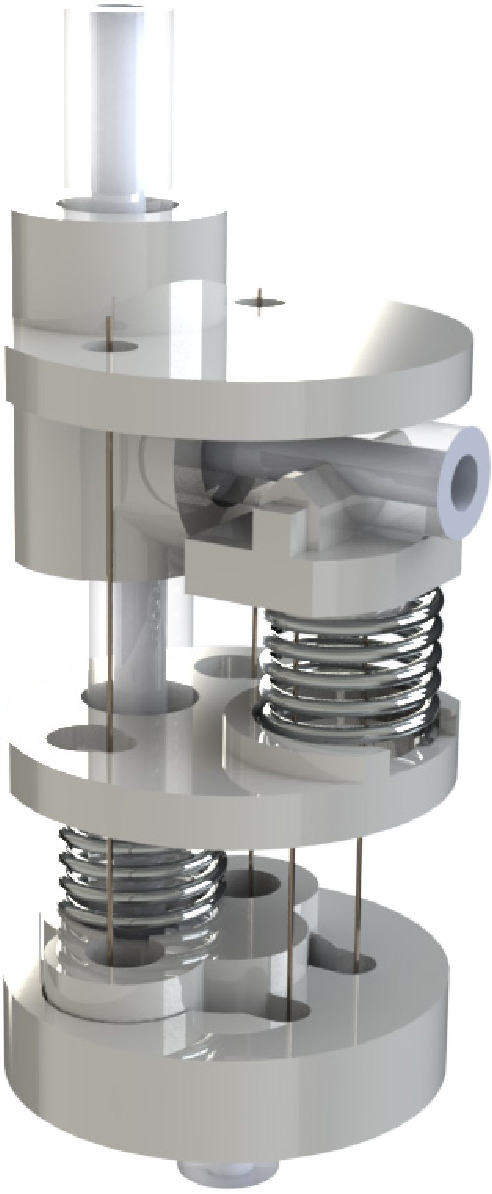


Figure 86: Final result valve with silicone tube: Solid works render

P. Integration of 3D printed tube

3D printed flexible tube

What & How

Different flexible tubes are printed to test if a printed tube can hold high air pressures up to 4 bar, but at the same time have the flexibility to be pressed to a fully closed position. For this experiments a PoliJet printer is used which enables to combine both a rigid and flexible material in one model.

First test

First, two flexible tube are printed, both with 100% flexible material. Both tubes have a thickness of 1mm and outer diameter of 4 mm. One tube is connected with a rigid part to test the connection between the two material. Unfortunately, both tube fail at around 2 bar and around 0.5 to 1 bar it starts to expand significantly. The connection remains intact. The tubes are shown in **figure 87**.

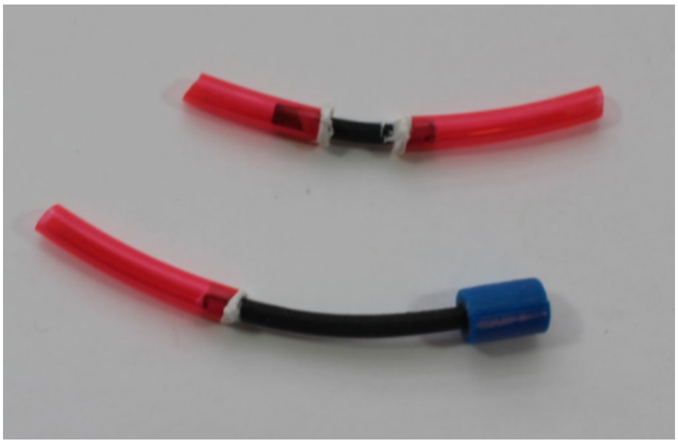


Figure 87: First 3D printed 100% FLX tubes

Set of flexible tube

Taken previous results into account, a collection of tubes is printed with varying flexibilities and thickness, explained below. They all have a diameter of 6 mm. To reduce prototype costs, only the flexible part is printed without the rigid connection. These are attached afterwards to connect the flexible tube with are and be able to supply the tube with air.

Flexibility (FLX %): 1000%, 65%, 50%, 15%
Wall thickness: 1.25, 1.5, 1.75 and 2 mm.

The flexible tubes can withstand a little less force than the silicone tube which is used in previous tests. But, according first results, pressure around 2 bar can be realized. This amount of pressure can actuate most of the soft robotics. Therefore, a valve will be designed which allows 2 bar. By keeping the inside diameter of the tube above 1mm, fast bending speed of the fingers can be contained.

Design of Flexible tube

What & How

First, the two separate tubes are connected to a compressor and pneumatic finger. Both tubes are pressed by a disk, used in previous prototypes. A newton meter is used to determine the required force to close the tube. Two iterations of valves are tested by placing the spring inside the model while supplying approximately 7.5N.

Prototypes

Figure 88 shows the 1ste iteration. Only a single valve is designed to minimize the printing costs. The part at the top is to be able to place SMA wires with the required length to open the valve. The tube has an angle of 90 degrees to minimize the width of the model. The bottom of the tube touches surface of the rigid body. 30% FLX requires a high amount of air pressure, but also a high amount of force is needed to close the tube. Because of the wide surface around the placement of the spring, it is hard to place the compressed spring. During this assembly step, the tube is damaged and tears at the middle. Therefore, no test can be performed with this model.

Figure 89, shows another single valve, but with 15% FLX. This model enables the spring placement wihout causing any damage to the flexible tube, but because of the lack in flexibility, the tube is very brittle. The tube tears at the middle where the disk presses the tube, and the corner which is 90 degrees. It seems 15% FLX is too brittle.

Figure 90 shows a double valve making use of straight flexible tubes and 50% FLX. A higher amount of FLX is used to prevent the tube from failing. But it fails at the transition of the material transfer. It also fails in the middle when supplied with the compressed spring for a longer period of time.

Figure 91 shows a double valve with 100% FLX tubes. Different shaped disks have been tried to figure out if a less sharp disk could prevent the tube from failure. SMA wires are attached, but air-leakage occurs. The transfer between the two materials fails again.

