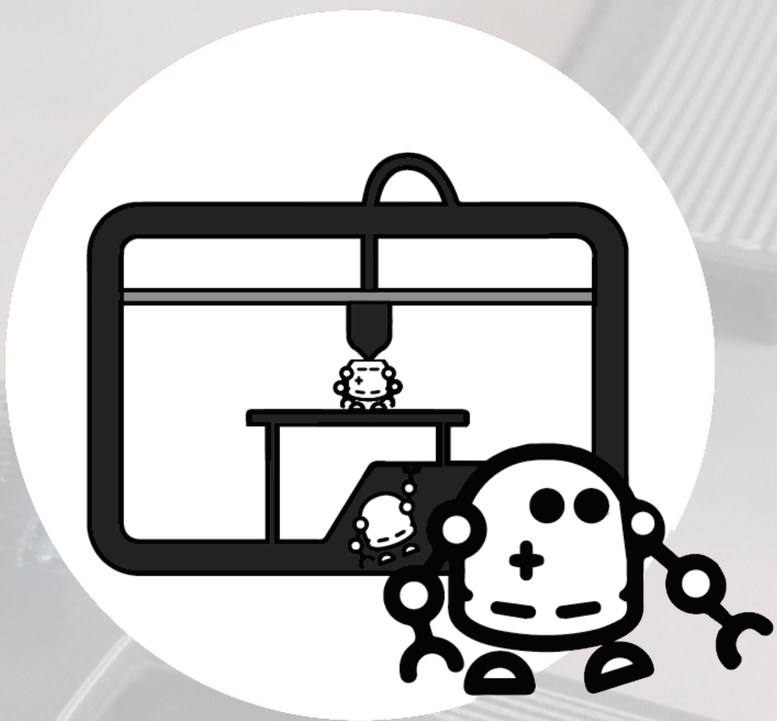
A ROBOT OUT OF A 3D PRINTER

An exploration of 3D Printed Thermal Actuators



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December 2017

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ACKNOWLEDGMENTS

“What separates the superstars from the average: they seek criticism, and actually listen to it.”
(Price, 2016)

This project has not become a success due to the effort of a single individual, but through a collection of smart and kind individuals that deserve some thanks.

First I would like to thank Kaspar Jansen to give me the opportunity to work on this incredible innovative project and giving me the freedom to tinker away. Song-Chuan for being my desk mate and coach. His insights and experience were very valuable for a successful completion of the projects.

I would like to thank Huib for supporting me through the highs and lows, and for making me both salads and cookies.

The participants of the creative session and the user research helped to create the insights needed to create a material experience vision and helped me to create a new appreciation for this smart material.

Special thanks to the other graduate students in the Applied Labs (Joep, Dirk, Bart, and Joost) for keeping me company while I was babysitting the 3D printer and during late night library sessions. Gerbera and Nathalie for our daily coffee breaks.

I’m very grateful to Veronique and Iris for proofreading my report and helping me to see mistakes I would have missed otherwise.

Finally, I want to thank my parents, my sisters and my brothers for checking in on me, cheering me on, bragging about my work and for proofreading my report.

EXECUTIVE SUMMARY

This report is an exploration of 3D Printed Thermal Actuators (PTAs). The goal of the project is to create a 3D printed demonstrator that shows the qualities of PTAs.

PTAs are created with a Voxel8 Multi-material printer which prints both PLA and a silver paste. When electrical power is applied to the silver trace, the plastic will heat up because of Joule heating in the silver trace the plastic will react to the heat by bending. This makes it an example of 4D printing. Compared to other 4D printed samples, PTAs have the advantage that they can repeat their motion. Additionally, PTAs are able to focus their energy locally, because of the placement of the silver traces. Robots are usually rigid and use rotation to move forward. Soft robots use their entire bodies to move and need air or water pressure from an external source. There are actuators that use electrical current to transform just as PTAs do. These actuators can be categorized in SMAs, DEAs and IPMCs, but have disadvantages compared to PTAs. SMAs need to be programmed into the correct shape and PTAs do not. Piezoceramics can make accurate but very small movements. DEAs need a very high current and frequency. And IPMCs need to be wet to perform their transformation.

There is much freedom in design in creating PTAs, but there is still a long list of design considerations to take into account. A PTA consists out of four different elements; a rim, a base, a silver trace and a connection to the power source. Designing a well working and predictable PTA takes some practice.

The movement of a PTA consists of three different stages; thermal expansion, transition and relaxing. When the PTA crosses the transition temperature because of the amount of electrical power that is applied, the PTA will transition into the relaxing stage and behave differently than before.

To create a better understanding of the potential of PTAs, the Material Driven Design Method (Karana, et al., 2015) was used and set of cards with the different qualities was created. The material experience vision has been defined as; a PTA should be admired, not handled. Just like a flower that is blooming or a ladybug that walks over your hand.

Multiple design ideas were generated by using the input from the set of cards with qualities, characteristics in nature and random words. With these ideas, three different concepts were created: Inchworm, Sloth and Turtle. Of these design ideas, the Inchworm and Turtle scored quite similar. However, the Turtle can also carry its own battery and therefore has the most design potential. The Turtle was chosen to be further developed into the 3D printed demonstrator.

The result of this graduation project is the Turtle Tinybot. Placing the active part under an angle, combined with a rough floor and Arduino controlled power supply, proved to be the best method to create locomotion. The pattern of the shell of the Turtle Tinybot has been carefully selected because it has several functions. The final design has a shell with a voronoi pattern, two hind legs and a tail.

In this graduation project, the possibilities of 3D Printed Thermal Actuators (PTAs) have been explored and a 3D printed demonstrator named the Turtle Tinybot has been designed. Further research can look into unexpected behavior displayed by PTAs: Extreme deformation, Heated rim, Torsion, Asymmetry, Modularity, and Intrinsic Oscillation.

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What is this project about?

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Figure 2 Bending behavior observed in June 2017 by the Emerging Materials team at Delft University of Technology

Project

The limits of 3D printed solutions are being pushed every day. With the introduction of the multi-material 3D printer, the Voxel8 in 2016, it has become possible to print conductive materials like silver. With these silver traces, it is possible to integrate sensors and circuits into 3D prints.

It has been observed that when applying power to these silver traces heat is generated because of Joule heating. This generated heat will cause the plastic in the 3D print to expand and bend (Figure 2). When power is removed the 3D print will return to its original position. Integrating the conductive heat elements into a 3D print to create movements has not be observed outside the Applied Labs at the Delft University of Technology. This movement can be used as an actuator in, for example, soft robotics or consumer electronics.

A 3D PRINTED THERMAL ACTUATOR WILL BE CALLED A PTA.

The movement has been observed but the details on designing an actuator have not yet been explored. The true potential of this actuator has been considered but not yet researched. That is where this project comes in.

Goals

CREATE MOTION USING A PTA

MAP THE DIFFERENT **TECHNICAL QUALITIES** OF PTAS THROUGH **HANDS ON EXPERIMENTATION**

MAP THE DIFFERENT **EXPERIENTIAL QUALITIES** OF PTAS THROUGH USER TESTS.

MAIN GOAL

CREATE A **3D PRINTED DEMONSTRATOR** THAT WILL MOVE IN AN ENGAGING WAY USING THESE PTAS

Figure 3 A Gamibot tinyrobot developed by HOWTOONS

ANALYSIS

What kind of research has already been done?

Before exploring PTAs it is useful to analyze what kind of research has already been done. In this chapter different insights are shared that have been made by other research groups all over the world in the field of 4D printing, robots, 3D printing with a conductive material, and unique actuators.

Figure 4 PLA is 3D printed on paper. After heating up with a heat source the flower will close. (Zhang, et al., 2016)

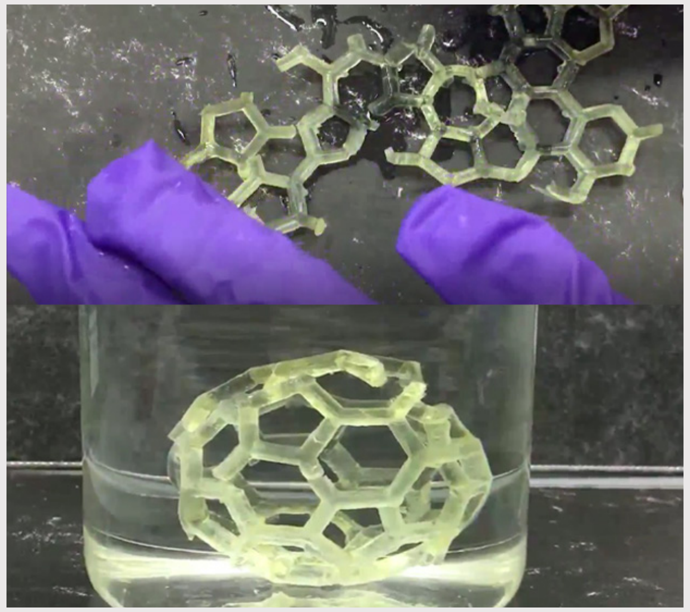


Figure 5 After this SLA print is heated up in water, it is stretched in the cooling phase. When returned to the hot water the ball will return to its original shape. (Choong, et al., 2017)

4D Printing

Printing is considered a method to transfer a digital image to paper using a printer. 3D printing is a method to transfer a 3-dimensional shape into different layers which can be placed on top of each other to create a static 3-dimensional shape. 4D printing is termed by a research team at MIT in 2013 (Tibbits, 2013). The extra dimension that is added is time (Figure 7). When using smart materials a static 3-dimensional shape can be created. When adding a stimulus the shape moves into a new shape. Different stimuli can be for example water, heat, light and a combination of these stimuli (Momeni, et al., 2017) When exposed to a stimulus the shapes can move in a number of ways. They can elongate, fold, bend, twist and display a change in surface texture (Figure 4 and Figure 5).

A PTA uses heat as its stimulus. This heat is generated by a current through the PTA which makes it different from known stimuli.

The majority of 4D printed models that use heat as a stimulus need to be stretched to end up in the desired or the original state. These pre-stretched models are not able to repeat the movement multiple times, these models can be considered shape-memory prints (Figure 5). Ptas are not constrained by the requirement of pre-stretching and are able to perform it's movement multiple times. This makes Ptas rather a shape-changing print than a shape-memory print.

This field of research is relatively new but shows a lot of potential. 4D printed shapes are able to self-assemble using relatively unconventional stimuli. Stimuli that can be found inside of a body or in remote environments and because their shape-changing behavior they can be easy to transport. Self-repair and multi-functionality are also considered potentials for the applications for 4D printing.

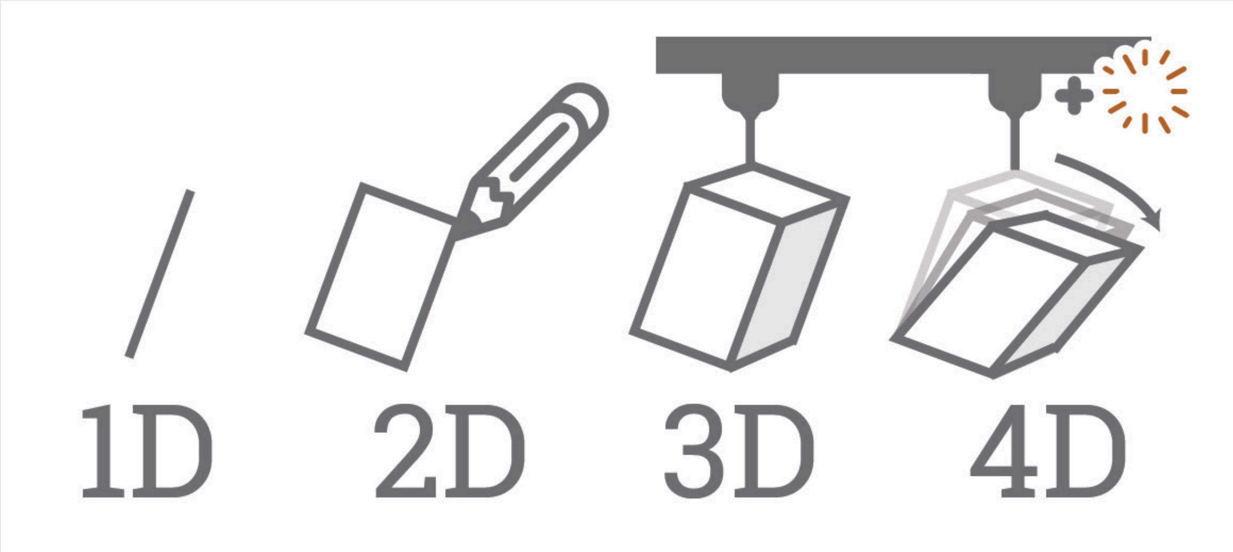


Figure 7 Visualization of the four dimensions

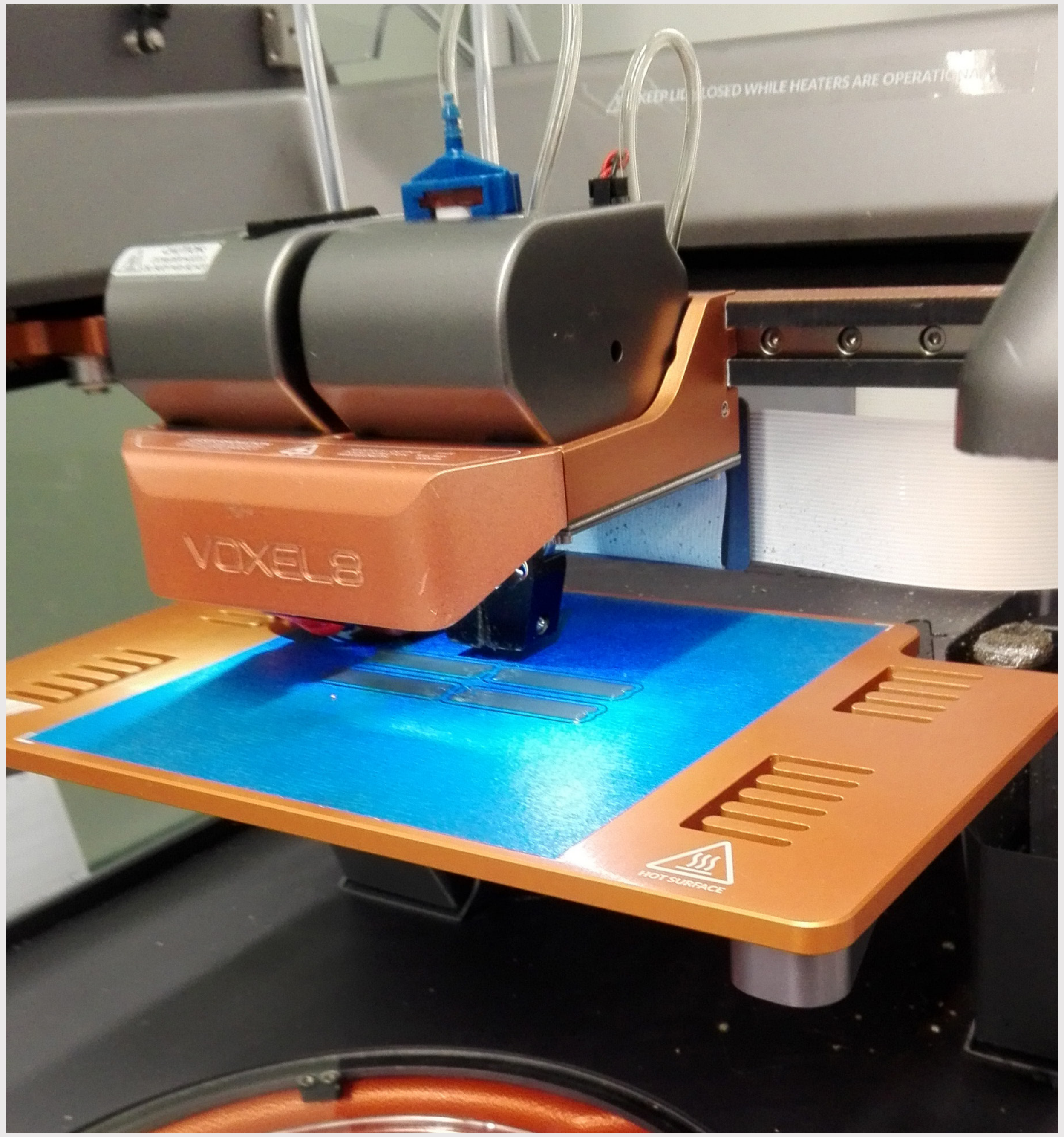


Figure 6 The Voxel8 printer printing a PTA

Voxel 8 3D printer

The 3d printer that is used for creating PTAs is developed in a lab in Massachusetts and is called the Voxel8 Developer's Kit (Figure 6). This 3D printer falls into the category of Fused Deposition Modeling. This method of 3D printing is the most common and low-cost way to 3D print prototypes. Using gears and a nozzle a long string of thermoplastic (called filament) is heated up and placed on the build plate. In a continuous motion, the 3D printer moves the nozzle around creating layer upon layer of the filament.

The Voxel8 has a nozzle that extrudes plastic, most commonly PLA heated up to 200 degrees Celsius with a diameter of 1.75 mm. It also has a syringe that is connected to a compressor. The syringe contains a fluid consisting of silver and a solvent. This solvent makes it possible to deposit at room temperature. The compressor creates a pressure between 14 and 18 psi to push the silver mixture out of the syringe and place it on top of the layers of extruded PLA. The Voxel8 is the first 3D printer, that is commercially available, that can mix plastic and metal in a single print using a single machine.

Voxel8 was founded in July 2013 by Jennifer Lewis together with three of her students who are still part of the company. Jennifer Lewis has a background in Material Engineering. From May 2015 the Voxel8 printers were available for purchase and in May 2017 more than a 100 have been sold and shipped to companies and researcher teams. The Voxel8 Developer's kit has been discontinued so it will continue to be one of the few printers in the world.

The Voxel8 printer is operated with an online slicer software called Euclid. To print something on the 3D printer multiple STL models need to be uploaded into the online slicer software. These different STL models can be assigned either plastic, silver or component. Depending on the assigned material the slicer software will take tolerances into account when defining the path the print head will travel.

This 3d printer has a lot of automated systems, for example, auto bed leveling with an implemented laser. Presumably, a lot of the processes are automated to protect the users from the harmful chemicals in the silver, and the pressure tank. Automating processes also increases the value of the 3D printer. Since a lot of this automation is based on software it leaves little room for adjusting and tweaking to improve print quality. This requires a lot of trust from the user of the printer. Making these systems automatic, hidden away and software based is not very common in 3D printers since the users often build and tweak the hardware themselves. Integrating these automatic systems makes this 3D printer easier to use for inexperienced users.

VALUABLE INSIGHTS

- A heated print head extrudes PLA filament at 200 degrees
- Pressure is used to extrude the silver solvent mixture at room temperature
- The Voxel8 printers have been available since 2015 so are relatively new
- Only a a few people have access to this printer since just over 100 of these 3D printers have been sold
- This 3D printer has a lot of automated systems leaving only little room for tweaking by the user

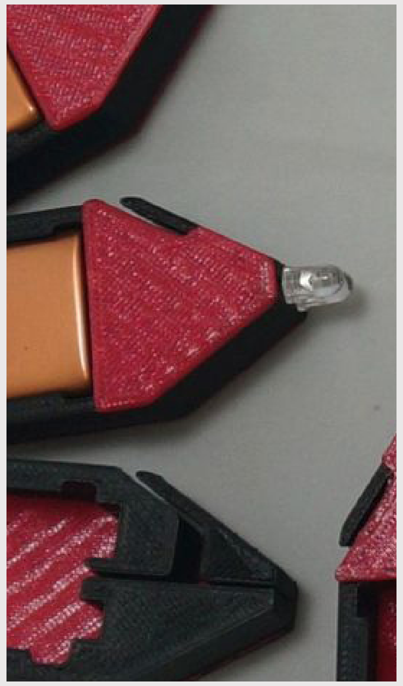


Figure 8 ProtoPasta conductive filament is used to create these flashlights (design by Dustin Cram)

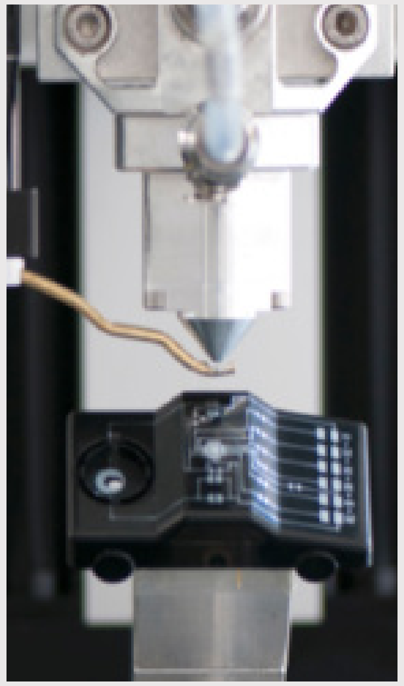


Figure 9 Aerosol Jetting is used to lay down conductive traces by Neotech

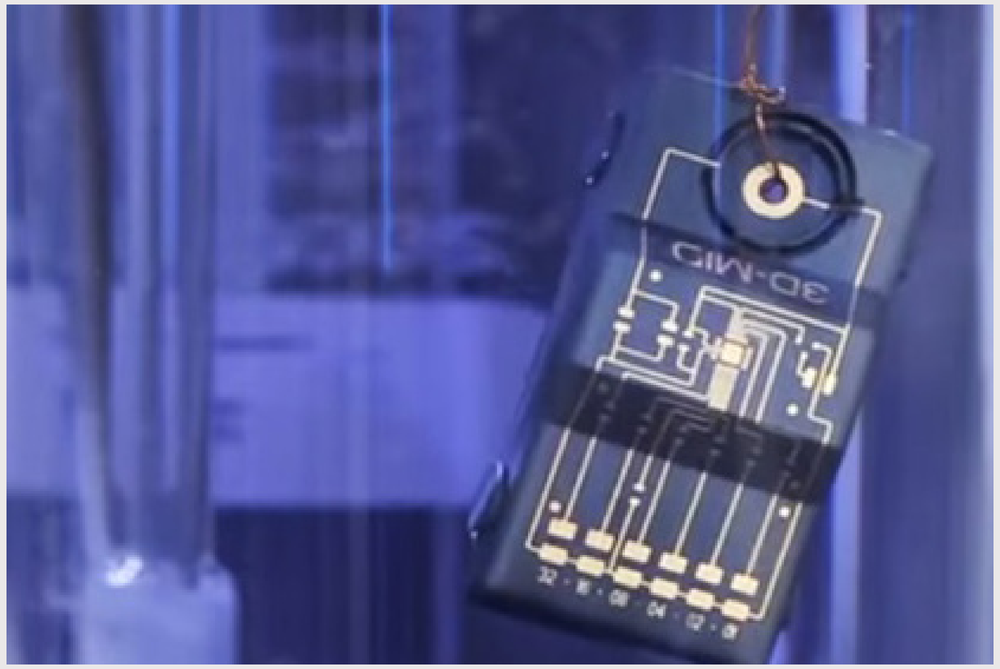


Figure 10 At 3D MID the model is coated and etched with a laser it gets plated in a chemical bath.

3D Printing with Conductive Material

3D printing with conductive and non-conductive materials is also possible using other methods. Three different methods are discussed here.

The most accessible way for hobbyists and consumers to 3D print with conductive materials is working with a filament created with graphene. This off the shelf filaments can be used in a lot of common Fused Deposition Molding printers. This mix of a polymer, polycaprolactone, and a graphene filler can be molded into a roll of filament. This filament can be fed to an FDM printer and common 3D structures can be created. An example of this filament is ProtoPasta in Figure 8. Benefits of this method are that it is accessible, relatively easy to use and the design limitations are low. Limitations of this method are that the consumers often find it expensive, the resistance is relatively high and to create working circuits the multi-material printing needs to be used to prevent short-circuiting.

Neotech is a company that claims to take any three-dimensional shape and applies a circuit to it. It does this by mounting the shape of a robotic arm with five degrees of freedom. Using aerosol jetting the conductive fluid is blown out of a needle and deposited onto the three-dimensional surface (see Figure 9) This results in a conductive circuit. It can do this and avoid any components that are already on there like resistors or sensors. Benefits of this method are that it is precise and effective. Limitations are that no ink can be applied where the object is grabbed except with manual intervention, the method is relatively slow, the surface of the object needs to be smooth and the ink needs to be able to stick to the object.

3D Molded Interconnect Device (MID) also known as Laser Direct Structuring (LDS) is a technique similar to how circuit boards can be produced. With a laser, and sometimes a robot arm, the pattern is created by engraving the part in select locations using a laser. The places where the coating is burned are activated. The object is placed in a vat of chemicals and the copper, nickel or gold will adhere to the places where the material is activated (see Figure 10) This results in a conductive circuit. After the components are glued to the model the connections are secured with a vapor bath which melds the solder and ensures a closed circuit. Benefits of this method are that it is effective, can be applied to many shapes and the process can be scaled up. Limitations of this method are that it is expensive, the material of the object needs to be compatible with the used chemicals and the surface of the object needs to be smooth.

VALUABLE INSIGHTS

- Filament with graphene (ProtoPasta) is the most accessible way for hobbyists to 3D print condu tive materials
- ProtoPasta has a high resistance in its traces compared to silver solvent.
- Neotech uses a robot arm to spray a conductive fluid on objects
- The object needs to be very smooth for the conductive fluid of Neotech to stick. A 3D print is not smooth.
- MID/LDS can be scaled up to produce multiple objects in a short time
- MID/LDS is an expensive technique and the surface of the object needs to be smooth

Robots

A robot can be defined as a device that automatically performs repetitive tasks. (Merriam Webster, 2017) Since robots move and the demonstrator needs to perform a motion it is interesting to look at small robots which will be called tinybots.

If a task involves moving or locomotion it uses actuators. The most accessible actuators are rotating motors like Servo-, Vibrating- and Stepper motors. These rotating movements are often transferred to wheels or four beam mechanisms into locomotion.

Some robots like the Gamibots (Figure 11) have no intelligence and just repeat their behavior and have a few components. Robot's like the Baxter (Figure 12) has a lot of sensors that sense position and need a lot of calculation power to move, record and repeat specific movements.

Figure 11 Gamibots are controlled with a roting motor

3D Printed Robots

When 3D printing is used to create robots it is usually to create structural parts like a casing, gears or legs. Rigid plastic and FDM printing make it possible to create custom shapes and sizes and allows to make fast iterations.

Flexible materials allow makers to create soft robots that are controlled by air pressure. These soft robots can be 3D printed entirely with material jetting machines like the Connex 3D printers. With FDM printers it is possible to create molds in which silicone can be poured and cured. These molds can be used to create silicone bulbous air muscles. (Sheperd, et. al., 2011) The shape of the chambers/bellows make sure that the air pressure is translated into a controlled motion (Figure 14). To control the movement a compressor (with solenoid valves) are needed. This means that these robots need to be tethered, always.

A research team at Harvard developed a soft robot that does not need a compressor for its movements (Wehner, et al., 2016). The air pressure comes from a chemical reaction inside the robot. The movements are controlled by a microfluidic chip and cause the robot to lift its legs. Silicone is poured into a mold and a 3D printer with a needle injects materials that will create the chambers and the correct liquids into the robot. It is still a proof of concept and cannot perform any other tasks than moving its legs at this moment. It does not need any power so it can move untethered but needs to be refueled when the chemicals are finished with their reaction.

Figure 12 Baxter Robot stationed in Applied Labs at the faculty Industrial Design Engineering

Figure 13 A soft robot with bulbous air muscles than can perform multiple ways of locomotion dependent on which air muscles are compressed

Figure 14 Octobot powered by chemical reactions

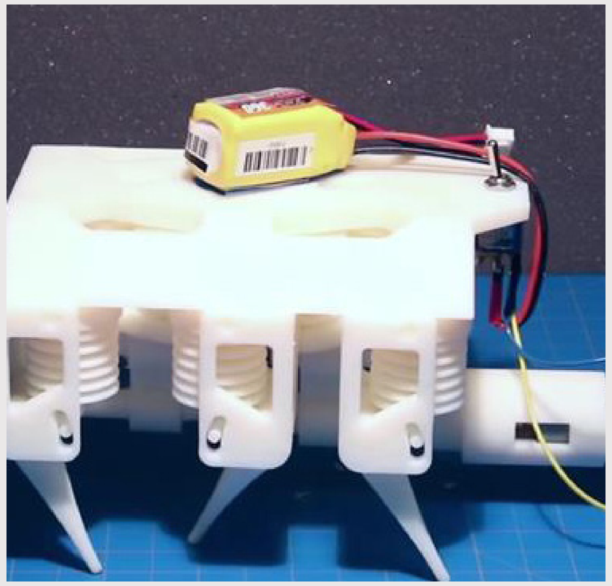


Figure 15 A 3D printed robot with hermetically closed bellows powered by a rotational motor

A research team at MIT CSAIL have created a robot they describe as "3D printed except for the parts that aren't" (Maccurdy, et al., 2016). This robot is powered by hydraulics rather than pneumatics. It is created with an altered Connex 3D printer. This printer can deposit three different materials. In this case flexible, rigid and non-curable. The flexible and rigid materials are deposited and cured with UV light. Because the model is built layer by layer the non-curable liquid is perfectly enclosed and stays liquid. The locomotion is created by a rotating servo motor that makes the fluids move and activate the bellows connected to the feet. Because the servo motor only needs a small power source they can be attached to the robot which makes it walk untethered.

These impressive robots show a lot of potential. But they do not move without the attachment of a motor, compressor or a microfluidic chip. After removal from the build plate and the appropriate cure time, a PTA can be attached to a power source and move.

