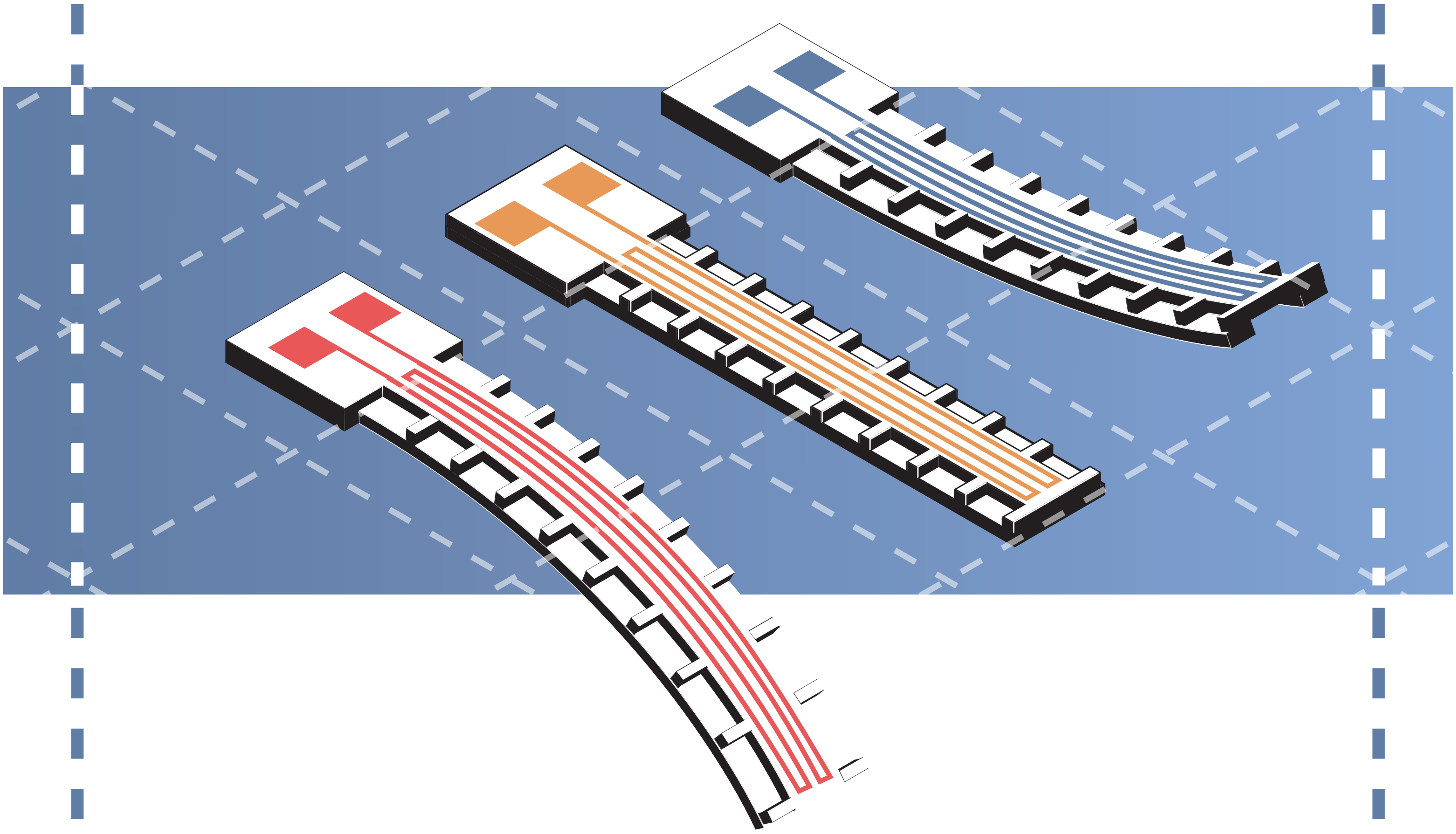
FlexTECH:

Taking the next step with 'Printed Electronics'



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Industrial Design
Design Engineering
Emerging Materials

Integrated Product Design Master Thesis
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Material-driven design and 3D printing have inspired me as a designer since the start of my education at Delft Technical University. It has been exciting for me to participate in the research of a new material technology at the early stages of its development. With this thesis, I hope to provide an academic contribution to the field of material research.

I would like to express my gratitude to the following people:

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- My family and friends for their support and encouragement, without which I would not have been able to finish the thesis.

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GLOSSARY

Term	Un-abbreviated	Definition
4D Printing	4-Dimensional Printing	The concept of 3D printing objects that can change shape after printing, time being the 4^{th} dimension.
Active deformation	-	The amount of flexion exhibited by the actuator during heating
Anisotropy	-	The concept of a material's property being different for different directions.
Base	-	Inner layer of a bilayer actuator
CAD	Computer-aided Design	Computer software that assists in creating, modifying, analysing, or optimising a design
CoM	Center of Mass	The balance point of a body where the net distribution of weight equals zero
CSP	Conductive Silver Paste	A conductive composite with a paste-like consistency
FDM	Fused Deposition Modelling	A type of 3D printing where plastic filament is extruded along a path
Flexion		A bending movement
FlexTECH	Flexural Thermal Expansion by Conductive Heating	A new type of 4D printing, and the subject of this thesis
Hotspot	-	A small area that shows a significantly higher temperature than its surroundings.
Inhomogeneity	-	The concept of a property being different at different points or locations
Locomotion	-	The act of moving from place to place
Permanent deformation	-	The amount of flexion exhibited by the actuator at room temperature
PET	Polyethylene terephthalate	A polyester plastic
PET-G	Polyethylene terephthalate, Glycol-modified	A modified version of PET that is permanently amorphous
PLA	Polylactic Acid	A type of plastic material used in FDM 3D printing
PSU	Power Supply Unit	A device that converts mains AC to DC power
Ratcheting	-	Incrementally shifting the actuator's range of motion in a certain direction
Rim	-	Outer layer of a bilayer actuator
RoM	Range of Motion	The distance between the minimal and maximal linear or angular movement of an object
Slicer	Slicing software	Computer software to convert a CAD model to instructions for the 3D printer by 'slicing' the model into printable layers
Tg	Glass Transition Temperature / Range	Range of temperatures where amorphous materials turn into a rubbery state
Trace	-	Conductive material pattern that acts as a resistor
TUD	TU Delft / Delft University of Technology	An academic institution in Delft, the Netherlands
USP	Unique Selling Point / Proposition	A product's feature that distinguishes it from its competitors

ABSTRACT

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By combining the recent innovations of 4D Printing and Printed Electronics, the Emerging Materials group at the Delft University of Technology has developed a new, printable, self-actuatable material that can continuously change shape in a programmable manner.

A specifically designed strip of conductive and non-conductive materials exhibits flexion when exposed to an electric current, which can be used to control the actuation. The resulting actuator is small, lightweight, and can be printed as a single component.

Several potential features of this phenomenon are explored, and its performance is quantified through a series of scientific experiments. The tools and knowledge obtained are presented in a series of comprehensive Design Guidelines and demonstrated by a locomoting robot.

The project redefines the material's properties under the new name "FlexTECH" and makes the technology more accessible to encourage designers in fields such as *Aerospace* and *Soft Robotics* to use FlexTECH actuators to solve future design challenges

1) INTRODUCTION

The introduction will discuss the starting point for the project and provide the necessary context for proper comprehension of the report. A description of the project's goal and corresponding approach will be given at the end of this chapter.

1.1) BACKGROUND

Ever since sustainability has taken a higher priority in design, so has choice of material. Frameworks like the Material Driven Design method (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015) show that designers are increasingly looking at material as a starting point for their design choices. Many product qualities such as structural integrity, sustainability, production method, assembly, customer experience, and aesthetics are all heavily dependent on the choice of material. The choice of whether to make a product out of aluminium instead of plastic has a drastic effect on all these design choices. This is why material selection plays a fundamental role in the design process, and why the Emerging Material group at Delft University of Technology is constantly looking for new materials to serve as a starting point for technological innovations.

The rapid uprising and evolution of 3D printing in the past years has shown that new material composites and structures can drastically change how products and prototypes are realised. *FlexTECH* is a continuation of that trend, and aims to further expand the prototyping material repertoire by providing a new type of material that exhibits controlled actuation and is easy to produce.

The 3D printing of moving materials is an existing field called '4D printing' (Figure 2), and although it has not been widely adopted yet, its benefits of reducing printing times, structural weak points, and assembly complexity have been well-researched (Momeni, Hassani.N, Liu, & Ni, 2017). However, further application of the technology into usable products appears to be limited by the highly specific conditions that are typically required to trigger actuation.

Printed Electronics is a relatively new addition to the 3D printing world. With the discovery of printable conductive material, additive manufacturing is now able to produce circuitry and other electrical components (Hou, et al., 2019). The application of this technology ranges from replicating entire components, such as electrical coils, to printing simple traces to connect contacts of embedded components (Figure 1). Unfortunately, very few 3D printers that can accommodate such materials exist. Nevertheless, the addition of conductive materials to the 3D printing repertoire carries great potential for the development of additional smart materials, as the rest of this report will show.

1.2) OPPORTUNITY

'Flexural Thermal Expansion by Conductive Heating', or "FlexTECH" (Figure 3), combines 4D printing and Printed Electronics to create new type of actuatable material that bends on command. Compared to existing forms of 4D printing, the electric current that is used as the stimulus offers much more control over the actuation and can operate independently from its environment by integrating a conductive circuit into the print itself. On top of that, the actuation can be repeated and reversed.

Figure 2: A self-assembling 4D printed object when it is printed (left) and after it has morphed into shape (right)

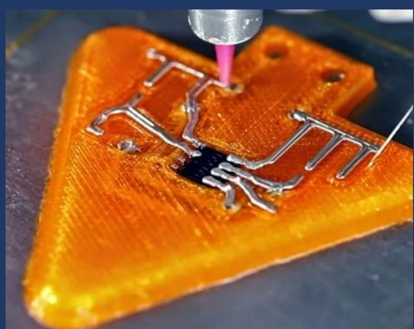


Figure 1: An inserted component being connected with the use of Printed Electronics

Figure 3: FlexTECH as observed in 2017 by the Emerging Materials team at Delft University of Technology, at the time called 'Printed Thermal Actuation'.

The actuator is a single component consisting of 2 materials and can be printed with a fully automated process at the click of a button. All of these features make for a technology that might have potential even outside of the usual production and assembly benefits of 4D printing.

A project by M. Maas (Maas, 2017) was the first exploration of FlexTECH technology in industrial design. Maas created several concepts of printed robots. The result of this project was the 'Turtlebot' (Figure 4). It consisted of a pair of curved FlexTECH actuators that would actuate back and forth several millimetres against the floor, nudging the turtle forward. The subject of locomoting robots was chosen because it served as a good visual demonstrator of what the technology was capable of.

At the same time, FlexTECH was being researched by other members of Delft University (Zhao, Maas, Jansen, & van Hecke, 2019), with particular interest in a new phenomenon called '*Ratcheting*', which greatly enhanced performance.

1.3) GOAL

The goal of this project is to build a foundation that future FlexTECH designs can build upon. Although there has been some experimentation with FlexTECH actuators that demonstrates its potential, additional research is needed in order to take it from experimental technology to an actual smart material that can be applied in commercial products. A solid foundation is needed before future designers can be expected to consider integrating FlexTECH into their own designs, and will lower the bar for material researchers to study the yet unexplored potential of FlexTECH.

1.4) APPROACH

The project's approach consists of theoretical and practical exploration, followed by experimentation and quantification of results, before ultimately formulating a comprehensive set of *Design Guidelines* that outline what FlexTECH actuators are capable of, how to use them, and how to adapt the technology for different designs. The practical application will then be demonstrated with a locomoting robot. This approach aims to deepen the understanding of FlexTECH technology, and builds upon previous work regarding the use of FlexTECH actuators in locomoting robots by gathering insights from literature, experience from tinkering, and data from experiments.

One of the biggest obstacles for adoption of conductive material printing is the limited availability of 3D printers that can accommodate conductive materials. To further lower the bar of entry into exploring the possibilities of thermal actuators, the project also features the realisation of an alternative, manual production method. Likewise, to encourage the adoption of conductive material printing in future 3D printers, the guidelines will conclude recommendations on what type of conductive materials would be best suited for further development, as well as recommendations on ideas for potential applications and future research.

The following schematic (Figure 5) provides a visual overview of the thesis' topics for reader comfort.

Figure 4: The 'Turtlebot' created by M. Maas

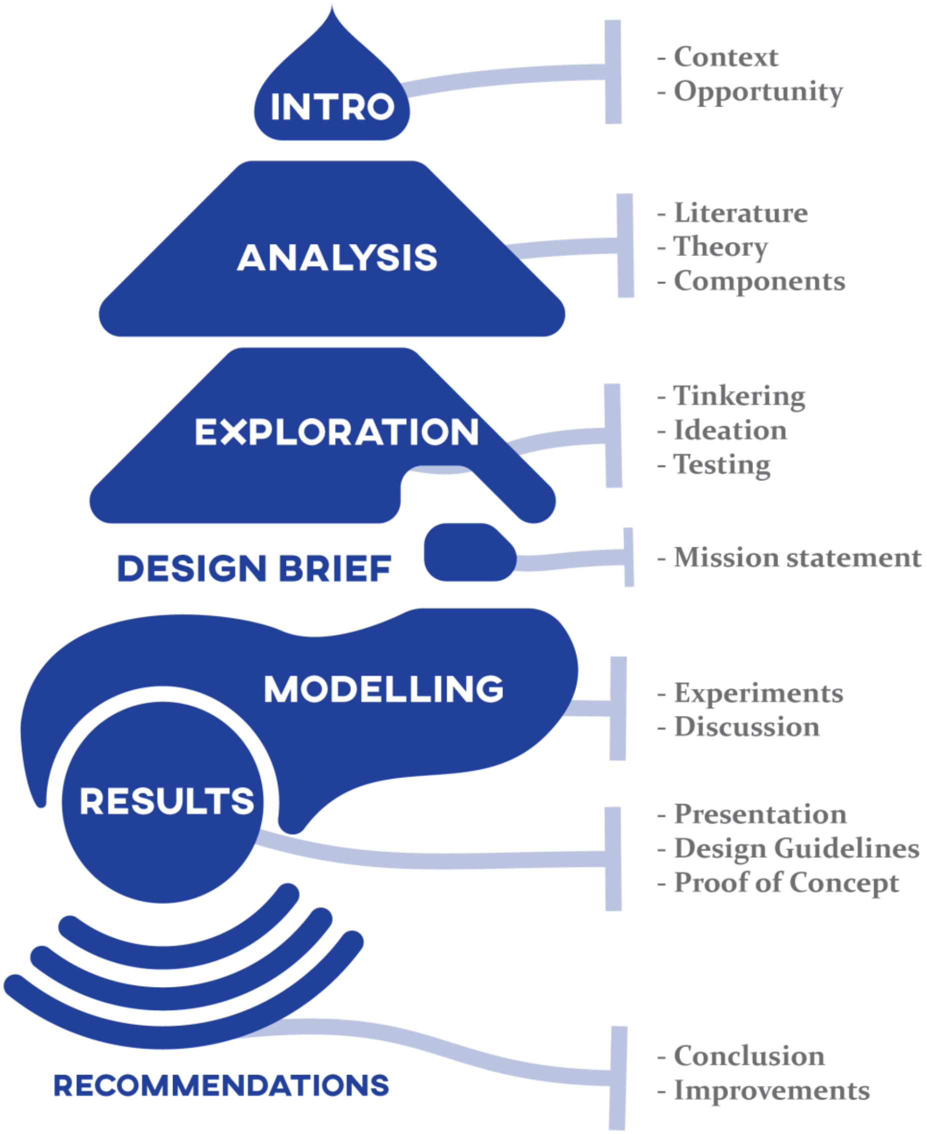


Figure 5: Thesis structure overview

2) ANALYSIS

This chapter will identify unique qualities, opportunities, and pitfalls in working with FlexTECH actuators. Existing literature on the topics of 4D printing and Printed Electronics will be explored and compared to FlexTECH technology. An in-depth look at the inner workings of the FlexTECH phenomenon will explain the underlying thermodynamics. A categorisation and analysis of locomotion in nature will extract a set of motion principles that can be used in FlexTECH robotics.

2.1) ADDITIVE MANUFACTURING

Ever since its inception, additive manufacturing has been known for its qualities of being able to produce complex and multi-material structures. Its layer-based approach greatly enhances form-freedom by freeing designs from the restrictions brought by moulds, as each layer can be crafted in whatever shape and/or combination of materials is desired (Figure 6). This makes the technique particularly suited for prototyping, iterative design, and highly personalised products such as prosthetics, as each individual product can be easily altered with the help of *Computer-Aided Design* (CAD). However, constructing each layer individually does come at the cost of taking significantly more time, making it generally unsuitable for mass-production.

Speed, accuracy, and resolution of this manufacturing method grew over time, becoming an increasingly viable alternative to regular production methods under the more popular name of "3D Printing".

The material properties of 3D printed objects and can be made inhomogeneous by switching between different materials or densities during the printing process. An interesting side-effect of the additive nature is the micro-scale variables that are introduced, which causes the material properties to be anisotropic. One example of a downside of this effect is that a weakness is introduced each time a layer is 'welded' to the one below it during the production process. This means the design of a printed product should take into consideration the direction in which it will sustain forces during use, so that the grain and layer direction can be adjusted accordingly to avoid failing due to excessive shear force along the weaker layer connections. This effect is most noticeable in the case of Fused Deposition Modelling (FDM), the most popular form of 3D printing (Alsop, 2021), where a layer is produced not all at once, but by extruding plastic filament along a path. The pathing of the extrusion introduces even more anisotropy to the material (Osswald & Menges, 2012).

Figure 6: A 3D printed object with different materials throughout its structure

3D printing already has a great variety of materials at its disposal, including plastic polymers, resins, metals, flexible plastics, and even ceramic paste. Recently, a new type of material has been added to its repertoire: conductive materials (Leigh, Bradley, Purssell, Billson, & Hutchins, 2012). A printable and conductive composite can be made by infusing a printable material with a conductive filler. This can be in the form of a solid filament or a viscous paste. The latter would be operated by a hydraulic syringe instead of the filament extruders typically seen in FDM printers. The *Voxel8* 3D printer at the Delft University PrintLab features a multi-material setup that accommodates both these types of materials, and will be used for the majority of this project.