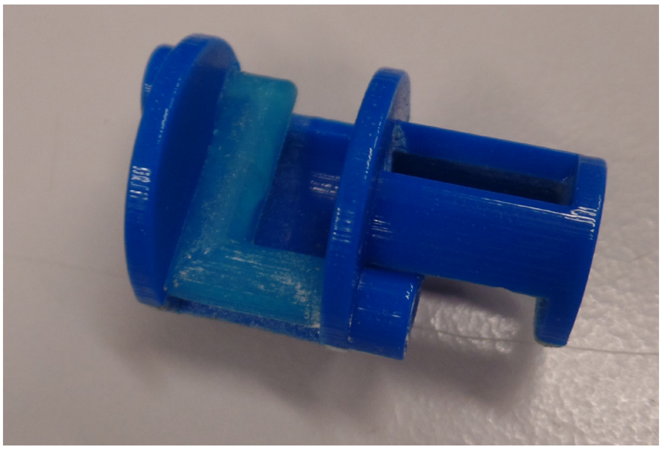


Figure 88: First iteration FLX 30%

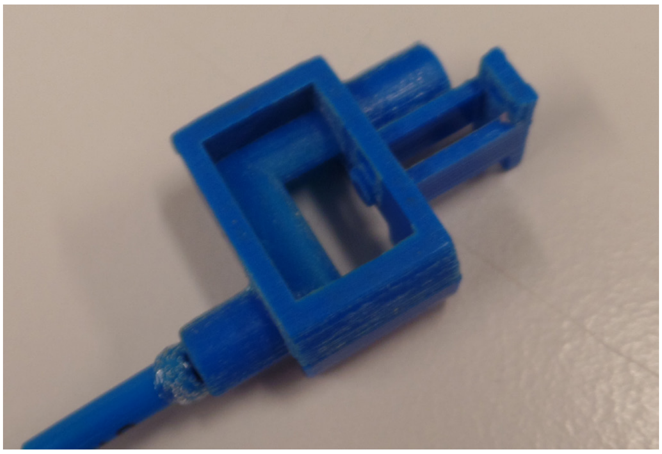


Figure 89: 2nd iteration FLX 15%

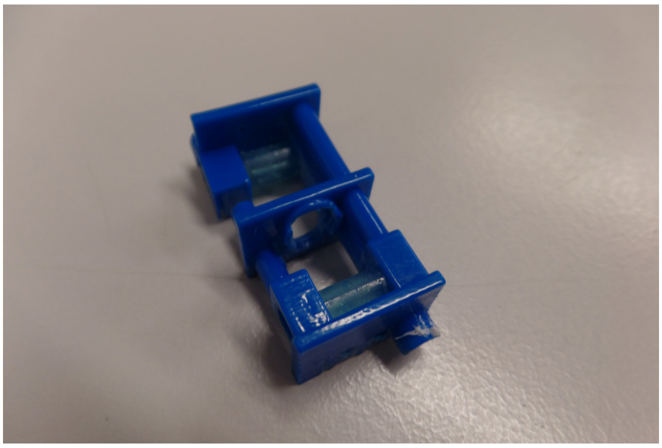


Figure 90: 3th iteration FLX 50%

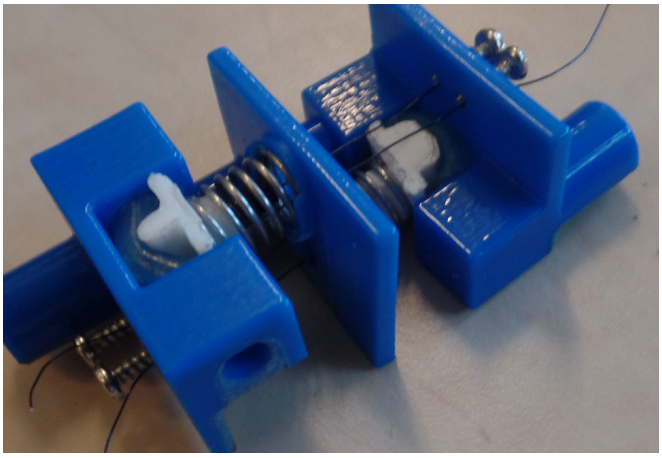


Figure 91: 4th iteration FLX 100%

Optimize tube Desgin

What & How

From the last prototypes, no working valve have been tested. Different variations in tube thickness, FLX% and cross section are tested.

The tubes are printed with an attached rigid parts which can be connected to the compressor. The body around of the valve is printed separately with an Ultimaker 2.0. The tubes can be placed and removed from the body. The part of the tube which is compressed by the spring floats only 0.3mm above the surface. The prototypes are designed to create as much as possible free space in length of the tube to deform. In this case, the tube can divide the deformation over its whole length.

The tubes of **table 1: Main report** are used to define the wall thickness with suited wall thickness to withstand 1 bar.

The inside diameter of the round tube is set to 2mm with all 4 tubes. This results of an area of 3.14 mm2. The oval shapes tubes have in inside width of 3 mm and height of 0.8 mm resulting in area of 1.8 mm2. This area of which the air flows through is significant less, but opening the valve with a round cross section by a 1 mm will only enables half of the areas to pass through. Therefore the assumption is made that both tubes will have similar flow speed.

Integration of tube

From the results in **table 1**, most promising tube is highlighted. 100% Flexible material seems to best by also only option the compress by placing a spring above it. Besides, the thinner the wall thickness, the less force is required to block the incoming air. A round shaped disk prevents the tube from tearing.

After assembly, the valve is connected to a below design. The valve works, but the deflation speed of the finger is too slow.

Integration of valve to finger

The last prototype is used to create the final prototype, but the dimensions of the tube is slightly enlarged, with a width of 3.5 mm and a height of 1 mm. Attaching the valve to the bellow design of the finger, the design is slightly adjusted to take into account the removal of the support material after the print is finished.

The final prototype results in fast flow speed through the valve. The finger bends deflated fast.

Flexible tubes supplied with 1 bar					
Wall thickness	FLX%	Cross section			
			Force to keep tube closed		
1.5	60	round	3.5	3.1	2.9
		oval	2.8	2.4	2.3
1.75	60	round	4.5	4	4.1
		oval	3.8	3	2.9
	100	round	2.7	2.3	2.5
		oval	3.1	2.9	2.9
2	100	round	3.2	2.9	
		oval	4.2	3.6	

Table 1: results of tubedesigns

Q. Calculate spring dimensions

Explanation formulas
By compressing a spring it is subjected to torque, resulting in torsional stress. The external force F, delivered by the flexible tube is applied along the axis of the helix. For springs made of solid round wire, the torsional stress is:

torque= 8FD/(pi*(d^3))

F= the external force which compresses the spring
D= is mean coil diameter
d= the wire diameter

In addition to this basic shear stress, the inner surface of the spring is subjected to two additional shear stress components: Curvature effect and transverse shear. Because of the curvature of the wire which can be seen as torsion bar, there is an increase in the intensity of torsional stress. The torque transmitted through the curved bar produces a 1° rotation between planes m and n, see figure 92. This effect is more when the spring index C has a small value. C is defined by the ratio of mean coil diameter to the wire diameter.

C=D/d

Besides the curvature stress, a transverse shear stress is caused by force F to the arbitrary cutting plane. See figure 93. Correction factor of transverse shear is defined as

Ks=1+ (0.5/C)

The transverse shear stress is 1.23F/A. Adding both effects to the nominal torsional stress gives:

stress = (8FD)/ pi*r*d^3 + (1.23*F) / (pi*d^2//4)

This can be formulates as:

Total stress = (8FD/ pd3 *)Ks = (8F/pd2)*C*Ks

Helical spring deflection can be formulates as:

deflection = 8F*D^3*N/ d^4*G

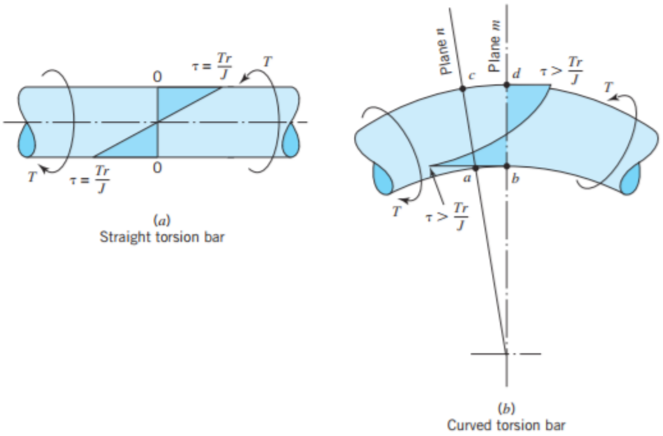


Figure 92: Torque

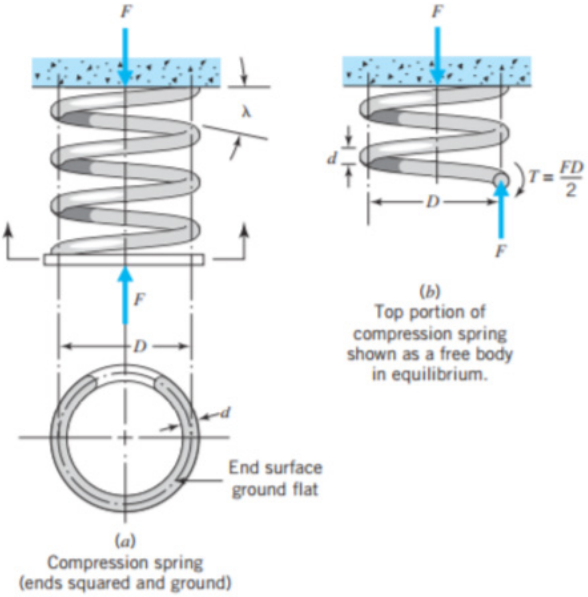


Figure 93: Forces on spring

k = F*deflection = d^4*G/ 8*D^3*N

Extracting the N, active amount of coils results in:

N := d^4*G/(8*F^3*k)

Sprig have normally a flat end at both ends. Both consist of a coil. For the formula, only the active amount of coils are used.