VALUABLE INSIGHTS

- Most robots use a rotating motor to create locomotion
- Soft robots can be created from a 3D printed mold
- The air used for a compression of a soft robot can also be created with a chemical reaction
- A soft robot can also be filled with liquid which can be hermetically closed

Figure 16 This Nitinol Inchworm moves by contracting an SMA

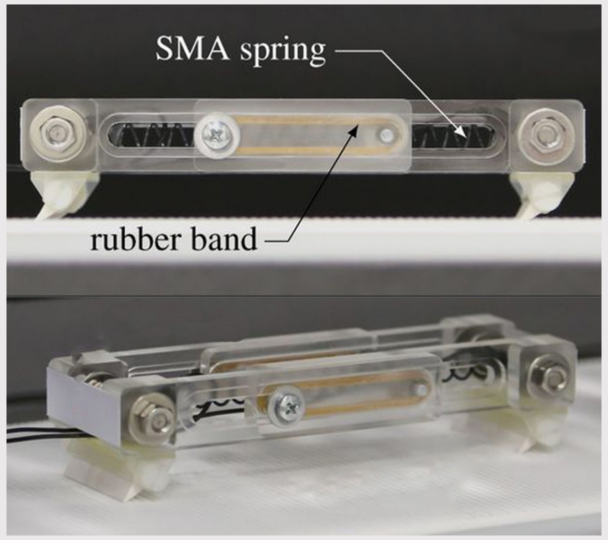


Figure 17 Contracting robot with SMAs and a spring. The bristles that are placed under an angle cause friction

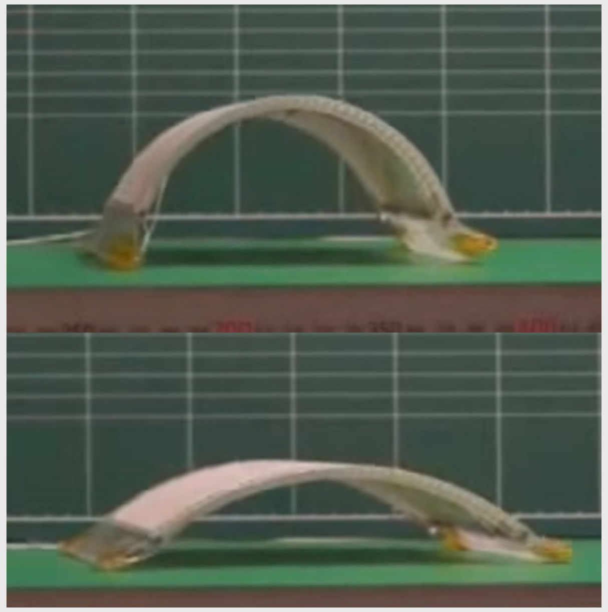


Figure 18 Two pairs of SMAs connected to soft vinyl

Unique Actuators

There are several shape changing actuators that are actuated with a power source because they are conductive, just like a PTA. Several research teams all over the world have been creating unique robots with these actuators. Some of these smart material actuators will be addressed in this chapter. Shape Memory Alloys (SMAs), Piezo Ceramics, Dielectric Elastomers (DEAs) and Ionic Polymer-Metal Composites (IPMCs)

SMAs (Shape Memory Alloys)

Shape memory alloys will remember the shape in which you program them. SMA's are usually thin metal wires that consist out of two or more elements often Copper Aluminum Nickel or Nickel Titanium. The wires are conductive and heat up when connected to a power source. When the wires are at room temperature they can be forced in a certain position for example stretched or bend. After heating up the wires above the transition temperature they will "remember" this shape. Once the wire is cooled down it can be deformed just like before it was programmed. But once the wire is heated up again it will "remember" the programmed shape and will deform into this shape until it is cooled down again.

Some SMAs can be programmed into a contracted state. This principle is used in the Nitinol Wire Inchworm (Figure 16). This tiny robot consists out of two feet connected with a single hinge and a spring. When the SMA is activated it will contract and pull the feet apart. Once the power is released the spring will pull the feet back together and because of the bristles under the feet, it will move forward. The bristles can be flexible feet, a strip of Velcro, or an actual brush. The main task of these bristles is to have more resistance in moving one way than another. This relatively simple robot is powered by two AAA batteries and a human pushing a button.

A similar approach of locomotion is used by a group of researchers at SISSA, Italy (Noselli & Desimone, 2014). They did not use a hinge to connect the two feet but dragged them over the ground with flexible bristles. They would have a high resistance when being moved in one way but little resistance when moved in another way.

A team of Seoul National University used the bending qualities of the SMAs to make their robot move like an inchworm. (Wang, et al., 2014) One set of SMAs would make a curving motion. The other set of SMA's would use the curving motion to change the amount of contact with the floor. With changing the contact with the floor the friction changes. They were able to create either a high resistance or a low resistance to push itself forward.

VALUABLE INSIGHTS

- Inchworms can serve as a good inspiration for robots with a simple actuator
- Friction with the floor is an important part of locomotion
- Contraction can be used to move forward.
- Contraction can also be created with bending
- Since SMAs heat up during use it is interesting to compare use scenarios of PTAs

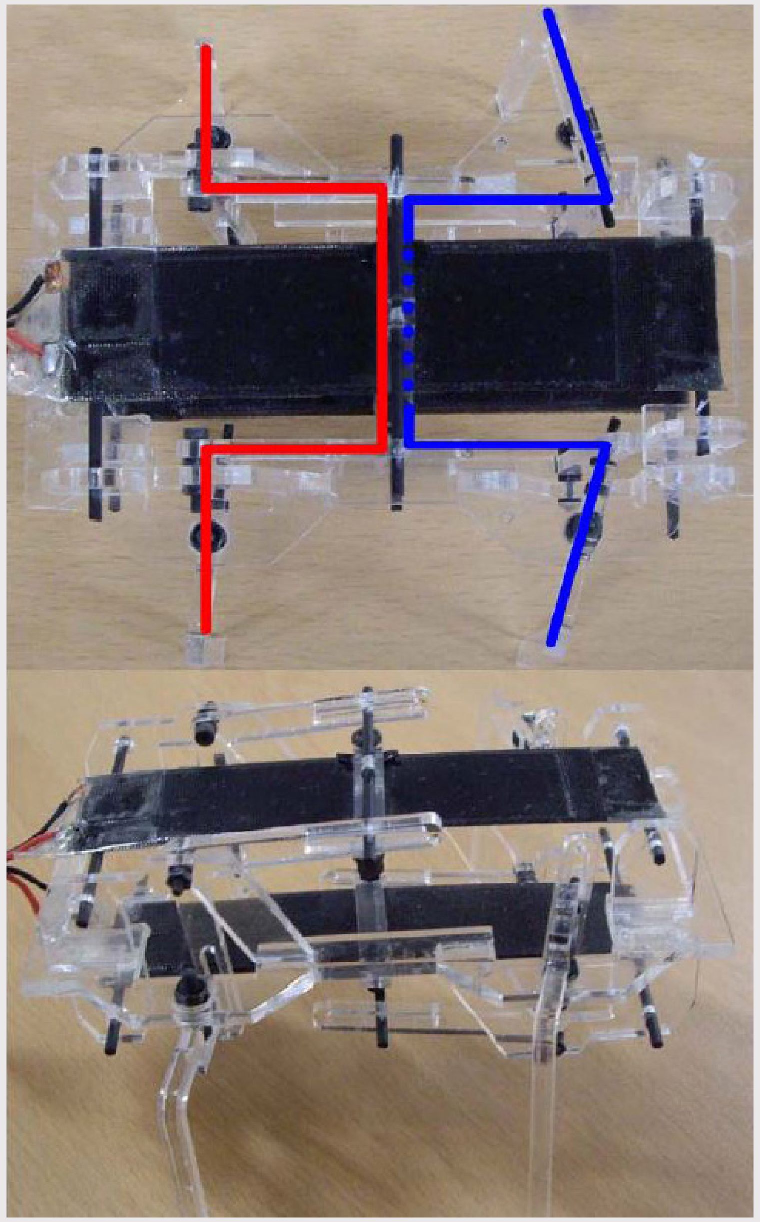


Figure 19 Fourlegged Robot with LIPCA actuators (piezo ceramic laminates)

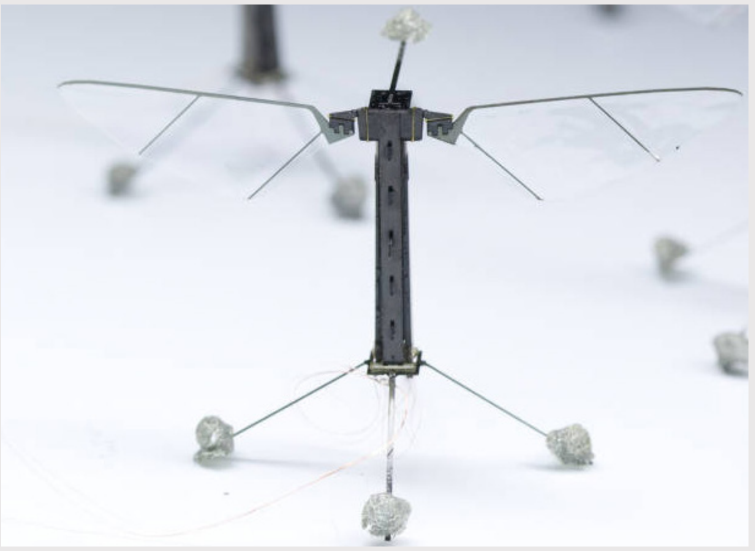


Figure 20 RoboBee with wings powered by the vibrations of a piezo ceramic actuator

Piezo Ceramic Actuator

Piezo ceramics are crystals that are often used as sensors. When compressed they will generate energy that can be measured and analyzed. However, when an electric field is applied to the ceramics, they will expand and become an actuator. They can be used to create sound when they receive a square wave with the appropriate frequency. This will deform the ceramics and produce a sound. This deformation can also be used to create tiny very accurate actuators. The amount of power and frequency an actuator need is depended on the thickness. Usually, the piezo ceramics come in very small sizes and are used in MEMS.

The accurate and high-frequency deformations a team at Harvard uses this actuator to make the wings move of their mini robot bee. (Ma, et al., 2014) Because the piezo ceramics are lightweight and can reach many motions in a reliable way it was ideal for this research team to make the wings move (Figure 20). To reach the small size they have reached they needed to create custom MEMS components. The 16mW the bee needs he receives from a small wire connected to the ground.

In Paris, a team connected two piezo ceramic actuators on an aluminum beam to create a wave. (Hariri, et al., 2013). This wave, Figure 21, is able to propel itself forward over difficult and inclined surfaces after the correct frequency was found.

There are also laminates with piezo ceramics called LIPCA. A team from Konkuk University in South Korea created a four-legged robot (Figure 19) actuated by LIPCAs. (Ho, et al., 2007). The LIPCA makes a vibrating motion that is translated into steps with a hinge construction.

VALUABLE INSIGHTS

- Vibration can be used to create propulsion
- Motions can be translated with hinges
- Motions can be enlarged with hinges
- Waves can be used for locomotion

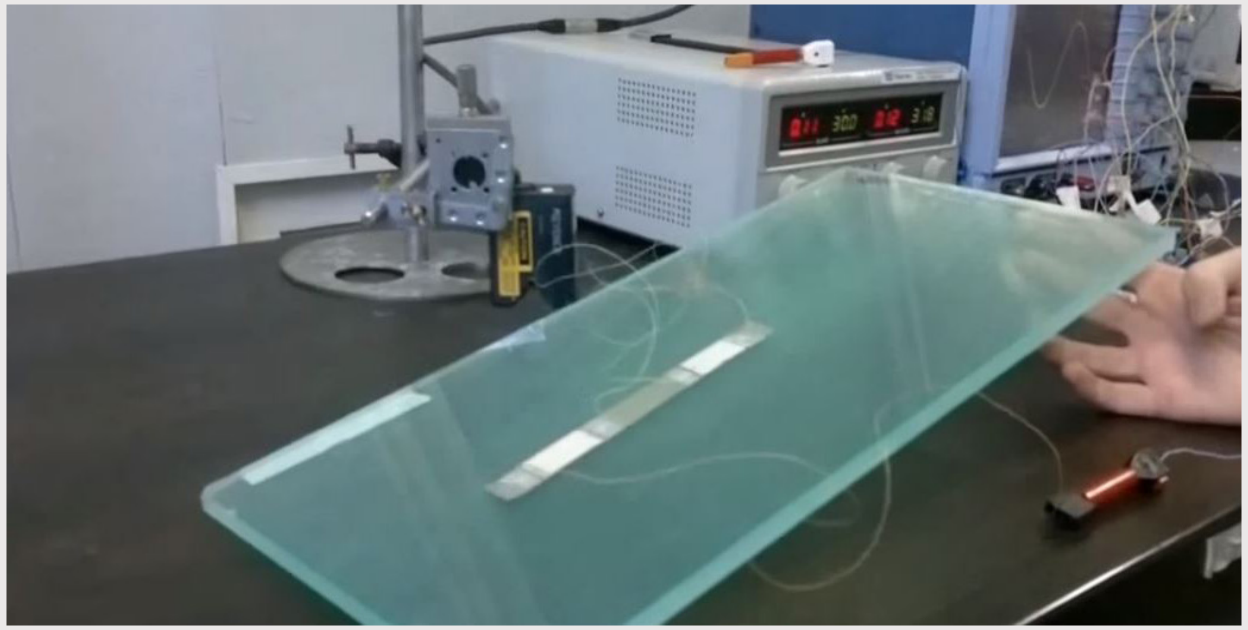


Figure 21 Two piezoceramic actuators are placed on an aluminum beam to create a moving waveform. With the correct frequency it creates locomotion over different surfaces

Figure 22 MERbot is able to walk with 6 roll actuators

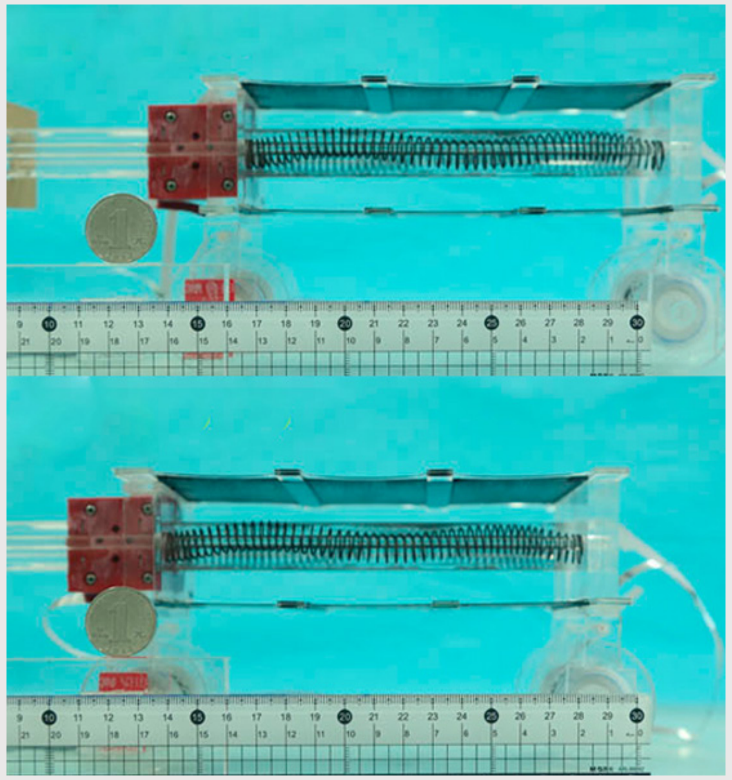


Figure 23 This robot uses a wheel ratched mechanism to create variable friction to move forward

DEA (Dielectric Elastomers Actuator)

Dielectric Elastomers can also be considered smart materials that are conductive. They mainly rely on being able to change their thickness and therefore being able to stretch and contract. The elastomer films are covered on both sides with conductive carbon black or graphene. When a current is applied to the conductive layer on both sides of the film the layers will be attracted to each other and squeeze the film between them. When the power is removed, the stress that is build up inside the elastomer will make it return to its original thickness. To use these smart materials as actuators a very high voltage and a low frequency is needed.

Several research groups have used DEAs to build robots. A group of researchers at Xi'an Jiatong University (Sun, et al., 2017) has used the contracting properties to create a similar inchworm as the team at SISSA (Figure 17). Instead of depending on the resistance of bristles or feet they build a wheel ratchet mechanism to pull the wheels forward (Figure 23). To activate the actuator 8.2 kV is needed.

A research group at the University of Auckland uses the contracting properties of DEAs to move the feet of Trevor the Caterpillar. (Henke, et al., 2017) Instead of being tethered with wires it uses its conductive feet to collect the power needed to move forward (Figure 24). Because of the motion, the feet also act as mechanical switches. This robot has multiple feet that each push the robot a little bit at a time.

At SRI international they attached several strips of Dielectric elastomer in a circle and were able to create articulating legs/muscles. (Pie, et al., 2003) These legs could be used to move the six feet of this hexapod robot (Figure 22).

VALUABLE INSIGHTS

- Power supply does not need to come through wires but can also come through conductive feet
- Moving legs can act as mechanical switches
- Resistance with the floor can also be generated with a wheel ratchet mechanism
- When placing actuators in a circle a muscle can be created with more freedom of movement

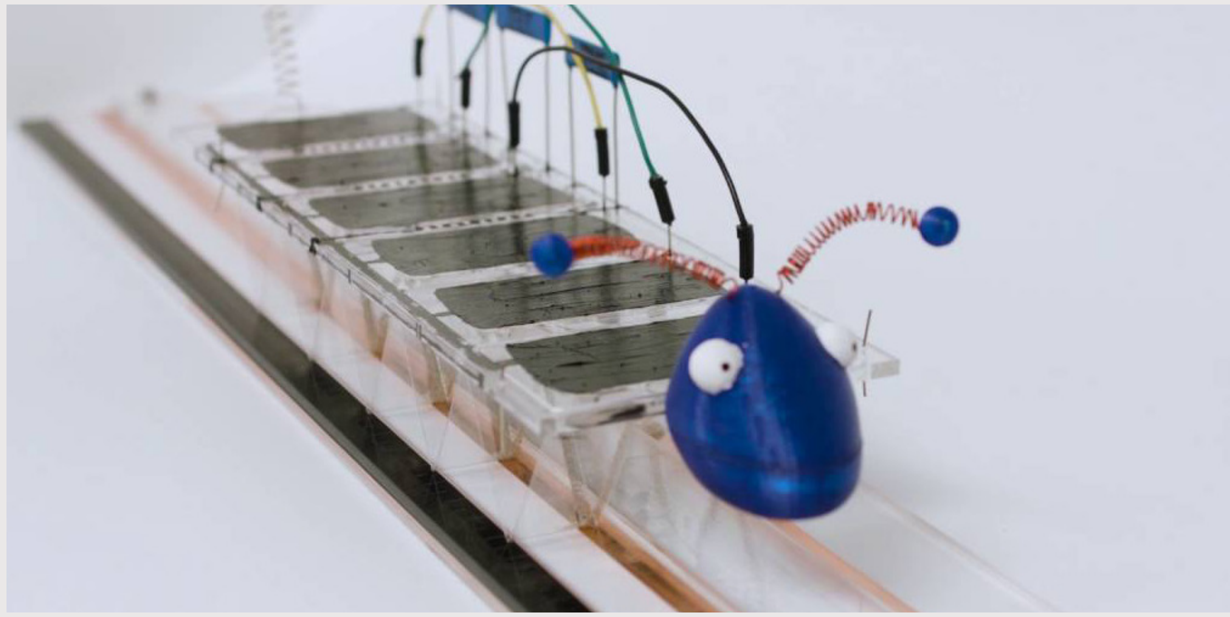


Figure 24 Trevor the Caterpillar is powered by its feet that touch the copper strip on the ground

IPMCs (Ionic Polymer-Metal Composites)

Ionic Polymer-Metal Composites are polymers pastes with highly adhesive and conductive properties coated with a highly conductive noble metal. What makes this conductive smart material actuators extra special is that it works well in a liquid environment making them a good choice for swimming robots. When one of the coated sides is negatively charged it will attract the ions and water molecules with a large mass. It will cause the IPMC to bend. When the power is released the molecules will distribute equally because of osmosis.

Where a DEA needs an alternating current to move an IPMC needs a low direct current and can hold its shape for a longer time. An IPMC has extreme displacement during bending while a DEA can reach high frequencies. (Park, et al., 2008)

Because the actuator is functional in wet conditions the actuator can be used in underwater robots (Figure 26). Like the fish robot created by a team at the University of Nevada (Hubbard, et al., 2014).The robot has a specific buoyancy and the actuator is used to act as the fins to propel the robot forward.

A research-team in Iran attached 6 individual actuators in a circle (Figure 27). By activating them in a specific pattern the deformable circle was able to roll over a surface. (Firouzeh, et al., 2012). Locomotion was reached by moving the center of gravity. The IPMCs are lightweight and only need a little power which makes it very well suited for this unique way of locomotion.

Imitations of inchworms have been mentioned in before but the University of Tartu has created an untethered inchworm (Figure 25) that utilizes the low power the actuator needs to move. (Must, et al., 2014). The robot carries its power source on its back with a 10-mAh LiPo battery. The robot uses custom brushes to create the correct friction to push itself, and its load, forward.

Figure 25 This inchworm robot carries it's LiPo battery on it's back using IPMCs actuators to move

Figure 26 The front fins of this fish consist out of two IPMCs the backfin out of a single IPMC

VALUABLE INSIGHTS

- Robots do not need to move over land but can also move in the air of in the water
- Actuators can also be attached in extension and activated individually
- If the actuator is strong enough it can carry it's battery on it's back.

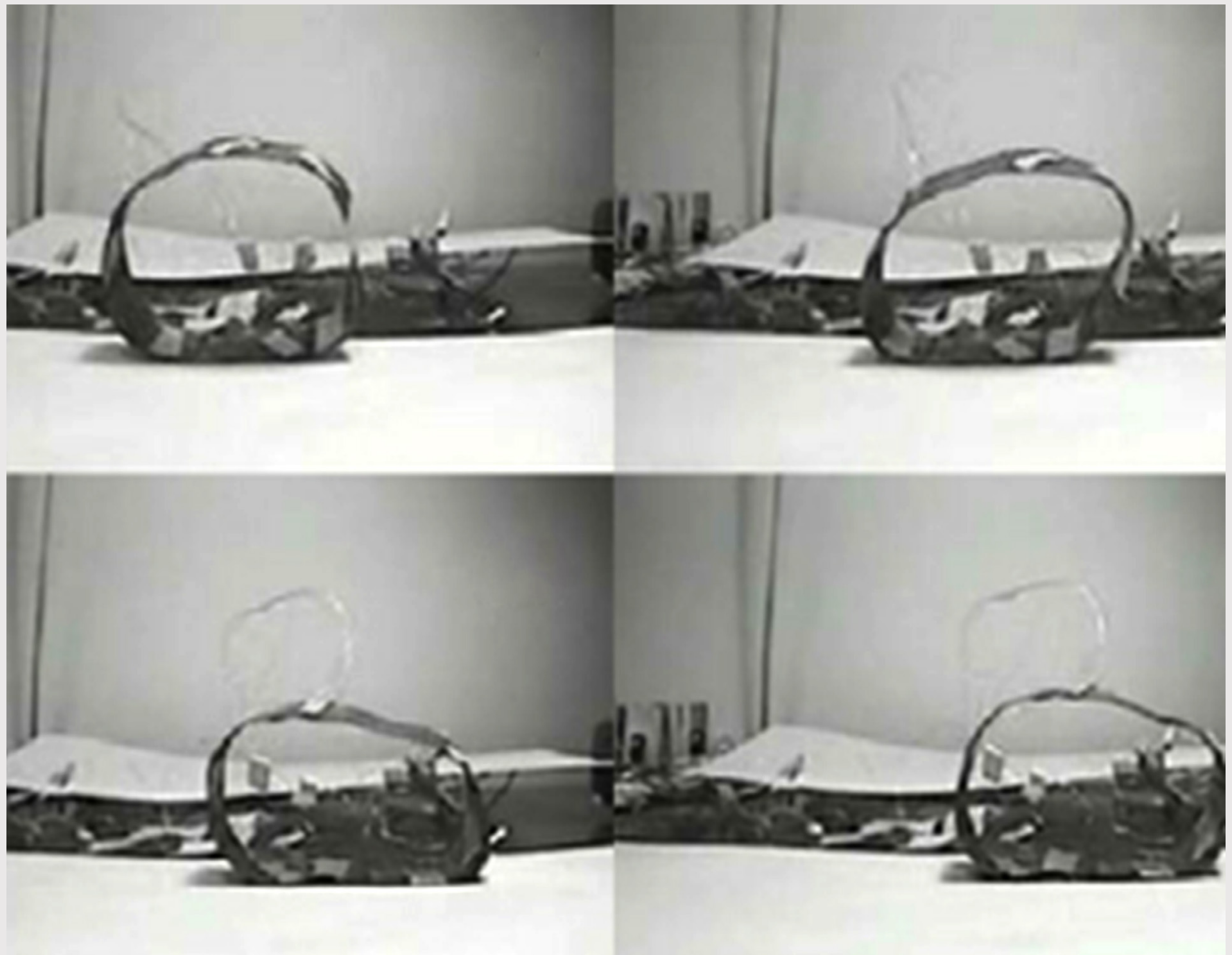


Figure 27 These IPMCs are connected in extension and can be activated individually to make it roll

Conclusion

Research in 4D printing is growing field. Compared to other 4D printed samples PTAs have the advantage that they can repeat their motion and that they are able to focus their energy because of the silver traces.

There are other ways to create conductive traces on three-dimensional shapes. The Voxel8 printer creates the most conductive traces in a way that is easy to use by makers.

Robots are usually rigid and use rotation to move forward. Soft robots use their entire bodies to move. They usually need air or water pressure from an external source. A PTA just needs a current which it translates into heat which then translates into motion.

There are actuators that use currently to transform just as PTAs do. SMAs need to be programmed into the correct shape, PTAs do not. Piezoceramics can make very small but accurate movements. DEAs need a very high current and frequency and IPMCs need to be wet to perform their transformation.

Tinybots made with these actuators can serve as inspiration. Insights from building these tinybots can help to skip iteration steps. But most importantly these insights can help find the unique characteristics of PTAs

Figure 28 A collection of different PTAs

PTA

What are 3D Printed Thermal Actuators?

PTAs are actuators that can be considered an example of 4D printing. They are uniquely different from other 4D printed samples. This is because they are able to repeat their motion and it creates the heat, that is its stimulus, itself. How a PTA is made and the unique characteristics are explained in this chapter.

Creation

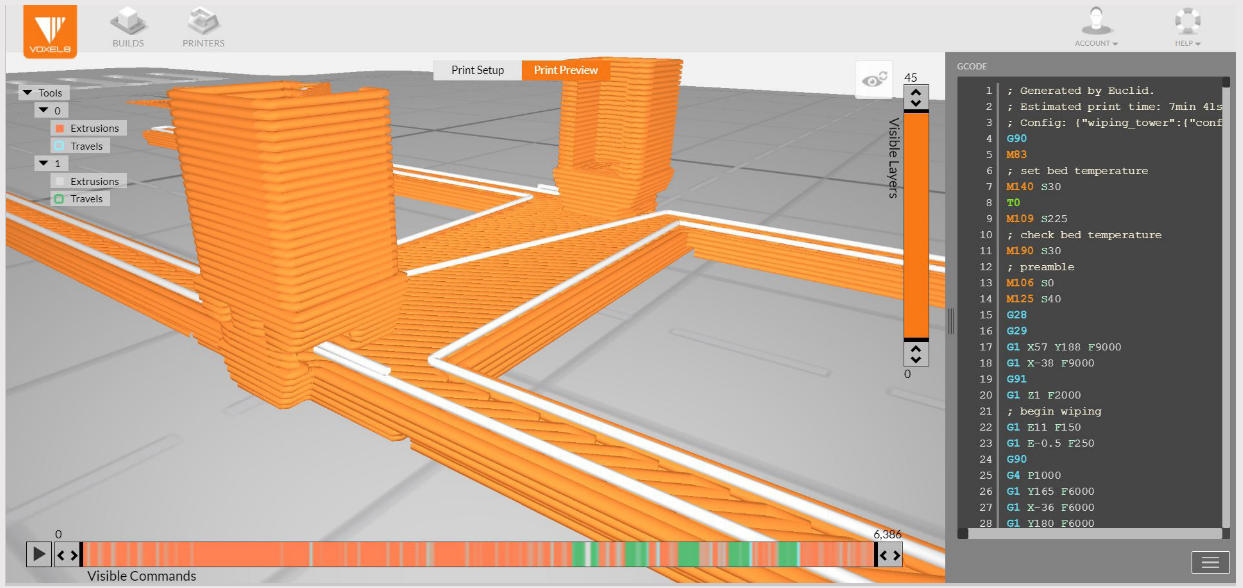


Figure 29 Voxel8 slicing software showing the planned path. This overview can be used to see which details will be skipped

The two materials that are used to create a PTA are the silver (with solvent) and PLA. PTAs are created by using a Voxel8 FDM 3D printer. Potentially a PTA could also be made with injection molding and screen printing. Other methods to create a PTA are not yet examined and are left out of the scope. Other methods that will create actuators that will transform heat into movement will probably not be called 3D Printed Thermal Actuators.

It usually takes about half an hour to create a PTA which is much faster than a lot of the other actuators. The Voxel8 comes with its own slicing software (Figure 29) that is accessible in an online environment. Based on the provided model the software will make decisions where to deposit material within the given bounding box provided by the model. If the provided details are too small (the minimal layer height of the PLA and silver trace are 0.15 mm) the slicing software may decide to skip these details. So it is always important to check the calculated path and travels in the slicer software before printing.

When designing the model it should be taken into consideration that the silver should not be directly deposited on the build plate or placed at an angle. Because the slicer software builds the model layer by layer this means that the line is not continuous and the circuit might not be closed.

DYNAMIC SLICE HEIGHT

After indicating which parts of the model will be silver and which parts will be PLA the software will make sure that the materials will not collide and will automatically calculate a tolerance. When "Dynamic Slice Height" is turned on, the software might create indentations for the silver to be deposited in, this is not necessary and may influence the symmetry and thickness of the PLA. When printing a PTA make sure that the "Infill Density" for both silver and plastic are 1.

SKIRT AND RIM

A "Skirt" can give an indication of how large the model is going to be, help prime the extruder and establish a smooth flow of filament. A "Rim" (not to be confused with the rim of a PTA) can be added to improve adhesion to the build plate and prevent warping of the model falling over. A warped model can cause a silver trace to be laid down incorrectly.

A WIPING TOWER

The slicer software can add aids to improve the printing of the model (Figure 30). A "Wiping Tower" is a triangular tower that can catch possible brittle silver left in the tip of the silver syringe.

PRESSURE WIPE

To find the correct pressure for the silver to be extruded from the nozzle a "Pressure Wipe" can be printed. In this pressures wipe the silver will be deposited on the print with different pressures, based on this print the user can decide which pressure is the correct one in this circumstance. A pressure wipe does not need to be printed every time and at our lab set-up, 16 PSI is usually enough.

SUPPORT

Support can be generated to create even more intricate designs. Support is usually generated if the detail has an angle smaller than 45 degrees to the build plate. The software will provide zigzag/accordion support. This support will ensure that the model will print correctly but the support takes force to remove from the model. During removal, the silver trace might be damaged. This support will also leave an ugly surface finish. If possible the design must prevent auto-generated support. Custom support can be built into the model by the designer. This can be a column with a 1.3 mm diameter (Figure 31) or a wall with the thickness of 0.3 mm/a single line of plastic (Figure 32). When using a wall support it is harder to bridge distances, when making the bridging layer broader (for example with 0.12 mm offset from the wall) the slicing software is tricked and will perform better bridging. A balance still needs to be found between the "sloppiness" of this bridging layer and achieving the actual bridging.

CURING

After the PTA is created with the Voxel 8 printer the silver trace is still wet. It takes at least half an hour to half a day to cure, or dry, the silver trace. The solvent in the silver is poisonous to humans so it is recommended to do this in a well-ventilated space. It is possible to check if the circuit is placed correctly by checking the resistance before the ink is cured. During curing the resistance of the silver trace will go down to the actual resistance. Take this change of resistance into account when determining the amount of power that needs to be applied.