Conductive material 3D printing opened up new possibilities for recreating electrical components, like coils and resistors (Hou, et al., 2019), through an additive manufacturing process, as well as connecting embedded electrical components inside prints of other materials. There have been other examples of this technology, such as Inkjet-Printed Electronics. However, such technologies typically only work in the 2D plane, whereas 3D Printed Electronics can make use of all the capabilities 3D printing has to offer, like 3-Dimensional structures (Figure 7) and embedding electronics within prints during the printing process.

2.2) 4D PRINTING

4D printing is a relatively new type of additive manufacturing introduced in 2013 (Tibbits, 2013). It expands upon 3D printing by printing smart or stimulus-responsive materials that can change their shape after they are printed, thus introducing 'time' as the 4th dimension (Figure 2).

There are several reasons why this is interesting. Firstly, by printing an object in a flat orientation and morphing it into shape *after* it is printed, the required number of layers to print the object is greatly reduced. This reduces print times and increases structural integrity by limiting the number of weak layer connections.

Since materials used in 4D printing are designed to respond to a specific stimulus (Momeni, Hassani.N, Liu, & Ni, 2017), one could also create a print where the actuation response to this stimulus fulfils a specific function as opposed to using it to simplify the print job. This is demonstrated by Figure 8 where the actuation of a printed shape memory polymer is used to grab a small object the moment it is submerged in warm water, and subsequently released when the water is heated even further (Wu, et al., 2016). We can also see from this example that the potential use-cases are quite limited by the required stimulus. Here, the print needs to be cooled beforehand, and the hook only works just below the water surface because it needs to switch from a cold to a warm environment. Additionally, the entire water volume needs to be heated to progress to the second actuation stage.

These specific demands make it difficult to implement 4D prints in any consumer product and could be a large part of the reason 4D printing has only really been

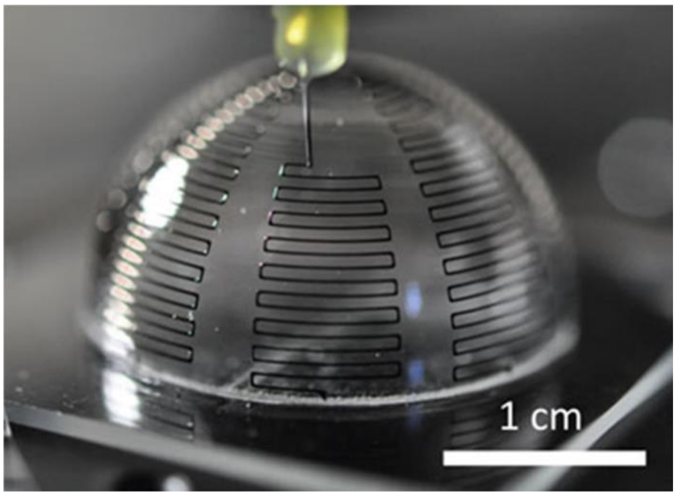


Figure 7: 3D Printed Electronics by means of a hydraulic syringe

applied to manufacturing where conditions are easier to control. Still, the potential functionalities of actuating materials is exciting. This includes various functions such as self-assembly, self-repair, self-sensing, or other kinds of multi-functionality.

Similarly, there are examples of other types of 'actuated materials' that are not (fully) printed, but do feature conductive materials. These materials usually offer more control over the actuation and are used in various types of robotics. Examples include Shape Memory Alloys, Piezo-ceramics, Dielectric Elastomers, Ionic Polymer-Metal Composites, etc. (Maas, 2017). However, actuating materials such as these typically require a very complex and intricate manufacturing process of multiple different materials and production methods. An example of which can be seen in Figure 9 (Must, et al., 2015) in the form of an inchworm-robot. Though its effectiveness is greater than most printed actuators, the manufacturing process is also many times more complicated.

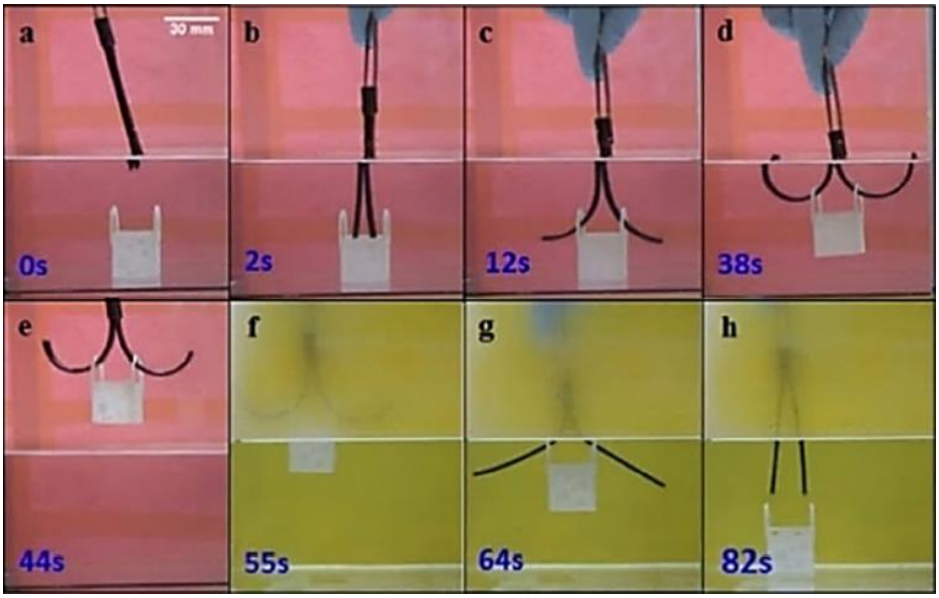


Figure 8: Example of a heat-sensitive 4D print grabbing an object in warm water (red) and releasing it in even warmer water (yellow)

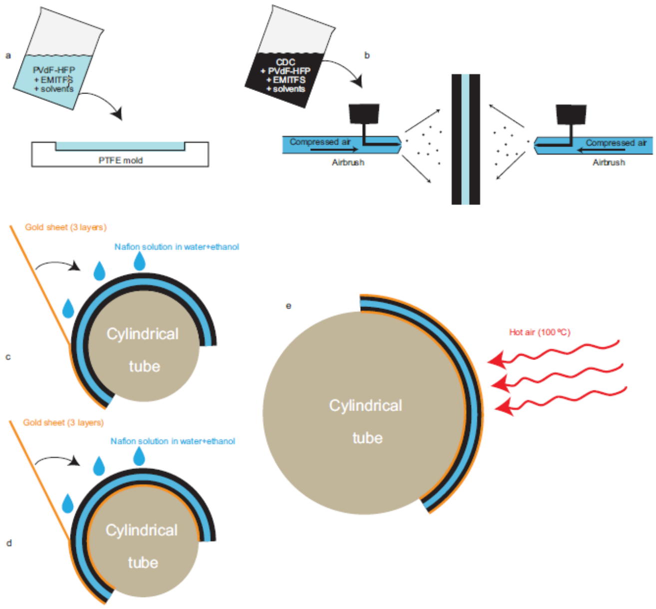


Figure 9: Manufacturing process of an Ionic Electroactive Polymer (IEAP)

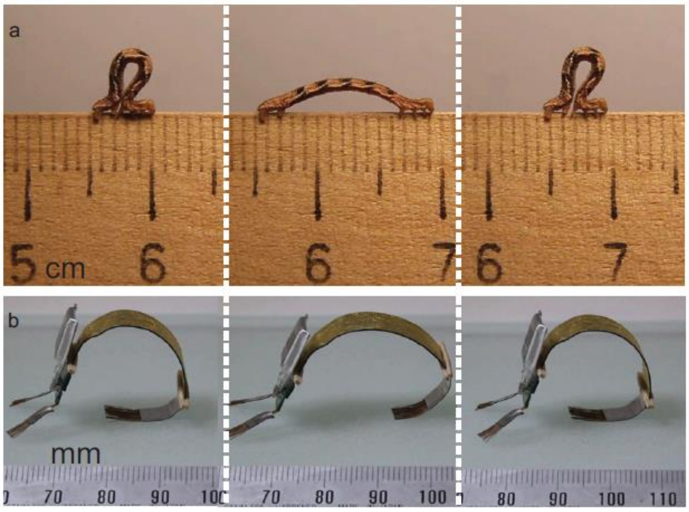


Figure 11: an Ionic Electroactive Polymer (IEAP) in action

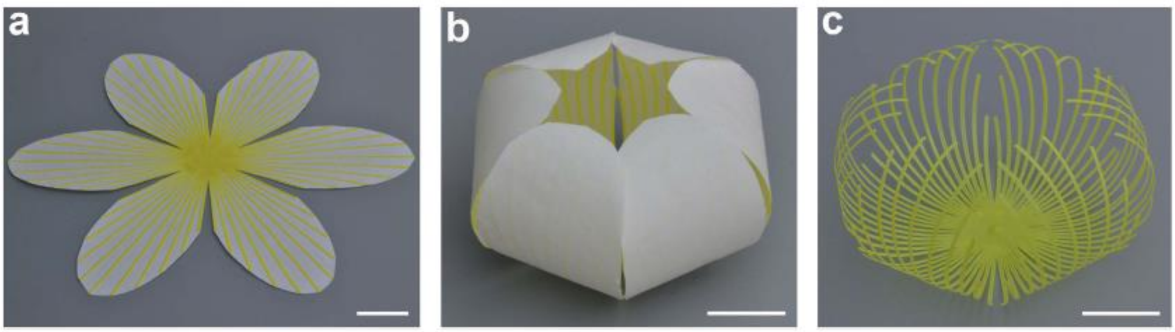


Figure 10: An actuator made from PLA 3D printed on a sheet of paper, triggered by the heated plate

As the FlexTECH name suggests, 'Flexural Thermal Expansion by Conductive Heating' can be considered a form of 4D printing It involves a structure that exhibits *flexion* when a stimulus in the form of *heat* is introduced by *conductive* elements stimulus. An extensive review of documented 4D printing cases has categorised them in a number of useful ways (Momeni, Hassani.N, Liu, & Ni, 2017). Following this categorisation, FlexTECH can be defined in the following ways:

- Its instant and spontaneous actuation makes it a **Shape Change Material**, as opposed to a 'Shape *Memory* material'. Shape Memory Materials require the desired shape to be manually introduced in advance, whereas Shape Change Materials do not.
- Its shape-shifting behaviour falls under **2D-to-3D bending**. The curvature is gradual (as opposed to folding), and most FlexTECH prints start out flat as they need a decent amount of surface area in order to work. Although there might be potential for '3D-to-3D bending' as well.
- FlexTECH provides **two-way** actuation, meaning it returns to its initial state after the stimulus disappears.
- The use of multiple materials makes a FlexTECH actuator a **multi-material structure**. Even though the actuator is digitally designed, it does not fully classify as a 'digital material', which is a more voxel-based approach of combining different materials. Instead, a FlexTECH actuator has two clearly defined and separated structures. A digital material variant could be possible in the future, however.
- The material structure uses **special patterns** to achieve its desired effect, as opposed to uniform or gradient distribution of different materials. The special patterns are the ways the silver traces are laid out to form a resistor circuit and distribute heat.
- Its shape-shifting mechanism is **unconstrained thermo-mechanics (UTM)** because it uses heat as its triggering stimulus, and does not require an external load to 'program' the desired shape like *constrained* thermo-mechanics does.

Some things need to be noted with this categorisation, as FlexTECH is slightly different in several ways that makes it not fit neatly into every category. In the review, stimulus-responsive materials are mentioned as a necessary component for 4D printing. With FlexTECH, however, it is the thermal expansion of PLA (*polylactic acid)* that drives the actuation, which is by any means a conventional, non-smart, printing material. It only 'reacts' to heat just as many other materials would, i.e. thermal expansion. Rather, it is the localisation of the stimulus to a specific part of the material, and the imbalance created by the geometry that makes the material 'act' and appear smart. This is of course possible with the help of the printable conductive material, which could be considered the actual stimulus-responsive material if electricity were to be defined as the stimulus and heating up from electrical resistance as the response. However, this would also be true for any kind of resistor, and this type of stimulus is not covered by any category presented in the review article.

An example of 4D printing perhaps most similar to FlexTECH is the one seen in Figure 10 (Zhang, Zhang, & Hu, 2016). Here, PLA (the same material that is used for FlexTECH) is printed on a paper sheet, and then heated through the heated plate which it rests on. While the construction method is similar, FlexTECH actuation is different in that it does not rely on the mismatching coefficient of thermal expansion between different materials. Additionally, as the paper/PLA structure features no conductive materials, it relies on an external heated plate to heat up the material.

2.3) FLEXTECH ACTUATION

The literature analysis shows that FlexTECH is different from existing thermal actuators, but how does it work exactly? This section will take a look at what is happening behind the curtains and explain what makes FlexTECH work. Firstly, a short description of the stages of actuation will explain *how* the actuator behaves. Secondly, an overview of its different components will illustrate *what* constitutes a FlexTECH actuator. Lastly, a closer look at the underlying thermodynamics theory will explain *why* the phenomenon takes place.

To recap, a FlexTECH actuator is a printed strip of material that bends when a current is applied and relaxes again when the current is switched off. The name FlexTECH stands for *'Flexural Thermal Expansion by Conductive Heating'*, and can be explained in the following way:

- *'Conductive Heating'* implies that heat is transferred into the actuator by a solid material (a conductor). This task is fulfilled by a circuit on top of the actuator that is printed with conductive materials.
- *'Thermal Expansion'* indicates that the heat from the conductor causes the underlying material to expand. This is an intrinsic material property for all materials.
- *'Flexural'* specifies that the final actuation causes the material to curve or bend (flexion). This happens because the heat is only supplied to one side of the material, causing an asymmetric expansion. When one side expands while the other does not, the material bends.

2.3.1) BEHAVIOUR

The movement of a FlexTECH actuator comes in different stages (Figure 12). Initially, the actuator is printed flat. Then, when a small amount of heat is supplied, the actuator will bend in a certain direction, only to return to its flat position when the power supply is turned off and the material cools down (Stage 1). This stage can be repeated.

However, if the actuator is subjected to a larger amount of heat, it will bend as usual at first, but then eventually return to its flat position *while still being heated* (Stage 2). It is at this point that the material approaches its '*Glass Transition Temperature'* (Tg). If the actuator now cools down again, it will stay in its bent state at room temperature. From this point onwards, heating the actuator will make it bend back toward a flat state (Stage 3), and this process can be repeated many times. Figure 2.7 also shows that the presence of a cold part (here called 'the rim') is required, and how the actuation will happen in an inverse direction when the hot and cold layers switch position. The actuation is typically very slow, taking multiple seconds to move an order of several millimetres, depending on the size and design.

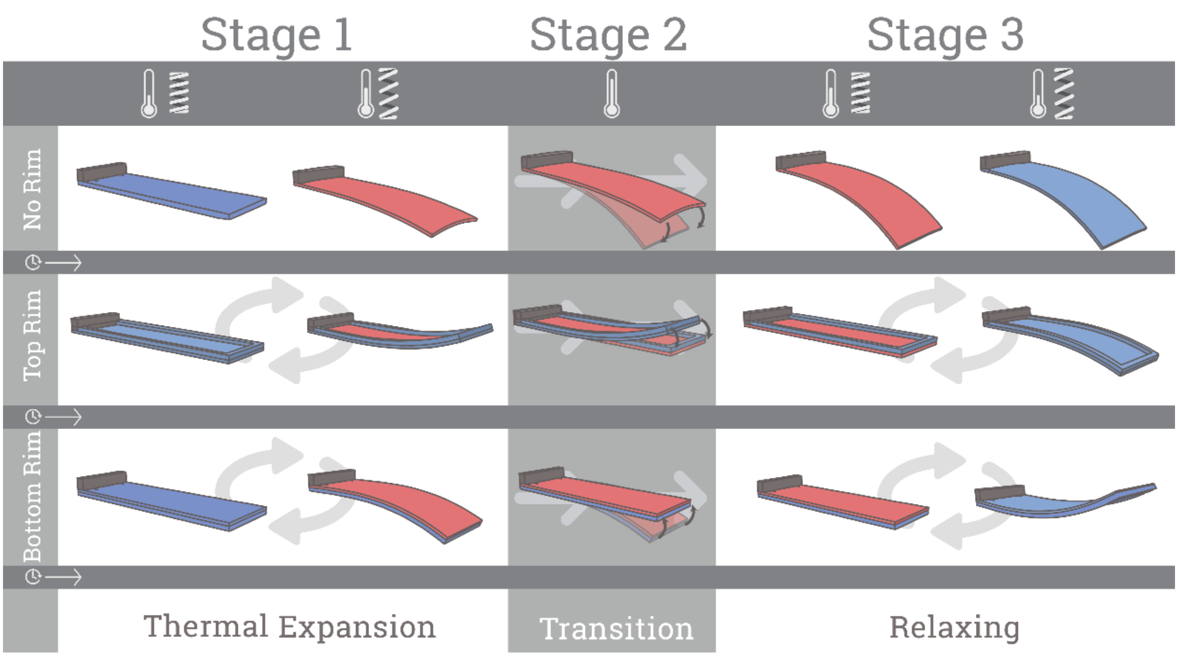


Figure 12: The actuation stages of a FlexTECH actuator

2.3.2) COMPONENTS

Even though a FlexTECH actuator has only a few components, each of them play a crucial role in making the phenomenon possible. This section will explain the function of each of its parts.