N := Nt-2

Springs have the property that the smaller the wire thickness, the greater the tensile strength is. Therefore it is important to notice the tensile strength is dependent on the wire thickness when using the formulas. See figure 94

The higher the tensile strength, more stress the spring can handle. Because the wire thickness will be smaller than mm, ASTM A228 Music wire can handle the most stress. Therefore, This material is chosen to work with. The exact date is retrieved from

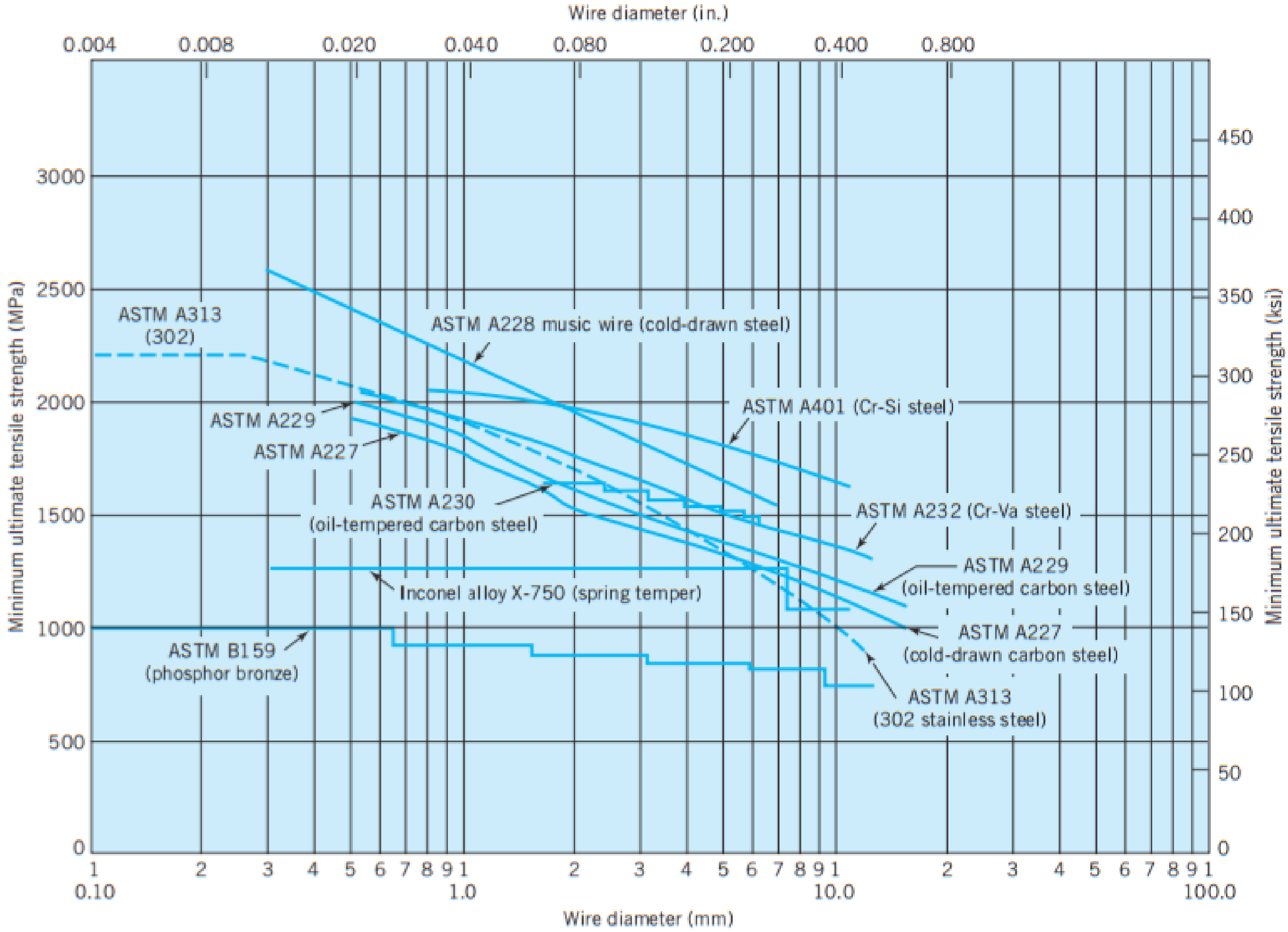


Figure 94: wire thickness related to tensile strenght

By setting the tension from a ferrous spring at solid state equal to 45% of the tensile strength, less than 2% long term ''set'' will occur. Associated Spring Corporation, "Design Handbook: Engineering Guide to Spring Design," Associated Spring Barnes Group, Bristol, CT, 1987.

A clash allowance of 10% is recommended from preventing the spring to reach full solid state due to combinations of tolerances, wear of parts, but also to make sure the spring is able to be placed inside the spaces it is intended for.

When a spring is fully compressed, all coils are pressed on top of each other. This is defined by the solid state. The force at this compressed state is named Fsolid, and the compressed distance is Lsolid. This compressed length of the spring is the amount of coils * the wire thickness.

Ls := Nt*d

The total length of the spring in non compressed state is called the free length of the spring: Lf. The free length is the length of the length in full compressed state plus the length of compressed distant:

Lf := Ls+fs
The last consideration to take into account is the possibility of a spring to buckle, particularly large ratio of free length to mean diameter.

Set graphs: 9.5N

```
clear
clc
syms Dm2
%look up table for ....
xx = [0.016 0.018 0.02 0.022 0.024  0.026  0.028 0.03  0.032  0.034  0.036  0.038  0.04  0.042  0.045 0.048 0.051 0.055 0.059 0.063 0.067 0.072 0.076 0.08 0.09 0.095];
%xx in inches
vv=  [362000  356000  350000  345000  341000 337000  333000  330000  327000  324000  321000 318000  315000  313000  309000  306000  303000 300000  296000  293000  290000  287000  284000 282000 282000 274000 ];
%vv in psi
% constantToInch=xxxxxxxxxxxxx;
% constantToMM= 1/constantToInch;
Fold = 9.5;% F = Force max (N)
Fold = 0.224808942443*Fold;%(lbs)
G = 11.5*10^6;% G = shear modules(psi)
% k = spring constant psi(lbs/inch)%old
i=1;
j=1;
% d = .157;% d= wire thickness (mm)
d1 = [0.016 : 0.002 : 0.028];% wire thickness in inch
k1 = [0.15 : 0.25 : 1.4];%new in (lbs/inch)
dx=1/25.4; %mm->inchof spring due to wire pull
for d = d1 %indexed by i
   for k = k1 %indexed by j
F = Fold + (k*dx);%new
tensilestrength =  interpn(xx,vv,d) ;
Shearstress = .45*tensilestrength;
 f(i,j) = F/k;             %f = maximale indrukking
 CA = (.1*F)/k;              % CA: clash alowance
 Fsolid(i,j) = (CA*k)+F;     % Fsolid: kracht bij volledige indrukken, verder dan maximaal toegestaan
 Fsolid2(i,j)= Fsolid(i,j)/ 0.224808942443;
 fs(i,j) = Fsolid(i,j)/k;     % fs= indrukking bij volledige indrukking, verder dan maximaal toegestaan
 C = Dm2/d;                 % C= Spring index
 Ks = 1+(.615/C);             % Ks= Wahl factor
 X  = (8*Fsolid(i,j)*Ks*C)/(pi*d^2)- Shearstress;
  Dm(i,j)  =  double(solve(X,  Dm2));        %calculting diameter of spring(center to middle of thread)
 N(i,j) = d^4*G/(8*Dm(i,j)^3*k);           % # of active coils
 Nt(i,j)= N(i,j)+2  ;                 % # of total coils
 Ls(i,j) = Nt(i,j)*d   ;               % lenght spring solid state
 Lf(i,j) = Ls(i,j)+fs(i,j)  ;           % free lenght spring
 bucklingRatio1(i,j) = fs(i,j)/Lf(i,j);
 bucklingRatio2(i,j) = Lf(i,j)/Dm(i,j);
 dd(i,j)=25.4*d;%d in mm wire thickness (mm)
  D(i,j)=25.4*Dm(i,j);%  inch  to  mm    diameter  of spring(center to middle of thread)
  Lss(i,j)=25.4*Ls(i,j);  %inch  to  mm  lenght  spring solid state
 kk(i,j)=k*0.17513;%lbs/inch->N/mm % new
 FF(i,j)= F / 0.224808942443;
 j=j+1;%indexing to keep all values stored
    end
j=1;
i=i+1;%indexing to keep all values stored
end
figure(1)
contour( kk, dd, Lss,’ShowText’,’on’)%
ylabel(‘d= wire thickness (mm)’), xlabel(‘k= spring constant (N/mm)’), title(‘ Ls= Length of spring in solid state (mm) contour plot’)
print(‘ContourLength1’,’-dpng’)
figure(2)
contour( kk, dd, Fsolid2, ‘ShowText’,’on’)%
ylabel(‘d wire thickness (mm)’), xlabel(‘k= spring constant  (N/mm)’),  title(‘  Maximum  force  (N) contour plot’)
print(‘ContourLength2’,’-dpng’)
figure(3)
contour( kk, dd, D, ‘ShowText’,’on’)%
ylabel(‘d=  wire  thickness  (mm)  ‘),  xlabel(‘spring constant  (N/mm)’),  title(‘  D=  spring  diameter contour plot’)
print(‘ContourLength3’,’-dpng’)
figure(4)
contour( kk, dd, N, ‘ShowText’,’on’)%
ylabel(‘d=  wire  thickness  (mm)’),  xlabel(‘spring constant (N/mm)’), title(‘Figure 2: contour plot  of number of active coils’)
print(‘ContourLength4’,’-dpng’)
% figure(1)
% plot(dd,D)
%  ylabel(‘Diameter  of  spring  (mm)  (center  to middle of thread)’), xlabel(‘Wire thickness (mm)’),
...
%    title(‘hier iets invullen over plaatje 1’)
%  print(‘plaatje  1’,’-dpng’)%meteen  opslaan  in matlab map
% figure(2)
% plot(dd,Lss)
%  ylabel(‘Lenght  spring  solid  state  (mm)’), xlabel(‘Wire thickness (mm)’), ...
%    title(‘hier iets invullen over plaatje 2 ‘)
%  print(‘plaatje  2’,’-dpng’)%meteen  opslaan  in matlab map
```