DESIGN CONSIDERATIONS

- The design must not contain plastic details smaller than 0.15 mm because these details will be skipped
- The design must not contain silver that needs to be directly deposited on the build plate.
- The silver trace in the design should not be placed under an angle
- The design must need as little support as possible
- If the design needs support, the support needs to be designed in such a way that it can be removed with scissors or little force
- Examples of custom support can be a wall (0.3 mm) or columns (⌀1.3 mm)
- When a distance needs to be bridged the slicer software can be tricked with a broader bridging layer (0.12 mm)
- The design must be small enough to fit on the build plate (140x140mm) and provide the possibility to create a wiping tower

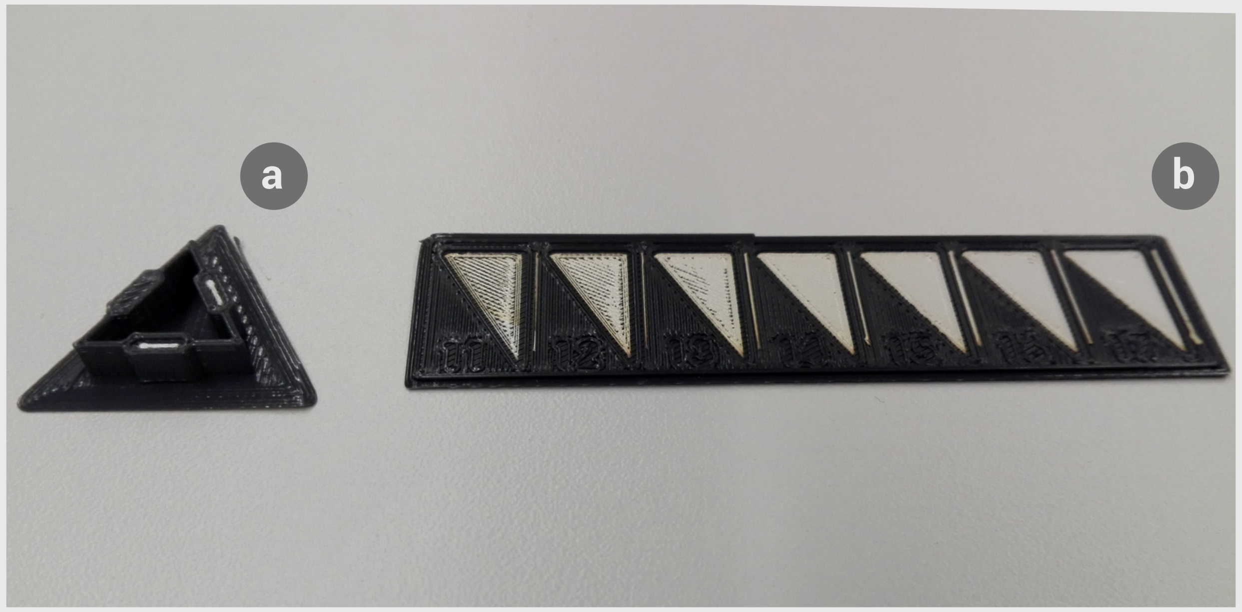


Figure 30 Printing aids to help with the multimaterial print: A wiping tower (a) A pressure wipe (b)


Figure 31 Custom support embedded in the model will ensure gentle removal: columns (⌀1.3 mm) with a brim

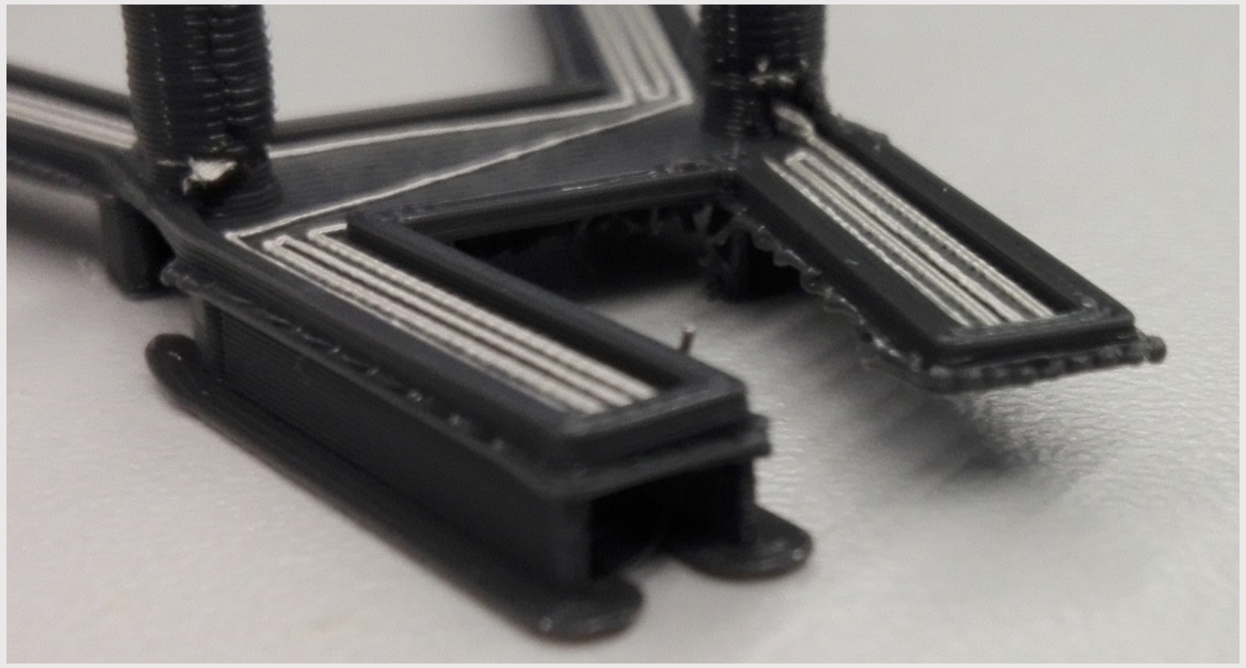


Figure 32 A custom embedded support with a single layer wall (0.3 mm), a broad layer for bridging and brim

Dimensions

A PTA consists of four important parts; the base, the rim, the silver trace and the connection to the power source (Figure 33) The most predictable behaviors come from symmetrical designs.

THE BASE

The base is the part of the PTA that will react to the heat and bend. One side of the base is equipped with a silver trace that generates heat. The base can come in a lot of shapes and sizes. It is recommended to make the base 2 layers thick (this is around 0.4 mm). The slicing software will generate the directions in which the layers of the PLA are laid down. It has been observed that the directions of the layers influence the behavior of the PTA. If the PTA shows undesirable behavior it can be considered to change the automatically generated directions by rotating the model on the print bed.

THE RIM

The rim is crucial in making sure that the PTA can repeat it's movement since it does not heat up like the base does. A rim that is too thick will prevent the PTA from bending. A rim that is too thin will prevent the PTA to repeat its motion. The recommended thickness for the rim is 1.5 mm wide and 0.4 mm depth. A rim placed on the same side as the silver trace will move down. A rim placed on the other side as the silver trace will move up. This changes depended on the stage of motion the PTA is in (“Stages of motion” on page 33).

THE SILVER TRACE

The silver trace is the only conductive part of the PTA. Ideally, the silver trace is deposited in one single line without interruptions. This can be accomplished by making sure that the silver trace can be found in the same horizontal plane. To create a single line the recommended dimensions for the silver trace are 0.2 mm high and 0.4 mm wide.

When the silver trace needs to go up vertically it is recommended to create a cylinder with a diameter of 0.8 mm. When the silver trace moves from a vertical into a horizontal direction it is recommended to deposit at least two horizontal layers for the first 5 mm as a buffer.

The dimensions of the silver trace can influence the heat distribution over PTA. Thinner traces will have a higher resistance and generate more heat. This can be used to program certain behaviors. It is also possible to concentrate heat by increasing the density of traces at a specific surface. More about this can be found in “Temperature” on page 34.

A silver trace needs to be open until it is closed by connecting the wires to the power source. Since the current will seek the route of the least resistance it may skip some parts if the circuit is already closed.

CONNECTION TO THE POWER SOURCE

There are multiple ways to connect a PTA to a power source (Figure 34). A socket can be created in which a jumper cable can be lodged. The tip will be placed in a small chamber filled with silver. It is also possible to create a stack of silver without a chamber, but because of the brittle nature of the dried silver trace, it is a lot less durable than a closed silver chamber.

Another possibility is to create a small single layered patch of silver on which a custom crocodile clamp can be connected. One with a smooth surface that does not damage the brittle silver trace. The clamps are quite large and are less desirable to be used in the demonstrator.

It is not possible to create a connection by soldering the connection. It is possible to use glue to connect a wire to the silver, this is not desirable since the silver trace is very brittle.

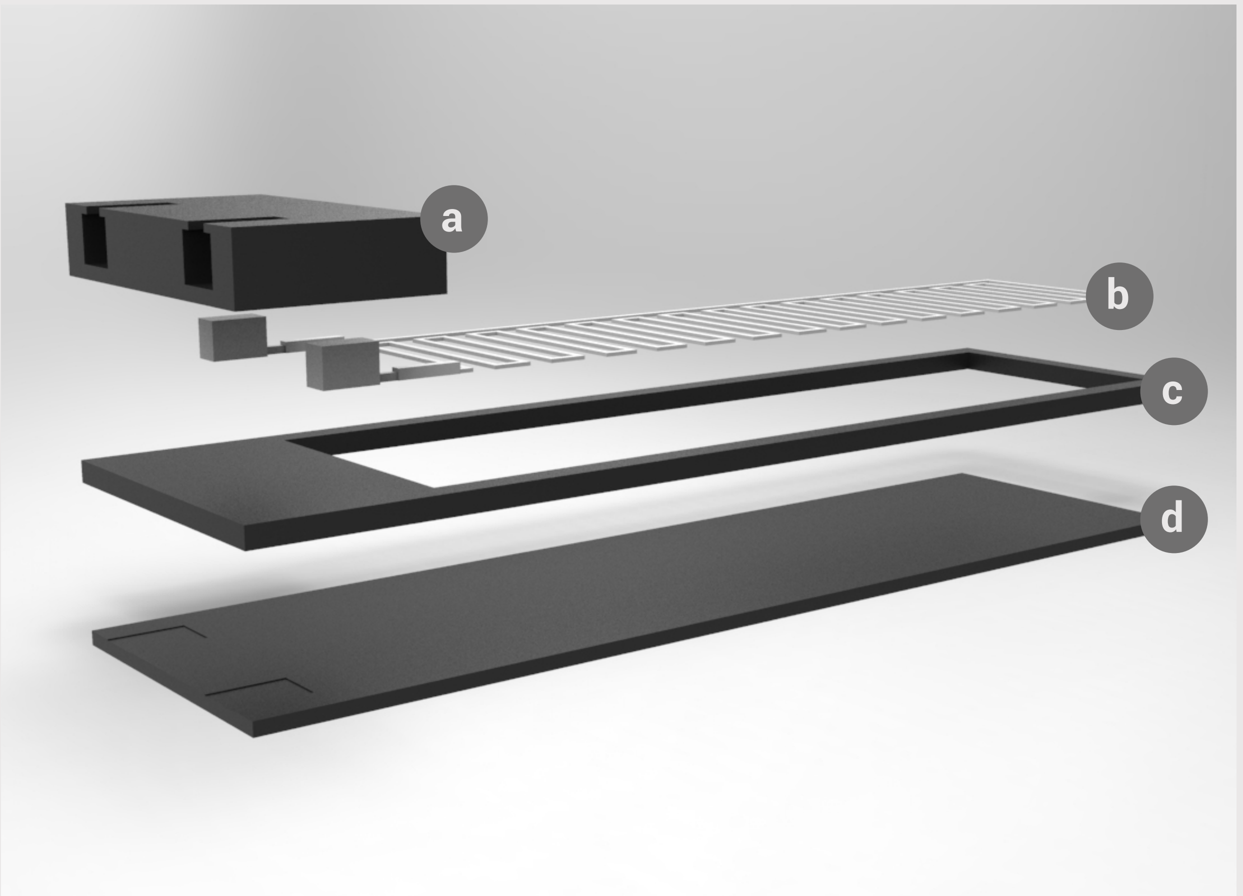


Figure 33 Elements of a PTA; connection to power source(a), silver trace (b), rim (c), and base (d)

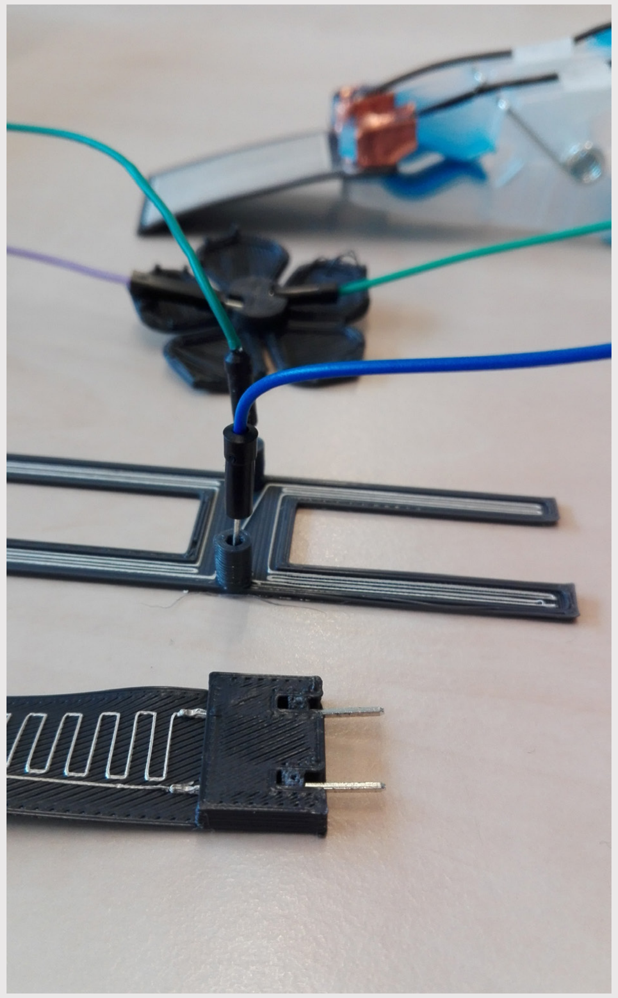


Figure 34 Different ways to connect a PTA to a power source

DESIGN CONSIDERATIONS

- The design of the PTA must be symmetrical
- The design must consist out of a base, a rim, a silver trace and a connection
- The base must be 0.4 mm high
- The rim must be 1.5 mm wide and 0.4 mm high
- The silver trace must be laid down in a single line in the same horizontal plane.
- A thinner silver trace will reach higher temperatures in combination with thicker traces
- A higher density of traces will increase the temperature of that surface
- The silver trace must be open until it is connected to the power source
- If the design has a vertical silver trace it must be a cylinder with a diameter of 0.4 mm
- When the silver trace transfers from a vertical to a horizontal plane it needs a buffer
- The connection to the power source can be created with a socket for a jumper wire or a custom crocodile clamp.

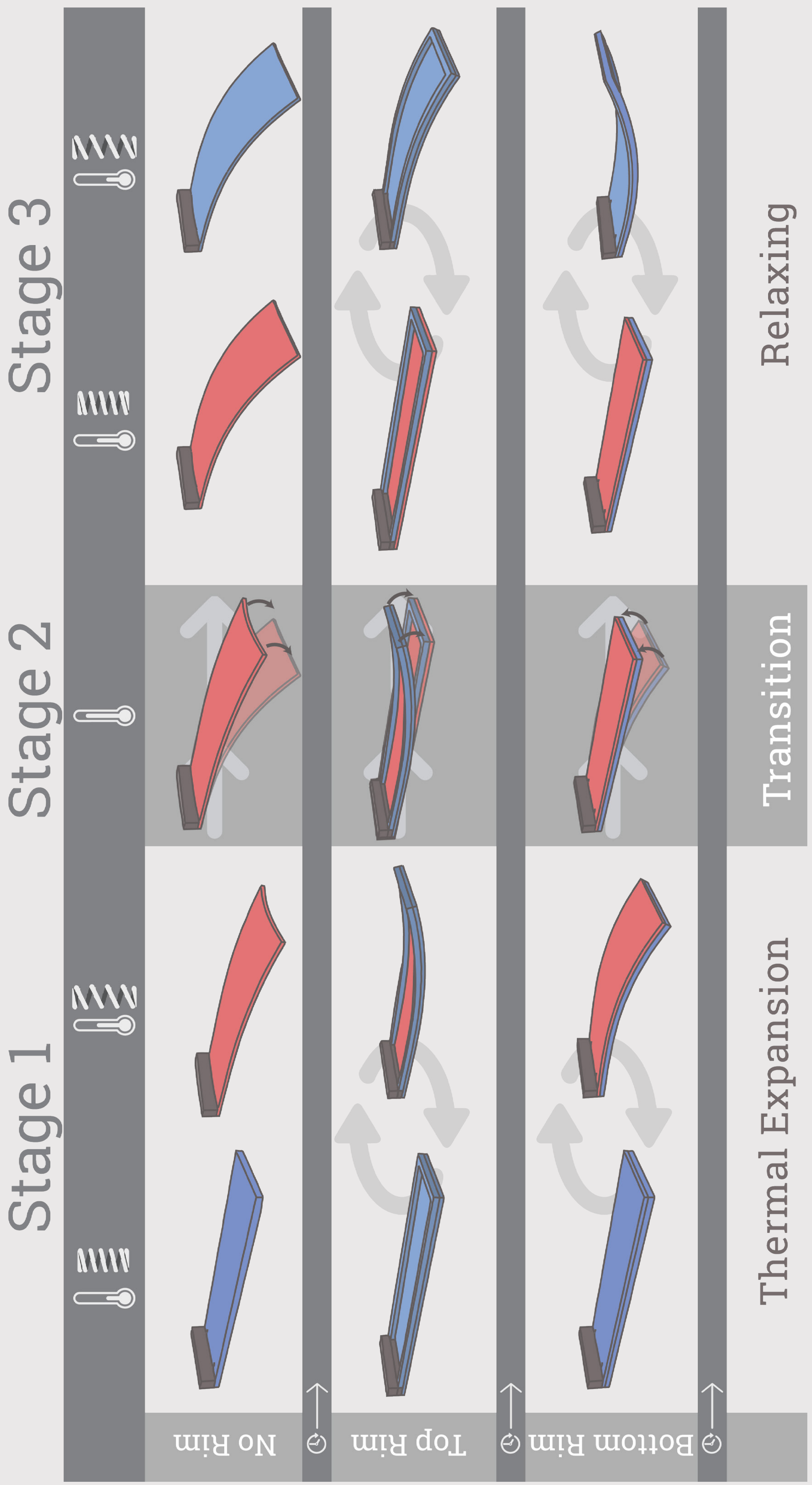


Figure 35 Stage Diagram of heating up a PTA

Stages of motion

How a PTA works depends on how much energy it receives. Knowing the energy history of a PTA helps you understand the motions it performs. Three stages can be observed that explain how a PTA moves (Figure 35). In the following paragraphs, the behavior of a PTA is explained where the rim is placed on the bottom and the silver trace on the top of the strip (Figure 36). The PTA has a height of 0.8 mm, a width of 15 mm and a length of 55 mm. The rim had a width of 1.5 mm. These observations and measurements have been done by Zhao (2017).

STAGE 1

When a PTA is created, it starts in stage one. The strip is completely flat. In this stage, the sample moves very predictably. When little power, up to 0.7 W, is applied the base will bend up. Because the rim stays cold the rim will be under compressive stress when the PTA is in bend position. When the power is removed, the PTA will return to its original flat position while it cools off and the rim will relax. Because the molecular structure of the PLA in the PTA will not change at this stage because the generated heat will create thermal expansion. The motion in this stage can be repeated often as long as the PTA has enough time to cool down.

STAGE 2

When a power between 0.7 and 2 W is applied to different behavior by the PTA is observed. First, the PTA has a high displacement but after a few seconds, the PTA will return to the flat state while remaining hot. Because of the heat, the molecular structure of the PTA changes. This behavior can be explained by viscoelastic transformation. Because the PLA heats up close to its glass transition point the thermal stresses relax and the PTA returns to a flat state (but still with a hot upper layer). After the power is removed from the PTA, it cools down in a new neutral state that is bent down instead of flat. Because of the viscoelastic transformation the new cool state causes stress in the rim in the cool state. This stress disappears in about three days when the PTA is kept at room temperature. If the sample is kept at a cooler temperature the stress will be preserved for a longer time. Repeating stage 2 increases the curvature of the cool state even more.

STAGE 3

After the PTA is overheated in stage 2 it has a bend cool state that is under stress. When the PTA is supplied with a small power (like in stage 1) it will move to a flat position and the rim will relax. No changes in the molecular structure will occur. After removing the power the PTA will cool down and return to its curved and stressed state. The most important differences between stage 1 and stage 3 are that the deflection in stage 3 larger is and in another direction. Once the sample has been laid to rest in stage 3 it will return to stage 1 in about three days.

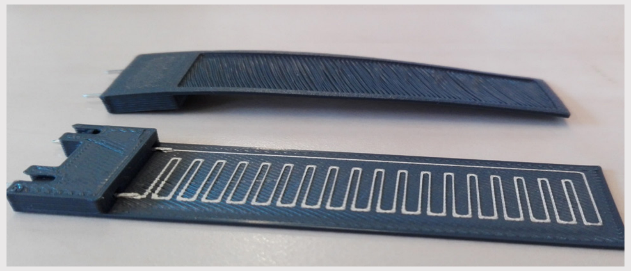


Figure 36 One of the PTAs used for observation for the stages of motion

DESIGN CONSIDERATIONS

- These measurements have been made with a PTAs that look like Figure 36. Other designs may show different results especially based on the amount of power supplied.
- Displacement in stage 3 is larger than in stage 1
- Stage 1 is the most reliable movement but also the smallest movement
- Cooling down in stage 3 is the most powerfull
- Samples that entered stage 3 loses its stress in three days and returns to stage 1
- Stage 2 can be repeated several times to find a new relaxed state

Temperature

Heat is a very important part of operating the PTA. The heat that is generated by the current running through the silver trace will cause the thermal expansion which creates the bending behavior.

A PTA will work predictably at room temperature. When you want to preserve the internal stress created in the last stage, after overheating the PTA, then it is best to keep the sample as cool as possible.

When the temperature is raised to 50 degrees a PTA becomes pliable. As long as the silver trace remains closed it is possible to change the shape and create for example flower petals by pressing them in the correct shape with your hands.

When the PTA is exposed to a temperature of 80 degrees the PTA will no longer work and will start melting. This will cause all the stresses to relax. The heat generated by the silver trace will have no effect on the motion of the PTA and the PTA will lose its intended shape.

When cooled down to room temperature and after checking the silver trace is still intact a PTA can be used again after being heated up to 80 degrees as long as the silver trace is still intact.

The thermal images in Figure 37 are made with a FLIR hand-held thermal camera. They show that the thickness and density of the silver trace has an influence on the temperature at the given spot of the PTA.

When heating a sample it is important to watch for symptoms of destructive temperatures.

- When smoke appears
- When the plastic around a silver trace becomes more reflective/shinier
- When the silver trace becomes detached from the base

DESIGN CONSIDERATIONS

- At 50 degrees a PTA becomes pliable, this can be used for decoration purposes
- Watch out for symptoms of overheating when using the PTA

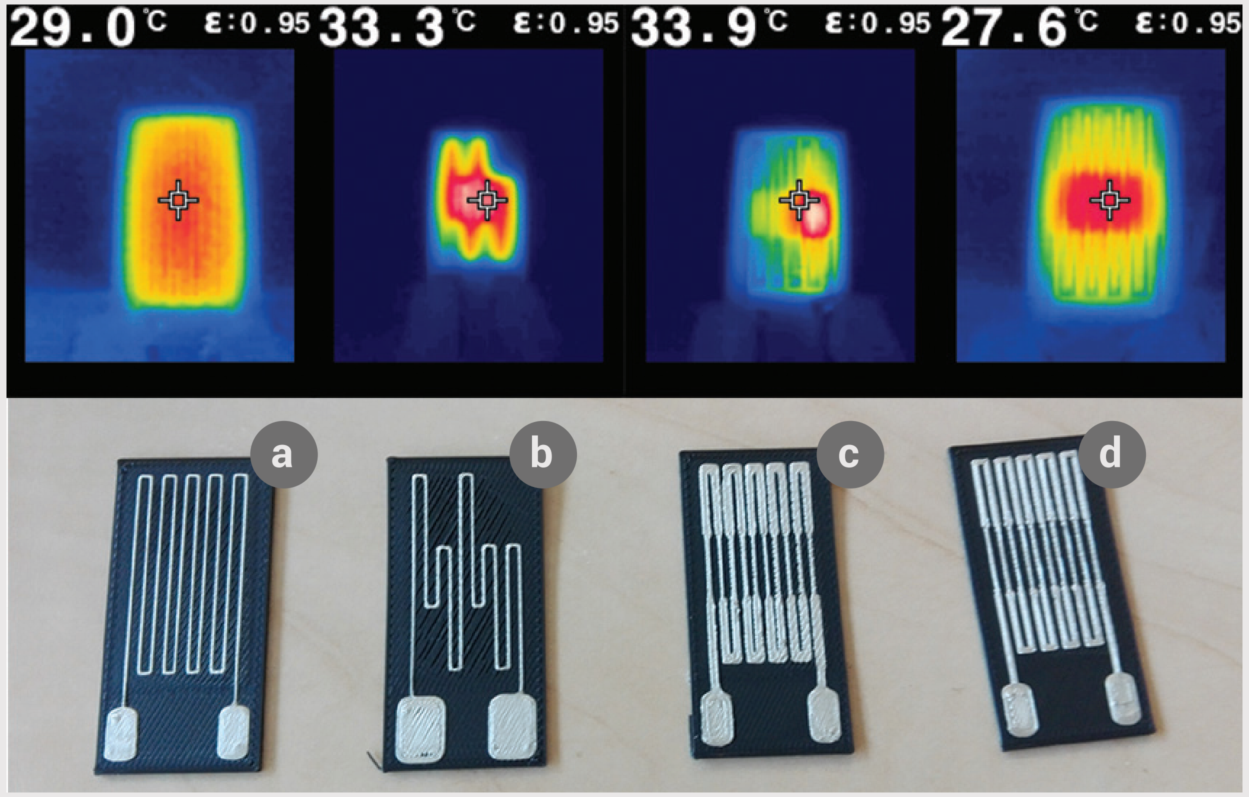


Figure 37 Observations of heat distribution on different designs of silvertrace. Common trace (a), trace with a higher located density (b), trace with partially one and two layers of silver(c), and trace with a thicker and thinner trace (d)

Lifting power

PTAs use thermal expansion to move. By connecting a PTA to a power source a current will go through the silver trace. The silver trace will heat up because electric energy is converted to heat through resistive losses in the material. This phenomenon is also referred to as Joule heating. Because of this heat, the plastic will expand through thermal expansion. This causes a PTA to bend because the top and the bottom of the PTA have a different temperature.

PTAs are able to lift more than just their own weight. When designing PTAs to lift weight it is important to take the momentum into account. If the weight is closer to the clamping point the PTA will be able to lift more weight. It has been observed that a PTA can lift between 3 to 5 times its own weight.

The PTA is stronger when cooling down opposed to heating up because heating the PTA will also make the plastic soft/pliable.

A force-clamp experiment has been conducted to determine the amount of lifting force a PTA can be exerted. The sample was clamped into a level position until 150 seconds when the power was turned off and the sample started cooling down. The PTA used for this experiments had varying lengths but had other than that the same dimensions as in (Figure 36). The graph (Figure 38) shows that at its peak the PTA is able to exert a power of 0.08 N. Over time the force exerted by the PTA declines in a relation with the amount of displacement the PTA shows.

DESIGN CONSIDERATIONS

- A PTA that is cooling down is stronger than a PTA that is heating up
- When designing a PTA to lift weight it is important to take momentum into consideration.
- A PTA can lift it's own weight at least 3 times

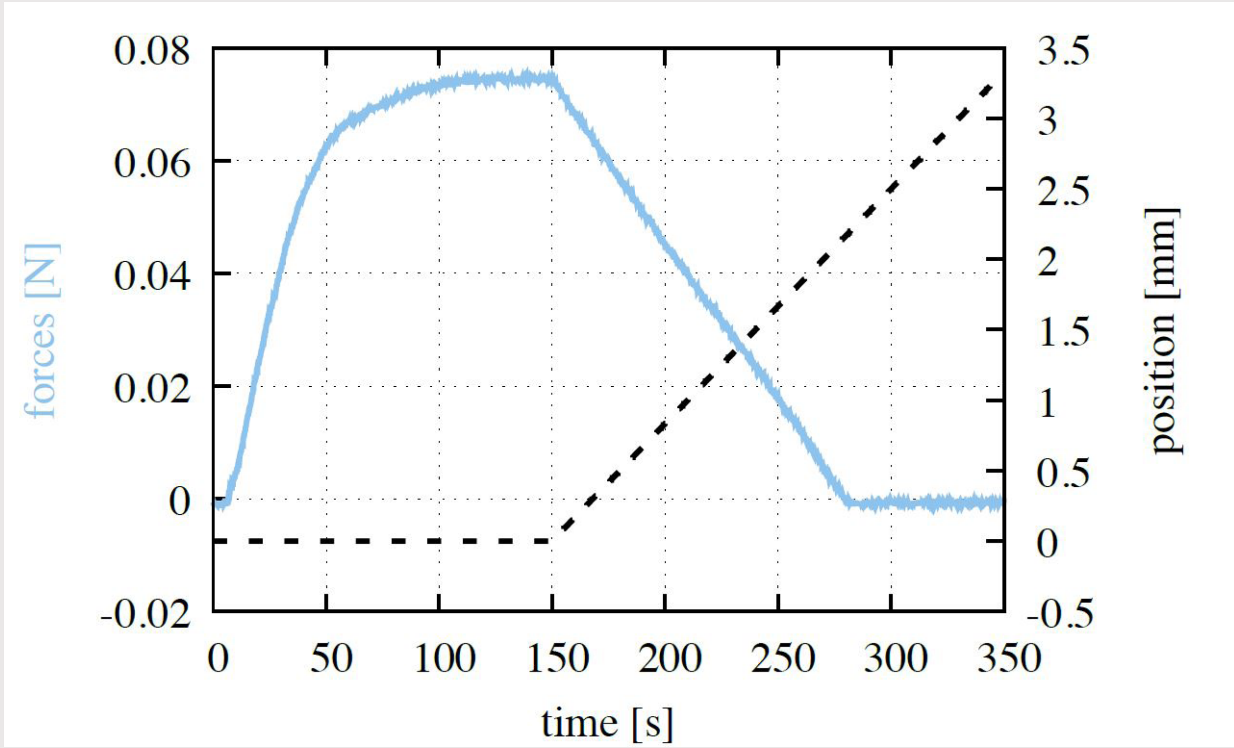


Figure 38 Amount of lifting force of a PTA when cooling down

Unique Characteristics

A PTA is a unique kind of actuator which has unique characteristics. These characteristics can help to define applications for PTA.

Because of the exposed circuit, a PTA will not function in wet conditions. Unless sealed properly it is not recommended to use Ptas in swimming robots.

A PTA is not sensitive to magnetic fields and can, for example, be used inside MRI machines.

A PTA will heat up when activated. The temperature is dependent on the amount of the desired deflection.

Touching a hot PTA can feel from comfortably warm to hot to the touch. Touching a PTA when it is activated is not recommended since it can cause an undesired deflection. It can also give the user a small shock.

A PTA needs to be tethered to a power supply. If a Tinybot carries the power source with it, its range of locomotion is not limited by the length of the wires.

The silver trace is brittle when cured. This has as a consequence that when the PTA is handled often and without care it can cause the silver trace to break. It is recommended to design ways to handle the robot without touching the silver trace.
The solvent used to print the silver for the silver trace is poisonous to humans. After curing the silver trace for half an hour to half a day it is safe to touch the silver trace. It is however still recommended to keep PTAs away from food and face.

Producing a PTA is not subjected to human error in contrary, for example, Dielectric Elastomers.

PTAs move slower than many of the unique actuators mentioned on page 38 but use less current, only about 1 Watt.