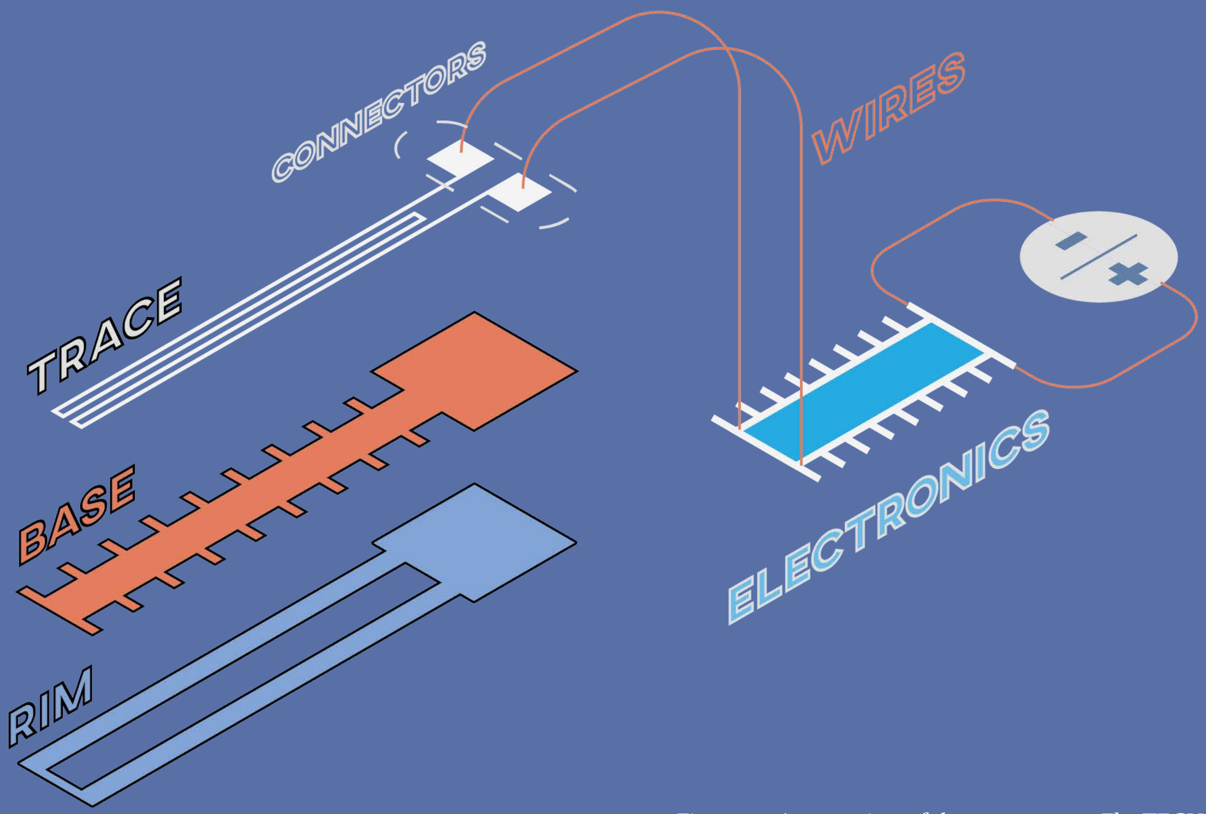


Figure 13: An overview of the components FlexTECH actuator

Materials: structural & conductive

In principle, a FlexTECH actuator consists of at least 2 different materials: A *structural* material, and a *conductive* material. As the actuator can be created in a single print, it is essentially one multi-material structure.

- The *structural* material provides rigidity to the structure and drives the actuation by thermally expanding.
- The *conductive* material supplies energy to a part of the structural material where thermal expansion is desired. It needs to be properly adhered to the structural material to increase heat transfer and stay attached during flexion. This also means the conductive material needs enough flexibility in order to avoid resisting the actuation or breaking under the resulting stress. A single break would disconnect the circuit and render the actuator useless.

Base & Rim

The '*base*' and '*rim*' are the names for 2 different areas of the same structure, composed entirely out of the structural material. The geometry of this structure is crucial to the function of the actuator. The base and rim are effectively 2 different layers, with *base* referring to the inner section, and *rim* to the outer section. This denomination stems from the first design, where the outer section formed a literal rim of thicker material on top of a 'base' plate. They need to be attached for structural integrity, but at the same time they should be insulated as much as possible to avoid too much conduction of heat between each other, as it is the temperature difference between these offset layers that determines the level of deformation. Likewise, the layers need to be printed at different heights for the thermal expansion forces to act in a specific direction. The base and rim are typically kept identical in other variables such as thickness and surface area in order to keep the actuation forces balanced in either direction. When either the base or rim are 3D printed, the printer needs to print at least 2 layers to from a well-connected surface. With a standard layer height of 0.2 mm, this makes the base and rim each about 0.4 mm thick.

Trace

The *trace* consists of the conductive material and is printed on top of either the base, the rim, or both. Preferably the trace is spread out as evenly as possible to ensure the entire surface is supplied with roughly the same amount of heat for increased consistency and effectiveness, but different designs are possible when differences in local temperature are desired. When the trace conducts electricity, it will act as a simple resistor circuit and produce heat according to a phenomenon called *Joule Heating*. Difference in local temperature can be achieved by varying the dimensions of the trace. When heat from the trace conducts to the underlying material, actuation will take place.

Because weak trace layer connections can influence local resistances and risk overall conductivity, it is preferred to print the entire trace in a single layer so it can be printed in one continuous motion without any potential inconsistencies or defects that might disconnect the circuit.

Connectors

The connectors are there to connect the printed trace to a set of wires. There are multiple ways to achieve this, and in theory anything that can reliably connect the two will do the job. It is, however, important to keep in mind that the resistance at this point should be kept as low as possible. Doing so will eliminate the risk of inducing a very high local temperature and accidentally melting the material. The connector's resistance should also not significantly impact any multimeter readings. Attempting a reading by attaching directly to the delicate trace will risk breaking it.

Wires

A set of wires connect the actuator to some form of power supply. It is preferable to use thin copper wires that add minimal strain on the actuator so that it can move freely. A crimped connection can be useful for connecting and disconnecting the actuator from the power source.

Electronics

The current that is required by the actuator is supplied by a *power supply unit* (PSU) or other kind of power source. To gain more control over the current, and thus the actuation cycles, a microcontroller such as an '*Arduino'* can be used. The Arduino is connected to a pair of relay switches that connect and disconnect the PSU from the actuator (see Appendix B for the schematic of the setup). This allows the actuator to be automatically controlled by scripts running on the Arduino, instead of manually having to switch the power supply on and off. The duration, timing, and synchronisation of these on/off cycles play a large part in the final behaviour of the actuator.

2.3.3) THERMODYNAMICS

Even though thermal expansion is the main driver of the actuation, there are several other thermodynamic phenomena at play that ultimately influence the choice of material, geometry, and electrical properties of the FlexTECH actuator. Taking a closer look at these underlying physics is important to understanding why a FlexTECH actuator is designed the way it is now, and what limitations must be considered in the future.

Thermal Expansion

First off, it is important to note that thermal expansion by itself doesn't induce a bending movement, but rather its combination with the temperature difference between the two parts of the bi-layer geometry, i.e. the rim and base. One of these parts heat up, and one does not. When viewed laterally, these two layers are shifted away from the neutral plane so that the force of thermal expansion will create an imbalance that produces motion towards one side. The motion and forces at play can be described by a double spring model, as explained by (Zhao, Maas, Jansen, & van Hecke, 2019) (Figure 14)

Joule Heating

The heating of the material works through a concept called 'Joule heating'. The printed silver paste (the trace) is an electrical conductor that acts as a resistor and is applied to the area that is to be heated according to the CAD model. According to Joule's first law: *"the power of heating generated by an electrical conductor is proportional to the product of its resistance and the square of the current: $P \propto I^2 \cdot R$."*

This phenomenon affects the whole electrical conductor, which means that the entire silver trace heats up in its entirety as a current is run through. The resistance and heating power of the trace can be calculated by monitoring the power supply's current and voltage and subsequently substituting Ohm's law of $V = I \cdot R$ in order to get $P = I \cdot V$.

From these definitions we can also note that parts where the resistance is higher, such as where the trace is thinner, produce more heat. This was also illustrated by test samples from M. Maas in her project (see Figure 15) (Maas, 2017). This effect can be used to heat specific parts of the heated area more so than others, even though the trace is subjected to the same current.

Aside from current and resistance, there are other variables that influence the effectiveness of the heating. As a two-way actuator, FlexTECH's actuation can be reversed by switching off the stimulus, i.e. the electrical current. By halting the heat supply, the material is allowed to dissipate heat into the environment and cool down to the ambient temperature, thus also reversing the thermal expansion. Although this cooling is a passive process (because we switched off our main method of control), there are still ways to influence how quickly the material cools down through design. The actuator is cooled mainly through passive convective heat transfer to the surrounding air. The formula for convective heat transfer is as follows:

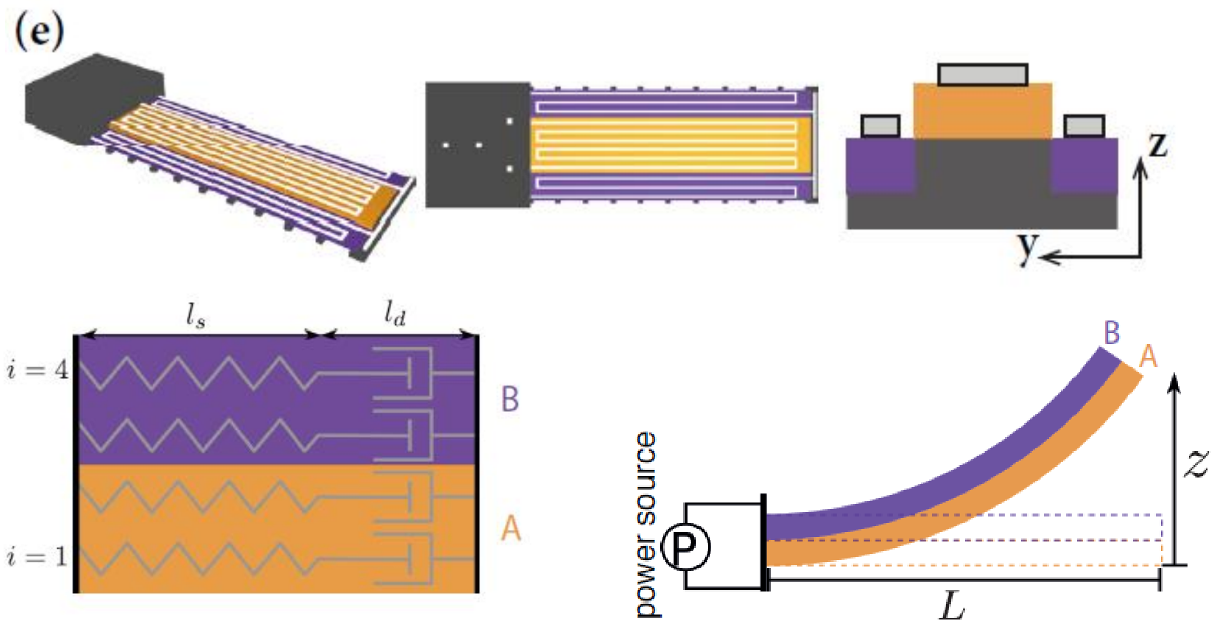


Figure 14: An analysis of the FlexTECH actuator structure and motion

$$\dot{Q} = h \cdot A(T_a - T_b)$$

- $\dot{Q}$ = *heat transferred per second* $[W]$
- A = *area of the object* $[m^2]$
- T_a = *temperature of surrounding fluid* $[K]$
- T_b = *temperature of solid surface* $[K]$
- $\hbar = \frac{q}{\Delta T}$ = *heat transfer coefficient (PLA/air)* $\left[\frac{W}{m^2 \cdot K}\right]$

The values of the heat transfer coefficient and temperature difference are set by the choice of materials and ambient temperature. This means we can only change the surface area to control passive cooling rate. An important distinction is that even though cooling *rate* is only dependent on surface area, cooling *time* is will also be dependent on amount of heat stored in the material (i.e. volume) and how fast it conducts outwards (i.e. thermal conductivity of the material). Since material conductivity is again determined by material choice, the surface-area-to-volume-ratio determines how much of the thermal mass is exposed and available for convective cooling and will be the most important variable to influence cooling time.

Passive cooling happens continuously, including during the heating phase. A greater cooling rate will inadvertently influence the heating rate. However, for heating rate there is the added variable of contact surface area between the conductive and structural material, and of course the input power itself.

The use of Joule heating allows FlexTECH to be more responsive and energy-efficient than traditional 4D printing methods that use environmental heating (e.g. resting on a heated plate or submersion in warm water.

Glass Transition Temperature

Another important factor at play is the '*Glass Transition Temperature*' (Tg). This transition, though not a proper phase transition, marks a point where viscosity (among other material properties) of the material changes significantly (Figure 16). It is named after the way glass becomes more viscous and malleable when heated, even though it does not turn fully liquid. The transition is sometimes also called a glass-rubber transition, as indeed, rubbers are materials whose Tg lies around room temperature.

In practice, this transition is more of a temperature range rather than a single point, and giving an exact value for Tg remains difficult. In a recent definition, the glass transition temperature *"corresponds to the temperature at which the largest opening between the vibrating elements in the liquid matrix become smaller than the smallest cross-sections of the elements or parts of them when temperature is decreasing"*. (Sturm, 2017)

The Glass Transition is unique to amorphous materials (or amorphous regions within other materials), where long-stranded molecules are able to move and slide between each other when temperature rises and thermal vibrations increase (Figure 17). In contrast, the more organized crystalline structures keep the molecules neatly in place. The rate of heating/cooling also influences this Glass Transition, as slow cooling allows the molecules more time to slip into a crystalline state before being 'frozen in place' by the temperature reaching a certain low point where the strands stop moving.

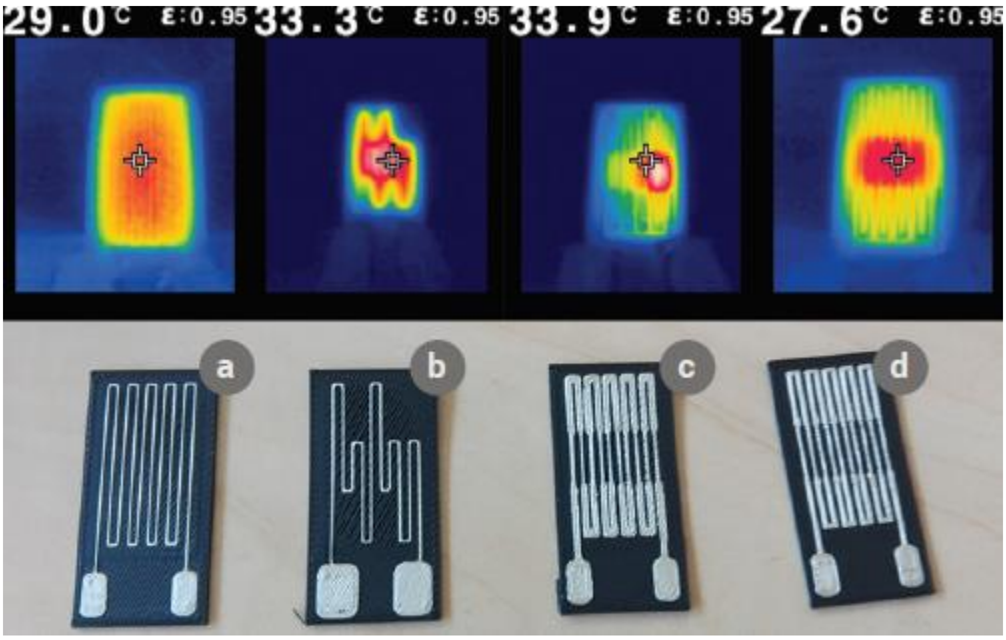


Figure 15: Demonstration how a thinner trace results in a higher local temperature

Many polymers lack a well-defined crystalline state and thus easily form glasses, even when cooled slowly. Relatively stiff chemical groups, such as benzene rings, will interfere with the flowing process and hence increase Tg. For example, *Polyethylene Terephtalate* (PET) has a benzene ring and as a result, a higher Tg than PLA It is partly due to this reason that PLA is used for the printed actuator. Later experiments in the project feature Glycol-modified Polyethylene Terephthalate (PET-G). The glycol-modification introduces a kink in the polymer chain which interferes with the crystallisation process, thus lowering Tg and making it a more suitable as a candidate for FlexTECH actuation. These structural materials (PLA and PET-G) are both thermoplastic polyester plastics and are widely used in 3D printing, thermoforming, etc., and have a Tg at around 56 and 86 degrees Celsius respectively (GRANTA EduPack Software, 2020). A thermoplastic is necessary for the material to be processed and shaped into filament, substrate, or granules, while still being available for reshaping into a final print (as opposed to thermosets that can be irreversibly cured).

The thermal history of a material affects the glass transition behaviour, and we can see this effect very clearly in our actuator as well. When a sample reaches a temperature beyond Tg, there is an irreversible change in the microstructure of the plastic, causing it to promptly change its orientation. This change only happens once and is likely a reversal of the flow-induced molecular orientations that were imposed on the material when it was forced through the 3D printer nozzle and rapidly solidified (Zhao, Maas, Jansen, & van Hecke, 2019).

Upon cooling or heating through the glass-transition range, a material also exhibits a smooth step in the thermal-expansion coefficient and in the specific heat. When this change occurs depends on the thermal history. Each time the actuator reaches a higher temperature than before, relaxation of the stresses and curvature occurs.

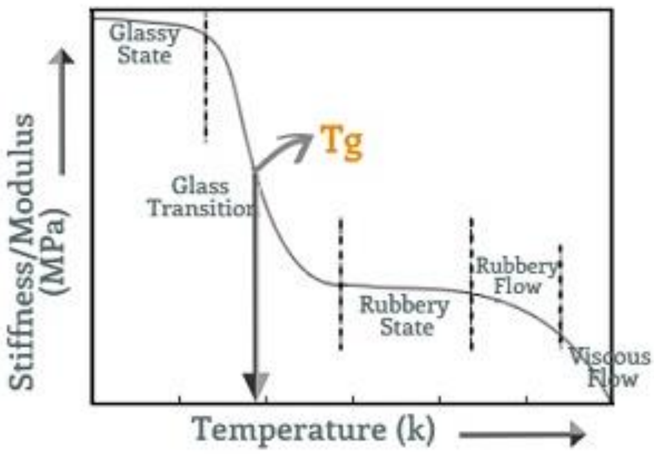


Figure 16: The Glass Transition, as illustrated by the drop in stiffness with temperature

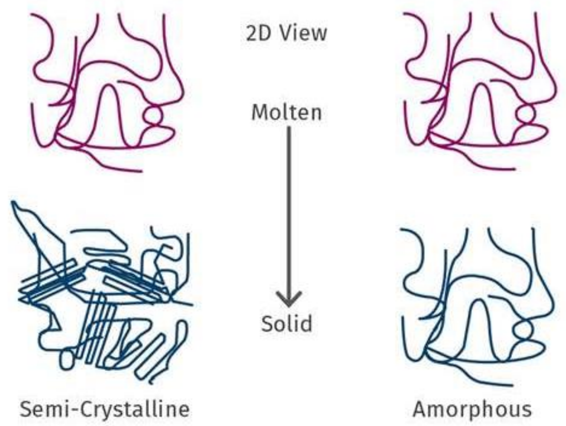


Figure 17: Structure difference between semi-crystalline and amorphous polymer chains

2.4) LOCOMOTION

An analysis of locomotion in nature will serve to identify important motion principles that can be put to use in FlexTECH-robotics.