Calculate exact dimensions: 9.5N

```
clear
clc
syms Dm2
%look up table for ....
xx = [ 0.016 0.018 0.02 0.022 0.024 0.026     0.028
0.03  0.032  0.034  0.036  0.038  0.04  0.042  0.045
0.048 0.051 0.055 0.059 0.063 0.067 0.072 0.076
0.08 0.09 0.095];
%xx in inches
vv= [  362000  356000  350000  345000  341000
337000  333000  330000  327000  324000  321000
318000  315000  313000  309000  306000  303000
300000  296000  293000  290000  287000  284000
282000 282000 274000 ];
%vv in psi

% constantToInch=xxxxxxxxxxxxx;
% constantToMM= 1/constantToInch;
Fold = 9.5;% F = Force max (N)
Fold = 0.224808942443*Fold;%(lbs)
G = 11.5*10^6;% G = shear modules(psi)

WireD = 0.42 %wire thickness in mm%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%CHANGE  HERE%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%
Stifness= 0.09% spring stifness in N/mm%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%CHA
NGE   HERE%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%

d1 = WireD/25.4;% mm->in inch
k1 = Stifness/0.17513; %metric to imperial
dx=1/25.4; %mm->inch of spring due to wire pull


d = d1; %indexed by i
k = k1; %indexed by j

F = Fold + (k*dx);%new

tensilestrength =  interpn(xx,vv,d) ;
Shearstress = .45*tensilestrength;

 f = F/k;                %f = maximale indrukking
 CA = (.1*F)/k;                % CA: clash alowance
 Fsolid = (CA*k)+F;       % Fsolid: kracht bij volledige
indrukken, verder dan maximaal toegestaan
 Fsolid2= Fsolid/ 0.224808942443;
 fs = Fsolid/k;         % fs= indrukking bij volledige
indrukking, verder dan maximaal toegestaan
 C = Dm2/d;                    % C= Spring index
 Ks = 1+(.615/C);              % Ks= Wahl factor


 X  = (8*Fsolid*Ks*C)/(pi*d^2)- Shearstress;
  Dm  =  double(solve(X,  Dm2));        %calculting
diameter of spring(center to middle of thread)


 N = d^4*G/(8*Dm^3*k)        % # of active coils
 Nt= N+2                     % # of total coils
 Ls = Nt*d   ;               % lenght spring solid state
 Lf = Ls+fs  ;           % free lenght spring
 bucklingRatio1 = fs/Lf;
 bucklingRatio2= Lf/Dm;




  D=25.4*Dm  %  inch  to  mm   diameter  of
spring(center to middle of thread)
  Lss=25.4*Ls  %inch  to  mm  lenght  spring  solid
state
 Lff=25.4*Lf%inch to mm lenght spring free length
 kk=k*0.17513;%lbs/inch->N/mm % new
 FF= F / 0.224808942443
```

Outcome:

```
WireD = 0.4400
Stifness = 0.4000
N = 3.1960
Nt = 5.1960
D =6.6236
Lss = 2.2862
Lff =15.7615
FF = 4.9000

>>
```

Set graphs: 4.5N

```
clear
clc
syms Dm2
%look up table for ….
xx = [0.016 0.018 0.02 0.022 0.024 0.026 0.028 0.03 0.032 0.034 0.036 0.038 0.04 0.042 0.045 0.048 0.051 0.055 0.059 0.063 0.067 0.072 0.076 0.08 0.09 0.095];
%xx in inches
vv= [362000 356000 350000 345000 341000 337000 333000 330000 327000 324000 321000 318000 315000 313000 309000 306000 303000 300000 296000 293000 290000 287000 284000 282000 282000 274000 ];
%vv in psi
% constantToInch=xxxxxxxxxxxxx;
% constantToMM= 1/constantToInch;
Fold = 4.5;% F = Force max (N)
Fold = 0.224808942443*Fold;%(lbs)
G = 11.5*10^6;% G = shear modules(psi)
% k = spring constant psi(lbs/inch)%old
i=1;
j=1;
% d = .157;% d= wire thickness (mm)
d1 = [0.016 : 0.002 : 0.028];% wire thickness in inch
k1 = [0.15 : 0.25 : 1.4];%new in (lbs/inch)
dx=1/25.4; %mm->inchof spring due to wire pull
for d = d1 %indexed by i
   for k = k1 %indexed by j
F = Fold + (k*dx);%new
tensilestrength =  interpn(xx,vv,d) ;
Shearstress = .45*tensilestrength;
 f(i,j) = F/k;                 %f = maximale indrukking
 CA = (.1*F)/k;                % CA: clash alowance
 Fsolid(i,j) = (CA*k)+F;     % Fsolid: kracht bij volledige indrukken, verder dan maximaal toegestaan
 Fsolid2(i,j)= Fsolid(i,j)/ 0.224808942443;
 fs(i,j) = Fsolid(i,j)/k;      % fs= indrukking bij volledige indrukking, verder dan maximaal toegestaan
 C = Dm2/d;                    % C= Spring index
 Ks = 1+(.615/C);              % Ks= Wahl factor
 X  = (8*Fsolid(i,j)*Ks*C)/(pi*d^2)- Shearstress;
  Dm(i,j)  =  double(solve(X,  Dm2));        %calculting diameter of spring(center to middle of thread)
 N(i,j) = d^4*G/(8*Dm(i,j)^3*k);           % # of active coils
 Nt(i,j)= N(i,j)+2  ;                  % # of total coils
 Ls(i,j) = Nt(i,j)*d   ;                  % lenght spring solid state
 Lf(i,j) = Ls(i,j)+fs(i,j)  ;           % free lenght spring
 bucklingRatio1(i,j) = fs(i,j)/Lf(i,j);
 bucklingRatio2(i,j) = Lf(i,j)/Dm(i,j);
 dd(i,j)=25.4*d;%d in mm wire thickness (mm)
  D(i,j)=25.4*Dm(i,j);% inch to mm   diameter of spring(center to middle of thread)
 Lss(i,j)=25.4*Ls(i,j); %inch to mm lenght spring solid state
 kk(i,j)=k*0.17513;%lbs/inch->N/mm % new
 FF(i,j)= F / 0.224808942443;
 j=j+1;%indexing to keep all values stored
    end
j=1;
i=i+1;%indexing to keep all values stored
end
figure(1)
contour( kk, dd, Lss,’ShowText’,’on’)%
ylabel(‘d= wire thickness (mm)’), xlabel(‘k= spring constant (N/mm)’), title(‘ Ls= Length of spring in solid state (mm) contour plot’)
print(‘ContourLength1’,’-dpng’)
figure(2)
contour( kk, dd, Fsolid2, ‘ShowText’,’on’)%
ylabel(‘d wire thickness (mm)’), xlabel(‘k= spring constant (N/mm)’), title(‘ Maximum force (N) contour plot’)
print(‘ContourLength2’,’-dpng’)
figure(3)
contour( kk, dd, D, ‘ShowText’,’on’)%
ylabel(‘d= wire thickness (mm) ‘), xlabel(‘spring constant (N/mm)’), title(‘ D= spring diameter contour plot’)
print(‘ContourLength3’,’-dpng’)
figure(4)
contour( kk, dd, N, ‘ShowText’,’on’)%
ylabel(‘d= wire thickness (mm)’), xlabel(‘spring constant (N/mm)’), title(‘Figure 2: contour plot  of number of active coils’)
print(‘ContourLength4’,’-dpng’)
% figure(1)
% plot(dd,D)
% ylabel(‘Diameter of spring (mm) (center to middle of thread)’), xlabel(‘Wire thickness (mm)’), ...
%    title(‘hier iets invullen over plaatje 1’)
% print(‘plaatje 1’,’-dpng’)%meteen opslaan in matlab map
% figure(2)
% plot(dd,Lss)
% ylabel(‘Lenght spring solid state (mm)’), xlabel(‘Wire thickness (mm)’), ...
%    title(‘hier iets invullen over plaatje 2 ‘)
% print(‘plaatje 2’,’-dpng’)%meteen opslaan in matlab map
```