DESIGN CONSIDERATIONS

- A PTA needs to be kept dry
- A PTA does not react to a magnetic field
- A PTA heats up
- A PTA should not be touched when it is activated
- A PTA should not be touched when the silver trace is still wet
- A PTA must be attached to a power supply
- Creation of a PTA is not subject to human error
- A PTA moves relatively slow but uses less current

Examples

Now that a number of design considerations have been established, the different designs that resulted in these considerations can be analyzed.

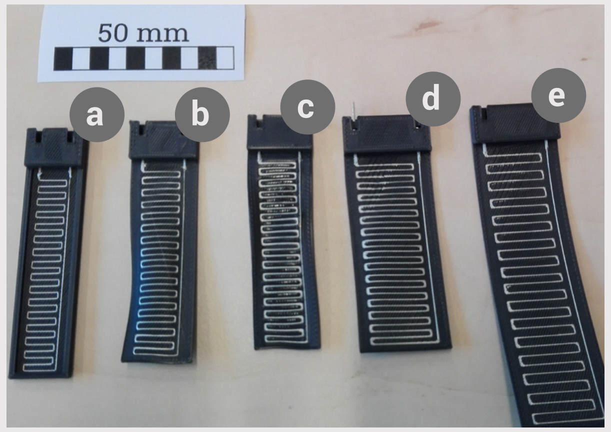


Figure 39 Iterations with different brims and different lengths and widths

The iterations in Figure 39 are similar to the first PTA that has been observed in June 2017. These iterations differ in their length and width, they also differ in where the brim is placed. The broader samples (d and e) tended to show arching behavior over bending behavior. This probably has to do with the way the layers have been laid down since that was how they tended to arch. The absence of a brim (b) also results in arching behavior but this is compared with unrepeatable behavior.

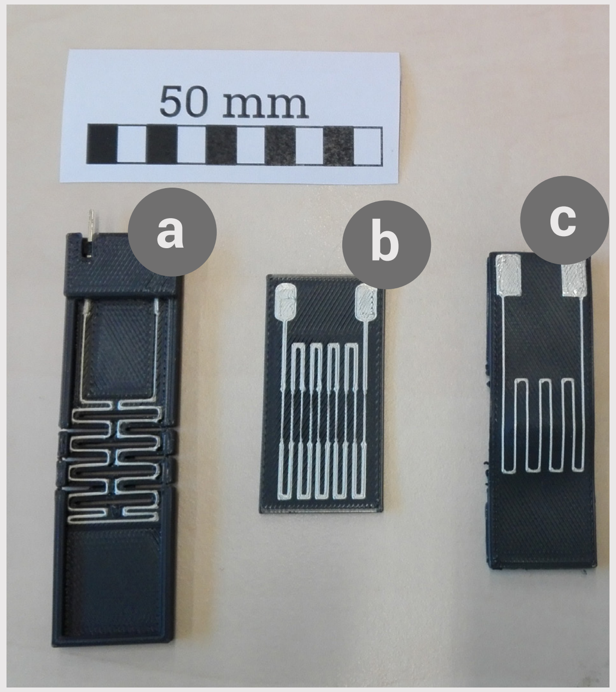


Figure 40 Iterations of hinges

The radius of the movement of PTAs is large compared to hinges. The silver trace was placed on a living hinge often used for laser cut prototypes (a). The hinge bent because the links went soft and gravity pulled the sample down. The sample was not able to repeat it's behavior. A sharper bend was also attempted by localizing the heat with a thinner silver trace (b). There was a localized patch of heat but this did not result in a sharper bend. The final attempt was a PTA that had fewer layers of plastic in the middle than the beginning and the sides. This also meant that this part did not have a brim resulting in the arching behavior that has been observed before.

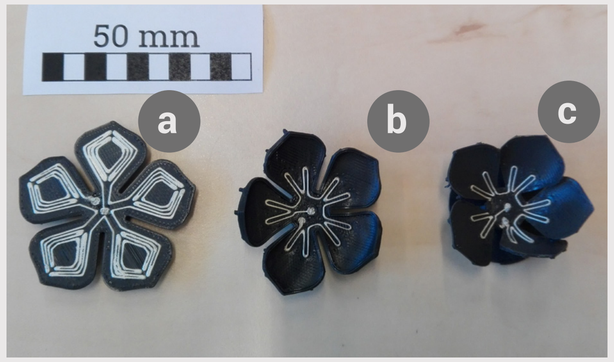


Figure 41 Iterations of a flower with petals

Inspired by flower related 4D printing projects (Zhang, et al., 2016) an attempt has been made to create a blooming flower. During the printing, the silver trace often broke when transitioning from vertical to horizontal which led to adding a buffer. Covering the petal with silver trace (a) ended up not being functional. The flower would not perform uniformly ("Asymmetry" on page 82) and was not able to repeat it's motion.

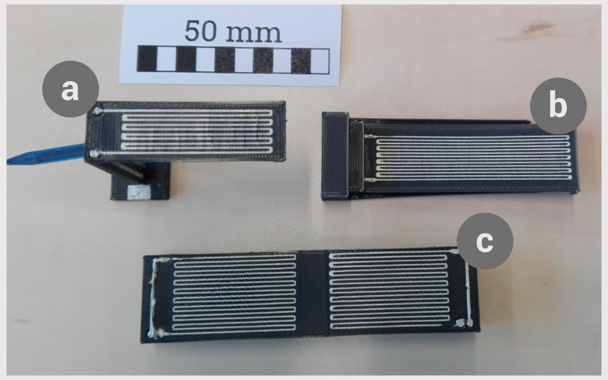


Figure 42 Iterations of different flexure mechanisms

Attempts have been made to print mechanisms. They were inspired by flexures which depend on bending. Sample a was the first and only iteration that was created with “normal” support. Removing this support ended up breaking both the model and the silver trace. Iteration b was the first attempt at reaching locomotion which ended up just lifting the sample from the floor. Sample c was a complete circuit out of the printer by accident which ended up not heating the complete sample.

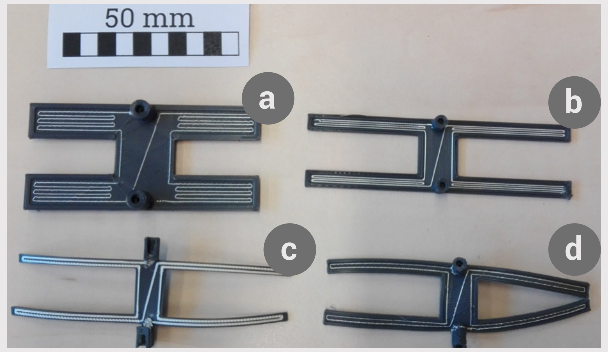


Figure 43 Iterations of an Hshape

These H shaped models showed extreme and repeatable deformation. Sample c even showed some torsion (“Torsion” on page 81). These samples could perform a “push up” motion once they were lifted from the floor. This way the floor did not influence the temperature of the PTA. After placing the connection to the power source on top of the sample instead of on the side they were influenced less by the shape memory of the wires.

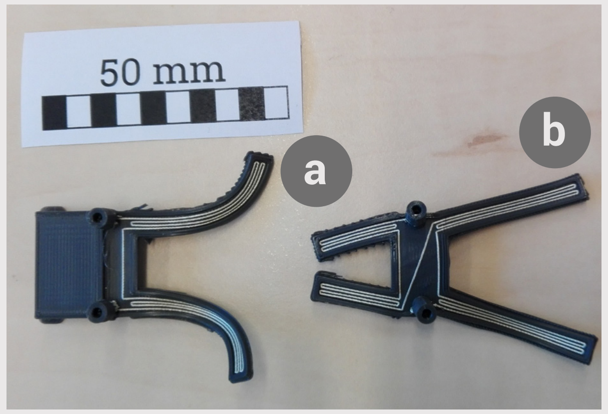


Figure 44 Iterations of an asymmetric Hshape

Based on the insights of the H shaped models a kind of asymmetry was implemented in the models while remaining line symmetry. The idea was that by asymmetric actuation could initiate locomotion. Because of a modeling error sample a ended up not being symmetric from the start which resulted in asymmetric behavior (“Asymmetry” on page 82).

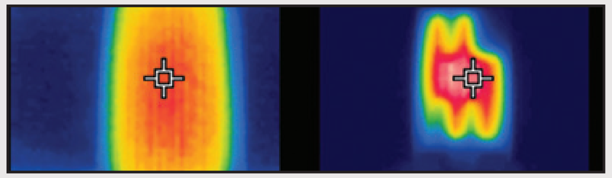
Conclusion

There is a lot of form freedom in creating PTAs but there is still a long list of design considerations to take into account. Designing a well working and predictable PTA some practice. But making them is not subject to human error.

An understanding of the different stages motion needs to be created to use the PTA as an actuator for a tinybot.

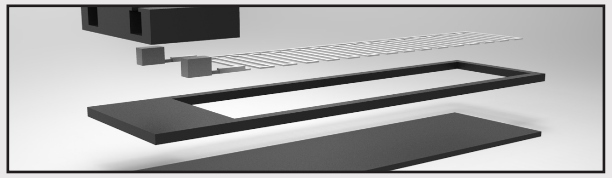
POWER

A PTA needs power to be activated



HEAT

A PTA heats up because of joule heating

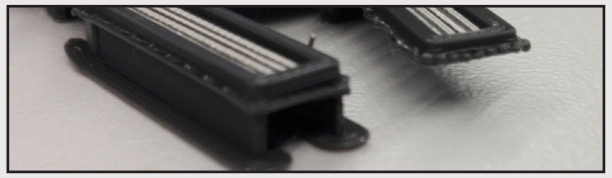


FOUR ELEMENTS

The design must consist out of a base, a rim, a silver trace and a connection

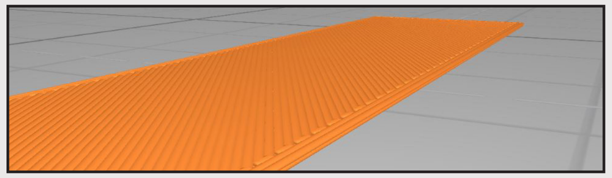
SILVER TRACE

The silver trace should be placed in a single line and not under an angle.



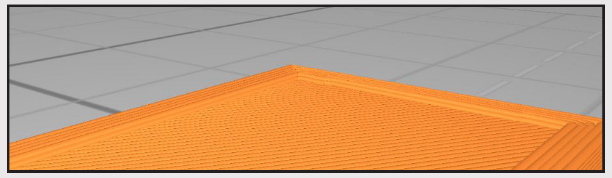
SUPPORT

Examples of custom support can be a wall (0.3 mm) or columns (1.3 mm)



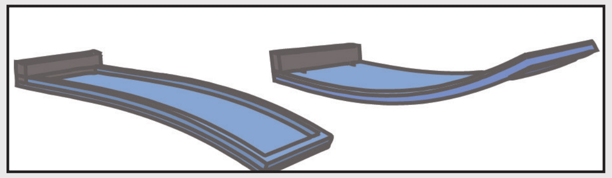
BASE

The base must be 0.4 mm high, which is 2 layers of plastic



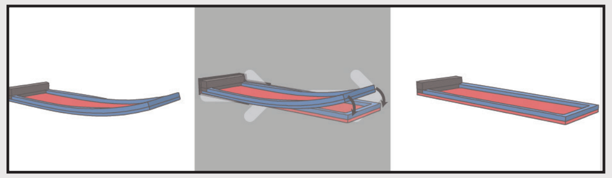
RIM

The rim must be 1.5 mm wide and 0.4 mm high



TOP BOTTOM

The rim can be on the top and on the bottom and will result in different motions



STAGES

Three stages of motion can be observed; Thermal expansion, transition, relaxing.

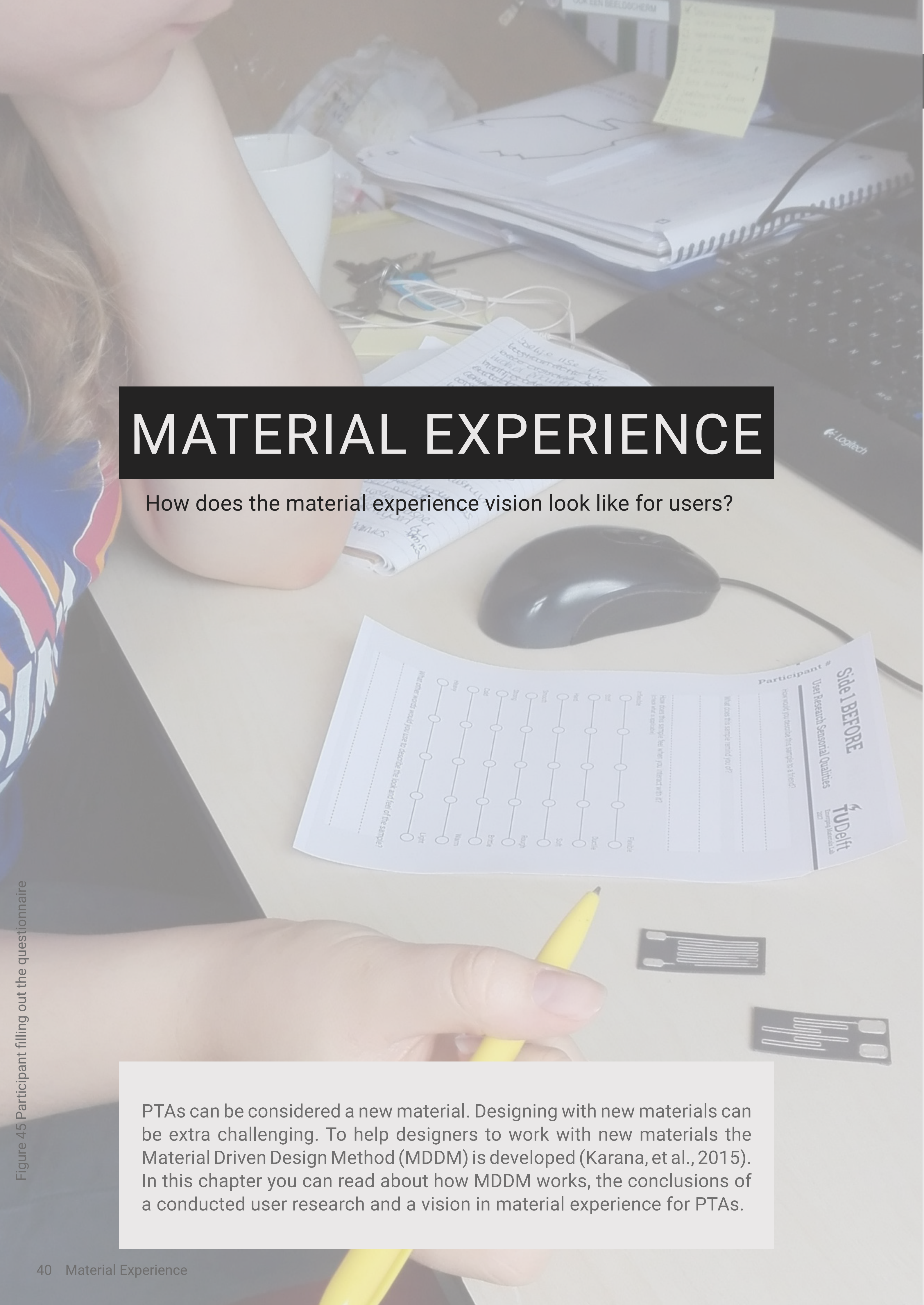


Figure 45 Participant filling out the questionnaire

MATERIAL EXPERIENCE

How does the material experience vision look like for users?

PTAs can be considered a new material. Designing with new materials can be extra challenging. To help designers to work with new materials the Material Driven Design Method (MDDM) is developed (Karana, et al., 2015). In this chapter you can read about how MDDM works, the conclusions of a conducted user research and a vision in material experience for PTAs.

MDDM

A common workflow for designers is to start with an experience, design a product that fulfills this experience and finds a material that fits with the function of the product and is still affordable. The Material Driven Design Method has been developed to help designers to design for experiences when the process starts with a material and ends with a product. It does this in four phases, first the designer analyzes the current situation, secondly, a new vision is formed, then patterns are analyzed and finally, a product is designed to fulfill this vision. This way of designing is especially useful for new and unexplored materials.

The MDDM starts with a thorough understanding of the material. This includes both tinkering the material.

When the designer starts tinkering with the material he/she gets familiar with the material and is able to discover constraints, opportunities, and insights in manufacturing the material.

The MDDM suggests that the experience of users with the material is recorded in multiple levels, how users perceive the look and feel, what meanings users associate the material with, how they feel about the material, and how they interact with the material.

Before creating an experience vision the material should be compared to other similar materials and their applications. This reflection can be done with a benchmark.

With the insights that have been gained in these steps, a material experience vision can be generated which can help the designer to create a product that fits this material the best. This material experience vision is often illustrated with a metaphor. In the next phase, the designer finds a way to accomplish the experience with the material qualities. In the final phase, the designer creates a product with his insights.

The 3D Printed Thermal Actuators can be perceived as a new and unknown material. Since this behavior is uniquely observed at the Delft University of Technology in 2017 not a lot of information is known about this material.

Results of the material tinkering and exploration can be found in the chapter “PTA” on page 26. Results of the material comparison, or in this case actuator, can be found in the chapter “Analysis” on page 10. The other steps of the method can be found in this chapter, starting with the user research.

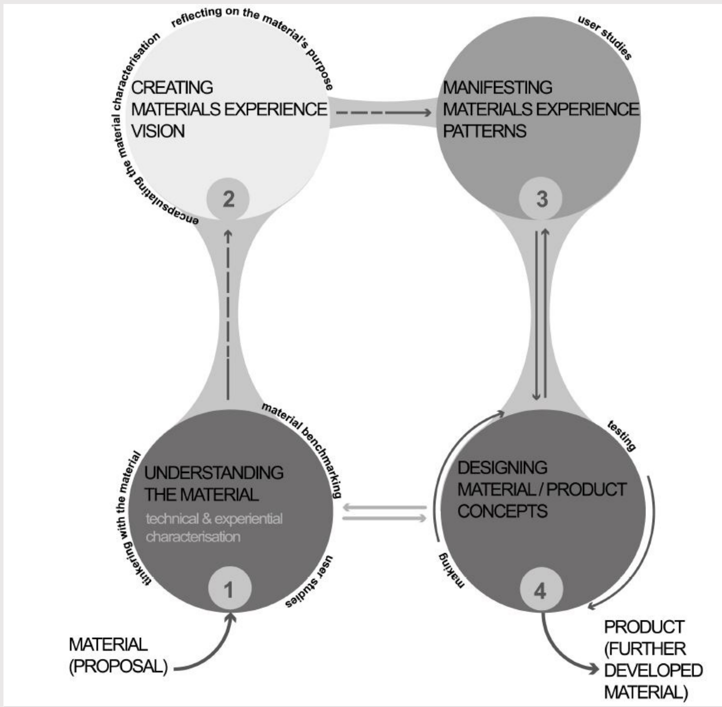


Figure 46 Visualization of the Material Driven Design Method

User Research

Method

To find out how users experience PTAs a user research has been conducted. The research has been set up in a way that the four different evels of experience are tested; sensorial, meaning, emotion and interaction.

PROCEDURE

Participants were handed a PTA without any explanation and were asked to complete one side of the questionnaire asking how they would describe the PTA and what they thought it would be used for. After completing Side 1 they got an explanation on how PTAs are made and videos were shown on how they move. After this explanation, they were asked complete the other side on how they felt about the PTA and what connections they made.

Before filling in the questionnaire the participants were told that there were no wrong answers, that their answers were recorded anonymously and they were asked to elaborate on their answers.

PARTICIPANTS

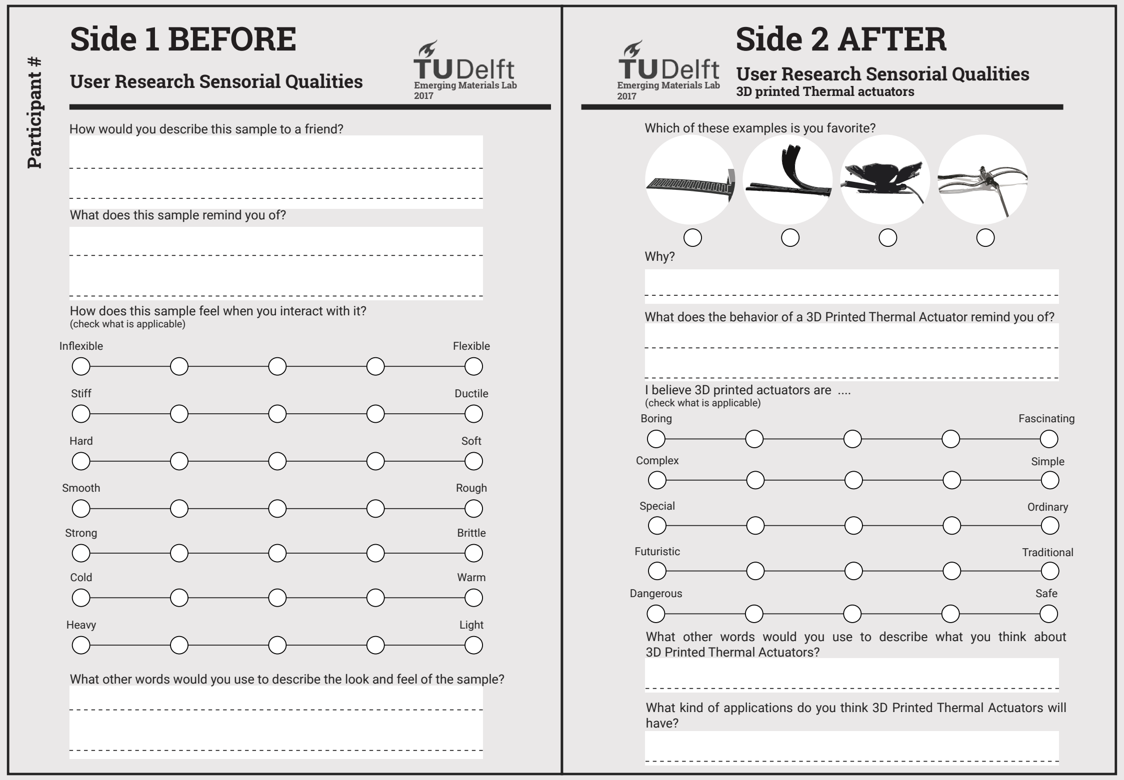
The participants were students from different study background. They were mainly engineering studies. They were aged between 19 and 29 years old. 17 participants participated in the research.

STIMULI

Participants were provided with a small PTA (Figure 49), a paper with the questionnaire on two sides of an a5 paper (Figure 47), and a pen. After filling in the first side of the questionnaire participants got shown a picture of the Voxel8 printer and four gifs of four moving samples.

MEASURES

Their observations were written down on the questionnaire form and recorded anonymously. Participants were allowed to answer in Dutch or English. Participants were observed when handling the PTA and observations were recorded by hand by the researcher.


Side 1 BEFORE
User Research Sensorial Qualities
TUDelft Emerging Materials Lab 2017
Participant #
How would you describe this sample to a friend?
What does this sample remind you of?
How does this sample feel when you interact with it?
(check what is applicable)
Inflexible – Flexible
Stiff – Ductile
Hard – Soft
Smooth – Rough
Strong – Brittle
Cold – Warm
Heavy – Light
What other words would you use to describe the look and feel of the sample?

Side 2 AFTER
TUDelft Emerging Materials Lab 2017
User Research Sensorial Qualities
3D printed Thermal actuators
Which of these examples is you favorite?
Why?
What does the behavior of a 3D Printed Thermal Actuator remind you of?
I believe 3D printed actuators are ....
(check what is applicable)
Boring – Fascinating
Complex – Simple
Special – Ordinary
Futuristic – Traditional
Dangerous – Safe
What other words would you use to describe what you think about 3D Printed Thermal Actuators?
What kind of applications do you think 3D Printed Thermal Actuators will have?

Figure 47 Questionnaire form

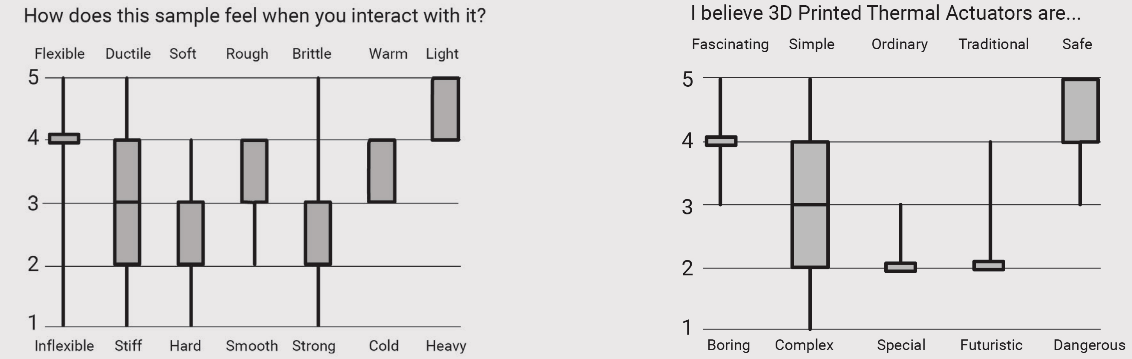


Figure 48 Results of the questionnaire displayed in a boxplot

Results

GENERAL OBSERVATIONS

The raw results can be found in “Appendix 3” on page 89. Initially, participants were very puzzled. They knew how to describe the sample but did not know what it was used for. They were really curious what it was and understood the explanation.

The participants were not instructed to handle the sample with care. After about 10 participants the sample needed to be replaced because it lost it’s silver trace as seen in Figure 49. The sample often broke when the participants bend the PLA and the silver was not able to survive the bending.

SENSORIAL

An interesting observation that multiple participants mentioned was that the visible lines in the printed PLA reminded them of a woven/fabric like structure. A lot of the participants were surprised at how light the sample was. Some participants received a partially damaged sample and had a different opinion on how brittle it was compared to participants who received a complete sample.

Figure 49 PTAs after being handled by the participants

MEANING

After discovering what the function is of a PTA they found the sample overwhelmingly fascinating, special and futuristic (Figure 48). Multiple participants mentioned that they found the sample innovative. Surprisingly the sample was labeled safe. Participants were told that the sample would heat up with a power supply but not that the solvent is poisonous to humans.

EMOTION

Participants were surprised by the function and motion of the PTA. Participants mentioned reactions like “Wow” and, “But How?”. The majority of the participants reacted with: “Cool!”. Participants that reacted differently did not make an attempt to understand how the PTA works since they thought it was too complicated or they did not understand the added benefit of a PTA over other actuators.

INTERACTION

Participants held the sample in their hand like they would do with a coin when they would fill in the questionnaire. In other moments they would rub the sample to feel the silver trace but also the lines that the 3D printer created with the PLA. They would also try to bend the sample so they could check it’s flexibility. This sometimes resulted in the silver trace breaking.

FAVORITE SAMPLE

The sample with the blooming flower received the most votes. Participants noted a similarity between the slow movement of the PTA and of a blooming flower. The Hshape sample came in second, it was perceived as funny and quirky.

ASSOCIATIONS

The participants often made the association that the silver traces indicated a use related to consumer electronics like a PCB or an SD card. Because of their association with an SD card, some participants expected the silver trace to be the back of the sample and the black side would be the front and it was just missing a label.

Participants also made associations based on the way they saw the sample move. They compared it to a party blower, growing plants, paper that curls when it burns, muscles and a spring.

APPLICATIONS

Finally, the participants were asked to imagine a use for PTAs. This was considered a hard question by the participants. Participants that did come up with a use mentioned; robots, toys, gadgets, sensors, and prototypes.

Figure 50 Participants filling in the questionnaire

Discussion

Participants did not get a chance to see a PTA move in real time and did not experience the sample actually heating up. This decision was made consciously since they would not have been allowed to touch the sample when it was connected to a power source and this way the test was portable so it could reach a lot of participants.

Not experiencing the sample heating up might have influenced the experience of the participants.

Some participants had trouble with some definitions in English since English is not their first language. The ones who asked got a definition in Dutch but it isn't sure that all the participants who had trouble with the English definition indicated this to the researcher.

The interaction qualities have not been filmed but written down by the researcher, this could result in an information or recall bias.

The participants were familiar or even friends of the researcher. Even though, it was clearly indicated that the participants remained anonymously this could have resulted in socially acceptable answers.

Finally, it is important to take into consideration that the participants with an interest in engineering, this makes them extra curious about gadgets and new techniques. Compared to an ordinary user they might be more excited and interested.

Qualities of PTA

When combining the insights from chapter "PTA" on page 26, the insights from the user research and the insights from "Analysis" on page 10, a set of cards is made. These cards explain the range of the different qualities of PTAs. The cards can be found in "Appendix 5" on page 92.

With these cards, different patterns can be recognized. Some core qualities can be recognized that make PTAs special. When creating a demonstrator these special qualities should be showed off. Eight properties have been selected.

LIGHTWEIGHT

PTAs are often about 1 gram which is lighter than users expect. To move a mass like this only a small force is needed.

MOVES SLOWLY

Compared to other actuators a PTA moves slowly. This is also what makes a PTA elegant.

NEEDS LITTLE POWER

A PTA needs just about 1 Watt of power which is lower than most actuators. To transport this power only a small battery is needed.

DELICATE

A PTA will not work if the circuit is broken. The circuit breaks if PTA is not handled with care. After a few days, the internal stresses in a PTA disappear and the behavior is less predictable.

BENDS

When a power is supplied a PTA will heat up and transfer this heat into a motion.