The Turtlebot

The 'Turtlebot' (Figure 18) created by M. Maas (Maas, 2017) is currently the only documented FlexTECH-driven robot. It features a single FlexTECH actuator that covers both 'front legs' of the turtle and actuates back and forth several millimetres against the surface. The actuator is slightly angled in order to push the robot up and forward. Inclined protrusions at the back of the body ensure the backwards motion encounters more friction, resulting in a net positive forward movement.

The resulting motion is one where the robot moves 100% forward, and then roughly 80% backwards again on the return path. The use of friction anisotropy is not completely reliable and depends on local surface topology, resulting in the robot often diverting towards its right or left rather than going in a straight path as intentioned.

The purpose of this robot was to serve as a proof of concept and demonstrate the possibility of using FlexTECH technology in robotics, not to maximise the effectiveness of its locomotion. However, as noted by M. Maas herself, a next iteration of a robot could probably show off more potential features than just the single-direction actuation.

A major *unique selling point* (USP) of FlexTECH technology is its independence from external heat sources or other environmental control methods through integration of a stimulus-delivery method. To promote the robot's versatility and autonomy even further, the locomotion method should ideally be independent of local friction as well.

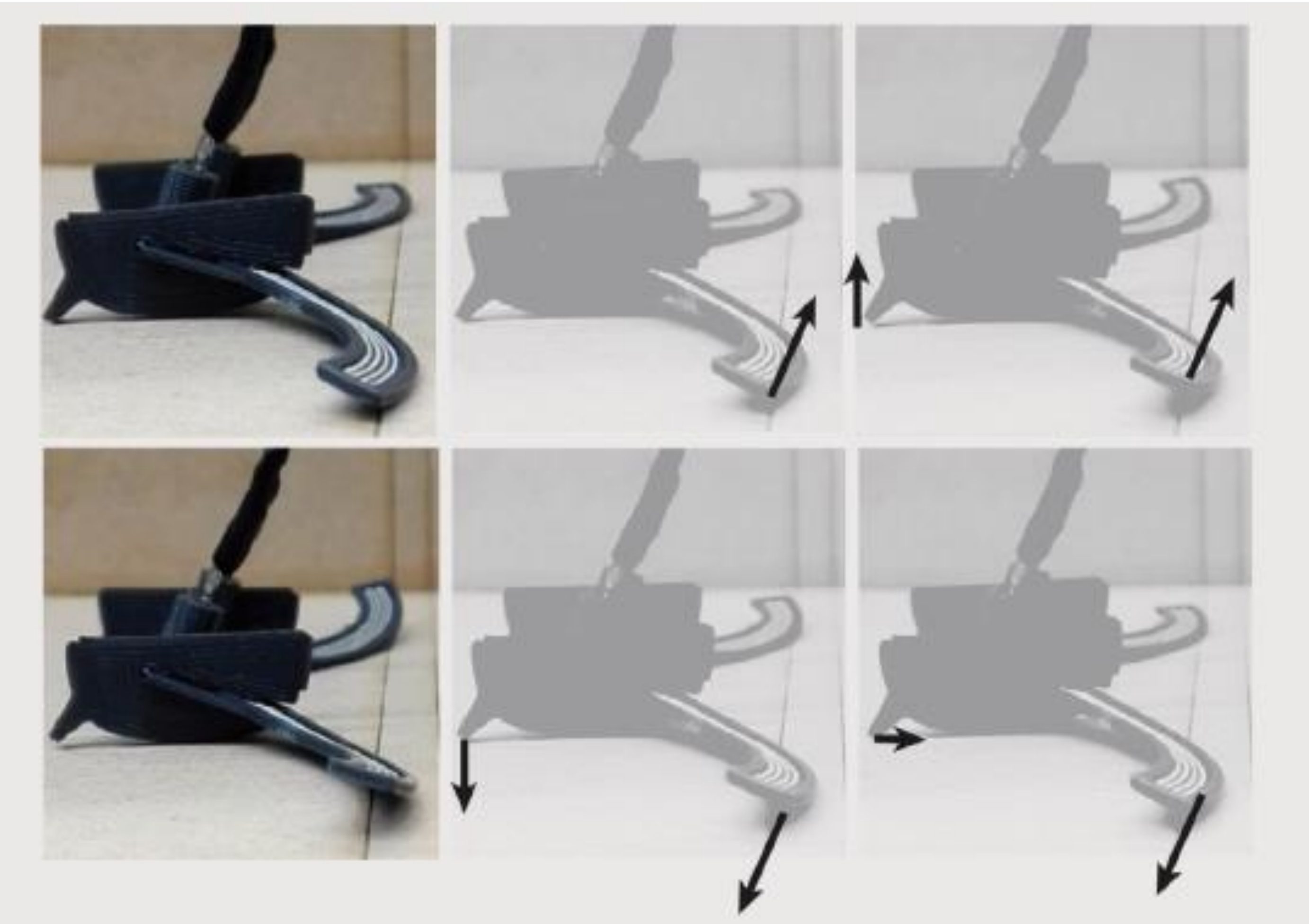


Figure 18: The locomotion of the 'Turtlebot'

Locomotion summary

A closer look at existing forms of locomotion can provide insights into the kinds of movements and interactions used, which would be of interest for robotics. Through evolution, nature has optimised the process of locomotion in a variety of different ways. Each family of organisms has evolved a unique method of locomotion by adapting to their environments and utilising the biological mechanisms at their disposal. As a result, there is an immense variety of types locomotion. The different types of terrestrial locomotion have been collected and categorised as can be seen in Figure 19.

Aquatic and Aerial locomotion were excluded as the technology has not yet been tested in these environments. Likewise, types of locomotion featuring an airborne phase or otherwise required the use of momentum were also excluded from this analysis, because of the slow nature of FlexTECH actuation.

The types of locomotion that contributed the most valuable insights are discussed here. For a more detailed look at the other types of locomotion and the resulting categorisation, see Appendix A.

Limbless locomotion:

Despite the fact that snakes have evolved no limbs with which to grab, push, or pull, they have developed 5 distinct forms of locomotion to navigate different types of terrain. A closer look at the different way a snake employs its singular locomotory organ could provide valuable insights about performing locomotion with limited resources.

In **rectilinear** locomotion, a snake keeps its body relatively straight. Small elements of the body are extended to propel the body forward, while alternating segments in between are lifted slightly from the ground and contracted to repeat the motion. If you were to follow an individual body segment, it would appear to make small circular motions (Figure 21), very similar to how a millipede's legs would move if they were all connected to each other. This type of locomotion is often employed by heavy snakes.

The most common type of locomotion is **lateral undulation**, sometimes also called *serpentine* motion. As the name suggests, the snake moves its body in a wave-like pattern (undulation) from side to side (laterally). While doing so, each bend pushes outwards against the surface where it catches on things like small rocks and sticks. The multiple inward vectors from each bend cancel each other out to create a net forward momentum. Because it relies on irregularities in the surface to push against, lateral undulation is not effective on flat, slippery surfaces.

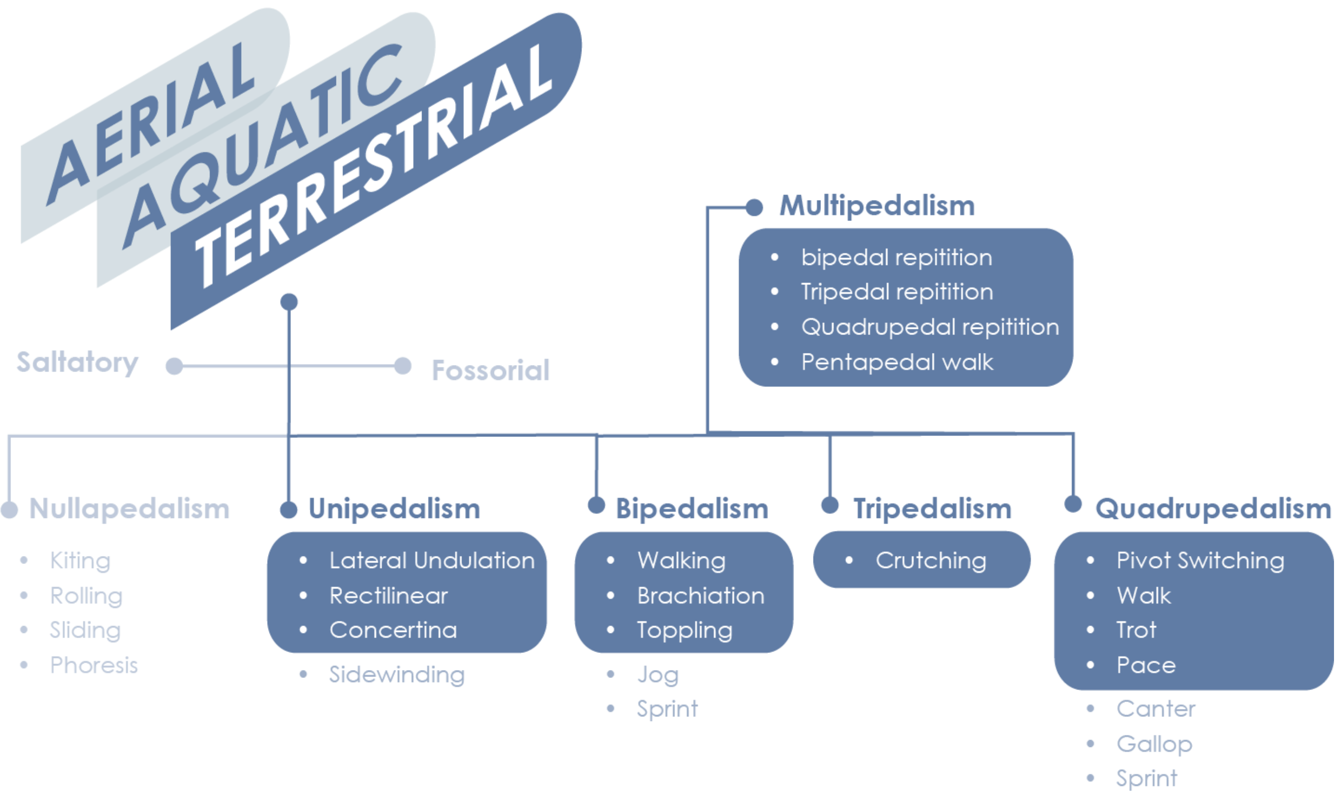


Figure 19: A categorisation of different forms of locomotion, divided by number of limbs

Figure 21 snake locomotion

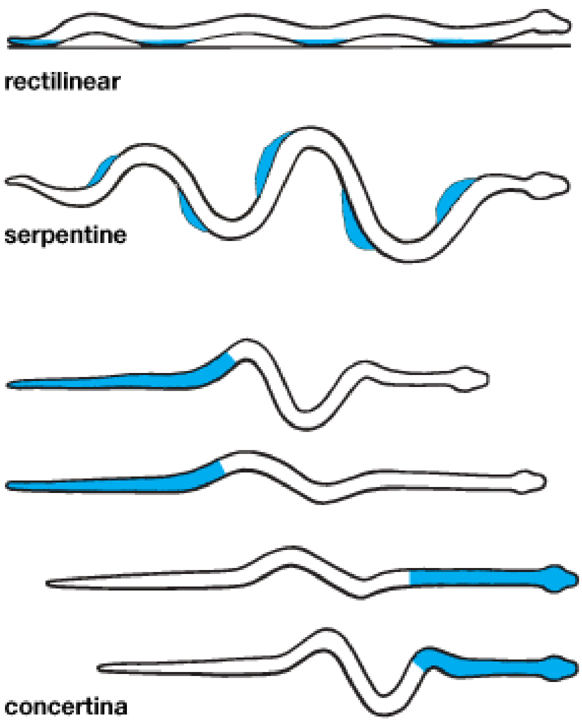
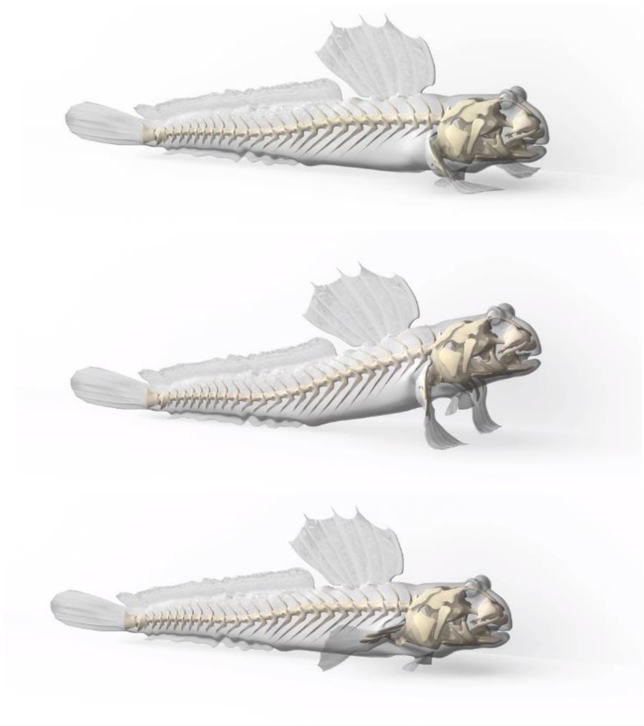


Figure 20: Mudskipper locomotion



With **concertina locomotion** the centre of the snake's body acts like a spring, contracting and extending, while the ends of the body act as alternating anchor points, one part pulling and the other part pushing. Activating entire muscle groups at once instead of more continuously like with the other types of locomotion results in a very slow and strenuous movement. Typically, snakes use concertina locomotion when space is limited. When crawling through tight tunnels, they use a variant of this motion called **tunnel concertina**, where, instead of anchoring parts of the body by pushing them vertically against the ground, the body is anchored by curling up, essentially making their body expand, to wedge themselves in the small space of the tunnel. Snakes can even climb using this method.

Mudskipper:

Some animals were built for the water, but still occasionally come onto dry land to nest or hunt. These creatures often struggle to perform terrestrial locomotion with the limited tools at their disposal.

The mudskipper is a fish that normally swims in the ocean, but performs a motion known as **crutching** when coming onto dry land to feed. To do so, it rotates its front fins so that it lifts most of the body and carries it forward. The second half of the rotation lifts the fins from the ground and deposits them forward again. Because the mudskipper uses only 1 set of synchronised fins, the motion is halted when the fins are lifted, resulting in a start-stop pattern. The fact that the fins only provide two points of contact means the mudskipper must keep part of its body on the ground to keep balance, which adds resistance when being dragged across the surface.

Quadrupedal gaits:

Quadrupedal locomotion is the most common type among mammals. Horses in particular are famously known for their distinct gaits. In order from slow to fast, they are walk, trot, pace, canter, gallop, and sprint (see Figure 23). The **walk** has each of the 4 legs moving slightly asynchronous, resulting in 4 beats. This makes it the most stable gait, as there are always 2 or 3 feet in contact with the surface. The trot and pace both have 2 beats and have at most 2 contact points. The difference lies in which pairs of legs are synchronised. A **trot** synchronises the diagonal pairs of legs, and is therefore more balanced and can be performed slower, whereas a **pace** synchronises the movement of the legs on either the left or right side of the horse, and needs to be performed faster to avoid the horse tipping over.

By using multiple sets of actuators, quadrupeds can avoid a start-stop pattern and instead move continuously at varying speeds. The many ways a horse uses its 4 legs serves as a good demonstration that not only the cycle speed, but also the interval and synchronisation of different actuators determine the pace and balance of the locomotion.

Some quadrupedal reptiles like lizards and crocodiles have developed a unique trick to compensate for their shorter stride length that results from their bodies being closer to the ground and their hips and legs extending sidewards. To do this, they bend their spine to pivot their body mass around the two legs currently in contact with the surface (see Figure 22). By alternating the set of legs they pivot around, the lateral bending of the spine increases stride length and could even make the animal move forward without the legs themselves performing any kind of forward push. We call this type of movement **pivot switching.**

Figure 22 Reptile locomotion

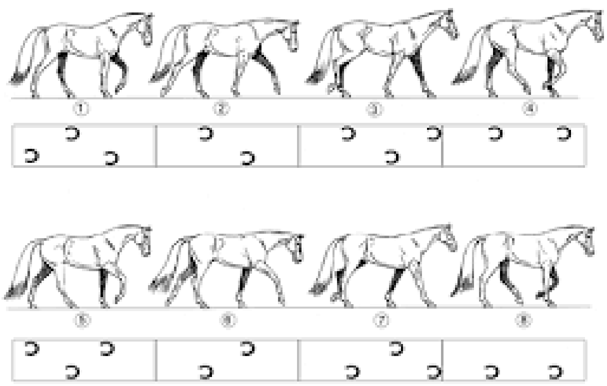


Figure 23 Horse gaits

Identification & Insights

Looking at this collection of locomotion, we can identify 4 important 'principles' that are describe the different elements of these motions. All selected locomotory movements are combinations of one or more of these principles.