Calculate exact dimensions: 4.5N

```
clear
clc
syms Dm2
%look up table for ....
xx = [ 0.016 0.018 0.02 0.022 0.024 0.026 0.028 0.03 0.032 0.034 0.036 0.038 0.04 0.042 0.045 0.048 0.051 0.055 0.059 0.063 0.067 0.072 0.076 0.08 0.09 0.095];
%xx in inches
vv= [ 362000 356000 350000 345000 341000 337000 333000 330000 327000 324000 321000 318000 315000 313000 309000 306000 303000 300000 296000 293000 290000 287000 284000 282000 282000 274000 ];
%vv in psi

% constantToInch=xxxxxxxxxxxxx;
% constantToMM= 1/constantToInch;
Fold = 4.5;% F = Force max (N)
Fold = 0.224808942443*Fold;%(lbs)
G = 11.5*10^6;% G = shear modules(psi)

WireD = 0.42 %wire thickness in mm%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%CHANGE   HERE%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Stifness= 0.09% spring stifness in N/mm%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%CHANGE    HERE%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

d1 = WireD/25.4;% mm->in inch
k1 = Stifness/0.17513; %metric to imperial
dx=1/25.4; %mm->inch of spring due to wire pull


d = d1; %indexed by i
k = k1; %indexed by j

F = Fold + (k*dx);%new

tensilestrength =  interpn(xx,vv,d) ;
Shearstress = .45*tensilestrength;

 f = F/k;                  %f = maximale indrukking
 CA = (.1*F)/k;                  % CA: clash alowance
 Fsolid = (CA*k)+F;       % Fsolid: kracht bij volledige indrukken, verder dan maximaal toegestaan
 Fsolid2= Fsolid/ 0.224808942443;
 fs = Fsolid/k;          % fs= indrukking bij volledige indrukking, verder dan maximaal toegestaan
 C = Dm2/d;                      % C= Spring index
 Ks = 1+(.615/C);              % Ks= Wahl factor


 X  = (8*Fsolid*Ks*C)/(pi*d^2)- Shearstress;
  Dm  =  double(solve(X,  Dm2));         %calculting diameter of spring(center to middle of thread)



 N = d^4*G/(8*Dm^3*k)         % # of active coils
 Nt= N+2                      % # of total coils
 Ls = Nt*d   ;                 % lenght spring solid state
 Lf = Ls+fs  ;            % free lenght spring
 bucklingRatio1 = fs/Lf;
 bucklingRatio2= Lf/Dm;




  D=25.4*Dm  %  inch  to  mm   diameter  of spring(center to middle of thread)
  Lss=25.4*Ls  %inch  to  mm  lenght  spring  solid state
 Lff=25.4*Lf%inch to mm lenght spring free length
 kk=k*0.17513;%lbs/inch->N/mm % new
 FF= F / 0.224808942443
```

```
Outcome:
WireD = 0.4200
Stifness = 0.0900
N =14.4831
Nt =16.4831
D =6.185
Lss = 6.9229
Lff =63.0239
FF =4.5900
```

R. Demonstrator case study 1: Pneumatic finger

This chapter will elaborate further on the details of the valve designed to control a pneumatic finger. In **figure 95**is the cross section of the flexible tube shown. The inside dimensions are 1x3mm. The wall thickness is 1.75 mm. The outside dimensions are: 6.5x4.5mm. The spring delivers a force of 4.5 newton to close the tube. The vales are placed next to each other with a minimal amount of space in between. The length of the SMA wires is set to 25 mm. This enables the valve to open 1 mm, which is the distance of the inside height of the flexible tube. Because the spring probably compresses the tube a little, the actual opening would be a little less than 1 mm. **Figure 96** shows both disks are placed at the middle of the length of the tube. By creating enough distance between the point the disk presses the tube and the point the flexible tube is fixated to the rigid body, the chance to prevent failure of the connections is as small as possible. **Figure 97** shows how the spring is placed inside the body of the valve. The red line represent the surface of the spring to rest on. A ridge of 1 mm is placed at the side to be able to place the spring. This distance is to prevent the spring the bend but still makes it easy to place the valve without compressing the to much which makes it more

Figure 95: Side view of valve which shows dimensions of cross section of the flexible tube.

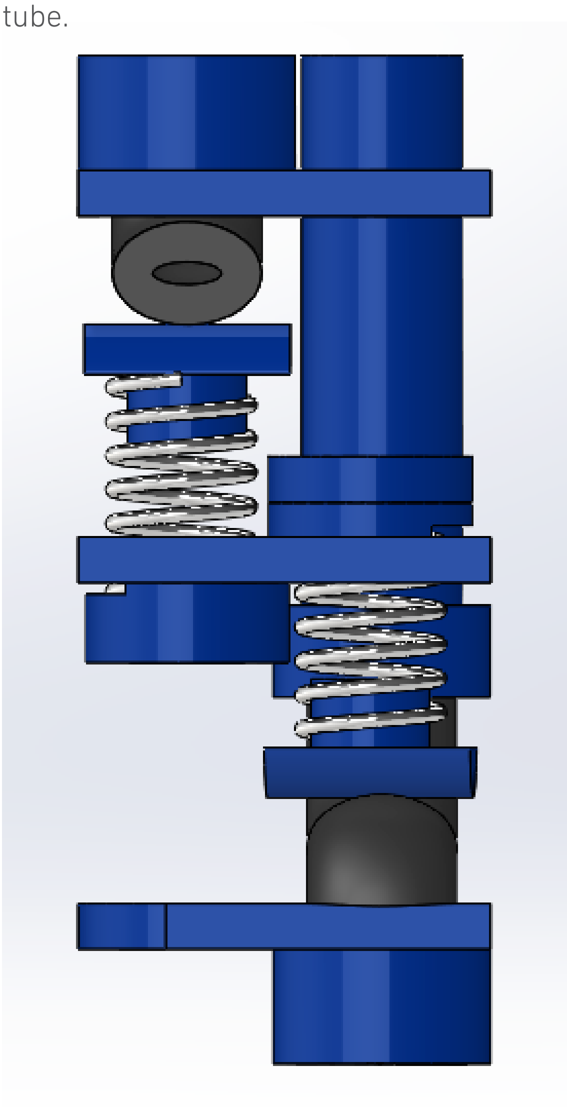
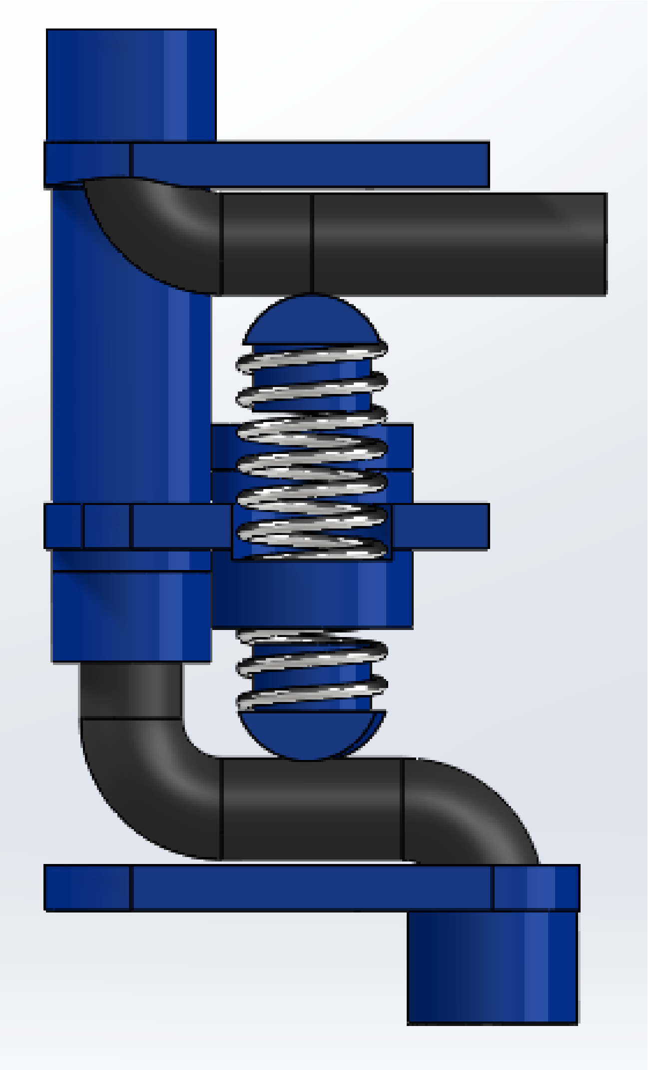


Figure 96: Disk are place at the middle of the tube



difficult to place the spring.