REPEATS ITS ACTIONS

Unlike other 4D prints, a PTA can repeat it's motion multiple times

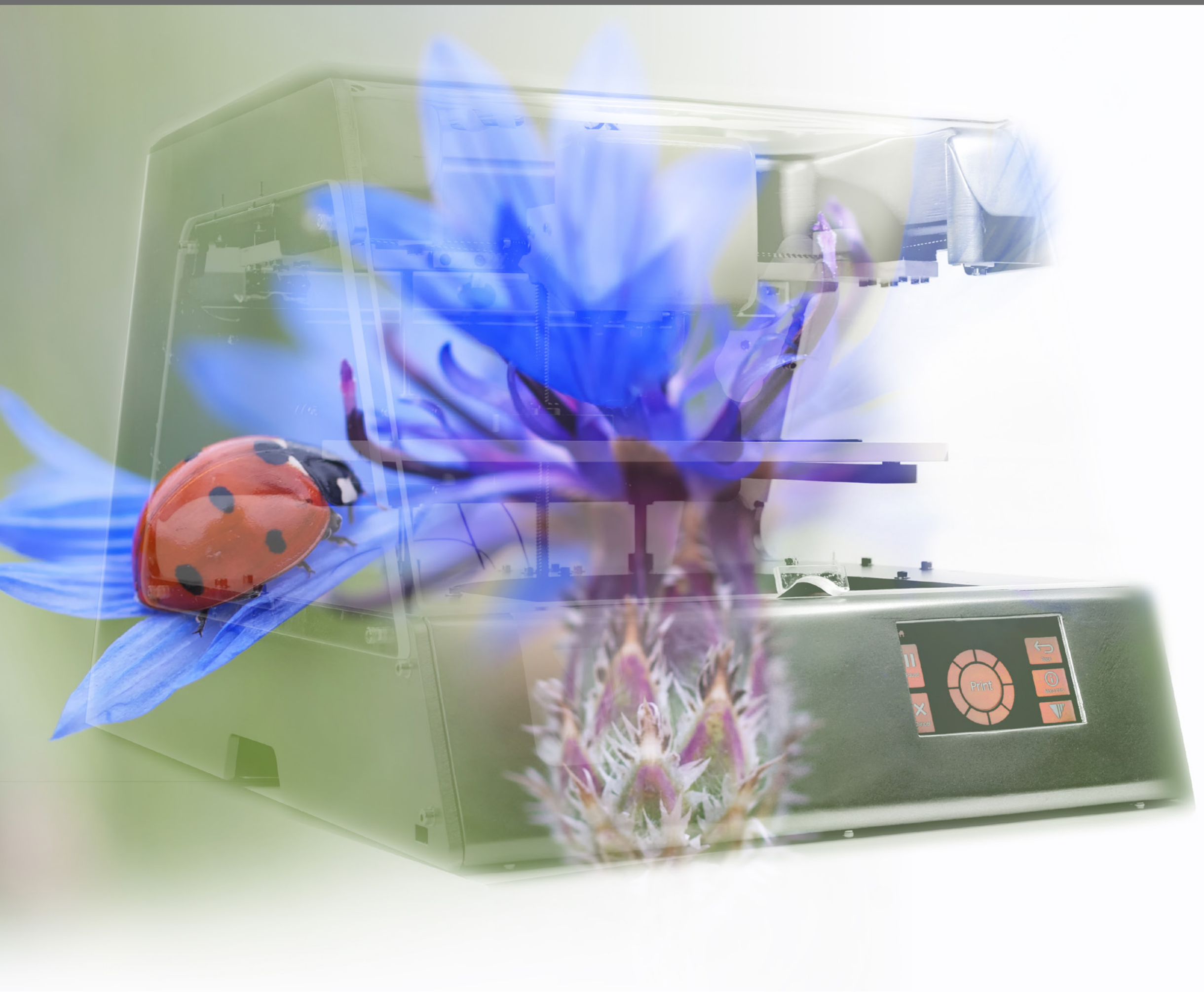
HEATS UP

A PTA will heat up when power is applied due to Joule heating. This is different than most actuators.

3D PRINTED QUICKLY

A PTA is designed by a designer but created with a 3D printer. This means that a PTA is not subject to human error.

Vision



3D PRINTED THERMAL ACTUATORS SHOULD BE ADMIRED, NOT HANDLED. JUST LIKE A FLOWER THAT IS BLOOMING OR A LADYBUG THAT WALKS OVER YOUR HAND.

These organisms move slowly and are observed attentively by people with different backgrounds. Since these organisms are so small and delicate people handle them with care. While observing them people experience joy and curiosity and like these organisms, they have a short lifespan.

There is an interesting contrast between the association with nature and the fact that PTAs are designed by man and created by a machine. PTAs can, therefore, be used to show the beauty of nature with a machine-made object.

Because there are only about 100 Voxel8 printers in the world that can produce PTAs and the large range of form freedom the number of duplicates will be low. This means that the applications of PTA are either personalized/specific solutions or demonstrators.

Applications

The design considerations, unique characteristics, and qualities of PTAs are defined. For this project PTAs will be used to create a demonstrator but if the creation is not limited to this printer other applications could be defined.

ROBOT ACTUATOR

Since actuators are often associated with robots this was an obvious application. The PTA will react to a current and will translate this current into movement. A robot can use this for locomotion or other motions.

OFFICE TOYS

Since the silver trace is exposed and the movement is slow tech enthusiasts can show off and closely examine the PTA working. Since the energy that is needed can fit in a small battery this gadget can serve as an ornament, conversation starter or an office gadget.

NATURE DISPLAYS

As mentioned in the vision the slow and curved motion can also be found in nature. Because the PTA can repeat it's motion it can be integrated into displays for nature museums or animatronics in amusement parks.

VISUAL EFFECTS IN MOVIES

Movie props will be only used once or twice. Designs are usually very specific and need to be produced quickly. PTAs can be hidden in the background or in masks of horror villains. With some movie magic, the PTA can move as quickly as the director wants.

COSTUME DESIGN

With the rise of cosplay and maker-movement, there is a growing demand for movable actuators to bring costumes to live. Costumes that defy physic laws, since they were only be meant to be drawn or simulated by a computer, can be brought to life in real world. The lightweight and low power that is needed make PTAs easy to hide.

Conclusion

The Material Driven Design Method is used to create a material experience.

Thanks to a user study quantitative qualities of PTAs are collected. These range from "Fascinating" to "looks like a PCB". Based on these insights and those found in the previous chapters a set of cards describing these qualities have been made.

Based on patterns that have been recognized in this card set a set of eight qualities have been labeled to show off in the demonstrator: lightweight, moves slowly, needs little power, delicate, bends, repeats its actions, heats up, and 3D printed quickly.

A vision for a material experience has been described with the metaphor "Observing a flower that blooms". With this vision of material experience, some potential applications have been addressed which were: Robot actuator, office gadget, nature display, the visual effect in movies and costume design.

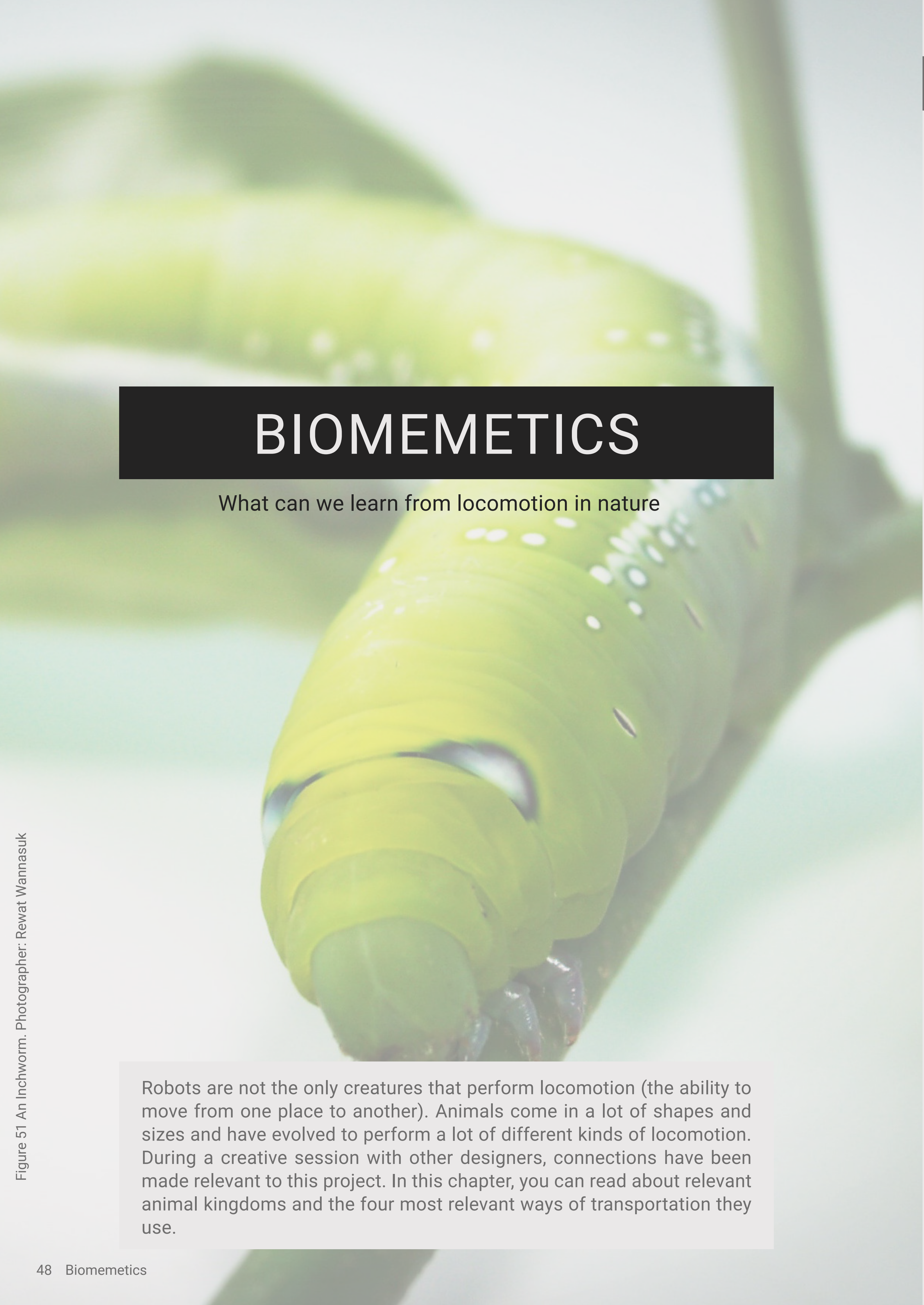


Figure 51 An Inchworm. Photographer: Rewat Wannasuk

BIOMEMETICS

What can we learn from locomotion in nature

Robots are not the only creatures that perform locomotion (the ability to move from one place to another). Animals come in a lot of shapes and sizes and have evolved to perform a lot of different kinds of locomotion. During a creative session with other designers, connections have been made relevant to this project. In this chapter, you can read about relevant animal kingdoms and the four most relevant ways of transportation they use.

Scope

Figure 52 Designers during a creative session making connections between animal an robotic locomotion

The different animal kingdoms have a lot of different organisms in them so eliminating some can help to find some focus. It has been concluded that the PTAs will not work underwater unless they are coated well so creatures that live underwater like fish or octopuses will be excluded. Flying creatures are also excluded because the movement of PTAs is not fast enough to create enough propulsion to lift off.

Humans are not the only animals that walk on two legs, apes, kangaroos, and birds do this as well. It is important to realize that bipedal locomotion (locomotion with two legs) depends on switching the center of gravity and catching the “fall” with the correct leg. This is realized with meticulous sensing/calculation and articulate knee and ankle joints. This type of locomotion is complicated and needs multiple actuators to realize. Because of this, it has been decided that bipedal locomotion falls outside of the scope.

With these scope decisions and biological symmetry in mind, we will be looking at animals with four or more legs. This will still include a lot of animal kingdoms like Amphibians, Reptiles, Mammals, Insects, Crustaceans, and Arachnids

Creative Session

On August 17th four designer students came together to attend a creative session (“Appendix 4” on page 91). The session was facilitated by the graduate student.

The group tackled the following challenge: **Define ways to translate the motion of a PTA into locomotion.** Together the group drew inspiration from the way that robots and animals move. At the end, the mechanisms were constructed with Meccano and straws.

CONCLUSION

There are a number of ways to create locomotion.

- Animals that climb use their limbs to grab onto branches like sloths.
- Animals that climb can also use friction in their paws to grab onto tilted surfaces like trees. Geckos use physical structures to grab onto flat surfaces, spiders have tiny claws which they can use to climb their web.
- Animals roll their entire bodies like armadillos and pill bugs. Plants like tumbleweeds also use rolling as a form of locomotion
- Animals with limbs, like mammals, use muscle contraction and joints to make their limbs move one way or the other.
- Animals that have a low intelligence like insects use a lot of paws to navigate over difficult terrain.
- Animals that jump release a lot of energy at once like a frog or a kangaroo

These observations show the diversity of nature. When this is translated back to locomotion by robots four main principles are observed. Lift-Land-Push, Anchor Push - Anchor Pull, Wave, and Pivot-Switch.

Figure 53 Designers cluster the different ideas they came up with

Styles of Locomotion

Lift - Land - Push

PRINCIPLE

To reach locomotion with legs, the leg first needs to be lifted from the surface. It moves to a new location and lands. With the friction between the surface and the base of the limb, it pushes the body forward while retaining its position. Then the leg is lifted etc.(Figure 54)

ANIMALS THAT DO THIS

A lot of animals use this principle for locomotion. These animals have limbs, at least a single joint and ways to create friction with the surface, like claws or hooves.

DESIGN CONSIDERATIONS

- At least one hinge is needed for lift and land
- Rotating parts and four beam mechanisms are needed to achieve this complicated movement
- More than one limb is needed to create locomotion and support the body
- The base of the limb needs to create friction with the ground

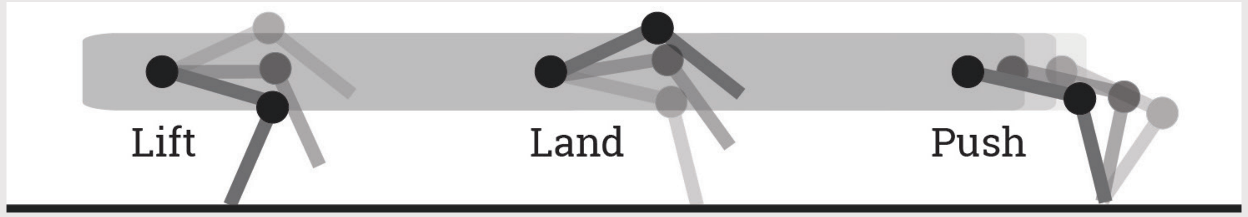


Figure 54 A limb performing Lift - Land - Push

Anchor Push - Anchor Pull

PRINCIPLE

In this motion, the entire body is involved and a lot depends on variable friction with the surface. The body has two connections to the surface. First, the back connection acts as an anchor and pushes the body forward. When the body is stretched the front connection acts as an anchor and drags the body over the surface as it pulls the body in. Then the back connection acts as an anchor etc. (Figure 55)

ANIMALS THAT DO THIS

Animals that move with their entire body do this. Example of an animal that does this is an inchworm.

DESIGN CONSIDERATIONS

- Frictions with the surface needs to be created
- This friction needs to be variable in different directions
- The friction can also be in one direction but not the other direction
- The design of the body needs to be lightweight since the body will be dragged
- The PTA needs to perform contraction
- The body needs to be able to fold/contract

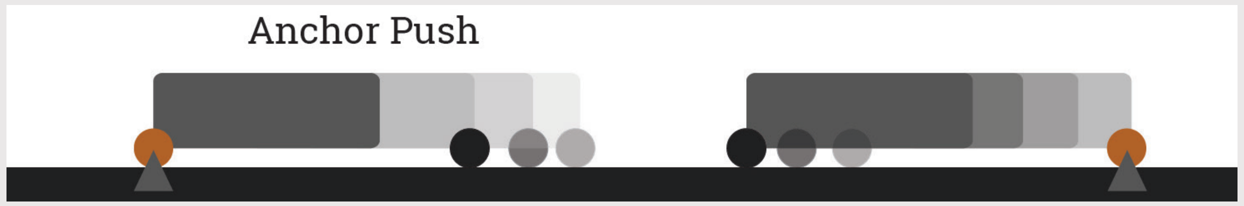


Figure 55 A body performing anchor push anchor pull

Wave

PRINCIPLE

For this type of locomotion, the body needs to be segmented. It looks like the body touches the floor at some stationary points but actually, the segments take turns supporting the body weight and using the floor to push the other segments forwards. When the body has been moved forward, a new touch point is created and the segments take turns supporting the weight and pushing the other segments forward etc.

DESIGN CONSIDERATIONS

- Dividing the amount of force between several segments can reduce the amount of force needed for locomotion
- Translating this locomotion into a mechanical solutions requires a lot of connections and hinges
- This type of locomotion can be used on multiple types of terrain.

ANIMALS THAT DO THIS

This type of locomotion is mainly performed by snails and snakes.

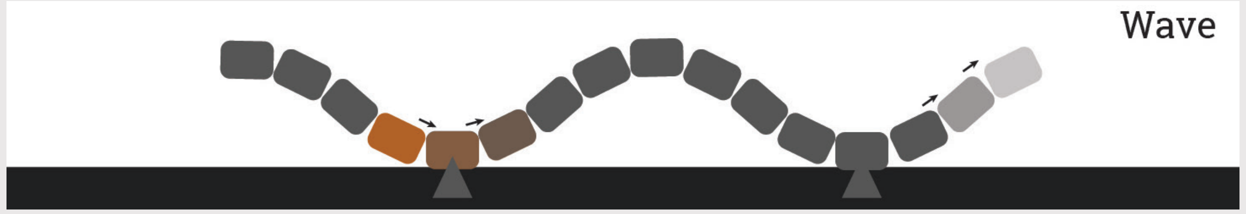


Figure 56 A wave performing locomotion

Pivot Switch

PRINCIPLE

Four limbs are required to perform this motion. At all times two limbs are touching the surface. The two limbs are anchor points but they are free to pivot. When the spine bends the two lifted legs move forward. Then the two legs land and create new pivot points for the other two legs to move. The anchored/pivoted legs are diagonal across from each other.

DESIGN CONSIDERATIONS

- Four limbs and a spine are needed to perform this motion
- For this movement at least three actuators are needed.
- The legs need to have enough grip to push forward but room to pivot

ANIMALS THAT DO THIS

This type of locomotion is usually performed by reptiles such as salamanders and geckos.

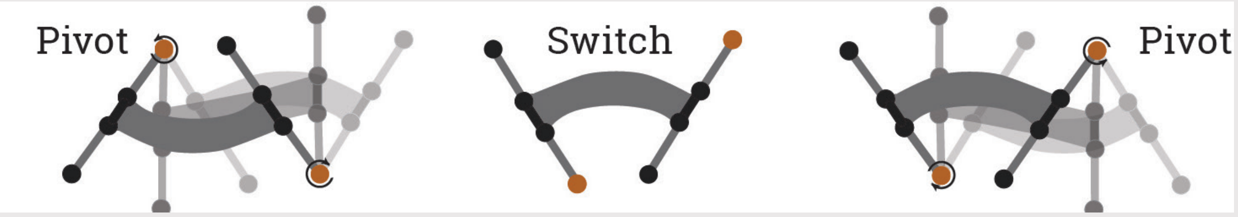


Figure 57 A body with spine and four limbs performing Pivot Switch

Conclusion

Locomotion of animals can be used for inspiration when creating a walking tinybot. Taking into consideration that PTAs will not work in water or in the air the animal kingdoms Amphibians, Reptiles, Mammals, Insects, Crustaceans, and Arachnids remain.

In a creative session, patterns have been recognized that resulted in four modes of locomotion.

The movements of these animals can be simplified in four different movements. These are Lift - Land - Push, Anchor Push - Anchor Pull, Wave, and Pivot - Switch. When designing a tinybot these principles can be used to create locomotion.

Figure 58 Generating ideas for a PTA demonstrator

IDEATION

How will a PTA demonstrator look like?

Until now we have learned relevant research, how to design a PTA and how animals move. We have learned about technical and experiential qualities of PTA. There is one goal left to accomplish: Create a 3D printed demonstrator that will move in an engaging way using these PTAs. In this chapter, you can read about the design brief the ideation and three different concepts.

Design Brief

Together with the graduation committee a list of requirements, wishes and restrictions has been created. The concepts must meet the requirements to be considered a concept. The wishes should be used to select the best concept. The restrictions are the most important limitations that designing with a PTA brings with them.

REQUIREMENTS

- The demonstrator needs to showcase unique qualities of a PTA
- The demonstrator needs to perform at least 5 cycles
- The demonstrator needs to be perceived as fascinating
- The demonstrator needs to be perceived as intriguing
- The demonstrator needs to be perceived as exciting

WISHES

- The demonstrator carries its own battery
- A user can operate the demonstrator without instructions
- The demonstrator does not need any post-processing
- The demonstrator is printed in a single print
- No electronic components should be used to operate the demonstrator

RESTRICTIONS

- A PTA should be tethered to a power supply
- A PTA should not get wet
- A PTA is created with the Voxel8 printer
- A PTA is made out of PLA and conductive silver
- A PTA is made needs to fit on the print bed

Ideation

During the ideation the PTA was considered to be a an actuator that can bend up and down repeatably. With this abstraction, ideas were able to flow more freely. During this phase, the Voxel8 printer was down since there was not silver ink. This hibernation turned out to be a blessing in disguise. The idea generation was not limited to the thought "but that will not work".

Two distinct stimuli were used to generate ideas.

PATTERN RECOGNITION

Using the card sets that were created using the Material Driven Design Method ("Appendix 5" on page 92) and the characteristics found in nature ("Appendix 6" on page 95) clusters were made. These clusters revealed patterns and sparked creativity resulting in ideas being generated.

RANDOM STIMULUS

The other method used to spark creativity was a random stimulus. A website called TextFixer.com can supply a number of random words with a simple mouse click. These random words make you think outside of the box and let you make connections you have not made before.

With these two different stimuli, ideas were sketched and clustered in different categories.

Figure 59 Finding patterns with the MDDM cards

The ideas that have been generated have been divided into four different categories.

MOVING ANIMALS

In moving animals different animals can be found that perform locomotion with different methods. A zombie that uses his arms to pull his body forward. A turtle that also uses just it's front legs to move forward. A gecko that performs Stick-Pivot. An Inchworm that performs Anchor Push - Anchor Pull. A snail that is a kind of sled. A ladybug that has six feet and a sloth that moves over a custom branch.

STATIONARY NATURE

In stationary nature, the samples will not perform locomotion but still, show off the bending qualities of PTAs. A snake that lifts its head. A flower that opens it's leaves. A dragonfly/butterfly that moves its wings. An elephant lifting its trunk and a hedgehog that turns into a ball.

PRACTICAL

Practical has just two ideas. A hand with moving fingers that can perform a handshake. And a gripper that grabs small objects like balls or squares.

MODULAR

Modular has some ideas that have replaceable parts. Parts that can be replaced for decoration reasons, like the shell of a hermit crab. The caterpillar/butterfly can move like a caterpillar until the wings are attached. The wings have a lower resistance and will receive energy to move up and down. Finally, the millipede that has detachable segments. Each segment can perform locomotion but the segments can be connected into one long centipede that perform their motion together.

Ideas have been selected and combined to make three concepts; Inchworm, Sloth and Turtle.

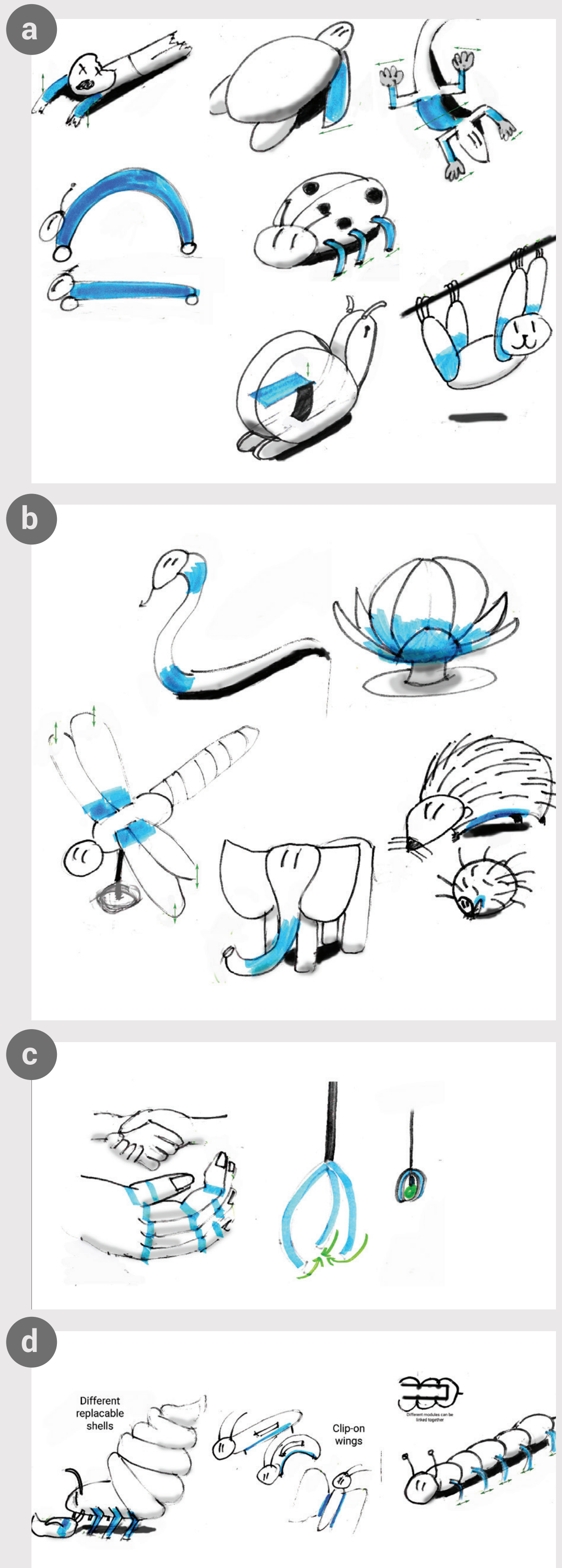


Figure 60 Generated ideas in four different categories Moving Animals (a) Stationary Nature (b), Practical (c) , and Modular (d)

1 Inchworm

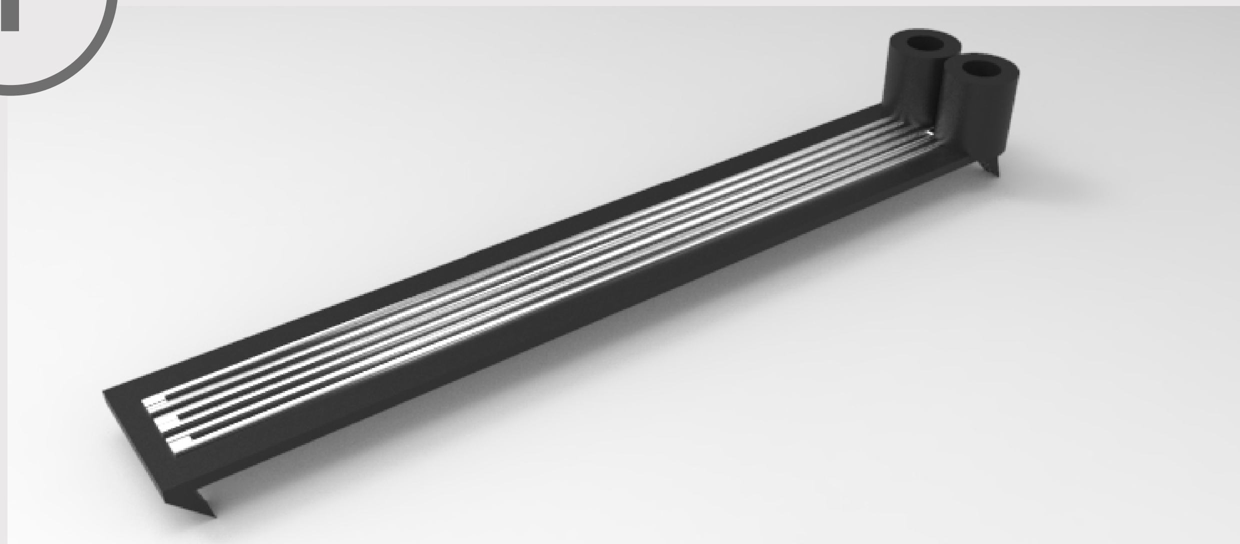


Figure 61 Design of concept Inchworm

INSPIRATION

A lot of the smart actuator researchers show robots that are inspired by the inchworm. The simple motion that the inchworm performs with its entire body is easy to replicate.

LOCOMOTION

This inchworm performs anchor push - anchor pull by bending its entire body. By bending its body the distance between the beginning and the end will decrease (Figure 62). The motion is depended on the friction with the surface on which it moves. In this case, placing the feet of the inchworm under an angle can help creating friction in one way and not in the other way.

LOOKS

This simple design can easily be printed in one go. The challenge will be to create the feet. The feet need to be at an angle and are preferably as thin as possible so they can act as bristles. A heat gun can be used to soften the feet and increase the angle needed for locomotion. This design will probably not be strong enough to carry its own battery so it needs to be tethered.

CHALLENGES

The biggest challenge was to create enough friction for locomotion. This was reached in multiple ways. First, the front feat was heated up and placed at a sharper angle. Secondly, a weight was placed on the front of the model. This was only two grams. In a final design, this weight can be replaced by a head for the inchworm. Finally, different floors were used; a foam, sandpaper and felt. Foam served the best balance a lot and a little friction.

ADVANTAGES

This sample shows the clearest locomotion of all the concepts. It also shows clearly the purest example of a PTA.

CONCLUSION

The inchworm clearly shows locomotion and a PTA. However, it does not need a lot of further development other than a head that needs to be added. This limits possibilities of making the design more attractive for a curious audience.