The most common one is **anchor switching**. Almost all the locomotion types that were studied involved some sort of alternating between anchor points that connect with the surface. There are 3 different distinctions to be made:

1) **Single-set & multi-set:** The number of actuator sets or groups (so not the number of actual actuators) has a big influence on the resulting motion. Each actuator will eventually need to traverse back to its original position after performing its motion. During this 'reset' phase, the actuator needs to avoid reversing the forward movement it has just created. Because of this, 'single-set' locomotion types will often feature a phase where the body stays at rest, to allow time for the actuators to reset. However, a 'multi-set' locomotion could potentially have one of its other actuator sets take over and perform the same type of motion, but out of phase with the other one, thus creating a continuous forward momentum for the locomoting body.
2) **Actuator lift & Body lift**: Another distinction lies in how exactly the 'reset' phase is facilitated. In most cases, actuation in 2 different directions is necessary to create locomotion. Actuation from front to back in order to gain forward momentum, and up-down actuation to lift the anchor points from the surface in order to reset without creating equal backwards momentum. The difference lies in the default state of the anchor points. With an actuator lift, the actuators themselves are moved upwards by a different set of actuators to allow them to reset. With a body lift, the actuators are instead moved downwards to lift the entire locomoting body. After which the actuators will carry it forward, and deposit it further ahead. This distinction is most notable in single-set locomotion.
3) **Push, Pull, & Pivot anchors:** This classification is determined by the type of movement applied to the anchor point. An actuator can extend against a surface, creating a pushing anchor, or it can contract while maintaining enough friction with the surface, making it a pulling anchor. Additionally, some actuators were observed to pivot a body around an anchor point.

A different principle altogether is **rotation**. Here, switching anchor points is not necessary due to continuous circular motion that propels the body forward in one direction. This principle can also be found in many artificial forms of locomotion, e.g. wheels and electric motors. However, true continuous rotation requires axes, which is not viable for organisms, and, in our case, single-component actuators. Therefore, the only way to apply rotation is by rotating the entire locomoting body, e.g. **toppling** the body's centre of mass over a certain labile equilibrium so that gravity can rotate it the rest of the way towards a point where this process can be repeated. In this case, the reversal of the initial actuator does not reverse the motion as the gravitational momentum carried the body to a different position after the threshold was reached.

Anisotropic friction makes use of uneven contact surfaces so that movement in one direction will be subject to more friction than the reverse motion in the opposite direction. Even though the anchor points and the performed motion is the same in both forward and backward movement, the difference in friction will still net it a forward gain. The use of friction makes this principle less efficient than the others, and highly dependent on the type of terrain.

Lastly, all these locomotion principles (except pure rotation) make use of some form of **asymmetry**, i.e. the path taken by an actuator in one direction is different than the path taken in the opposite direction. Such asymmetry is necessary to create momentum and is ultimately the secret of locomotion. The asymmetry can be created through friction, a second (out-of-phase) set of actuators, or a labile equilibrium.

2.5) TAKEAWAYS

The analyses of 4D printing, FlexTECH actuation, and locomotion have provided numerous insights that will prove valuable in the following exploration of FlexTECH's potential. This conclusion will list the takeaways of the analysis by highlighting the opportunities and pitfalls of the current state of FlexTECH technology.

Opportunities: *where lies the potential that can be used to our advantage?*

- 4D printing mechanics can be used to simplify print jobs
- Smart materials can reduce number of necessary components, cutting down on failure rates, maintenance, and assembly.
- FlexTECH does not require an external load to program the material, as many other types of 4D printing do
- FlexTECH uniquely integrates the stimulus delivery method into the material and therefore does not rely on environmental heating
- FlexTECH uniquely makes use of local temperature difference instead of mismatching thermal expansion coefficients, which means the structure can be made from a single material
- FlexTECH actuators can be pre-shaped to increase their effectiveness.
- The Turtlebot utilises inefficient friction anisotropy and can be improved upon. By switching away from friction anisotropy the locomotion will become even less dependent on its environment
- Several locomotion 'principles' have been identified that could be applied to FlexTECH robotics
- Gravity can sometimes be used as an advantage in locomotion
- All forms of locomotion need some sort of asymmetry

Pitfalls: *what are the hurdles that we need to look out for?*

- No mathematic models to predict FlexTECH actuation exist as of yet
- Material changes in the glass transition range are hard to predict
- FlexTECH actuators need to be 'tethered' to a power supply in order to function.
- FlexTECH actuators are delicate. A single break will disconnect the circuit
- FlexTECH actuators are slow, taking tens of seconds or even minutes to complete the actuation cycle
- FlexTECH actuators are lightweight and might not support the weight their own battery.
- FlexTECH pre-shaping permanent deformation can only be performed once
- Stresses in the actuator will relax over time due to stress relaxation.
- Effective locomotion requires 2 planes of motion, while the printer is typically suited for only one plane.
- Many locomotion types utilise momentum, which is difficult to achieve with the current low speed of FlexTECH actuation.
- Printable conductive materials as well as 3D printers that can accommodate them are rare
- Undoing the actuation relies on passive cooling that can not be easily influenced.
- Glass transition effect also significantly weakens the material during actuation
- FlexTECH actuation is temporary. An actuator can't be kept in an actuated position for long because temperatures will equalize.

3) EXPLORATION

Now that the available information on the subject has been analysed, it is time for a thorough exploration of the identified potential in a period of ideation and tinkering. This chapter will feature all the explorative research that was performed with this goal in mind. Firstly, a demonstration of the new actuator design shows what improvements were made. What follows is a collection of several ideas for potential new features that make use of FlexTECH's properties and could make the technology even more unique. Afterwards, two conceptual robots show some of these features in action: A mannequin that moves into different 'poses' by assuming different configurations of its FlexTECH segments, and a new locomoting robot that does not rely on friction anisotropy. Additionally, an alternative production method based on screen printing that can synthesize FlexTECH actuatorsin the absence of a conductive material 3D printer is shown. The chapter will conclude with the Design Brief that decides on the final goal of the project.

3.1) ACTUATOR IMPROVEMENTS

Pretty soon after the start of the project, the default FlexTECH actuator design underwent some changes from its original design used in Maas's previous project. At this moment there was a lot of interest in adding a second heating element on the rim. This would not only make the actuator bidirectional by heating either layer, but it also spawned a new phenomenon that was dubbed '*ratcheting*'. Ratcheting will be explained in full detail later, but in short: it is the act of incrementally shifting the actuator's neutral position (like a ratchet gear) by alternately heating the two different layers, dramatically increasing the total range of motion.

Rim geometry

It seemed that bidirectionality and ratcheting would become a major USP for FlexTECH. To accommodate these features, the new actuator design was made to easily fit a second silver trace on the rim (Figure 24). The shape of the rim was altered to have the same surface area and thickness as the base. The only geometric difference between the layers is that the rim is divided in two sections on either side of the base in order to preserve symmetry. The trace pattern was divided in to odd-numbered loops so that the middle rim segment could easily travel around the base, while still maintaining an equal coverage pattern as the base.

These changes ensured that actuation in either direction was equally effective, embracing and applying the bidirectional property of the actuator observed in previous research. Several other different design options were also explored, such as swapping the height of the rim-and base, potentially making the overhangs easier to print. However, in this case it appeared that the Voxel8 *slicer* that was used to print the models produced some inconsistent print patterns that caused most of the overhangs to fail. Due to the limited customisability of the slicer, the other design was kept as the default instead.

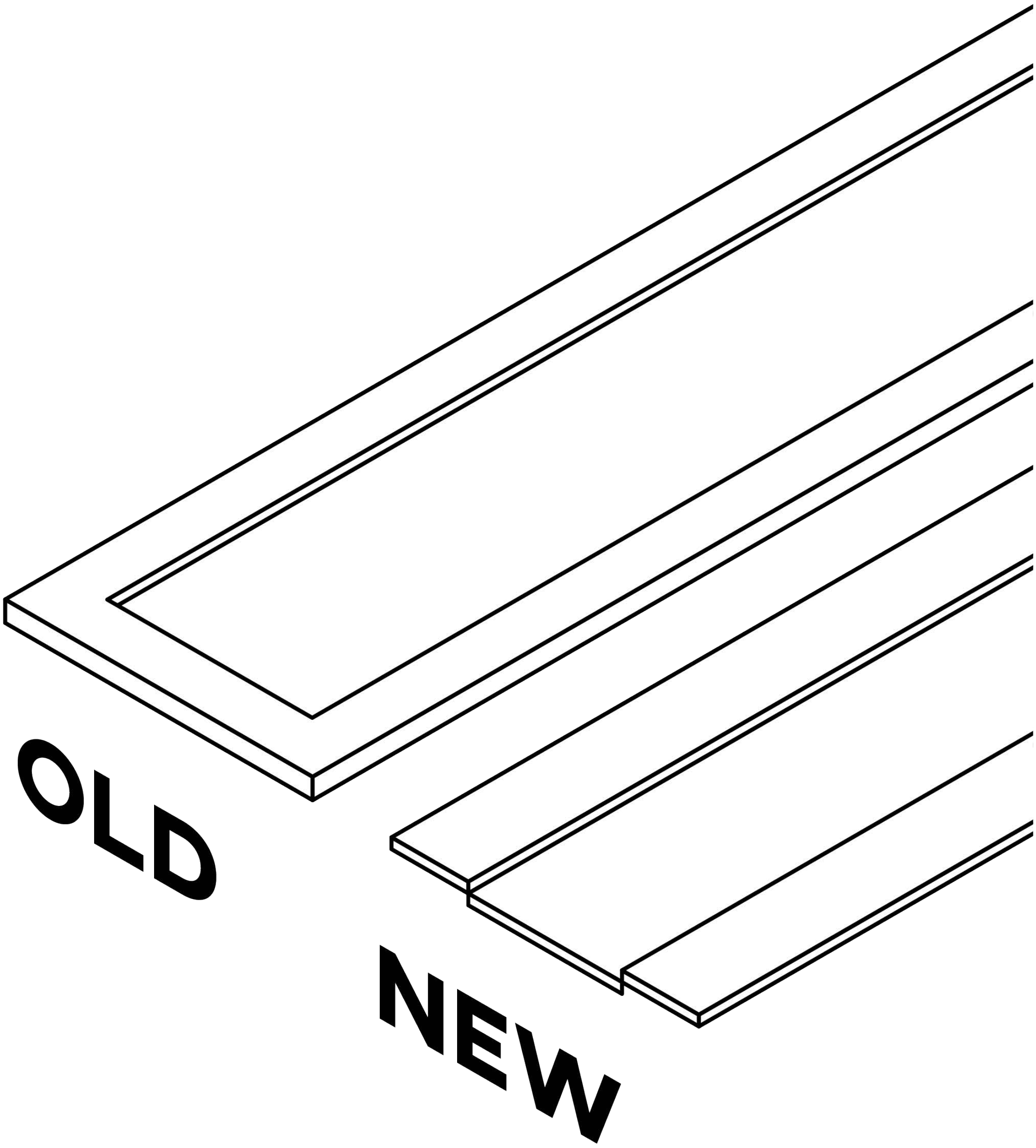
Layer overlap

Song-Chuan Zhao, collaborator and temporary mentor for the project, discovered that less overlap between the base and rim layers in the z-direction increased range of motion. The new design aims to minimise this overlap, maintaining only the necessary support structures required to print the upper rim layer. The distance between the support structures depends on the bridging capabilities of the 3D printer.

Miscellaneous

To assist with future iterations, the actuator design was made in a single parametric CAD model that could easily modify any geometry.

The connector block was redesigned in order to fit standard pin headers. These could then be inserted and glued in place post-print as the silver paste had not yet dried. This would save a lot of trouble as the trace disconnecting somewhere within the enclosed connector was a regular occurrence, and impossible to repair. It also allowed the wires to be easily disconnected.



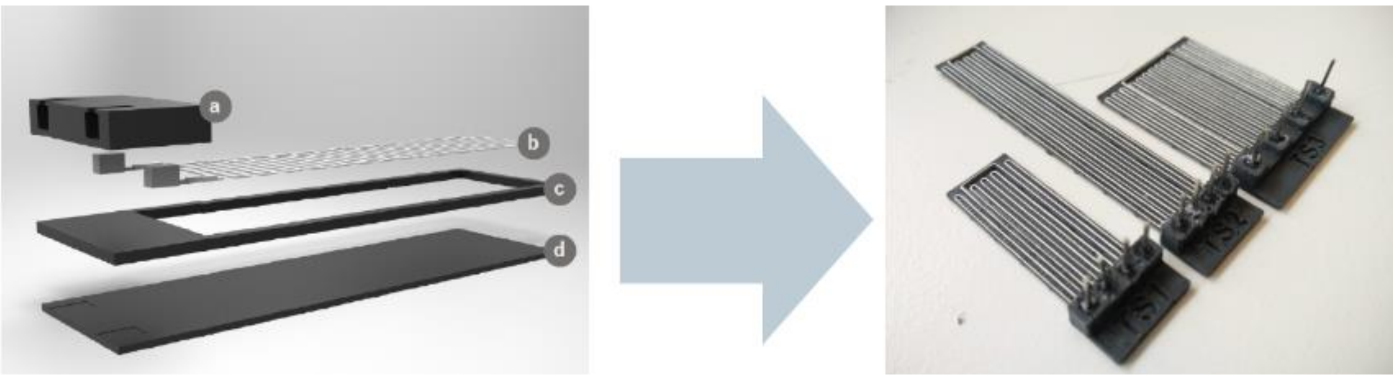


Figure 24: The old actuator design (left) versus the new actuator design (right)

3.2) FEATURE IDEATION

Simultaneously to getting familiar with FlexTECH technology and improving upon the design, the exploration phase also included ideation on potential new features that would significantly improve the FlexTECH robot. Some of the ideas and their considerations are presented here. A select few of the ideas were tested with prototypes afterwards.

3.2.1) ASYMMETRIC MOTION

Finding a way for the actuator to take different paths when moving back and forth would open up a lot of different ways to achieve locomotion, as asymmetry in motion was observed to be a core principle in virtually all forms of locomotion. Typically, this happens through the use of a hinge mechanism or some form of rotation. At a first glance, asymmetric motion with FlexTECH actuators might seem improbable: heating and cooling the actuator will make the material contract and expand in the same manner. But there are ways to circumvent this, even with a single actuator. **Error! Reference source not found.** shows a collection of ideas that might be used to achieve this result.

The easiest solution would be to attach two actuators end-to-end, and have them actuate asynchronously (see Figure 26). It is also possible to feature multiple circuits on a single actuator instead of two separate ones. This way each part of the actuator can be actuated by activating the corresponding circuit, creating asymmetry by activating the circuit at different intervals.

In theory it is possible to create asymmetry with a single circuit, though the effects would likely be minimal. By designing two different sections with distinct geometry, these sections can be made to have mismatching heating and cooling rates. Specifically, variables like volume, surface area, and contact-area with the trace would need to be tweaked.

Alternatively, any of the previously mentioned pair of elements could be positioned side-to-side rather than end-to-end. This would likely result in a movement pattern similar to rectilinear locomotion.

A more brute-force approach would be to force the motion along a path by locking a protruding pin in a slotted surface. A specially designed cam with angled surfaces would force the pin along different paths in different directions after it reached the end.

Finally, a slight change in starting position can be used to influence the direction of motion. When both sides are squeezed together, the crosslink bends up or down depending on which side it was already bending. All that is required is a small nudge in either direction when the crosslink is flat, which could potentially be performed by a different actuator.

3.2.2) INTRINSIC OSCILLATION

Intrinsic oscillation refers to the actuator regulating its own on/off cycle and was initially observed by accident during the previous project by Maas. When a silver trace broke due to stress from flexion, the disconnected circuit stopped the current, prompting the actuator to start moving back to its original position as it cooled down. In doing so, the broken ends of the trace moved closer together and reconnected to close the circuit and start the process over. This caused a perpetually oscillating movement.

Intrinsic Oscillation has the potential to replace the microcontroller and relay switches currently used to cycle the power source to control the heating cooling of the FlexTECH actuator. This feature would be a big step towards the robot's autonomy, useful in any FlexTECH robot or design, and a novel feature to showcase.

After gathering a couple of ideas, a core problem presented itself: the issue of the actuator becoming stationary at an equilibrium point. If, along its motion, there was a single fixed point where the power source would turn on or off, the actuator would likely reach an equilibrium due to the slow movement having virtually no momentum. To avoid this, the circuit should be closed for the complete range of motion in one direction, and open for the complete range of motion *in the other direction*. However, a solution for mechanically switching and detecting the *direction* of the motion, without any external components or electronics, proved to be challenging.

One example of a solution would be a *'gravity switch'*, where the movement of a FlexTECH actuator would 'tip over' a see-saw-like structure that would fall onto a different circuit and closing it with a conductive tip. The initial circuit that tipped the switch is now disconnected and will move back to its original position, while the other will now repeat the same process from the other side.

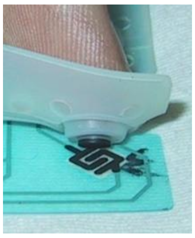
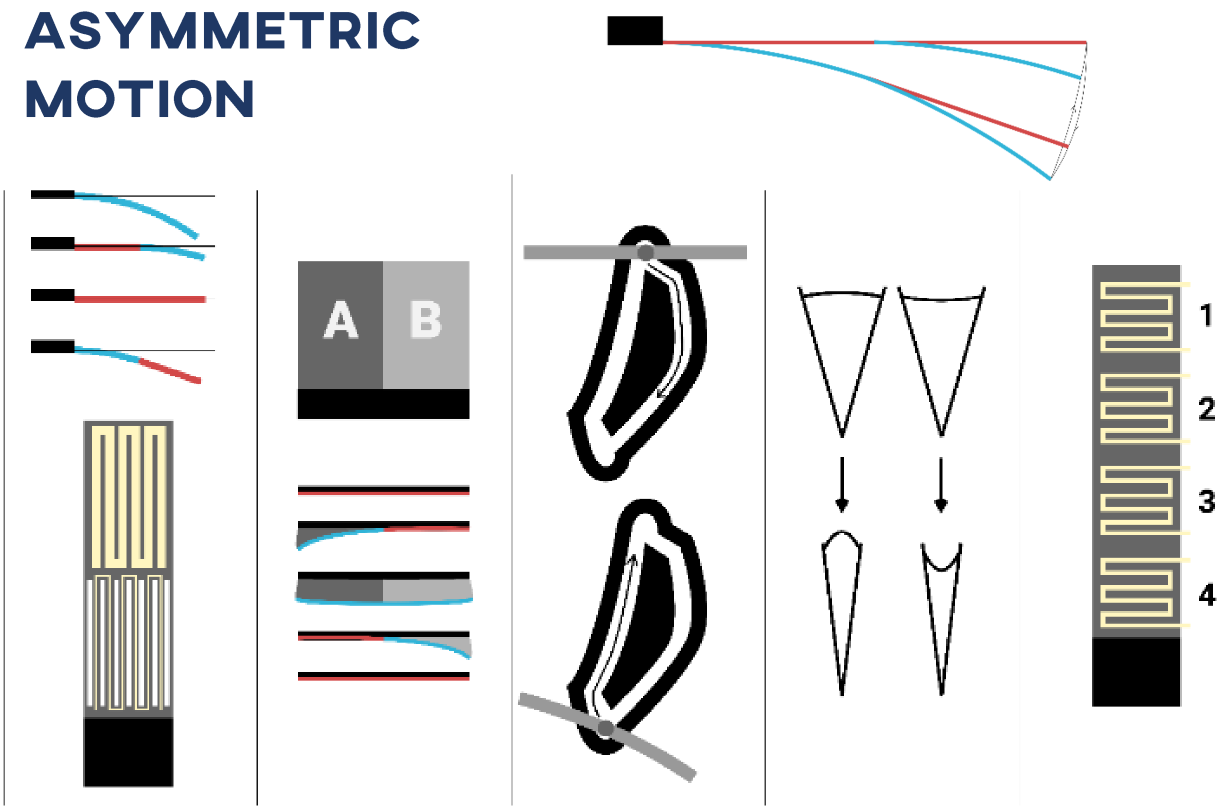


Figure 25: A membrane push-botton

The idea would require some form of pressure applied to the circuit to make a proper connection. It is reminiscent of a membrane push button (Figure 25). It is unknown if the actuating forces of FlexTECH would be strong enough to make a stable connection.