Figure 98 and 99 shows how the flexible tube is connected to the rigid body. The outside surface of the tube makes contact with the rigid body over 3 mm to prevent the connection to cause any air leakage. Also, the end of the tube is attached to rigid body for the same reason.

The flexible tube floats with a distance of 0.3 mm above the surface it is pressed towards by the spring. A distance between the two surfaces is required to enable the tube to deform while being pressed to the surface of the body. This prevents the chance of failure of the tube at the place the tube is compressed by the shape of the disk.

The disk has a width of 8 mm. When the tube is closed it expands a little in width. The width of the tube is 6mm. The 8 mm of the disk is large enough to compress the whole tube in length.

Figure 98 shows also how the bottom of the tube is attached to the body of the valve. The tube makes no contact at the inside angle of the tube. This enlarges the freedom of the tube to deflect while being pressed.

The rigid body of the valve has a wall thickness of 2 mm to make the valve strong enough to handle with the forces acting on it together with prevent any air leakage inside the tube.

The radius of the angle of the middle of the tube is 4 mm. When a too small radius is applied, the tube fail, but using a large radius creates larger dimensions of the valve. The radius used in this prototype seems to work perfectly.

The SMA wires are placed 4 mm apart form each other and fixated by using screws. Placing the SMA wires to close to each other will affect the cooling time while both wires radiate heat while cooling down.

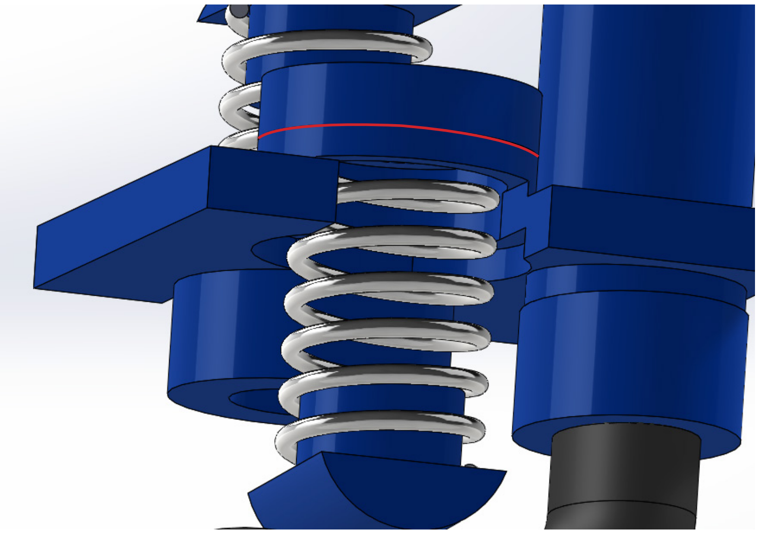


Figure 97: placement of the spring

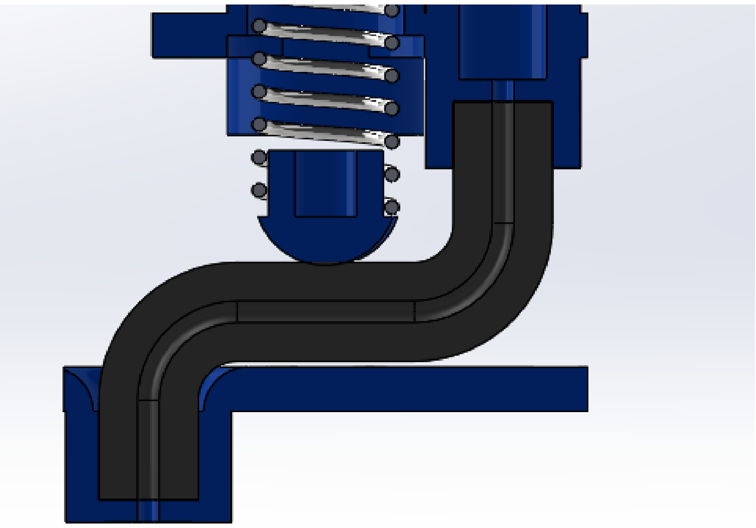


Figure 98: fixation of the flexible tube to the body of the valve

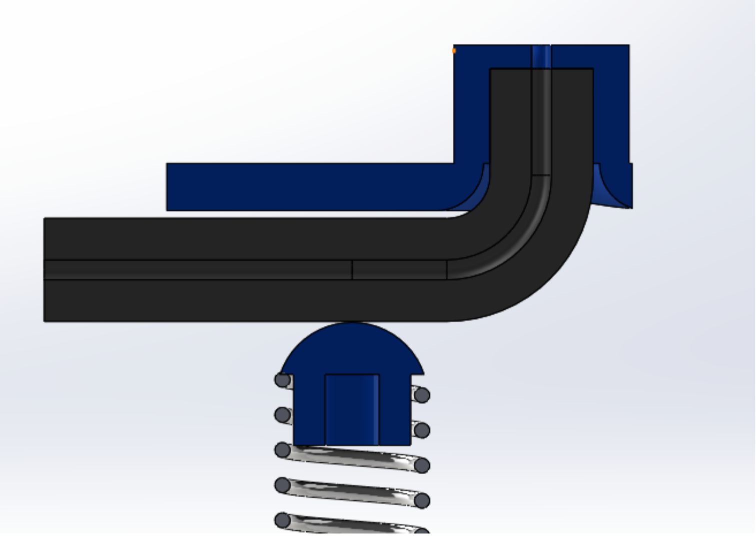


Figure 99: fixation of the flexible tube to the body of the valve

S. Demonstrator case study 2: Walking Robot

This chapter will elaborate further on the details of the valve designed to control a waking robot. In **figure 101** is the cross section of the flexible tube shown. The dimensions are kept the same: The inside dimensions are 1x3mm. The wall thickness is 1.75 mm. The outside dimensions are: 6.5x4.5mm. The spring delivers a force of 4.5 newton to close the tube.

In **figure 100** is the top view of the entire valve shown. The valve is mirrored to be able to supply both bellows from the middle and creating the exact same path to the bellow. Because the bellows are placed in opposite direction, the design of the valve is changed in comparison with the firt demonstrator. The goal was the design a valve within the outside dimensions of the bellow. The distance between the bellows is kept as minimal as possible.

Figure 101 shows the fixation of the flexible tube to the rigid body. Again, a length of 3mm is used where both surfaces meet.