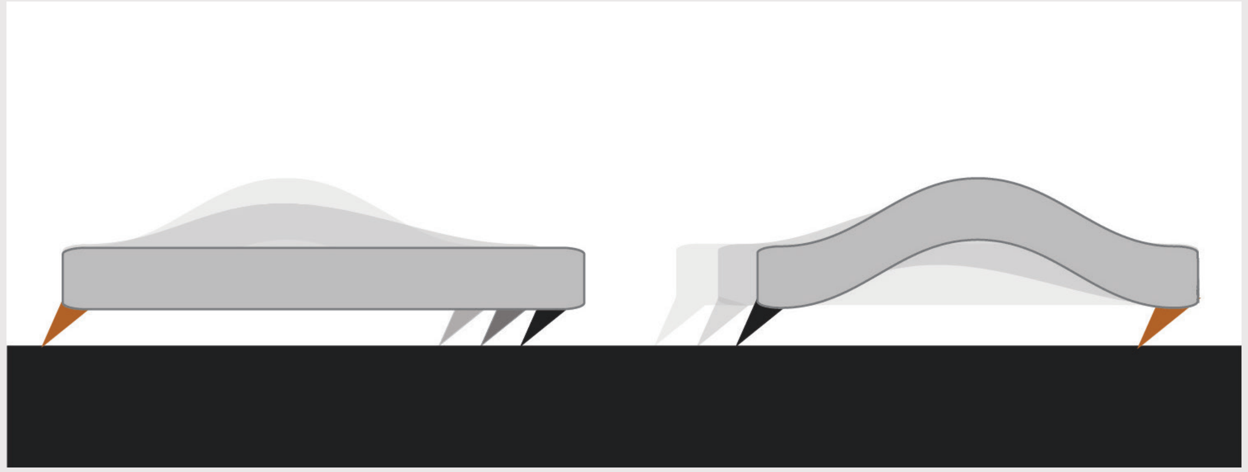


Figure 62 Locomotion principle of Inchworm

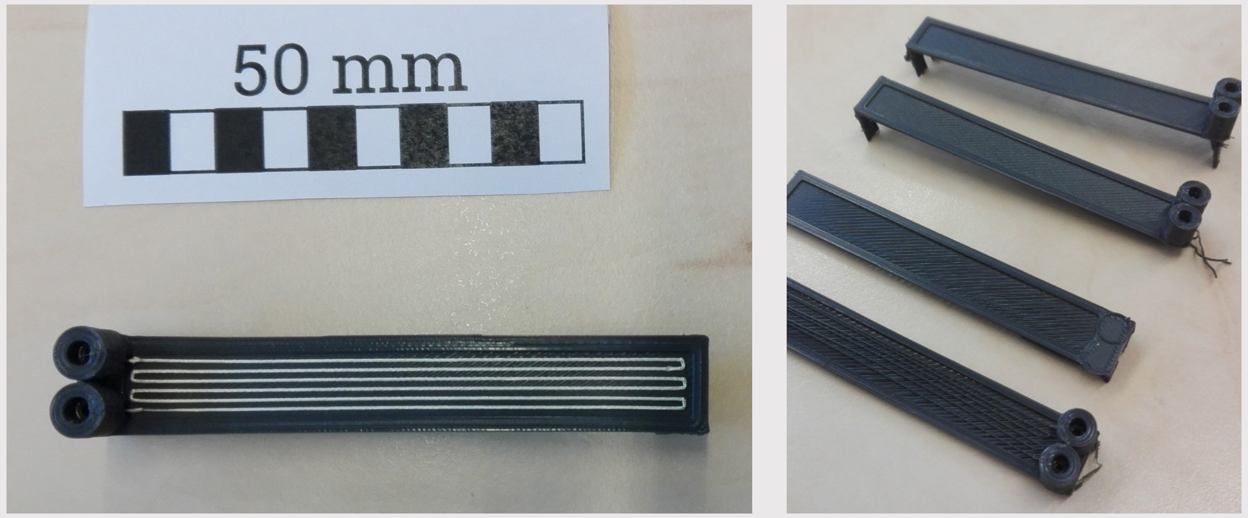


Figure 63 Iterations of concept Inchworm

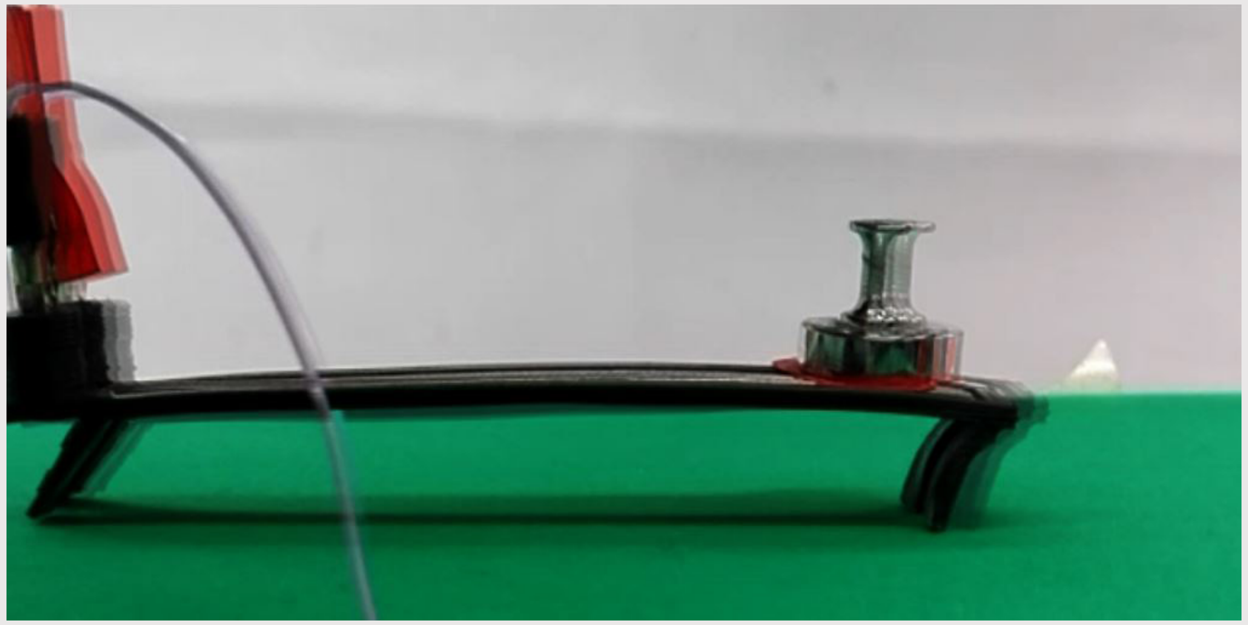


Figure 64 An inchworm iteration performing locomotion

2

Sloth

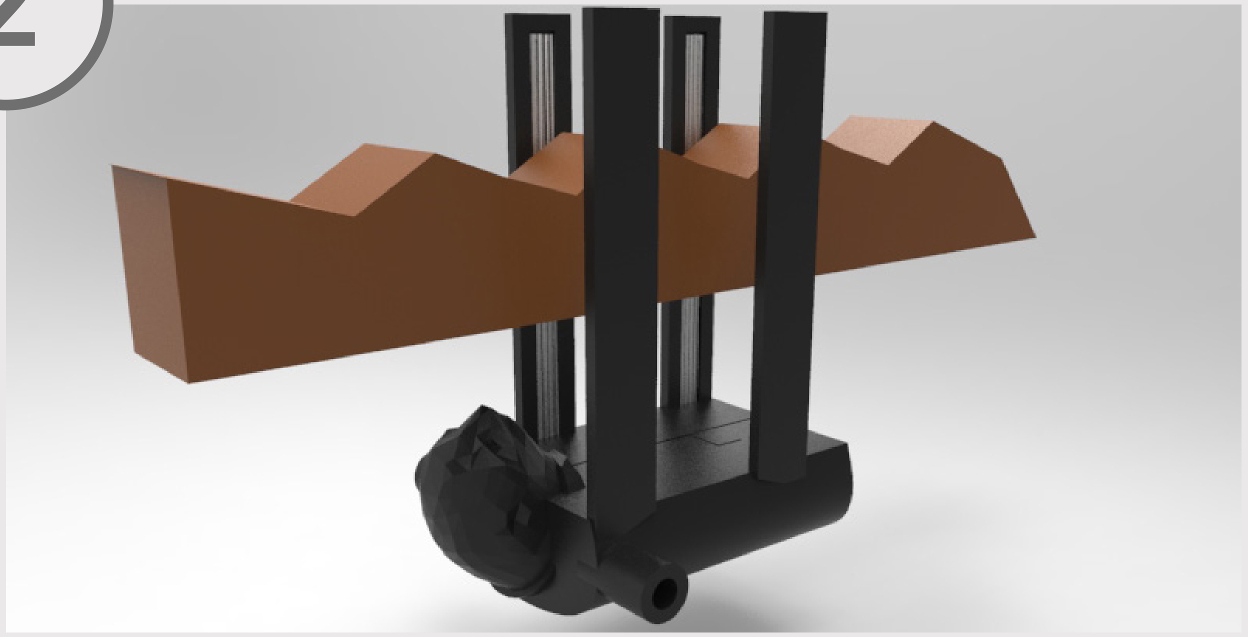


Figure 65 Design of concept sloth with branch

INSPIRATION

Sloths are very slow moving animals. Sloths have a growing fan base in pop culture and are considered to be cute. It is unknown why but the large eyes of a sloth have definitely something to do with it. They are known to hang upside down on branches which is different than the Hshapes that have been explored before.

LOCOMOTION

The sloth will use four legs and a special branch to create locomotion. The legs will start in a bend position. It will stretch the legs in pairs diagonally across from each other. Because of the specially designed branches, similar to a gear rack, gravity will pull the sloth forward over the slope (Figure 66). After all the arms have returned to a bend position the other two legs will stretch.

LOOKS

This will be a hard model to print in one go. The four legs (two pairs) have a silver traces facing each other. The model will be divided in two and connected after the print. It will be challenging to ensure that the silver trace is also connected. This can be attempted with male/male pins or with clever modeling.

If the battery is not hidden in the body of the sloth it can be supplied via the designed branch since the silver traces will touch the branch.

Sloths are known for their very large eyes and large limbs. They also have a lot of bushy hair. These can be taken into account when designing the aesthetics of the sloth.

CHALLENGES

The biggest challenge was definitely connecting the two halves together. Creating both halves and a closed silver trace has been unsuccessful. Next to that, it would have been challenging to activate the pairs independent of each other.

ADVANTAGES

Sloths are very popular animals. Using gravity to create locomotion can increase the speed of locomotion and reduce the energy needed to be generated by the legs.

CONCLUSION

Since no successful proof of concept was created, this concept had a high chance of not making it through the concept selection

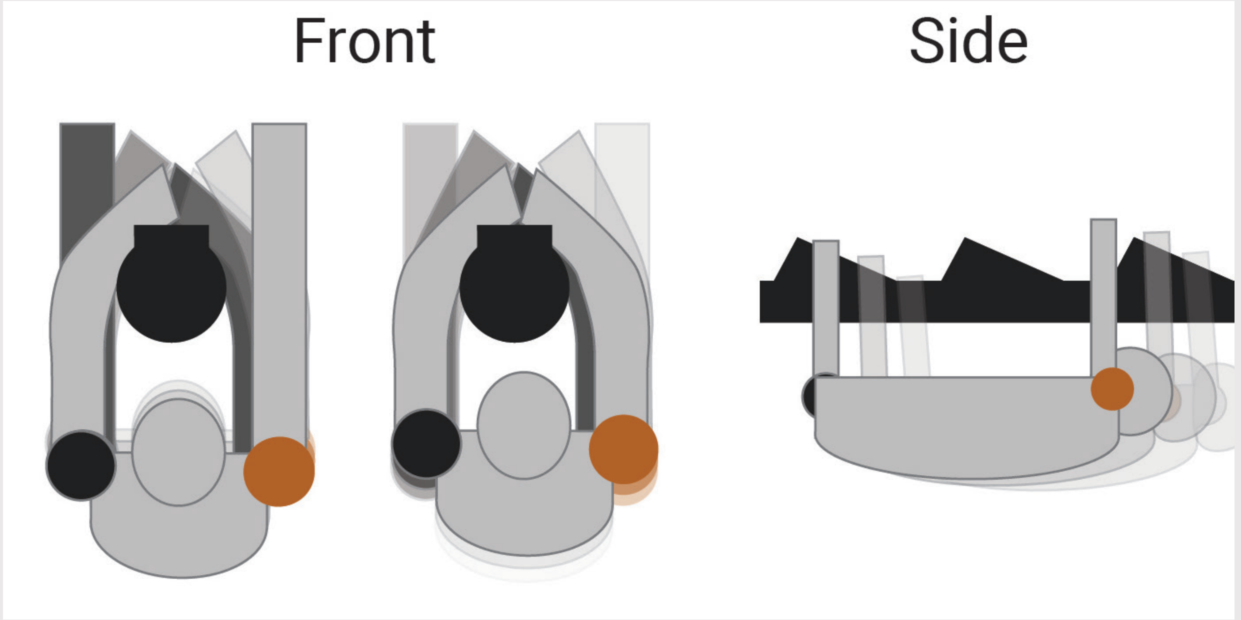


Figure 66 Locomotion principle of Sloth

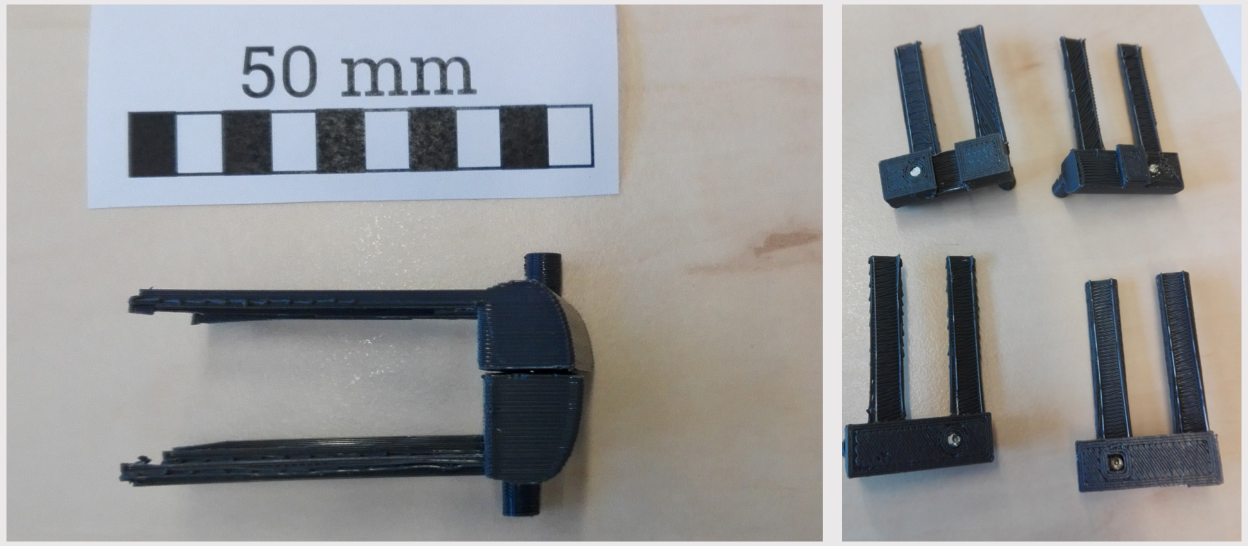


Figure 67 One of the iterations of Sloth

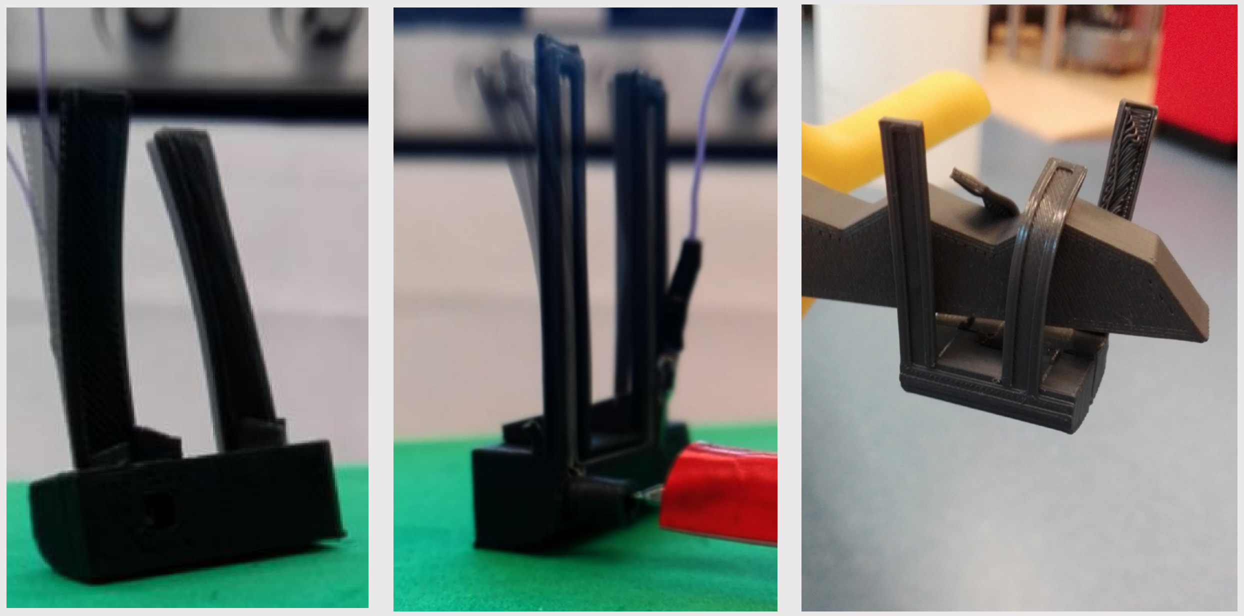


Figure 68 An iteration of Sloth in motion

3 Turtle

Figure 69 Design of concept turtle

INSPIRATION

Turtles are known to be slow moving animals (even though some can swim and run very quickly). The attempts of locomotion of Hshape have been described as a fish on dry land. The Hshape can be embedded in the front two legs of the turtle.

LOCOMOTION

The turtle will only use it's front two legs to push itself forward. This forward push can be reached by making the contact points as small as possible. The surface as a big influence on how well the locomotion is executed.

LOOKS

Since a turtle has a shell it can hide its battery in there and move around untethered. The shell can have a number of interesting patterns and the ratio between the head and the shell can create the difference between a realistic and a cute turtle. The silver trace will not be much different from the curved Hshape and exist in the same horizontal plane.

CHALLENGES

There were a lot of variables that need to be played with to create locomotion. Which variables are the most important were unclear and needed to be tested.

ADVANTAGES

The link between a slow repeating motion and a turtle is made by the curious audience. The shell can give both shelter to a battery and opens up a lot of possibilities for interesting designs.

CONCLUSION

No locomotion had been observed but this concept had a lot of potential to create an interesting design especially in the shell.
The shell can also potentially harbor a small battery.

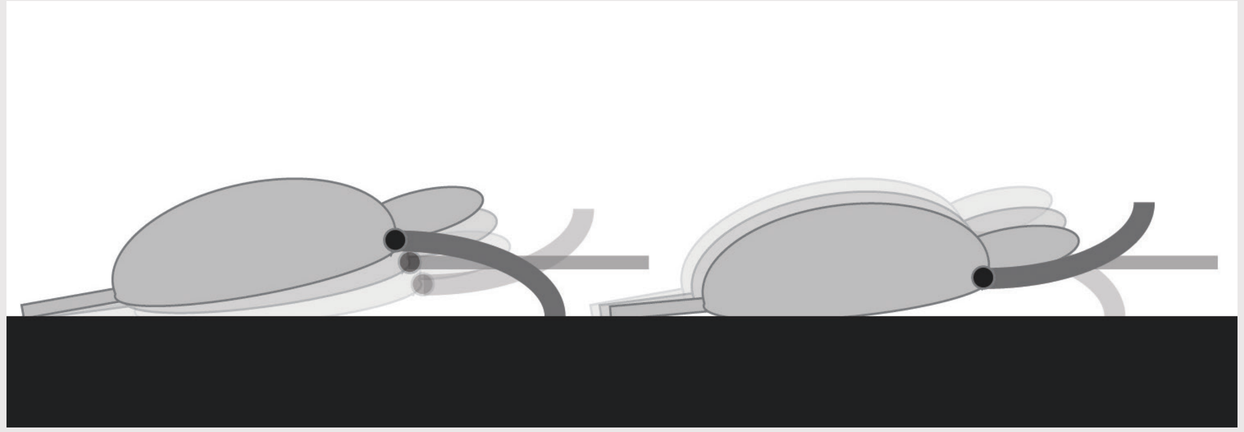


Figure 70 Locomotion principle of concept turtle

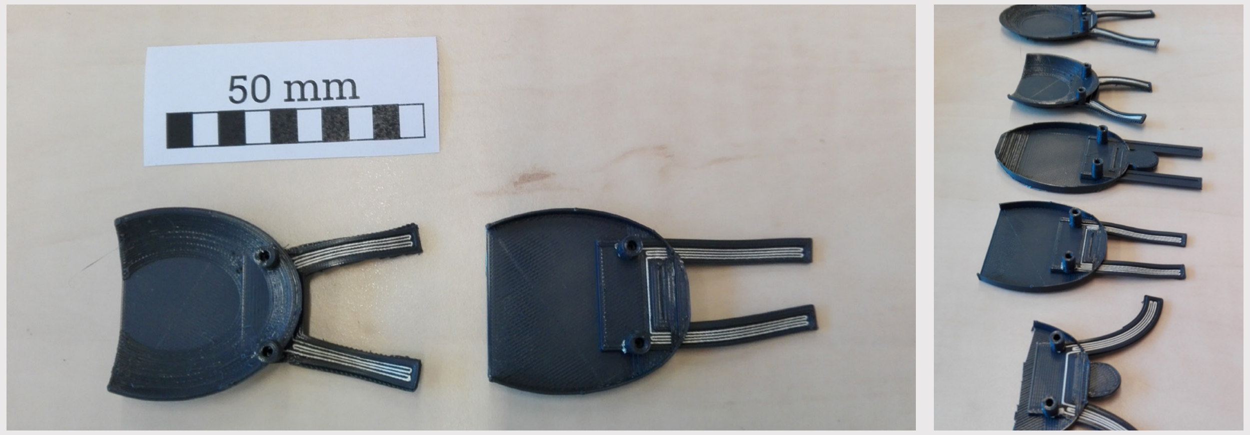


Figure 71 Different iterations of Turtle

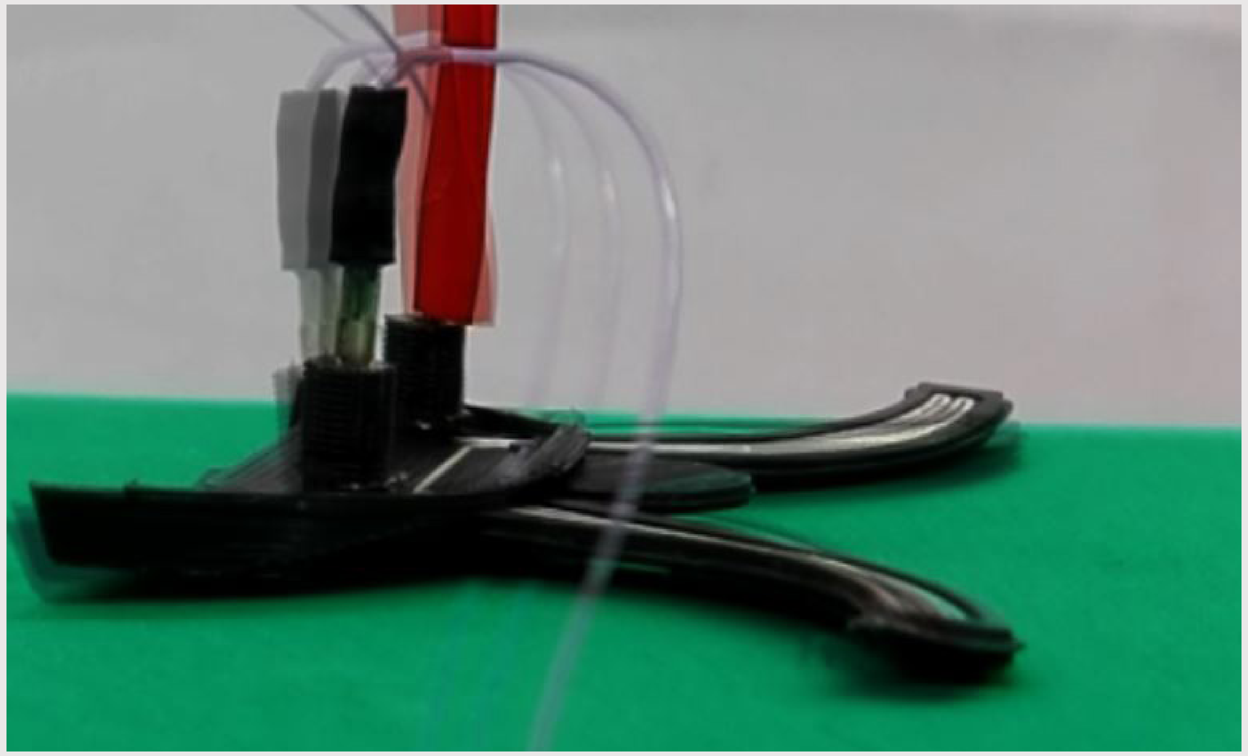


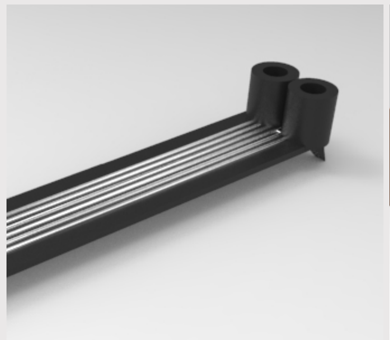
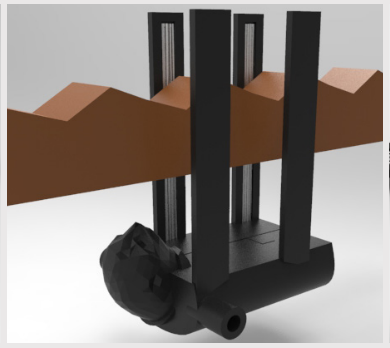
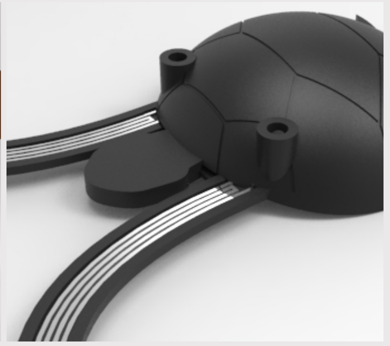
Figure 72 An iteration of Turtle in motion

Concept choice

The next step in the process is to select one concept to continue with. To help select a concept it is common practice to look back at the wishes that have been created at the start of the ideation process. The wishes have been ordered on importance.

WISHES

1. The demonstrator carries its own battery
2. A user can operate the demonstrator without instructions
3. The demonstrator does not need any post-processing
4. The demonstrator is printed in a single print
5. No electronic components should be used to operate the demonstrator

	Inchworm	Sloth	Turtle
1	The inchworm will not carry a battery since it's entire body needs to be flexible	The sloth can carry a battery in it's body	The turtle can carry a battery in it's shell
2	Yes, this is plug and play	The sloth needs it's actuators to be overheated once to create enough curvature to grip onto the branch. It also needs the legs to be actuated in pairs.	Yes, this is plug and play
3	Some support needs to be removed	The two halves need to be attached together and support needs to be removed	Some support needs to be removed
4	Yes, it has a single actuator	The two parts can fit on a single build plate	Yes, the actuators are printed in one go
5	Other than an oscillating power source, it does not need any	The pairs need to be activated independently, this will take extra components	Other than an oscillating power source, it does not need any

The sloth clearly does not meet the wishes, as well as the Inchworm and Turtle, do. When looking at the Inchworm and Turtle they have a lot of similarities except the carrying of the battery, the most important wish. So even though the Turtle has not shown any locomotion it has the most potential to have an exciting design and carry its own battery.

The concept that will be made into the 3D printed demonstrator for this project is the Turtle.

Conclusion

The final goal of the project is to create a 3D printed demonstrator. To do this first a list of requirements, limitations and restrictions were created.

Using input from the card set, characteristics in nature and random words multiple ideas were generated.

With these ideas, three different concepts were created. Inchworm, Sloth, and Turtle.

Inchworm has a simple design, similar to robots that other research groups created and is the only concept that showed locomotion.

Sloth consists out of two parts that need to be connected together. It moves over a specially designed branch. Compared to the other concepts it showed the most design challenges.

Turtle will only use it's front two legs to move. The shell has the potential to hide a battery and interesting designs possibilities.

When the concepts are compared based on their wishes the Inchworm and the Turtle are quite similar but the turtle can carry it's own battery and has the most design potential.

The concept Turtle will be used to create a 3D printed demonstrator.

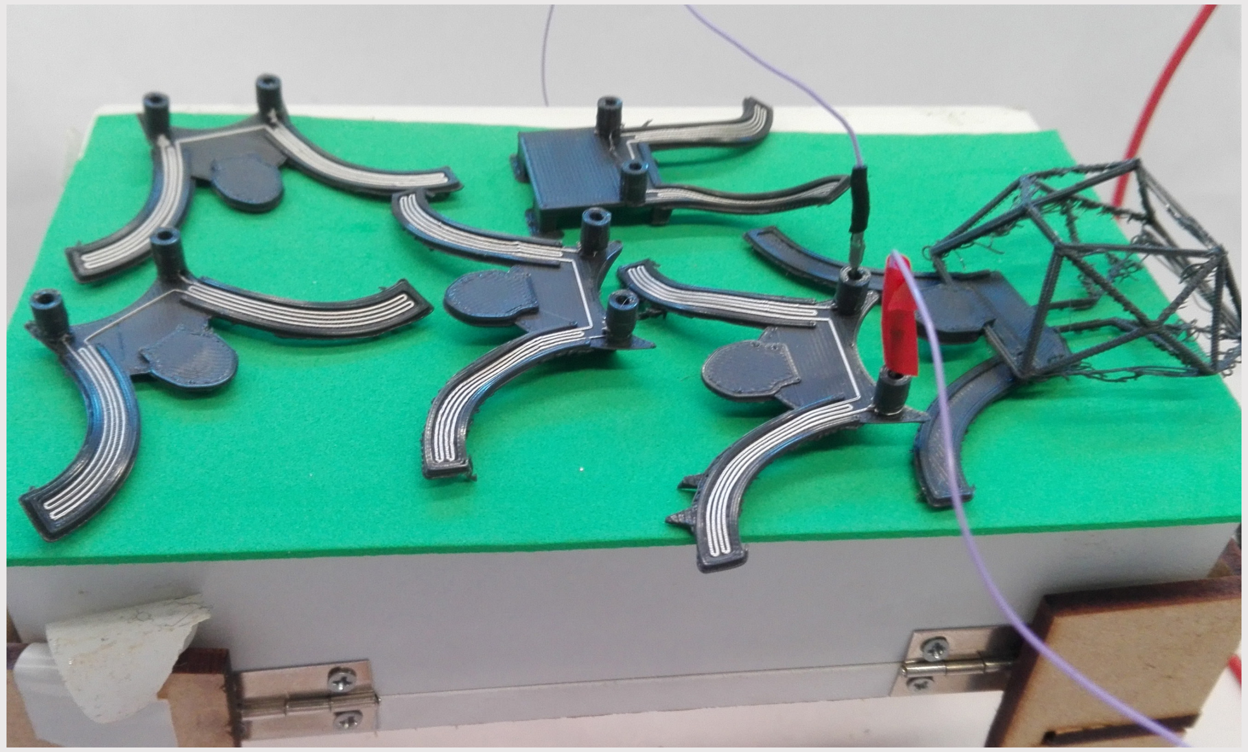
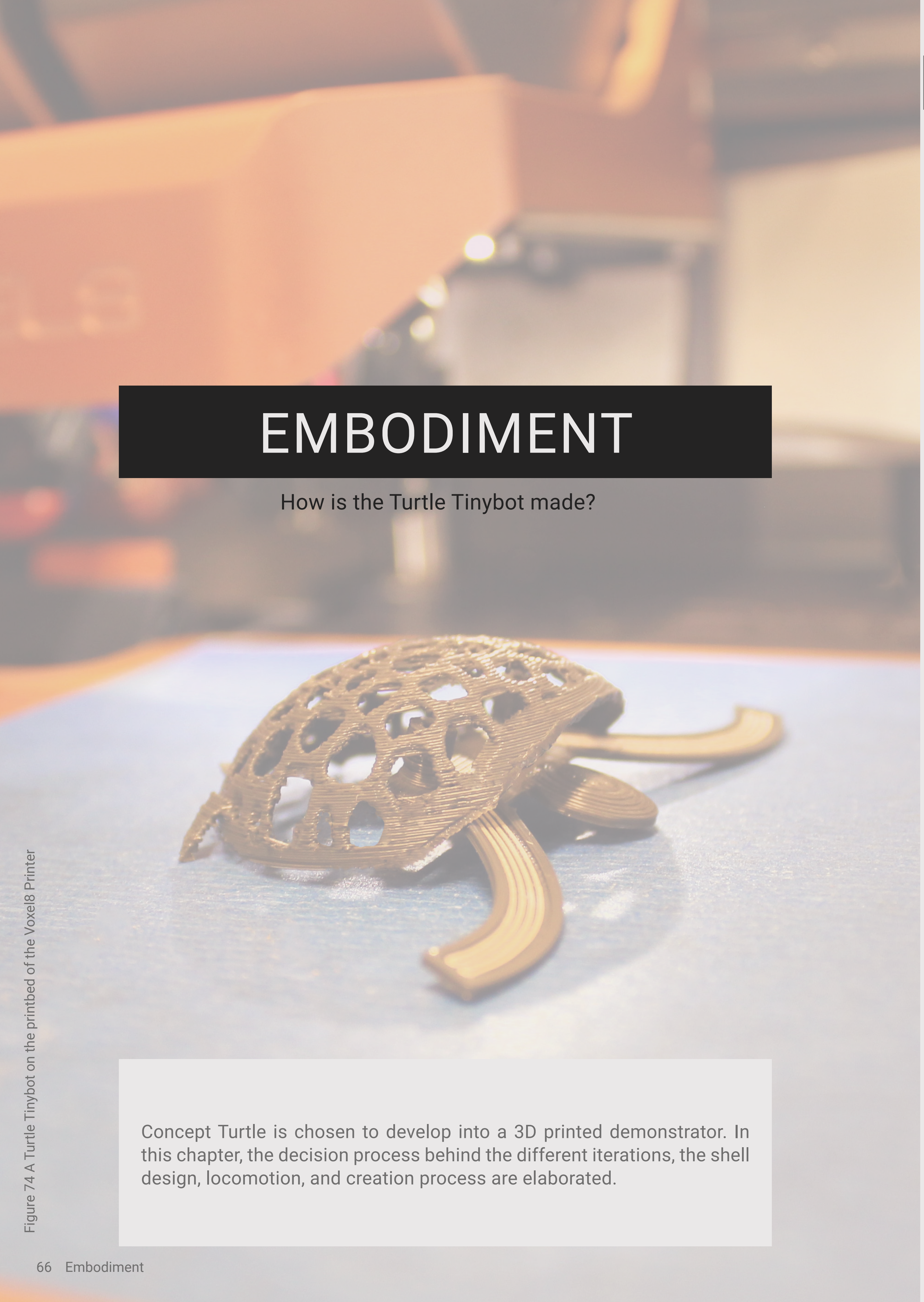


Figure 73 Different iterations of Turtle



EMBODIMENT

How is the Turtle Tinybot made?