Alternatively, the switch could be achieved by pulling on a tethered lever.

Figure 26: Ideation for Asymmetric motion. From left to right: end-to-end heating asymmetry, side-to-side asymmetry, came guide, starting position, multiple circuits.



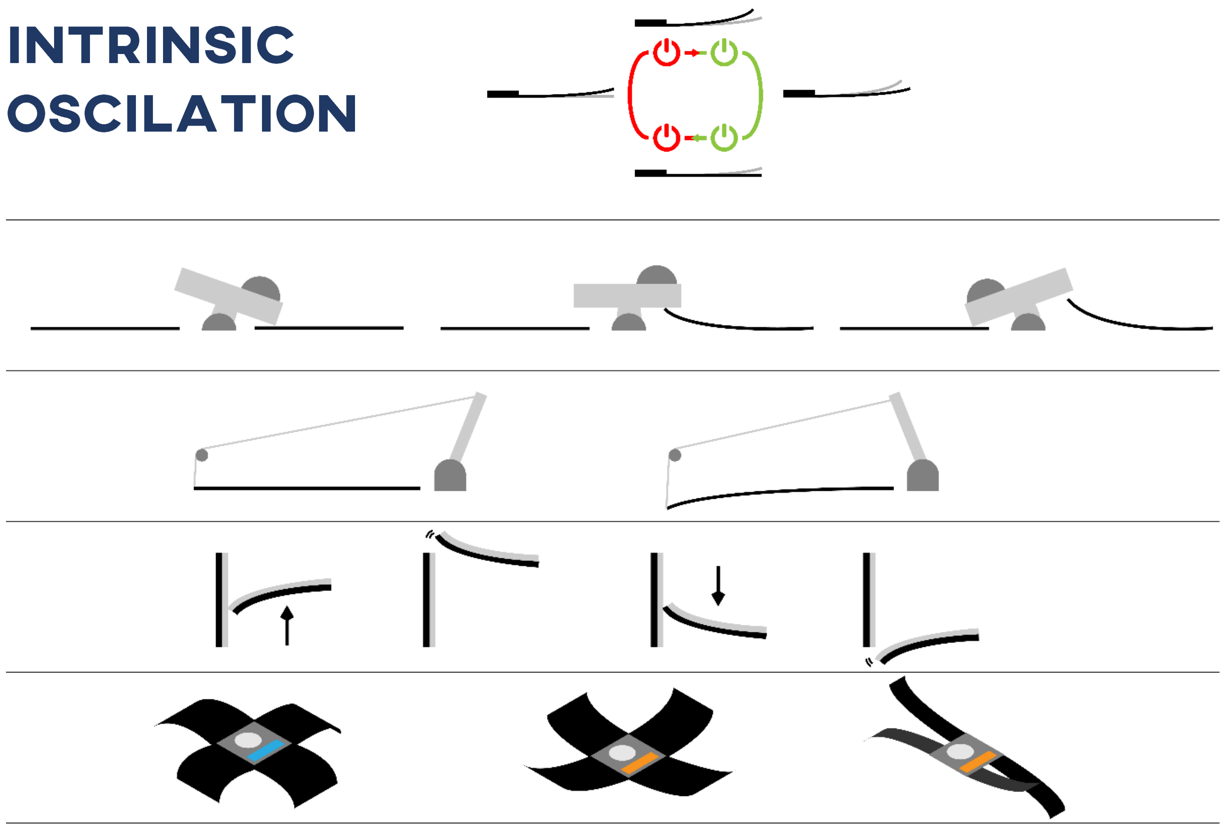


Figure 27: Ideation for Intrinsic Oscillation. From top to bottom: gravity switch, tethered lever, surface brush, 'blank-bots'

Another idea would be to make the actuator have a conductive and non-conductive side. By making the actuator brush against a conductive track, it would deform slightly, exposing one of either sides in different directions. The movement would encounter some resistance from the continuous contact. At the end of the track, the deformed actuator would spring free and be able to connect with the other side.

A completely alternative solution to intrinsic oscillation would be to create a miniaturised version of the electronics that is designed to be easily 'plugged in' to a FlexTECH robot. These 'chips' would contain the actuation instructions in the form of a microcontroller with an actuation script, relay switches, and a small battery to provide power, and would connect to the necessary trace circuits via pins. The chips could be switched out through a 'pick-and-place' approach, enabling the same FlexTECH robot to perform different movements according to what chip is plugged in. Alternatively, the same chip could be plugged into different FlexTECH robots for different results. The same effect could of course be accomplished by updating the script on the microcontroller, but the pick-and-place method would provide an easy to understand visual aid of physically swapping out the electronics.

Though not technically the same as intrinsic oscillation, containing the necessary electronics on the robot would still be a step towards autonomy and showcase the versatility of FlexTECH actuators.

Eventually it was decided to halt the exploration of intrinsic oscillation, because the topic was deemed too complex and time-consuming to fit within the scope of the project. Intrinsic oscillation would likely become the topic of a new research project instead.

3.2.3) RATCHETING

Ratcheting was discovered after a second circuit was added on the rim. By alternately heating the two layers, the amount of permanent deformation as a result of pre-shaping was seen to increase. The process could then be repeated for small stepwise increments of permanent deformation with every cycle. The cycle can also be executed in reverse order to reverse the effect. (Figure 28)

A more detailed explanation of the ratcheting phenomenon goes as follows: First, the base is heated above its glass transition temperature (Tg), and then cooled. If the temperature of the base were to be kept below Tg, it would normally return to its starting position when cooling. However, when the base is heated above Tg you can already see the actuator return to the starting position during the heating process. When the actuator then cools down it returns to the deformed state and stays there. Afterwards, the rim is heated to slightly below Tg. The actuator now moves farther in the same direction it was already deformed in, but because the temperature is kept below Tg, it returns to the same state once it cools off. At this point, when the base is heated again, it will no longer return completely to its original, flat position, but instead rest a couple millimeters away from it. As mentioned before, this process can be repeated to gain even more total deformation, or the heating of base and rim can be switched to ratchet in the opposite direction.

Through a lot of trial-and-error experimenting with different voltages and heating times, eventually a power

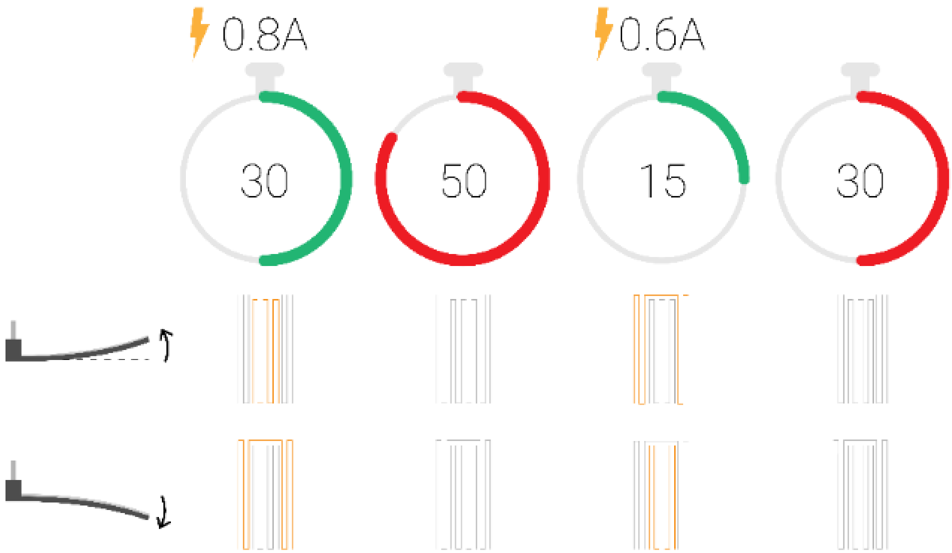


Figure 28: Instructions for a ratcheting cycle: The rim and base are heated alternately at different Wattages, for different durations

cycle was discovered that seemed to generally yield good results for ratcheting (see Figure 28)

Figure 29 demonstrates a notable difference between 2 samples, one of which has been subjected to 80 ratcheting cycles, the other to 10. The former has achieved much greater deformation, although it is also clear that the process is not linear as the total deformation is not 8 times as large. During some experimentation with these samples the ratcheting very obviously showed diminishing returns the more ratchet cycles were applied, and after roughly 80 cycles there was no noticeable difference registered by eye.

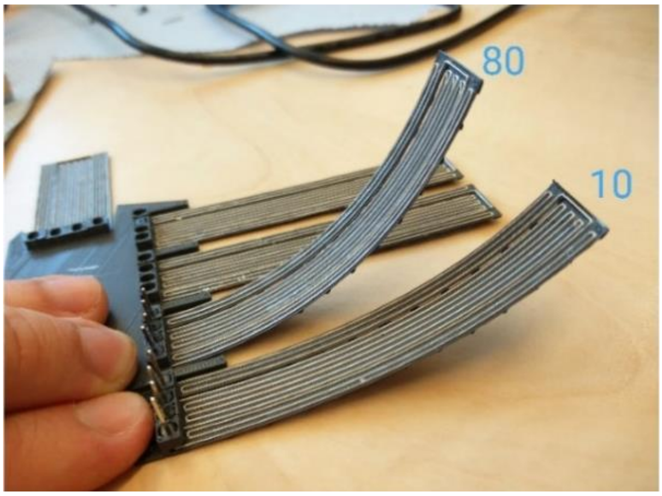


Figure 29: A significant difference in permanent deformation between two samples. One has been ratcheted 80 times (left) and the other 10 times (right)

Ratcheting was also discovered to be equally effective in either direction. Figure 30 shows two samples that have each been ratcheted 20 times, but in opposite directions. By doing so, a significant relative difference in deformation can be achieved in only a few ratchet cycles, whereas reaching the same relative deformation in a single direction would have required a lot more due to the diminishing returns.

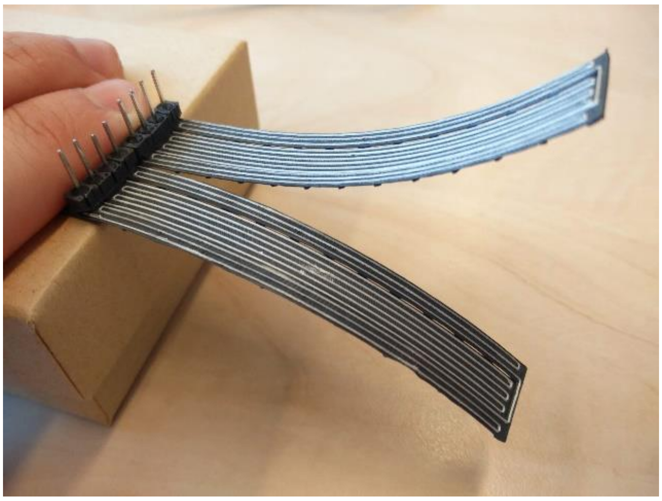


Figure 30: Both samples show similar ratcheting deformation in different directions

Ratcheting allows FlexTECH actuators to reach more significant bends and keep them there in a cold state while being reversible and effective in either direction. All that is required is to run the actuator through a number of ratcheting cycles, which takes some time (about 2 minutes per cycle).

The control over large, cold-state deformations could be demonstrated by making a single robot take on different 'configurations'. By connecting multiple samples together, each of them could individually be ratcheted to multiple different positions, creating different configurations with each combination. To make such a demonstration appealing, each configuration would ideally have an easily recognisable meaning. After an ideation session, 3 concepts were selected that would be able to convey easily recognisable configurations (Figure 31): A hand that makes different gestures, a body that assumes different poses, and a face that shows different expressions.

The facial expressions concept was disregarded because of its dependency on external components (such as a strings or cloths to form the mouth and eyes) and the fact that it needs multiple separate prints to be put together. It seemed preferable to have one single, connected 'test piece' that came out of a single print, as the lack of need for assembly is one of the USPs.

The hand gesture concept was initially attempted due to its perceived simplicity (see Figure 29). The intended gestures were a counting motion (holding up 1, 2, and 3 fingers respectively), and then ending in a 'thumbs-up' pose. A quick sample piece was designed and printed to test the feasibility, but it was quickly discovered that the maximum bend of the fingers did not really convey a (partially) closed hand.

The body poses concept seemed to pose a solution to this last issue, due to the advantage of bidirectional ratcheting mentioned earlier. The limbs in a body can move both forward and backward to form different poses, as opposed to fingers that don't tend to bend backwards. This way it is easier for the sample to gain a larger relative deformation.

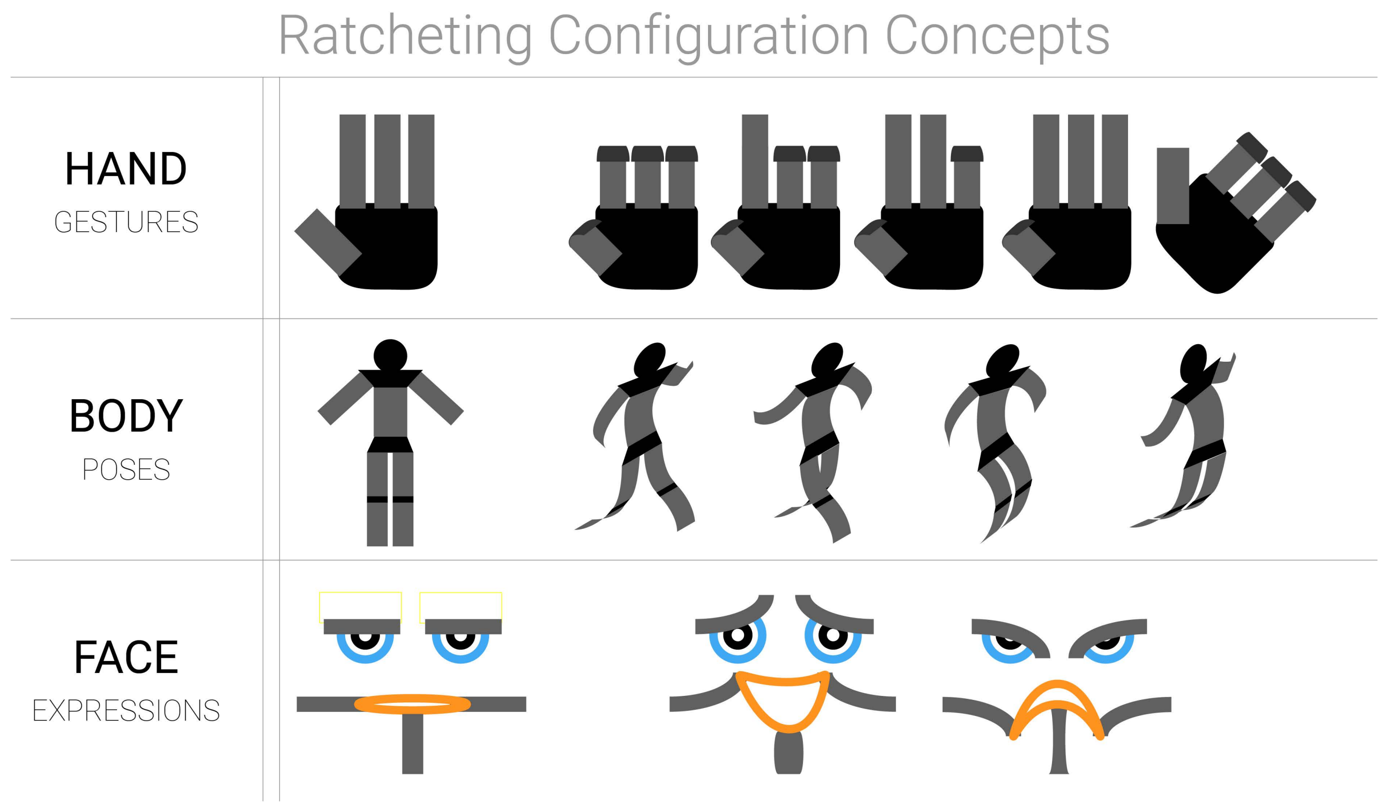


Figure 31 Ideation for different actuator designs that could illustrate meaningful configurations for different shape orientations

3.2.4) MISCELLANEOUS

The ideation resulted in more features apart from the 3 aforementioned ones. However, these were not as extensively researched or experimented with, mainly due to scope and time constraints.

Miniaturisation

Testing the limits on how small the actuator can be made while still functional could potentially enable applications in micro- and nanotechnology. The fact that the actuator features only a single component and has no need for assembly would be a big advantage for this field.

Torsion

By disrupting the balance of the forces and symmetry of the design it could be possible to create an actuator that would twist instead of bend. Doing so would add an extra dimension to the actuator and simplify the recreation of many types of locomotion.