Again, the length of the flexible tube is made as long as possible to prevent connections of the flexible

Figure 100: Disk are place at the middle of the tube

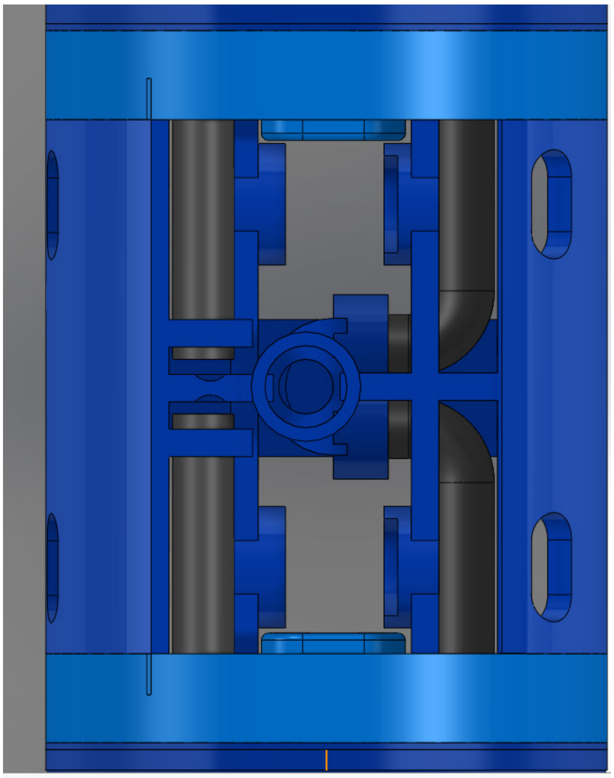
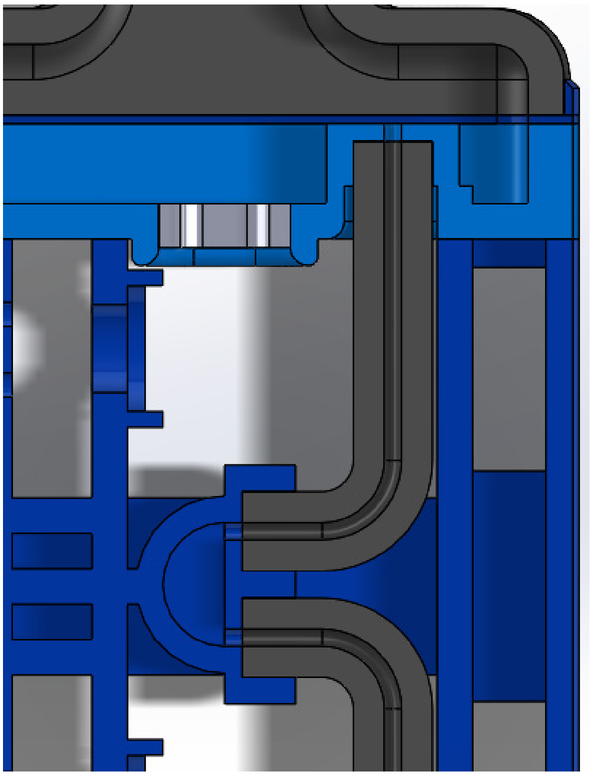


Figure 101: Disk are place at the middle of the tube



tube form failure. The flexible tube is actually attahced to the rigid boy inside the design of the bellow to save space.

The length of the SMA wires is set to 21mm. This enables the orientation of the valves how it is. The result is that the valve open by 0.84 mm instead of 1 mm, which is assumed to be neglect able.

Figure 102 shows how the spring is placed inside the body of the valve. The same solution is used as with the pneumatic finger.

Figure 101 shows how the flexible tube is connected to the rigid body. The outside surface of the tube makes contact with the rigid body over 3 mm to prevent the connection to cause any air leakage. Also, the end of the tube is attached to rigid body for the same reason.

The red line in **figure 103** shows the distance between the flexible tubes which is only 1.5 mm. Because the disk have a width of 8mm which is more than the width of the tube, the disks interfere with the body around the spring of the opposite valve. This has been a small design mistake. The tubes need to be placed about 2 mm further form each other to prevent this interference. Increasing this distance will still allow the valves to be placed inside the diameter of both bellows.

The wall thickness and radius in angle of the tube are kept the same:

The rigid body of the valve has a wall thickness of 2 mm to make the valve strong enough to handle with the forces acting on it together with prevent any air leakage inside the tube.

The radius of the angle of the middle of the tube is 4 mm. When a too small radius is applied, the tube fail, but using a large radius creates larger dimensions of the valve. The radius used in this prototype seems to work perfectly.

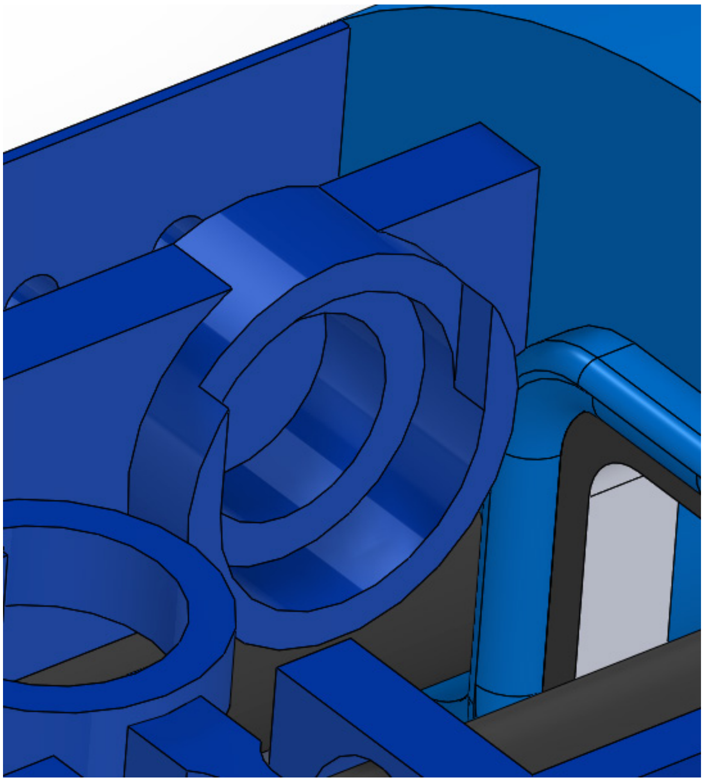


Figure 102: Placement of the spring

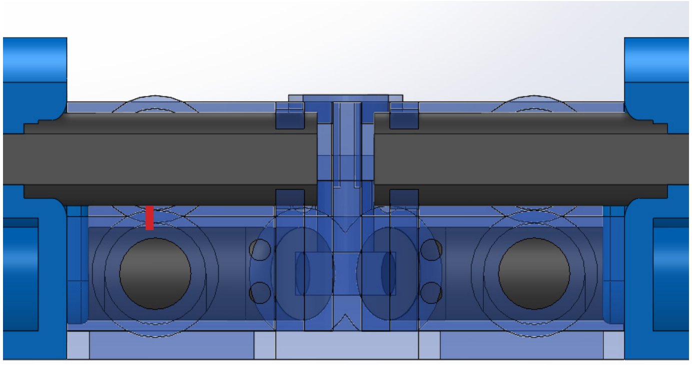


Figure 103: Distance between flexible tubes

Some different plugs are 3D printed to be able to test the walking robot to move forward. **Figure 104** shows three different plugs. The black surface is flexible material serves as grip. The two plugs are also printed in a variant which the bottom is covered by this surface acting as grip layer.

The bellows needs to be able to inflate and deflate after each other. The most promising sequence seems to be:

1. Inflate front bellow and make the grip layer pull the robot forward.

2. Inflate the back bellow without making a grip surface to touch the ground. Wen entirely inflated, the bellows should make the top part covered with a grip surface to touch the ground to keep it in position.

3. By deflating the front bellow, the robot should keep its position and make the grip layer of the front bellow touch the ground again when deflated.

4. Deflate the back bellow and make the front bellow keep the robot in position. When fully deflated this routine of 4 steps can be repeated.

Unfortunately, it didn't worked as expected. More time is required to optimize the design to make the robot to move forward.