Concept Turtle is chosen to develop into a 3D printed demonstrator. In this chapter, the decision process behind the different iterations, the shell design, locomotion, and creation process are elaborated.

Figure 74 A Turtle Tinybot on the printbed of the Voxel8 Printer

Iteration variables

At the start of this phase, both motion and a large displacement were observed. This motion did not yet result in locomotion. For the iteration process, the shell and hind legs were kept out of the designs process, since they had no direct connection to locomotion other than their weight. Figure 75 shows a general shape that was used as a basis for the different iterations.

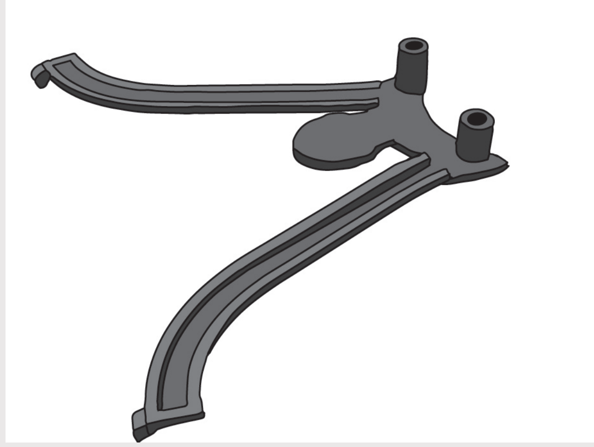


Figure 75 The active part of the body has the most variables that can be influenced

To achieve locomotion different variables were determined and examined. The different iterations can be found in these categories. The categories that will be mentioned are; Hooks, Arms, Body, Floor, and Power.

Hooks

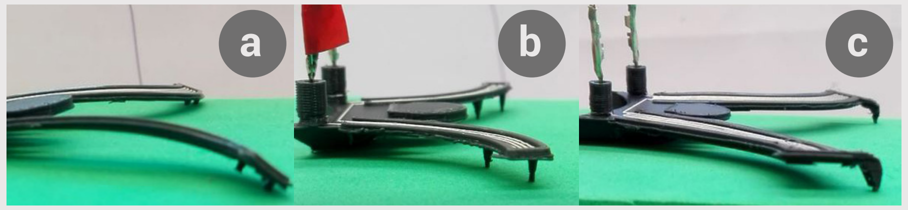


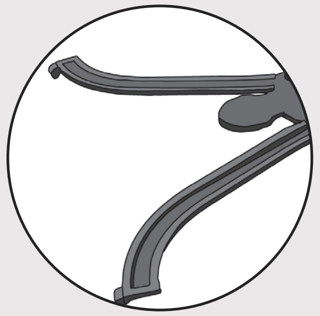
Figure 76 Bumps (a), Spikes (b) and Hooks (c)

To improve grip on the floor different kind hooks were added to improve the grip on the floor. The smaller the hooks were, the harder they were to print. A steep angle also posed a challenge for the printer.

First bumps were added at the end of the legs since there is where the legs touch the ground first. The idea was that these bumps would provide extra grip to pull the body forward. The bumps did not provide the desired grip and slid over the floor.

The sturdy spikes and hooks were easier to print than angled bumps. The sturdiness added weight to the legs, but not so much that the legs failed to lift. The biggest difference was observed during cooling down. When the warm and soft actuators cooled down they drooped on the side where no spike was. Since the spikes were placed at the end of the actuators they stopped the motion locally and influenced how the actuators cooled down, which was not uniform.

This variable did not have enough positive influence on the locomotion and has been left out of the consideration.



Arms

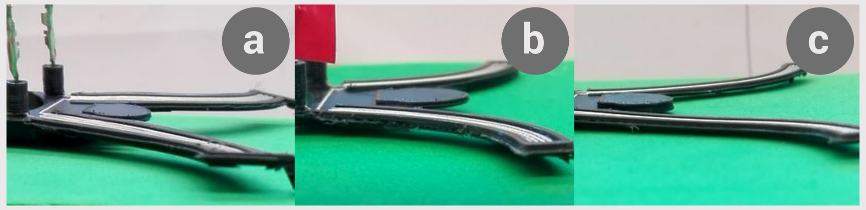


Figure 77 Broad (a), Short (b) and Long(c)

The arms are basically two long thin PTAs. PTAs have a number of design limitations. The length, width, angle, and height could still be experimented with.

Longer arms showed a lot more displacement. Broader arms needed more silver trace and higher power. Shorter arms ended up having more predictable behavior. If the angle between the arms increased the energy was put into forward motion instead of lifting up the body.

Iterating with the arms provided two very important insights; the importance of symmetry and the center of gravity.

During modeling, mistakes tend to slip in. When the model is asymmetrical the Voxel8 slicer software will plan the lines of plastic different for the different. This resulted not in the expected behavior (“Asymmetry” on page 82). Asymmetry was avoided as much as possible.

The other observation was that the center of gravity moved forward with long arms. When the arms move up the body could fall over. This resulted in the legs touching the cold floor during cooling down. This resulted in irregular cooling down and an unpredictable cold state.

Body

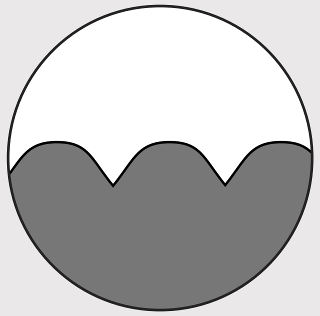
Figure 78 Thin and imbalanced (a), Broad and thin (b) and braced under an angle(c)

In modeling the body a balance needed to be found between the weight of the body, the number of contact points and the angle with the floor.

There have been iterations with a complete shell, half a shell, and the bottom of the shell. All these designs had relatively more weight and large contact points with the floor. The most convenient body had just two walls that ended up on a plateau for the silver trace to rest on. The walls were rounded in a way that the sample could fall forward.

An observation was made that if the sample had long arms the sample would not just fall forward but also to the sides since the walls were placed close to each other. With a very broad and thin base, the sample would no longer fall sideways.

The most important iteration to reach locomotion was to place the legs at an angle. Since the PTA cannot be printed at an angle, two small braces were created where the PTA could be slid and glued in. This angle change resulted in real and measurable locomotion.



Floor

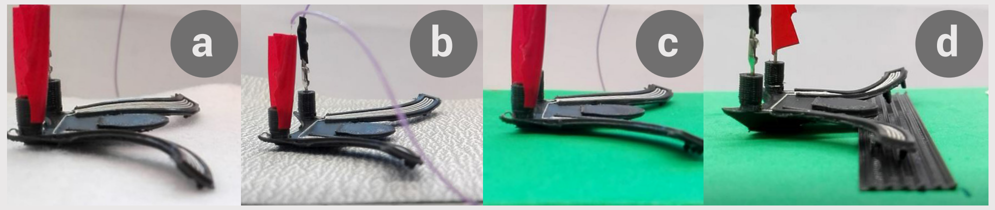


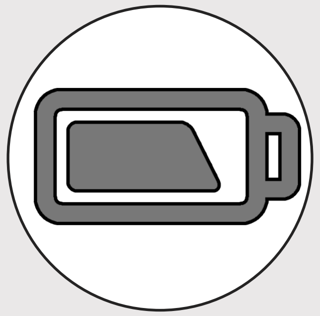
Figure 79 White Felt (a), Sandpaper (b), Green foam (c) and Barbed floor (d)

To achieve locomotion, resistance needs to be created. Preferably resistance in one way and not in another way. If the resistance is too high the PTA cannot deliver enough power to pull the body forward. If the resistance is too low the arms have not enough grip.

White felt had loose hooks and strings. Irregularities in the print resulted in the print getting stuck in the knots and not moving even being able to lift the arms from the floor.

Sandpaper and green foam showed similar qualities. Sandpaper has a rough surface and provided grip for the arms but also resistance with the body. The green foam does not have a rough but a soft surface. This meant that the small weight of the turtle would create an indentation which provided a little resistance. Interesting to note is that the green foam did not react well to heat so should be recycled if a sample overheats.

Barbs provide resistance in one way but not in the other way. With 3D printing, barbed strips were created. These were not successful because they were too high and needed the turtle to move in perfect straight line which is hard to achieve.



Power

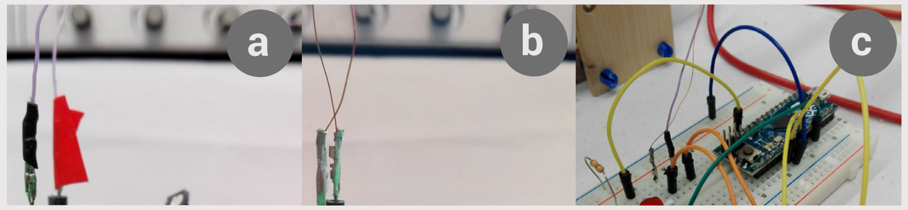


Figure 80 Purple wires (a), Thinner wires (b) and Switch circuit (c)

The connection to the power source was placed on top of the body to reduce the influence of the wires on the motion.

The purple wires that were used were one of the thinnest wires available but they still tended to have a mind of their own. Even these thin wires will have a little shape memory. The samples weigh about 2 grams which is too little to create a new shape memory.

Thinner copper wires replaced the purple wires. These wires influence the locomotion less. When choosing wires it is important to realize that thinner wires will also create more resistance than thicker wires. After trial and error, the correct power for the PTAs in this configuration is 2.8 Volt and 1.3 Ampere.

Oscillation in the legs is created by turning the power on and off every 60 seconds. For a long time, this oscillation was done by turning the Lab Power Supply on and off. To reach more accurate results (and relieve the student) a micro-controller and relay were added to the circuit. More about this circuit can be found in “Appendix 7” on page 97.

Locomotion

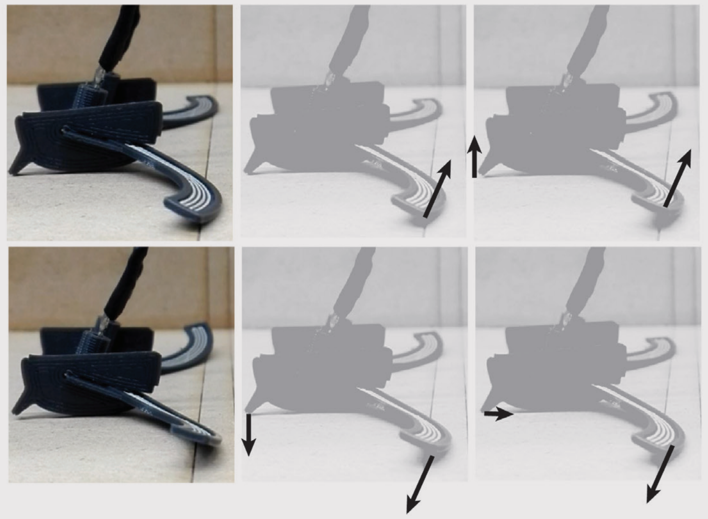


Figure 81 A single cycle of locomotion

A PTA exerts forces up and down since it bends up and down. By placing the PTA under an angle the vertical forces are rotated and can perform horizontal force.

In Figure 81 a single cycle of motion is pictured including the way that this Tinybot moves. First the arms will move up, because of the curve in the body of the Tinybot, the center of gravity and the tinybot will fall forward lifting the hind leg. When power is removed the arms will move down. This will push the hind leg back to the ground and these two hind legs become the only contact point to the ground. When the arms finish their movement they push the tinybot a little forward and the hind legs slide along. When power is returned this process repeats.

Creation

The creation of the Turtle Tinybot is quite straightforward. It is in the end a robot from a 3D printer. The process can be broken down into 12 steps (page 71).

STEP 1 This is the hardest, this is creating the actual model. In this case, the model is created in Rhinosceros 5.0 and required a lot of trial and error to create.

STEP 2 Two separate models are imported in the Voxel8 slicing software.

STEP 3 Turn off Dynamic slice height, make the brim 1, Plastic infill density is 1, and Silver Base Pressure is 16.

STEP 4 Try to spot errors in the print preview before printing the model

STEP 5 If this is the first print of the day, unclog the silver nozzle by printing a silver align.

STEP 6 After making sure the print bed is clear select the model to print.

STEP 7 Try to stay around when the silver trace is printed to make sure it is closed.

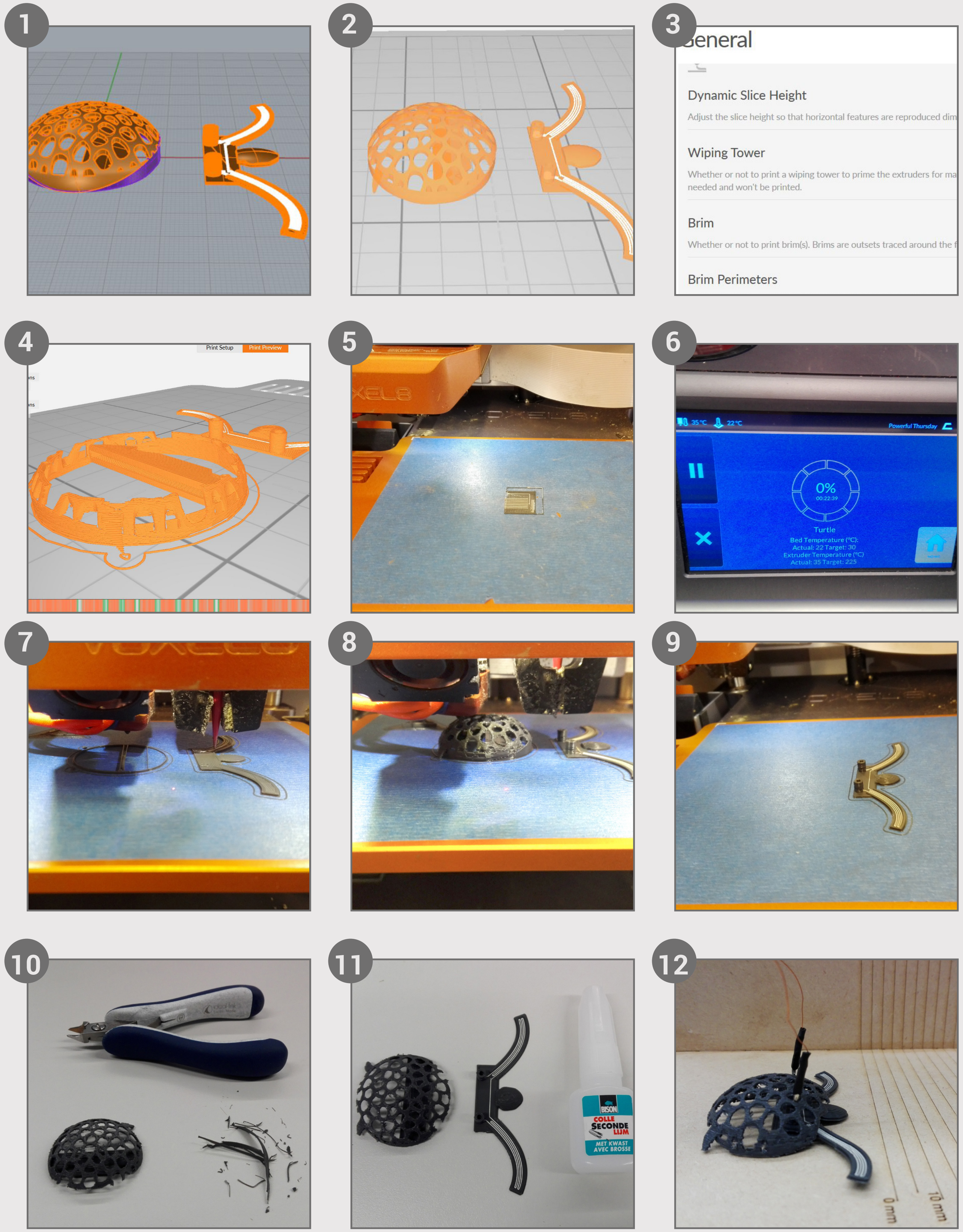
STEP 8 Wait until the print is finished.

STEP 9 Remove the shell but give the silver enough time to cure in a ventilated space.

STEP 10 Use pliers to remove the support from the shell.

STEP 11 Slide the arms into the shell and use instant glue to connect them together.

STEP 12 Connect the Turtle Tinybot to the circuit and watch it move slowly...



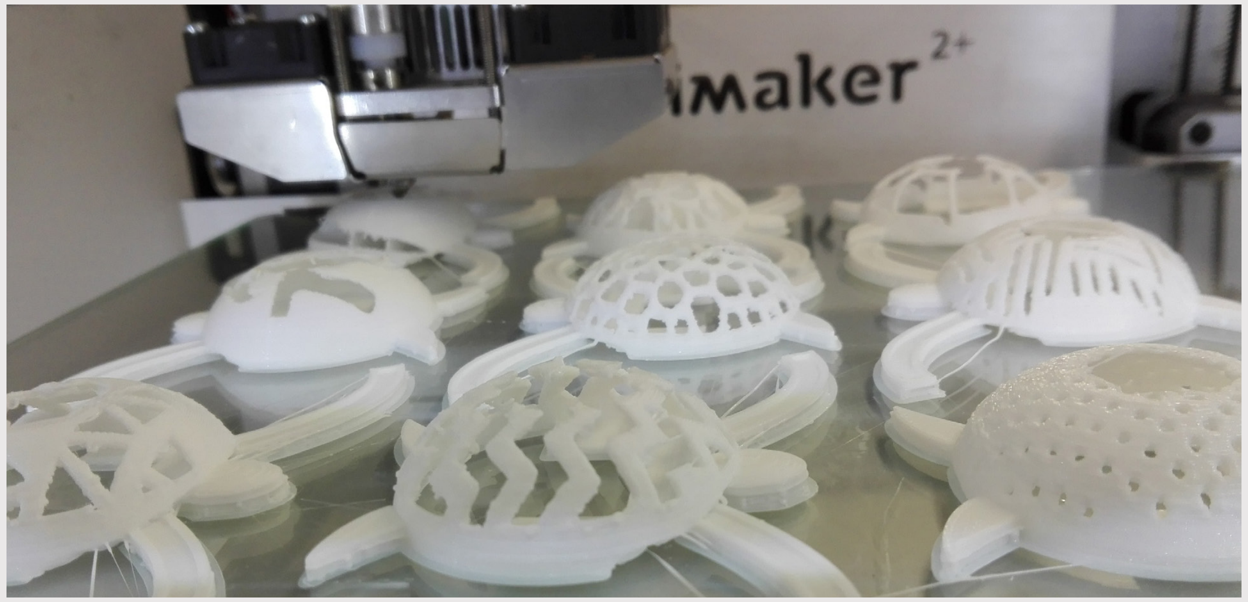


Figure 82 Different iterations being printed on an Ultimaker 2 with setting similar to the Voxel8

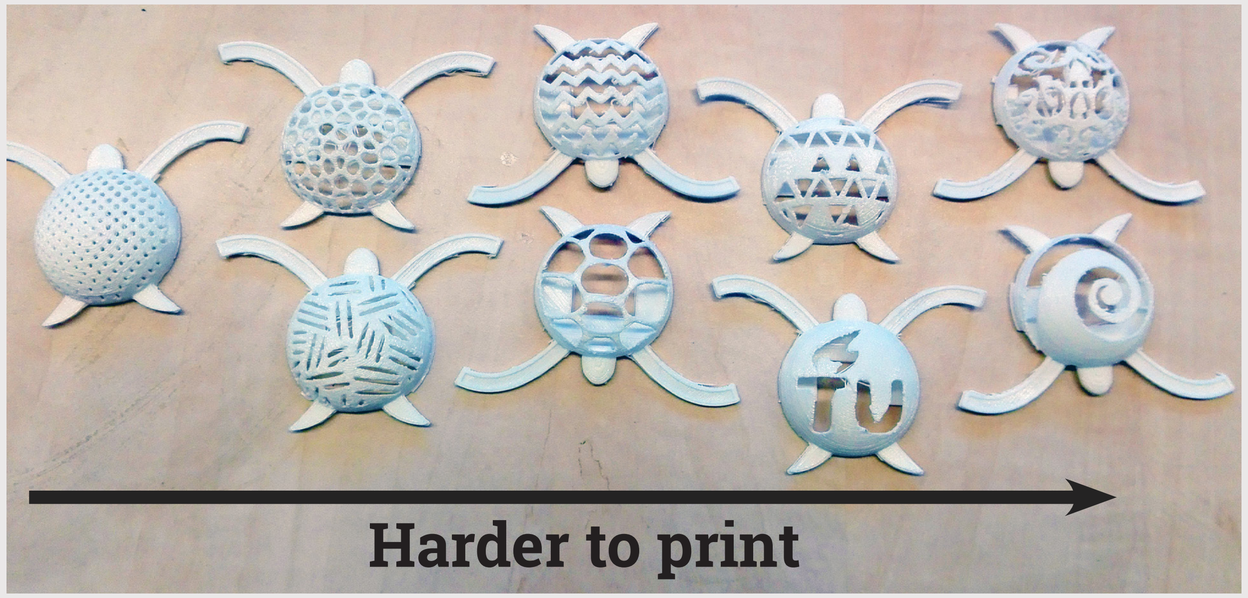


Figure 83 Different iterations placed in order from easy to hard to print

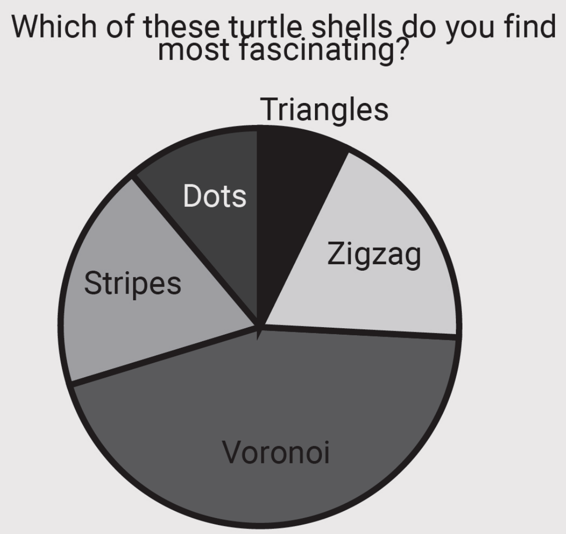


Figure 84 Result of a survey completed by 26 participants

Aesthetics

The Turtle Tinybot has a passive part consisting out of the shell, head, and hind legs.

The shell has five important functions.
1. Make the Turtle Tinybot look exciting
2. Facilitate wiring
3. House/Hide battery
4. Place active part under an angle
5. Minimize contact points

In designing the shell a balance needed to be found between low weight and easy to print. A completely closed shell like in Figure 85 does not need any support and will result in successful prints every time. But this shell uses more material which would add extra weight. This shell will need at least two holes to facilitate wires being placed to connect the active part to the power source.

Nine different designs were generated and printed on an Ultimaker 2 (Figure 82). Since the Ultimaker 2 uses a different slicer software (Cura) than the Voxel8 printer (Euclid) the settings were copied as closely as possible.

Just by printing the different designs interesting insights were gathered (Figure 83). The swirl and tribal shells needed extra support placed in the model to print. This support was very hard to remove and the models still did not turn out as beautiful as expected. Because of this, these iterations were kept out of consideration. Organic patterns were easier to print in than geometrical patterns.

Since the Turtle Demonstrator needs to trigger fascination in a curious audience, a curious audience was asked for their opinion. An audience was exposed to the different iterations in two ways. The first audience consisted out of visitors of the Applied Labs. The iterations were displayed in a dominant place next to a common walkway for students, teachers, friends of other visitors. If they stopped, triggered by their curiosity, the student would ask which of the iterations they perceived to be the most beautiful without

Figure 85 The battery that needs to fit inside the shell of the Turtle Tinybot

giving an explanation. This would trigger a qualitative conversation.

On the other hand, a quick survey was distributed under a handful of Industrial Design Master students. The survey (hosted by surveylegend.com) consisted out of two simple questions;
1. Which of these turtle shells do you find most fascinating?
2. How exciting do you find the previously mentioned designs?
The results of these survey can be found in Figure 84 and “Appendix 8” on page 98.

With the qualitative and quantitative results, the pattern that was chosen to continue with was voronoi. This pattern is relatively easy to print, leaves enough holes for wires to be connected and was received positively by the curious audience.

To make sure that the Turtle Tinybot would be recognized as a turtle hind legs, a tail and a head were added. As an added benefit the hind legs can be used as the spike that provides resistance one way but not the other way.

The final design can be found in Figure 86 on page 74 and in “Appendix 8” on page 98.

Figure 86 The Turtle Tinybot on the runway

Improvements

Perfection is in the details. If there is more time, adjustments can still be made to make this Turtle Demonstrator an even better demonstrator for PTAs.

PROPORTION TWEAKS

Since a new iteration can be created quickly with the 3D printer it is possible to make small adjustments to the model and test them to improve locomotion. Think about a small size change or change in the angle of the PTA arms. This way the ideal proportions can be found.

SNAP-FIT

The active and passive parts are now glued together. A more elegant solution would be a snap-fit. This should be modeled in both the shell and the active part. If this is done correctly the active part can be replaced if it breaks, fails or ages. The tricky thing is that this connection can not have any support.

STRAIGHT WALKING

At the publication of this report, there has not been a sample that walks straight forward. This has probably to do with the shape memory of the wires. A video of a Turtle Tinybot that walks in a straight line would change the focus from the discussion from; “Why is it walking this weirdly” to “How does it do this?”

PORTABILITY

The set-up is currently connected to a Lab Power Source. A portable set-up would make it easier for this demonstrator to reach more people. This could be done by integrating a battery and electronics in the shell of the Turtle Tinybot. A proposal on how this could be done can be found in “Portability” on page 78.

Conclusion

Concept Turtle was chosen to be developed into a PTA demonstrator. The Turtle Tinybot has a lot of variables that could be altered and have a potential to improve locomotion.

Placing the active part under an angle proved to be the best method to create locomotion. Together with a rough floor and an Arduino controlled power supply.

The creation process of the Turtle Tinybot is considered to be relatively simple and it deserves its name a robot out of a 3D Printer.

The pattern on the shell of the Turtle Tinybot has been carefully selected since the shell has several functions at once. The shell ended up having a voronoi pattern, two hind legs, and a tail.

EVALUATION

What needs to be improved?

Valuable insights have been collected about the different qualities and functions of PTAs. But there is still much more to learn. In this chapter, some recommendations for future research are mentioned. In this chapter ,you can also find a personal reflection of the graduating student and a plan to make a portable test set-up.

Reflection

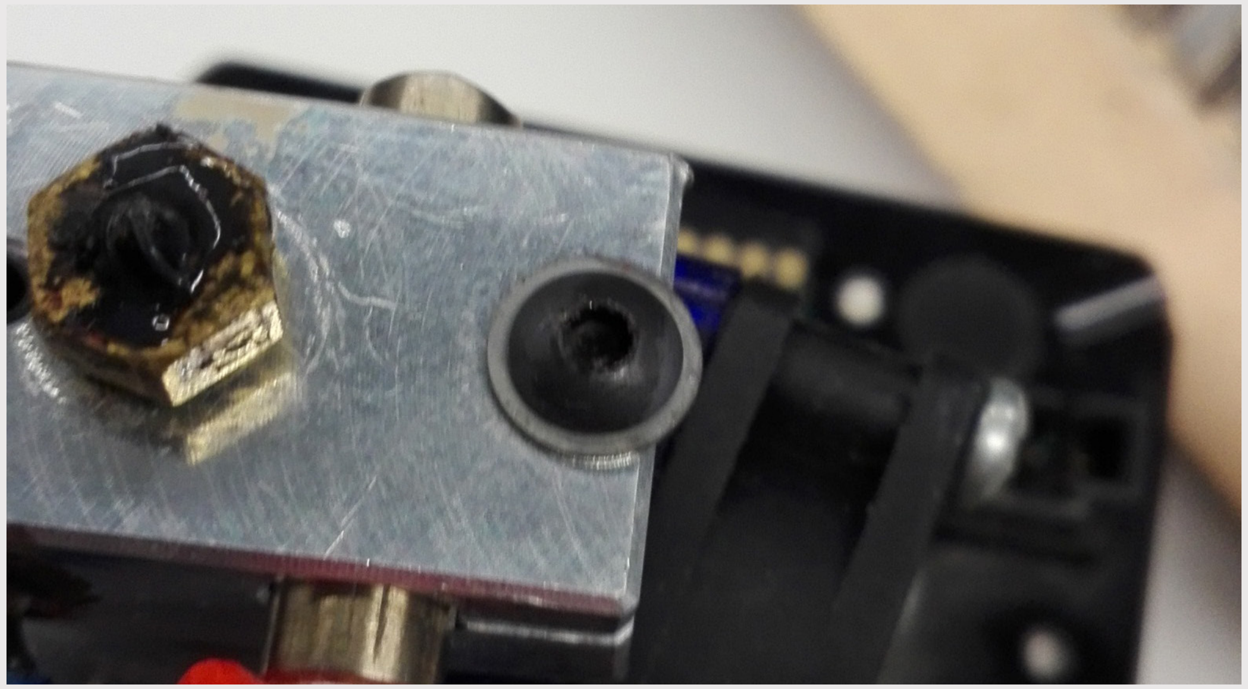


Figure 87 The nozzle of the hot end needed to be cleaned and unclogged

I am very grateful and fortunate to find a project that fit so well with both my interests and my skill set. In this project, I had the chance to work with 3D printers, modeling software, and electronics.

My modeling skills in Rhino 5 and FDM printer problem-solving skills have improved tremendously. Skills that I will definitely want to use in my career.

I'm very satisfied with the creative process in this project. The three-week hibernation of the Voxel8 printer came at a perfect moment and aided the creative process. It was both a blessing and a curse.

If I would redo the project I would do four things differently. First I would make sure that the test set-up and the procedure of doing tests were more scientific and professional from the start instead of messing around over time which makes it harder to compare the results.

Ask more. I lost a lot of time finding the correct variable to create locomotion of the Turtle Tinybot. If I would have asked more people sooner to provide input I wouldn't have lost this time and could have used it for something else.

I would take more time to experiment with different designs. I would look at different ratios of the body to the head and would try completely different turtle models.

Finally, I would have tried different materials to print with. A fear of getting bad results with other materials prevented a chance of finding a plastic that might enhance the performance of the PTAs.