Compliance-Controlled Composite

Thermal expansion is not the only effect of heating the material. When a material gets heated towards its glass transition range, some of its material properties change. The most notable of which is its stiffness, which causes the material to become more flexible as it is heated. A composite mesh of a glassy material and conductive material printed in such a way that it would heat all of the material equally would result in a composite of which the stiffness can be controlled by controlling the power input and heating the material in and out of its glass transition range.

3.3)-MANNEQUIN CONFIGURATIONS

To test the feasibility of ratcheting configurations, a prototype robot in the form of a mannequin was created, the design of which can be seen in Figure 38. The mannequin consists of 7 FlexTECH actuators: two for each leg, one for each arm, and one that spans across the torso to act as a spine.

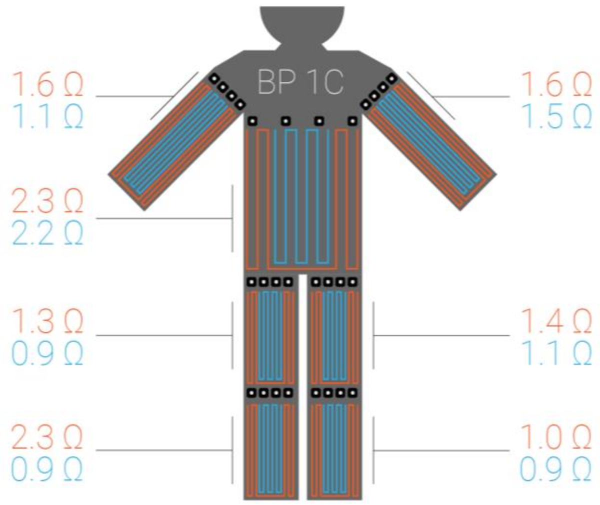


Figure 32: The design and measured resistance values of the Mannequin actuator design

It turned out to be challenging for the Voxel8 printer to get proper consistency on large prints such as these. Even after multiple iterations of printing the sample, there were multiple instances where the circuit was not properly closed around the pin headers. Such a broken circuit was only detectable after the sample had already been prepared and dried for 3 days. As a result, some of the actuators ended up not being operational in the final prototypes. In one case the torso and left arm failed to activate, in another it was the upper left leg.

To properly capture the movements, the mannequin was suspended in a custom-made photobooth, equipped with a mirror to show both a side- and ¾ view. To make a pose, each sample was ratcheted 20 to 40 times. With each ratcheting cycle taking around 2 minutes, the total time for a pose took around 3.5 to 5 hours. A camera was connected to the microcontroller to take pictures at regular intervals.

In the end, 3 different time-lapses were created (see Figure 33). The first shows a 'walking' animation where each segment was ratchet one by one in an order that looked similar to walking. The legs and arms would swing in different directions, and then back again. The goal was to ratchet the limbs back and forth to highlight the reversibility of the ratcheting process.

The second time-lapse attempted to ratchet all the actuators in a single direction as far as possible, putting the mannequin in a 'crouching' pose of sorts where all its limbs curled inwards. To save time, the bases and rims of

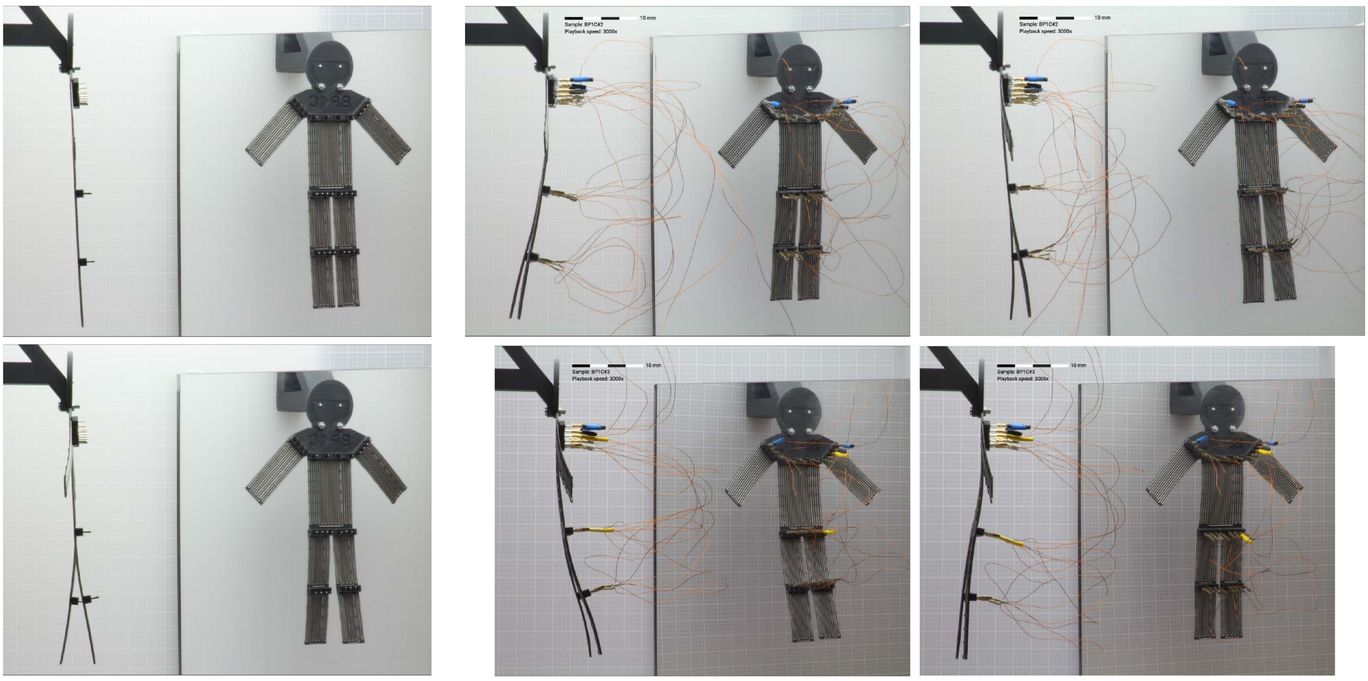


Figure 33: Stills from the 3 timelapses that show the moving mannequin.

each actuator were interconnected by wires to create two big circuits to ratchet them all at once. Some of the samples deformed slightly more or less due to the small inconsistencies in resistance values.

The third time lapse was an attempt to revert the ratcheting process. The ‘crouching’ pose was reversed into a ‘jumping’ pose that represented the mannequin pushing off from the ground. Towards the end some, samples were observed to deform significantly less from each ratcheting cycle.

In conclusion, Figure 34 shows the result of the different configurations. Typically, a 4D print requires the desired shape to be specified in the CAD design before the print, but the mannequin robot shows that a single FlexTECH design can take on different shape configurations depending on the inputs given after the print.

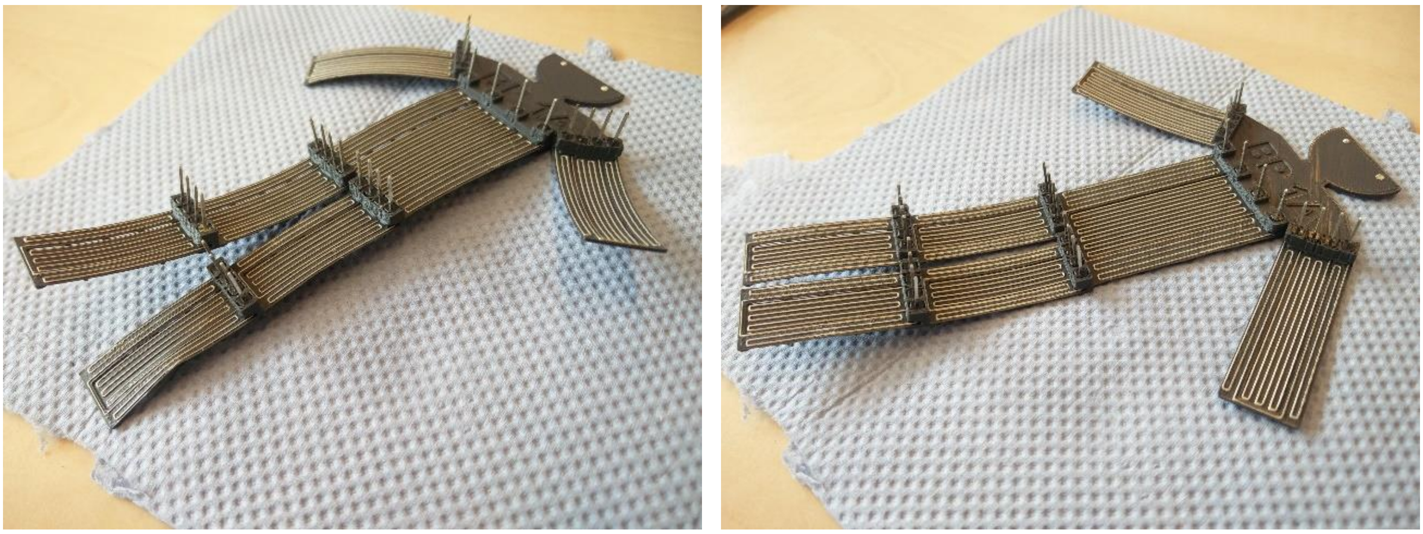


Figure 34: A comparison of configuration end results between 2 identically designed acutators.

3.4) LOCOMOTING ROBOT

An early explorative attempt at a locomotion demonstration was made to explore alternative ways to create asymmetric motion and gain a better understanding of FlexTECH-robotics as the robot's design went through multiple iterations.

The initial design was a fairly simple layout of 2 sets of 2 actuators arranged in opposite directions, with the actuators on one side pointing inwards, and the ones on the other side pointing outwards (Figure 35). The legs would alternate each other in diagonal pairs so that one set would 'catch' the returning motion of the other, negating its backward movement. Each pair would use the horizontal component of the bending curve to move the robot forward. In theory the order of activation can be switched to move in the opposite direction. This style locomotion was chosen for its simplicity and its independence from friction making it ideal for more types of terrain.

Unfortunately the robot was unsuccessful in gaining any horizontal movement because some of the legs failed to be lifted from the ground. A video recording of the prototype showed that some of the legs were not able to be properly lifted from the surface. The principle of the idea did seem to be working, as the legs that were lifted were shown to be 'scraping' against the surface in small rotating movements (see Figure 38). A Free Body Diagram (FBD) in Figure 36 illustrates the forces acting on the robot at rest. It shows that the leg that rests closer to the centre supports 11 times as much weight as the outer leg. By placing the 'foot' of the leg close to the *centre of mass* (CoM), it has to support almost the entire weight of the robot. This proved to be too much for a single actuator, and causes it to deflect enough so that the other pair of legs are not properly lifted.

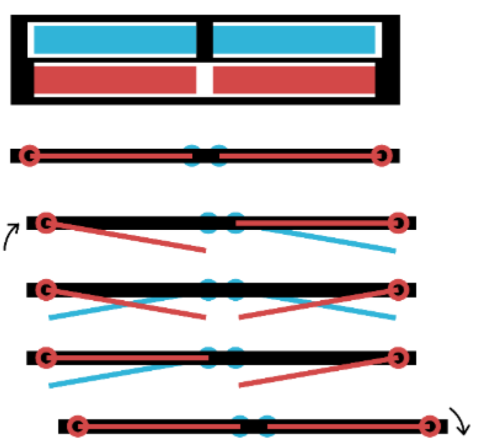


Figure 35: A locomoting robot design that moves its legs in diagonal pairs to move slightly to the right

The robot was redesigned by designating one pair of legs to be the 'lifting' legs, and one pair to me the 'pushing' legs. The pair of lifting legs was offset so that the CoM would fall roughly halfway between the two pushing feet (see Figure 37). However, this would make the CoM fall outside the support surface of the lifting legs, meaning the robot would backwards on its tail. This would make the robot's nose point upwards and may still allow the pushing legs to be lifted.

The design was tested with a prototype and recorded. The video showed the robot's body remained too close to the surface to achieve any real lifting of the pushing legs. Even so, a very minimal amount of locomotion was observed.

The robot was redesigned once more. The 'lifting' legs were put directly above the CoM so that they could lift the robot without tipping over to one side. However, since the CoM was not at equal distance from both the legs' lifting points, it would still result in the back leg performing most of the work. This would once again leave us with the initial problem of unevenly distributed weight, and as the prototype shows; the left leg was still not able to lift the robot with its increased workload.

Better dividing the lifting force between the two legs would mean that the CoM would have to be moved forward. Since removing mass from the back of the robot is not an option due to its minimal design, mass has to be added to the front. The first redesign kept the robot's total dimensions within the printer's build plate. Mass was added to the front in the form of metal screws (Figure 41). However, the increased lifting force proved too much for the actuators to handle. To minimise this the added weight, the mass can be placed as far forward as possible, where a small load can influence the CoM to a greater degree through the principle of leverage.

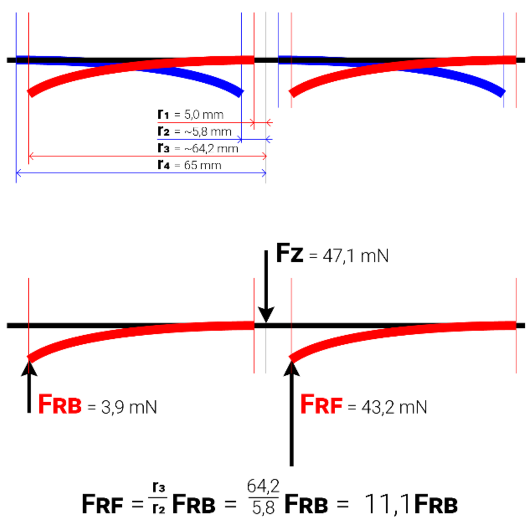


Figure 36: A FBD analysis indicating the difference in weight load between inner and outer legs of the robot

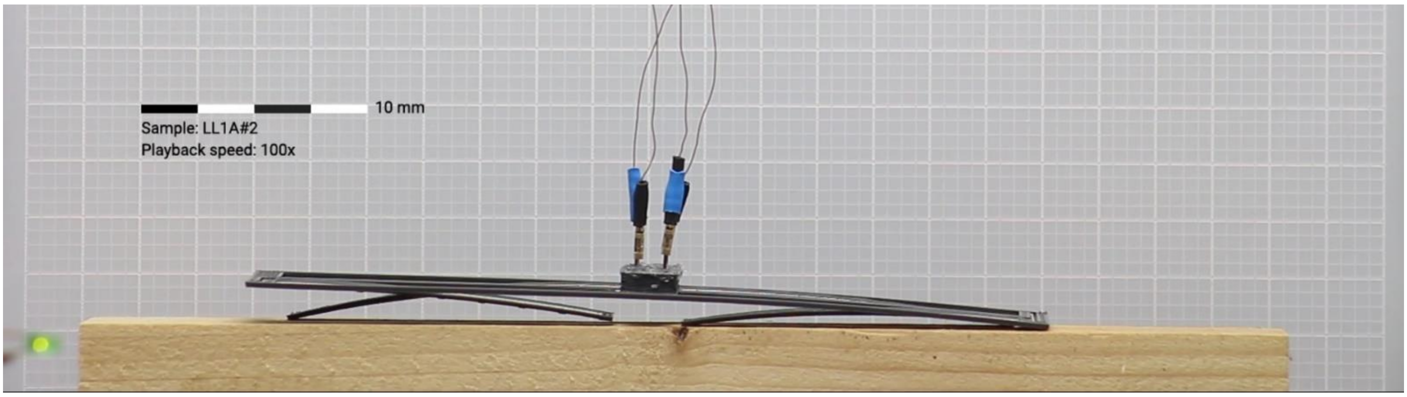
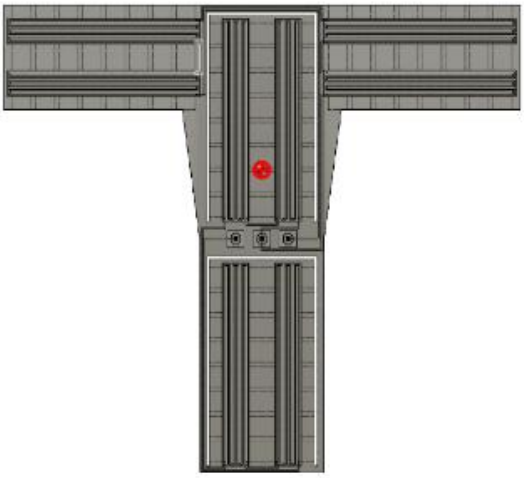


Figure 38: The first robot design struggling to lift itself



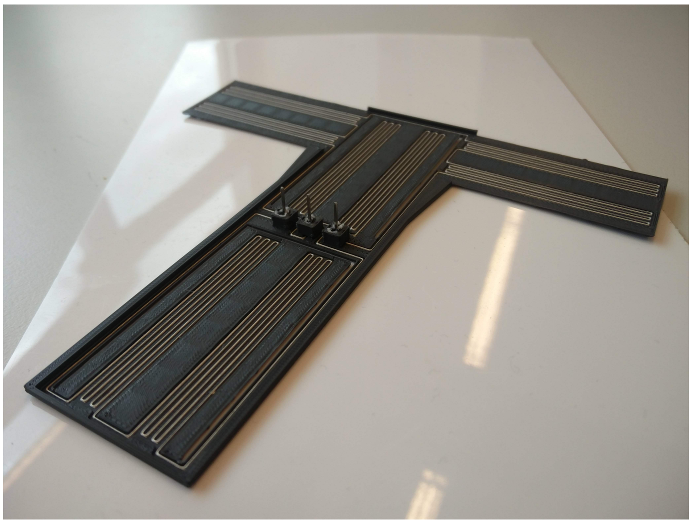


Figure 37: A redesign of the robot. It's centre of mass (indicated in red) is at equal distance from the two center feet

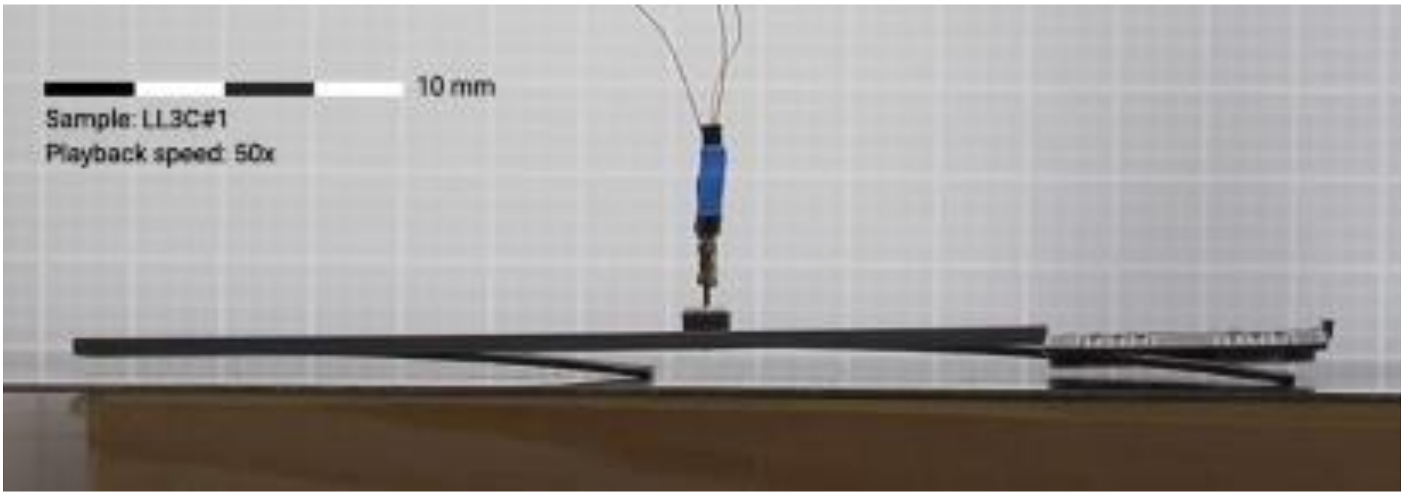


Figure 39: The second robot design lifting itself from the surface. Unfortunately, it was unable to clear its center feet when the weight was transferred to the two 'arms'

After multiple iterations without significant results, it seems the method with which the robot is trying to achieve locomotion is flawed. The horizontal component of the deformation arc proved to be too small to produce any forward movement, especially when factoring in the reduced deformation when the actuation is resisted by the robot's own weight. The actuators would need to actuate farther and with more force in order for this locomotion design to work.