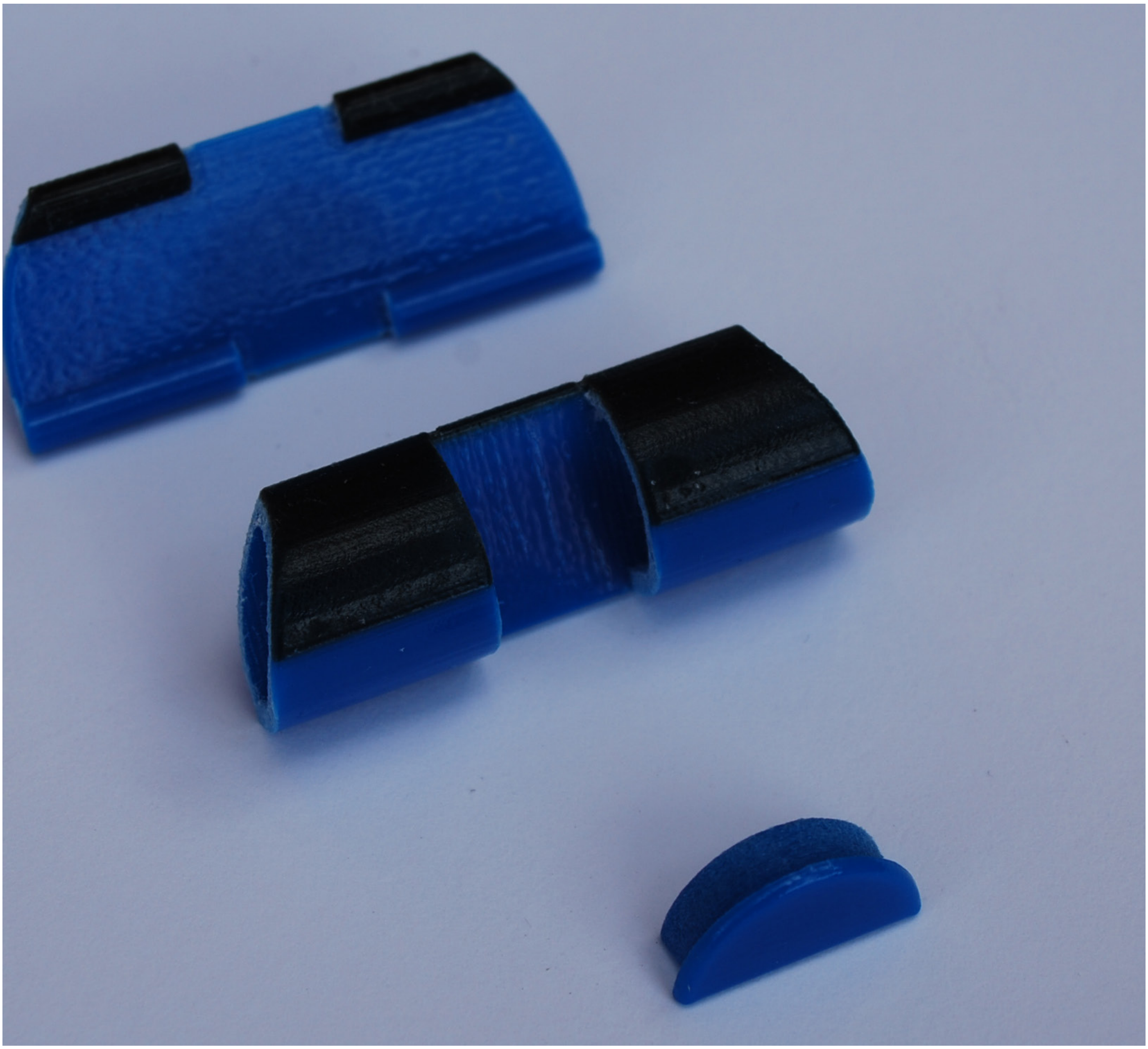


Figure 104: Plugs with different grip designs

T. Benchmark

Weight

Body of two valves= 8 grams, 4 flexible tubes= 3 grams, spring is 0.3 grams. SMA wire is neglectable. Two valves to control one bellow= (8/20+(4/2)+(0.3x2)= 6.6 grams

Volume

Te valves to control two bellows has the dimensions of 41x18x40mm. A valve to control only one bellow would result in half of the length resulting in 41x18x20 mm. By spending more time on designing a small as possible valve together with improved print qualities of the flexible material, an even smaller valve can be realized, but the total volume will not be drastically improved.

Integration

As proven with both demonstrators, the shape of the valve can be adapted to different desired parameters. It can be printed in one piece together with the attached bellow(s). Therefore, no extra connections are needed and no tube connecting the valve to the bellows. This safe space by making use of small available volumes. Therefore, the valve is very well able to be integrated into a soft robotic.

Control flow rate

During the prototyping is show that changing the applied current to the SMA wires influences the bending speed of the bellows, but enable also to control the deflation speed of the bellows. The bending speed of the finger seems constant, but there is a small increase in speed during the movement. By making use of a feedback control system, the temperature of the wires can be

Current Design

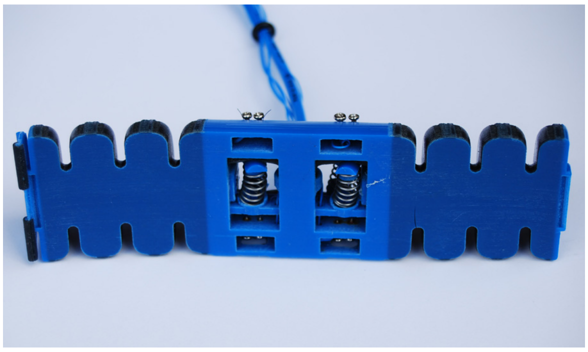


Figure 105: Miniature SMA valve

Weight:	🟩	🟩	🟩	🟩	🟩	6.6 grams
Volume:	🟩	🟩	🟩	🟩	⬜	41*18*20mm
Integration:	🟩	🟩	🟩	🟩	🟩	
Control flow rate:	⬜				🟩	No
Pressure:	🟧	🟧	⬜	⬜	⬜	1 bar
Flow rate:	🟩	🟩	🟩	🟩	⬜	20 l/m
Power	🟩	🟩	🟩	🟩	⬜	1.2 W
Price:	🟨	🟨	🟨	⬜	⬜	18$

Expectation

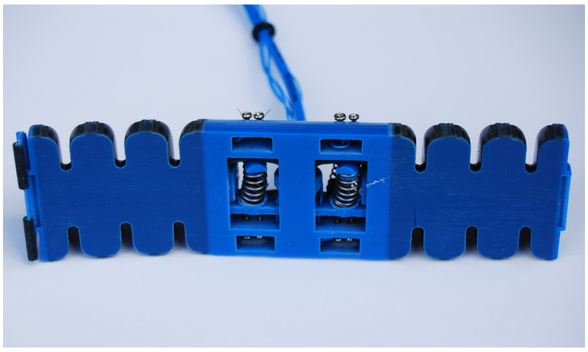


Figure 106: Potential miniature SMA valve

Weight:	🟩	🟩	🟩	🟩	🟩	5 grams
Volume:	🟩	🟩	🟩	🟩	⬜	<41*18*20mm
Integration:	🟩	🟩	🟩	🟩	🟩	
Control flow rate:	⬜				🟩	No
Pressure:	🟩	🟩	🟩	🟩	🟩	4-8 bar
Flow rate:	🟩	🟩	🟩	🟩	🟩	20-40 l/m
Power	🟩	🟩	🟩	🟩	⬜	0.25 W
Price:	🟨	🟨	🟨	⬜	⬜	18$

determined precisely which enable th valve to control the flow rate even better.

Pressure

The maximum allowable pressure is now 1 bar. An improved quality of the flexible tube can increase this amount. The valves being prototyped by making use of a silicone tube where able to block up to 4-6 bar. They failed due to the connections of the tube. Therefore the assumption is made that in the future, the vale will be able to withstand up to over 6 bar.

Flow Rate

The valve has an opening of 1x3 mm by making use of an oval shaped cross section of the flexible tube. The area where the air flows through is 6.68mm2. The area of a circle with a diameter of 2 mm is 6.28mm2 which is a little less. An orifice of 2mm enables a flow rate of 57 l/m. (TLC,2017). Assuming the SMA wires do not open the entire tube and some flow rate is lost due to the path of the valve, less flow rate is passing through the valve. The assumption can be made that the current valve can reach at least the same flow rate of the Electrostem II which is 20 l/m.

By improving the design of the valve by enlarge the dimensions of the tube or extend the length of the SMA wires, even faster flow rates can be reached. Possibly the flow rate can be doubled.

Power

Current Prototype : By opening the valve in 1 second with 2x 0.2 diameter wire, 1.7V and 0.7A is used. W=A*V= 1.7*0.7= 1.19 W.

Theoretically only a double 0.1mm diameter wire is used.

R= 3.2, A= 0.2 (less with a smaller diameter) V=0.63
W= I*V= 0.2*0.63* 2 (double wire)= 0.25W

Price

The price is not very low. This is because the print price is high. But, the body itself is already printed. Therefore, only the flexible tubes and some extra surfaces needs to be extra printed. The valve price of the print was not 9.30 euro's including only the valve. each spring was 3 euro's nd the piece of flexinol 0.25 euro. Together it costs 15.55 euros= 18$