Overall I believe that I have done my best with the time that I have given myself and I am proud of the result.

Portability

Right now the set-up for testing and demonstrating the PTAs and Tinybots is stationary in a selected spot in the Applied Labs at the Delft University of Technology. This is mainly because of the heavy Lab Power Supply.

Especially since PTAs need so little power the set-up could become portable if a battery is embedded. A smaller battery means that it will run out of power faster but since the Turtle Tinybot only needs to walk for 15 minutes the smallest battery will be sufficient.

A small battery has been selected Lithium Ion Polymer Battery (3.7v 100mAh). The voltage supplied by this battery is too high. When the battery is connected directly to the Turtle Tinybot smoke will be generated and the PTA will melt. To prevent this a voltage divider needs to be added. As shown by the calculations done in figure Figure 90, the resistance does not need to be very high but it needs to be able to endure some heat. For this reason, a potentiometer on it's lowest position is selected as a voltage divider.

This set-up has not been tested yet so it is not guaranteed to work.

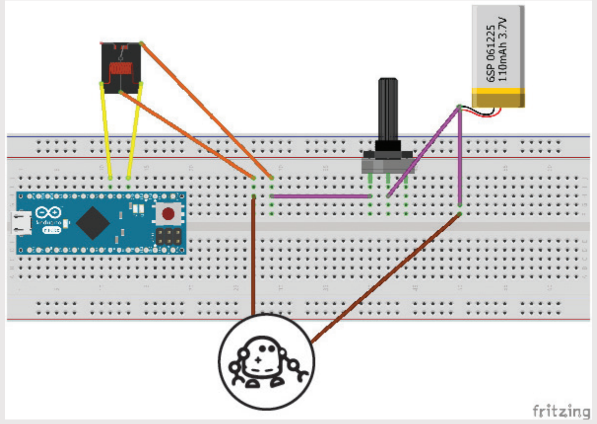


Figure 88 The circuit that could be used to make the set-up portable

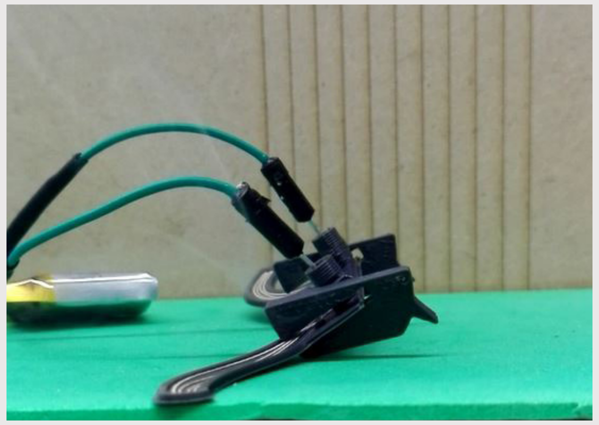


Figure 89 Smoke is being generated when a fully charged battery is directly connected.

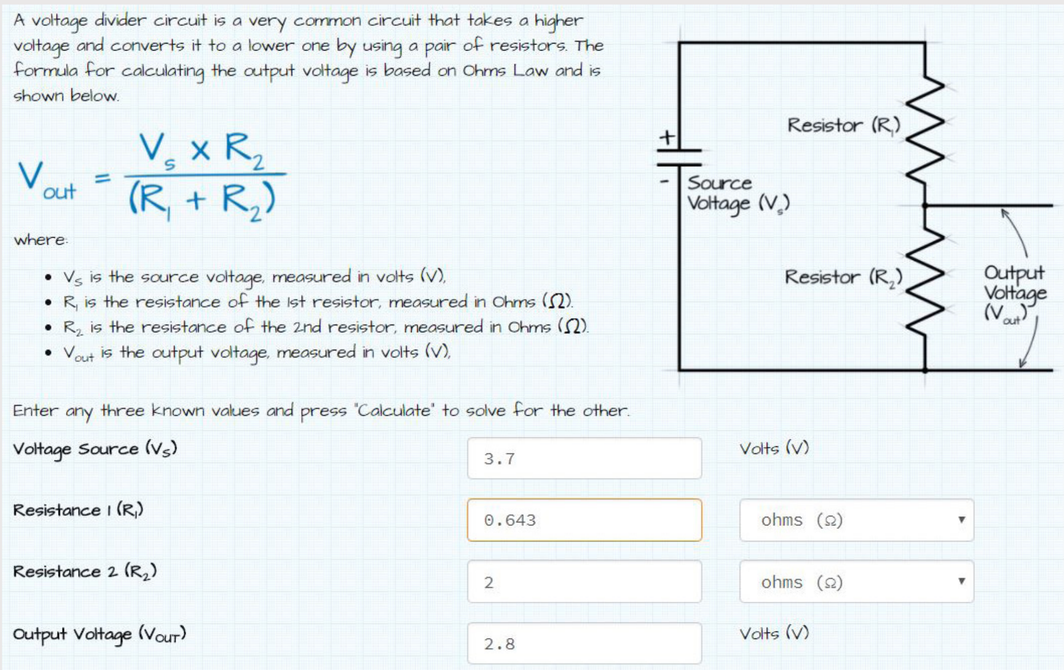


Figure 90 www.ohmslawcalculator.com/voltage-divider-calculator was used to calculate how much resistance the voltage divider needs to have

Recommendations

Extreme deformation

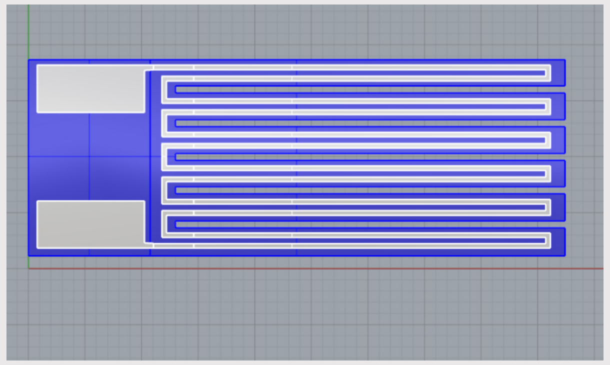


Figure 91 A sample with five fingers. The fingers have the following dimensions 2.5 mm x 0.8 mm x 34 mm

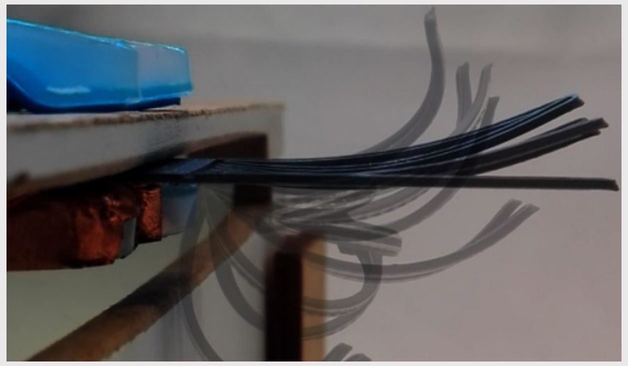


Figure 92 Even with this extreme deformation the circuit stayed closed. The sample was not able to repeat it's motion

This sample with thin fingers performed extreme deformation. After a power was applied the fingers curled up in the same direction independently from each other. This behavior ended up not repeatable and the sample remained in the extremely deformed state.

This behavior is not desirable when making an actuator because an actuator needs to repeat it's behavior. But there are some other interesting uses that can benefit from this behavior and need to be explored.

This print can, for example, be transported in a flat state and can assemble itself when it reaches it's destination once a little power is applied.

The Voxel8 only needs about 20 minutes to create this print and the power applied to the sample is 3.5V and 1.2 Ampere.

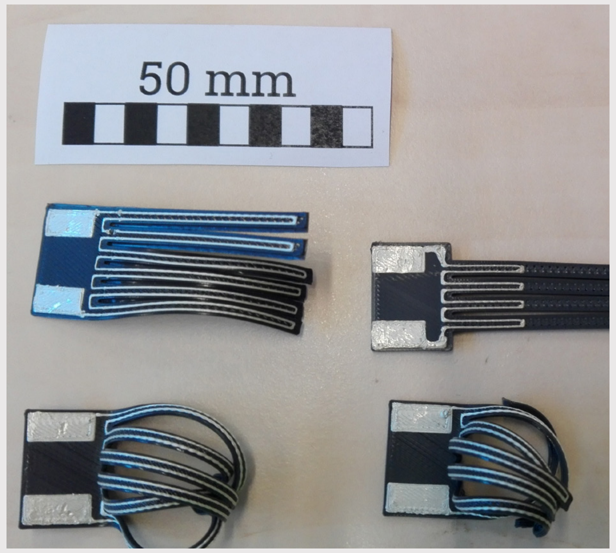


Figure 93 Samples that were used to create extreme deformation. They stayed deformed in their cold state.

Heated Rim

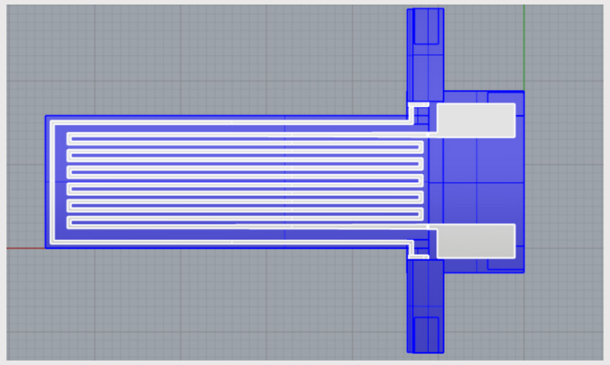


Figure 94 A sample with two separate circuits, one on the base and one on the rim

Figure 95 A sample with a heated rim can move up and down. The deflection is however little

The rim is an essential part of the actuator. Before the transition, the rim makes sure that the actuator returns to a flat state. After the transition, the stress in the rim will cause the displacement of the PTA even though the base is relaxed. During this process the rim remains cold.

When the PTA is altered and the rim is heated new behavior is observed. A heated rim makes the PTA move up when it is expected to move down. But the displacement is only little.

Heating and cooling the rim can be done multiple times in an attempt to move the flat state up or down from a level state. When this trick is repeated multiple times the flat state can be moved little by little like a ratchet. This behavior needs a systematic and scientific approach to observe.

This behavior can be used to expand the possibilities for robotic actuation even more.

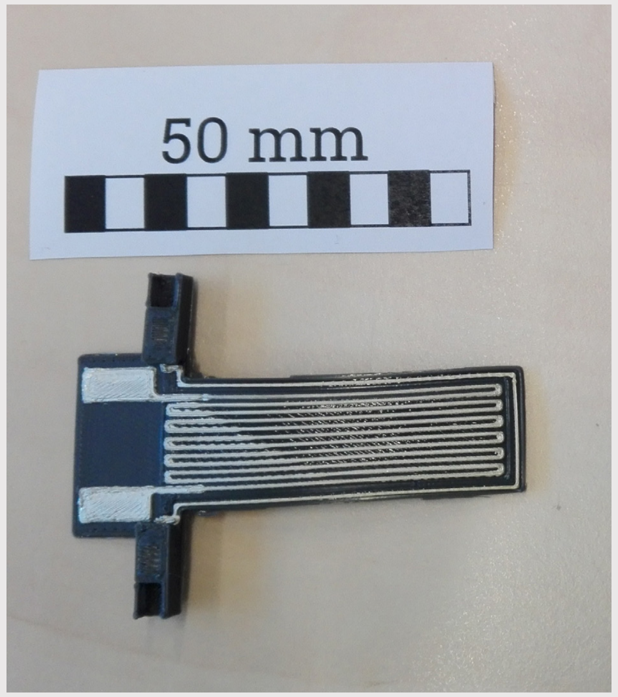


Figure 96 A sample with a heated rim can move up and down. The deflection is however little

Torsion

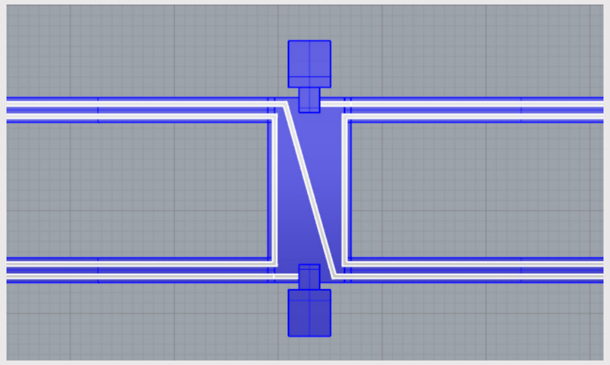


Figure 97 A sample that has performed torsion which was not it's intended motion

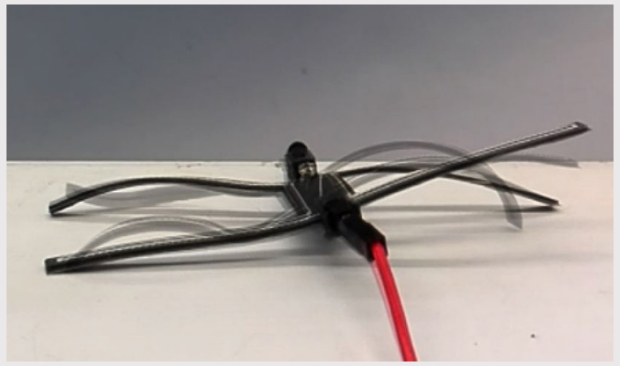


Figure 98 The sample performing torsion

Almost all of the displacements observed with the tested PTAs were up and down. The sample in Figure 98, however, showed legs that turned on their own axis and stayed this way after cooling down. Some iterations of the Turtle Tinybot also showed a little torsion when large hooks were placed at the ends of the arms but not as much as this sample.

In Figure 99 samples can be found that were attempts to recreate this torsional behavior. They did not perform any behavior other than moving up and down. The left sample can be heated completely or just partly. This sample moved up and down like any other PTA. The right sample had a silver trace that was placed on one side of the PTA. At the end of the PTA a little weight was added to have gravity help with the torsional behavior. This sample also moved just up and down.

A lot of robots use torsional energy to perform locomotion. If PTAs can perform torsional behavior a new range of locomotion can be explored.

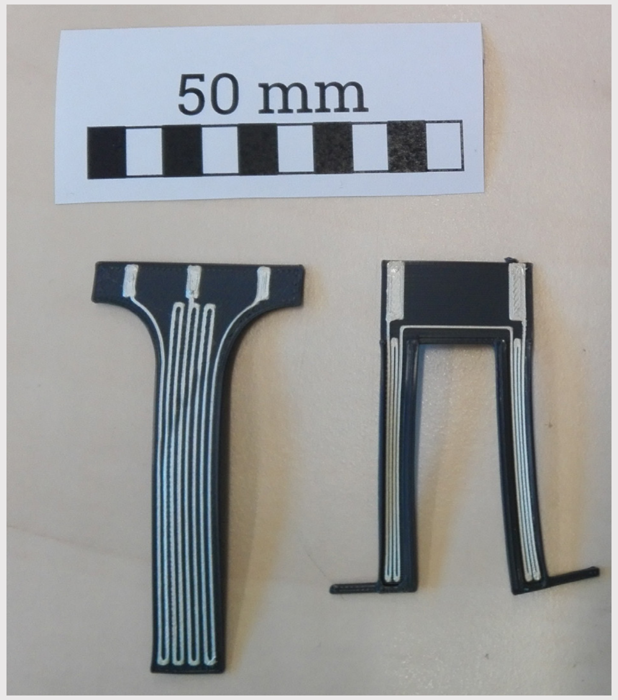


Figure 99 Samples that were created in an attempt to create torsion. They were unsuccessful.

Asymmetry

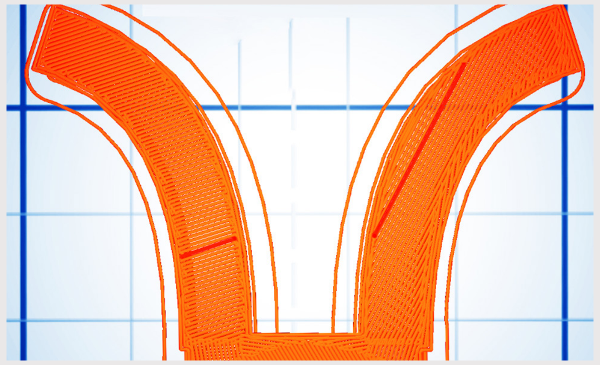


Figure 100 The slicer determined different ways to travel to create these two legs resulting in asymmetric behavior

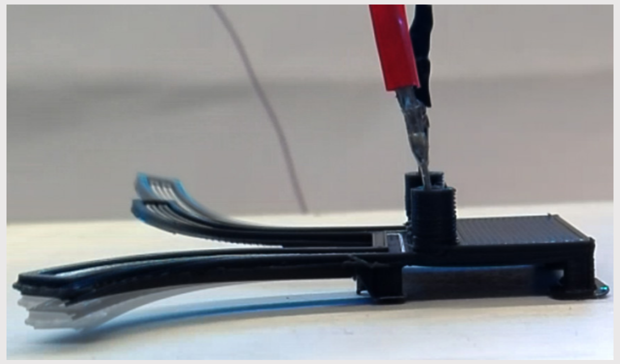


Figure 101 A sample that has his legs move in a different direction once it is activated.

The slicer software of the Voxel8 (Euclid) calculates the best way to lay down lines of plastic inside the model that it has been given. The direction in which these lines are laid down have shown to have a large influence on the behavior of the PTA.

When more than two PTAs are printed in a single print it is important to check that the model is symmetric. The sample Figure 101 has two legs that have been printed in a different way. When a power is applied these legs would behave differently independent from each other.

At first, this behavior was wrongly blamed on incorrectly removing the support that was used to print the PTA. The PTA remained to perform this asymmetric behavior even after the support was removed correctly and the arms were forced into the desired position in the hot state. The model was inspected closer and asymmetry were discovered. After restoring the symmetry the model would behave more predictably.

This behavior could be used on intentionally to control two PTAs with a different function at the same time. If studied more closely, this behavior could be used to control concept sloth with a single circuit.

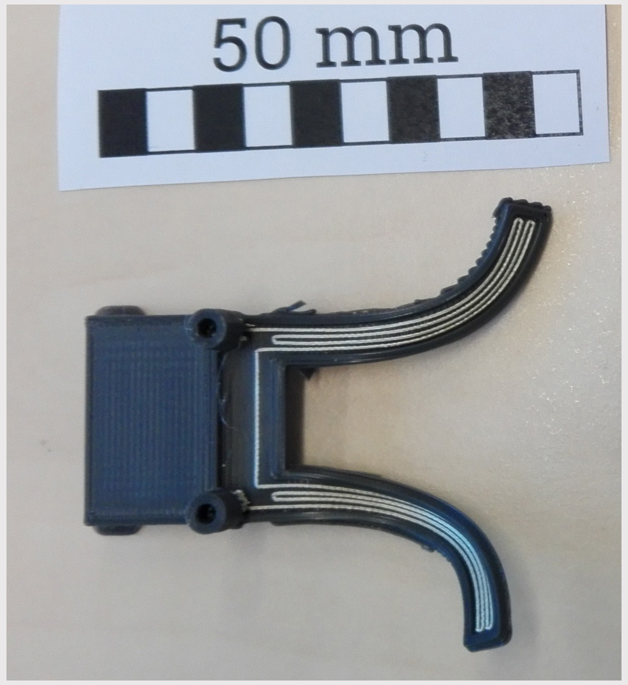


Figure 102 The sample that performed asymmetric behavior

Figure 103 These petals were printed in a different way and each reacted different to heat source they were exposed to

Modularity

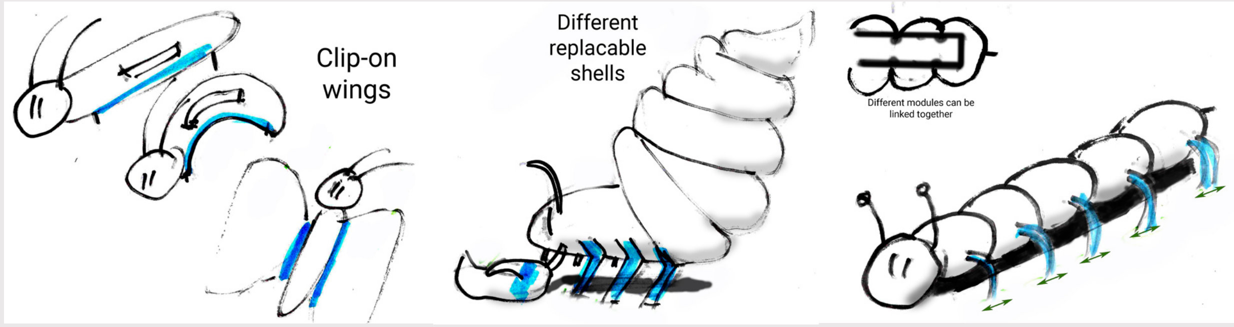


Figure 104 Generated ideas that fall in the category Modular

3D printing gives a lot of form freedom. When PTAs break they are easily replaced and when a user wants a different shape or size they can be helped within a day.

During the ideation phase, different ideas suggested connecting different models together making personalized solutions (Figure 104).

The parts that were added could even change the resistance inside the circuit prompting the model to change its behavior. Like a caterpillar getting moving its wings instead of its legs after they are attached.

Since the silver trace proved to be very fragile touching it was avoided as much as possible. Realizing these modularity ideas will involve parts touching and moving over the silver traces multiple times.

These ideas can still be realized but need extra research on their own to preserve these fragile silver traces.

Intrinsic oscillation

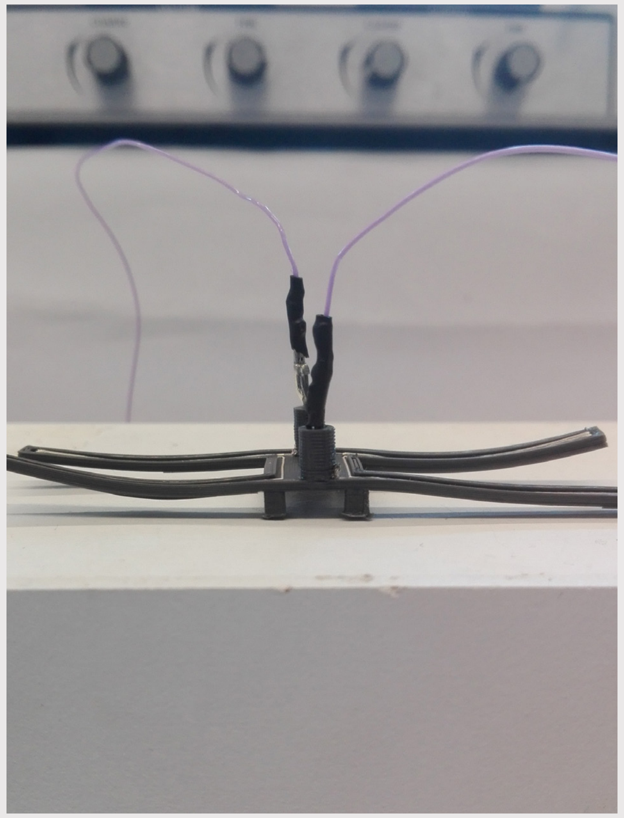


Figure 105 This sample showed intrinsic oscillation. When the sample would move it would break it's own circuit and restore it when cooling down

The final recommendation that can use a little attention is intrinsic oscillation. During the course of this project, the repeatable qualities of the PTA were highlighted. This repeatable behavior was reached by turning the power to the PTA on and off.

Some samples could reach this oscillation on their own. In these samples, the silver trace was cracked. Because of the displacement, the silver trace would disconnect and the PTA would cool down. When returning to the original position the parts of the silver trace would reconnect, closing the circuit again and restarting the motion.

If this behavior can be replicated successfully while maintaining large displacement the number of electronic components can be reduced which is super interesting. Ideally, a PTA tinybot would just need a battery.

REFERENCES

Choong, Y. Y., Maleksaeedi, S., Eng, H., Wei, J., & Su, P. (2017). 4D printing of high performance shape memory polymer using stereolithography. Materials & Design, 126, 219-225. doi:10.1016/j.matdes.2017.04.049

Firouzeh, A., Ozmaeian, M., Alasty, A., & Zad, A. I. (2012). An IPMC-made deformable-ring-like robot. Smart Materials and Structures, 21(6), 065011. doi:10.1088/0964-1726/21/6/065011

Hariri, H., Bernard, Y., & Razek, A. (2013). A traveling wave piezoelectric beam robot. Smart Materials and Structures, 23(2), 025013. doi:10.1088/0964-1726/23/2/025013

Henke, E. M., Schlatter, S., & Anderson, I. A. (2017). Soft Dielectric Elastomer Oscillators Driving Bioinspired Robots. Soft Robotics. doi:10.1089/soro.2017.0022

Ho, T., Choi, S., & Lee, S. (2007). Two types of quadruped robots: Bounding and walking. 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO). doi:10.1109/robio.2007.4522328

Hubbard, J. J., Fleming, M., Palmre, V., Pugal, D., Kim, K. J., & Leang, K. K. (2014). Monolithic IPMC Fins for Propulsion and Maneuvering in Bioinspired Underwater Robotics. IEEE Journal of Oceanic Engineering, 39(3), 540-551. doi:10.1109/joe.2013.2259318

Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design, 9(2), 35-54.

Ma, K. Y., Chirarattananon, P., Fuller, S. B., & Wood, R. J. (2013). Controlled Flight of a Biologically Inspired, Insect-Scale Robot. Science, 340(6132), 603-607. doi:10.1126/science.1231806

Maccurdy, R., Katzschmann, R., Kim, Y., & Rus, D. (2016). Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids. 2016 IEEE International Conference on Robotics and Automation (ICRA). doi:10.1109/icra.2016.7487576

Momeni, F., Hassani.n, S. M., Liu, X., & Ni, J. (2017). A review of 4D printing. Materials & Design, 122, 42-79. doi:10.1016/j.matdes.2017.02.068

Must, I., Kaasik, F., Põldsalu, I., Mihkels, L., Johanson, U., Punning, A., & Aabloo, A. (2014). Ionic and Capacitive Artificial Muscle for Biomimetic Soft Robotics. Advanced Engineering Materials, 17(1), 84-94. doi:10.1002/adem.201400246

Noselli, G., & Desimone, A. (2014). A robotic crawler exploiting directional frictional interactions: experiments, numerics and derivation of a reduced model. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 470(2171), 20140333-20140333. doi:10.1098/rspa.2014.0333

Park, I., Jung, K., Kim, D., Kim, S., & Kim, K. J. (2008). Physical Principles of Ionic Polymer–Metal Composites as Electroactive Actuators and Sensors. MRS Bulletin, 33(03), 190-195. doi:10.1557/mrs2008.44

Pei, Q., Rosenthal, M., Pelrine, R., Stanford, S., & Kornbluh, R. (2003). Multifunctional Electroelastomer Roll Actuators and Their Application for Biomimetic Walking Robots. Proceedings of SPIE - The International Society for Optical Engineering. doi:10.21236/ada525719

Price, A. (2016, November 8). The 7 Habits of Highly Effective Artists. Retrieved October 22, 2017, from https://www.youtube.com/watch?v=vM39qhXle4g

Robot (2017). In Merriam-Webster.com. Retrieved October 1, 2017, from https://www.merriam-webster.com/dictionary/robot

Shepherd, R. F., Ilievski, F., Choi, W., Morin, S. A., Stokes, A. A., Mazzeo, A. D., .Whitesides, G. M. (2011). Multigait soft robot. Proceedings of the National Academy of Sciences, 108(51), 20400-20403. doi:10.1073/pnas.1116564108

Sun, W., Liu, F., Ma, Z., Li, C., & Zhou, J. (2017). Soft electroactive actuators and hard ratchet-wheels enable unidirectional locomotion of hybrid machine. AIP Advances, 7(1), 015308. doi:10.1063/1.4975145

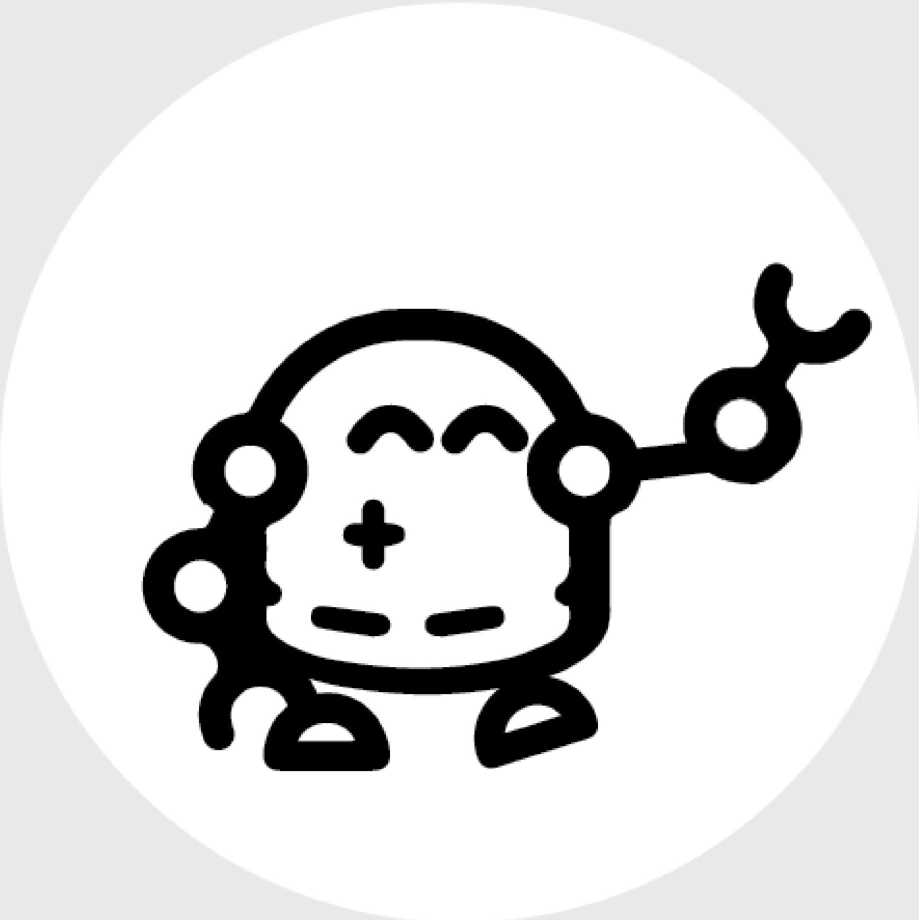
Tibbits, S. (2013, February). The emergence of "4D printing". Live performance at TED2013.

Wang, W., Lee, J., Rodrigue, H., Song, S., Chu, W., & Ahn, S. (2014). Locomotion of inchworm-inspired robot made of smart soft composite (SSC). Bioinspiration & Biomimetics, 9(4), 046006. doi:10.1088/1748-3182/9/4/046006

Wehner, M., Truby, R. L., Fitzgerald, D. J., Mosadegh, B., Whitesides, G. M., Lewis, J. A., & Wood, R. J. (2016). An integrated design and fabrication strategy for entirely soft, autonomous robots. Nature, 536(7617), 451-455. doi:10.1038/nature19100

Zhang, Q., Zhang, K., & Hu, G. (2016). Smart three-dimensional lightweight structure triggered from a thin composite sheet via 3D printing technique. Scientific Reports, 6(1). doi:10.1038/srep22431

Zhao, S., Hecke, M. V., & Jansen, K. (2017). 3D printed thermal actuating robot



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