In conclusion, it seems best to rely solely on the vertical component of the deformation. However, the robot needs to locomote horizontally. To create asymmetry we need at least 2 planes of motion. It's also important to keep paying attention to the centre of mass, potentially offloading some of the robot's weight by dragging it across the surface.

A proposed solution to this problem would be to create a design where ratcheting is applied to a part of the robot so that that part can be rotated, making it act in a more horizontal plane. Making a single print that could actuate in multiple planes is another way of putting ratcheting's increased deformations to use. In the current printing setup, FlexTECH actuators perform best when they are printed parallel to the build plate, and because the conductive material has a paste-like consistency it is very difficult to diverge from this orientation. However, using the mechanisms of 4D printing, ratcheting could be used to change the actuators orientation post-print.

Figure 40 shows a concept for a locomotion robot that requires actuation in 2 different planes but is made from a single component. Part of the robot 'self-assembles' into a different orientation, allowing the actuators attached to that part to act in a different plane.

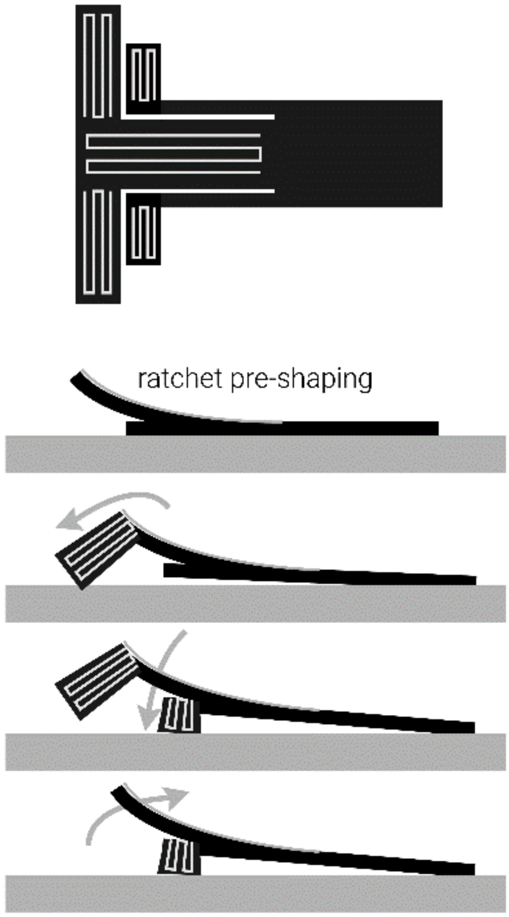


Figure 40: A locomotion concept that moves in 2 different planes and offloads some of its weight by dragging it.

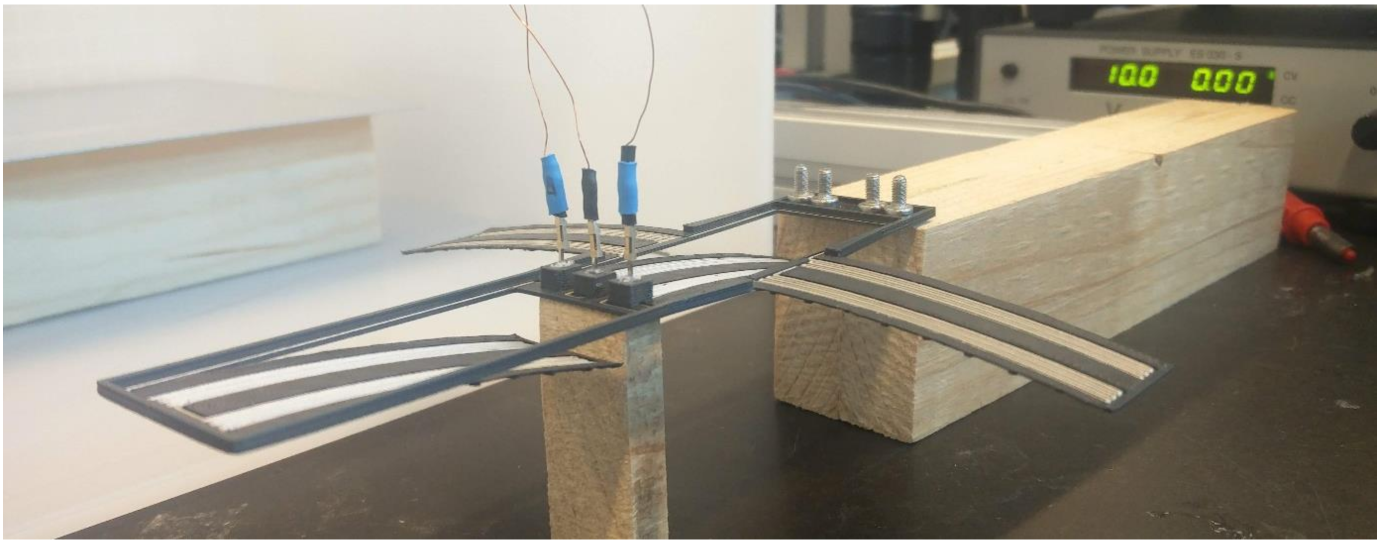


Figure 41: A final modification to the robot design contains added weight of screws at the front.

3.5) SCREEN PRINTING

Up until this point, the FlexTECH actuators were manufactured with the Voxel8 3D printer. The printer featured a standard filament extruder hotend and a hydraulic syringe system that allowed it to print the conductive silver paste sold by the same company. This unique multi-material system is allowed the quick and easy fabrication of FlexTECH samples.

Unfortunately, the Voxel8 printer stopped working during the iterations of the locomoting robot. Multi-material 3D printers that are able to print conductive silver paste are uncommon. The Voxel8 printer was the only printer available at the faculty at the time. Additionally, because the Voxel8 company had stopped supporting the printer model, no replacements parts could be ordered to repair the printer.

The printer's defect halted the project's progress, but also illustrated an important fact: The limited availability of conductive material printers could pose a big obstacle for future research. As a solution to this problem, effort was redirected from exploration to realising an alternative method of creating FlexTECH actuators. The following chapter will present the results of that effort, and will strictly focus on the step-by-step process of creating a screenprinted FlexTECH actuator. A more detailed explanation will be provided in a separate document. This supplement will provide more detailed descriptions, alternative options, and explain all the different considerations that went into the realisation of this production method.

Figure 43: An example of screen printing being used to print a poster

Screen printing

Screen printing is a technique where an ink is deposited onto a substrate by pressing it through a mesh or 'screen' (Figure 43). The screen contains a negative image of the desired result that is made impermeable to the ink, i.e. a stencil. This can be done by transferring a piece of vinyl onto the screen, or by use of photo-emulsion*. A squeegee (rubber blade) then wipes the ink across the screen, through the stencil, and onto the substrate.

> ** Photo-emulsion involves covering the mesh in an emulsion and hardening the emulsion by exposing it to ultra-violet light. A transparent sheet containing an opaque positive is interposed during the hardening to keep parts the positive shape soft. When the soft parts are washed away, the negative (stencil) remains*

This method is mainly used for printing inks on products such as posters and T-shirts, but has also seen use in Printed Electronics. Most notable, the fabrication of Printed Circuit Boards (PCB) often employ screen printing to deposit etch-resistant inks onto a substrate that will later be chemically etched to expose the conductive layer underneath the surface.

Screen printing is relatively simple and is able to accommodate paste-like materials, making it a good candidate for alternative FlexTECH actuator production. In our case, we will be printing the conductive paste directly onto the 3D printed substrate. Because the conductive material is costly and difficult to clean, no screen will be used. Rather, the vinyl stencil will be placed directly onto the substrate. This requires a new stencil for every print, but saves on material and cleaning efforts, a trade-off that is more favourable for our very limited production run.

Substrate

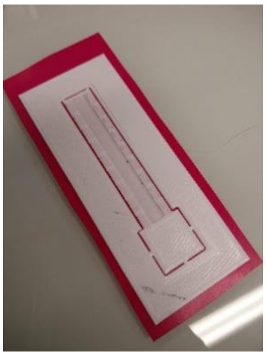


Figure 42: A 3D printed substrate attached to a bounding frame

First, the bi-layer substrate is printed using a regular FDM 3D printer. This process of PLA printing is the same as before. The conductive trace that will be printed later is very thin. Any small cracks or artifacts on the substrate surface can cause interruptions in the trace. It is preferable to have the substrate surface as smooth as possible. This can be achieved by 3D printing the substrate onto a smooth surface such as a glass heated build plate. The screen print also needs to be level to avoid any bumps or deformation in the stencil. Printing a frame around the substrate of equal height ensures the squeegee can move smoothly across the substrate.

Stencil

Figure 44: A substrate covered with a vinyl stencil containing a positive of the trace

A digital line drawing of the trace can be made into a stencil with a vinyl cutter. Through trial and error it was discovered that each line should have a minimum width of 0.6 mm, or else the vinyl will come loose during cutting. A piece of vinyl has one adhesive side that is attached to a release liner. The vinyl cutter cuts the vinyl, but not the release liner. The positive image is then removed by hand, and the stencil is transferred onto a piece of transfer tape with an adhesive backing. While the vinyl is stuck to the transfer tape, the release liner can be peeled off, exposing the vinyl's adhesive side. The vinyl stencil can then be transferred onto the substrate. It is crucial to properly line up the stencil with the substrate to ensure the trace is printed correctly. Small alignment holes that line up with the edge of the substrate can be put into the stencil design to assist with this. Finally, the transfer tape can be carefully removed, resulting in a substrate covered by a stencil.

Printing

Figure 45: A substrate with stencil after the print. Excess silver paste collects in the inconsistencies of the substrate

As the silver paste is hazardous, the printing takes place in a secure room with proper ventilation and proper equipment like nitril gloves, safety goggles, and lab coat. Protruding parts of the adhesive vinyl are used to secure the substrate to a workbench. A small amount of silver paste is deposited at the top of the stencil. A squeegee is used to smear the paste over the stencil in a swift motion while applying some force. For better results, a second smear can be performed in the opposite direction from top to bottom. The stencil is then peeled away from the substrate. This has to be done quickly while the paste is still wet and soft. The sample is then left to dry overnight.

A pair of copper wires can be attached to the trace by inserting them into the wet paste after the printing process (applying some extra paste as necessary. The connection points are covered with a piece of tape to secure them during the drying process. Finally, the actuator can be removed from the frame.

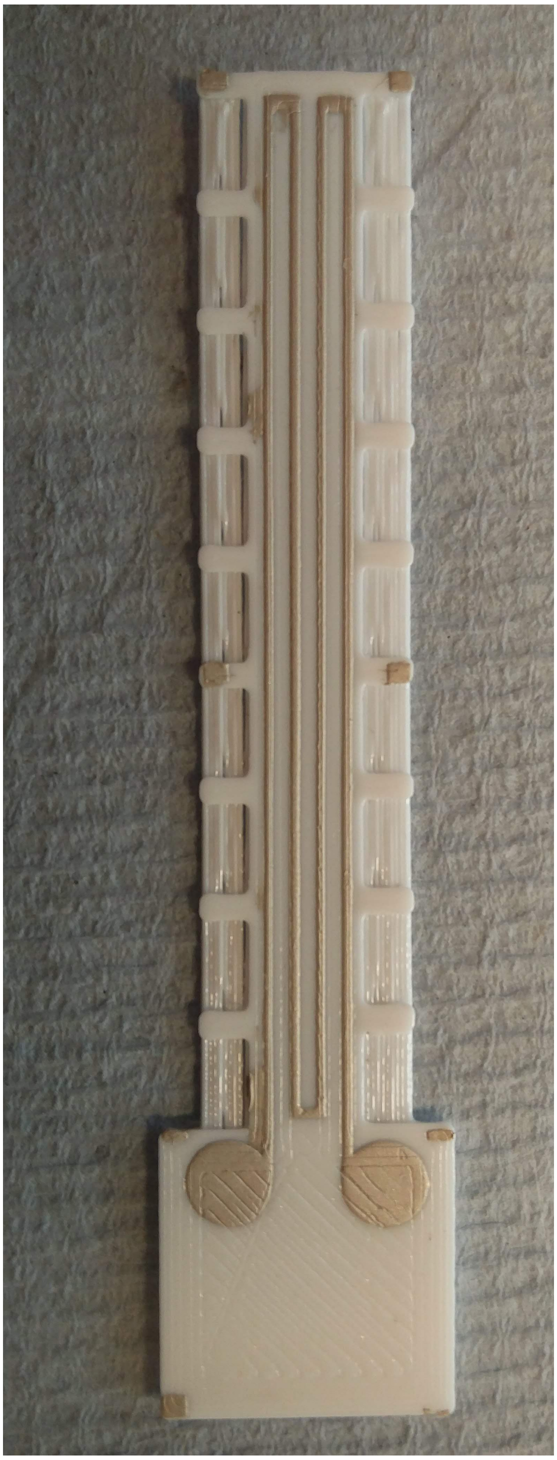


Figure 46: The final result of a screen printed FlexTECH actuator

Results

A quick test shows that the screen-printed samples perform well. Their deformation is similar to, if not greater than, what was observed with the 3D printed samples (see Figure 47). However, printing the trace by hand is very time-consuming and more prone to errors.

A comparison in shows the consistency of the final resistance of both screen printed and 3D printed samples. The screen-printed samples seem to have a decent consistency, save for the occasional outlier (Figure 49). It should be noted that the absolute resistance values differ quite a bit. As the conductive material supplied by Voxel8 was no longer available, a different conductive material was used (*SunChemical C2081126P2 Silver Paste*). Aside from the material having a different resistance, the dimensions of the trace were also different. With screen printing, trace height is limited by the stencil thickness; roughly 0.1 mmm, and width by the aforementioned limit of 0.6 mm imposed by the vinyl cutter. With 3D printing, width is determined by the nozzle size (~0.4 mm). Trace height is unlimited in theory, but in practice will likely sustain only a few layers before the paste structure collapses. See Figure 50 for a comparison of the different trace variables, and Appendix B for details on the Voxel8 trace dimensions.

An unfortunate side-effect of the new screen printing method is that printing can only be done on 1 surface, which means a second trace for the rim is left out. This second trace is required for bidirectionality and ratcheting. Adding a second trace can likely be done in one of two ways. Either the printing process is repeated on the other side, ensuring a smooth surface and being careful not to damage the first trace, or the layers can be printed separately and later joined together (see Figure 48). Both of these methods pose additional challenges and require more development into the production. Unfortunately, there was no time left in the project to develop the production method even further, so the realisation of a second circuit will have to be left to a future project.

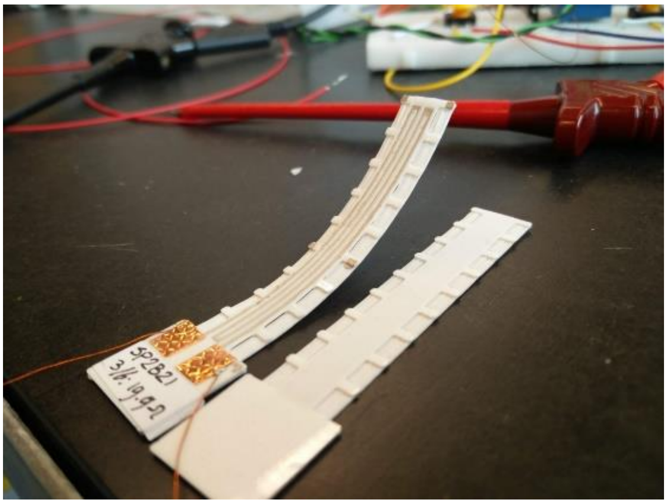


Figure 47: A screen printed actuator in action

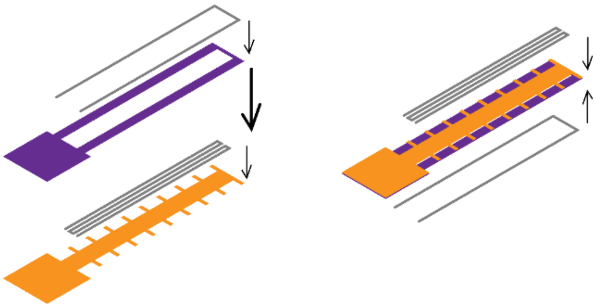


Figure 48: An illustration of the steps required for an actuator with a circuit on either side

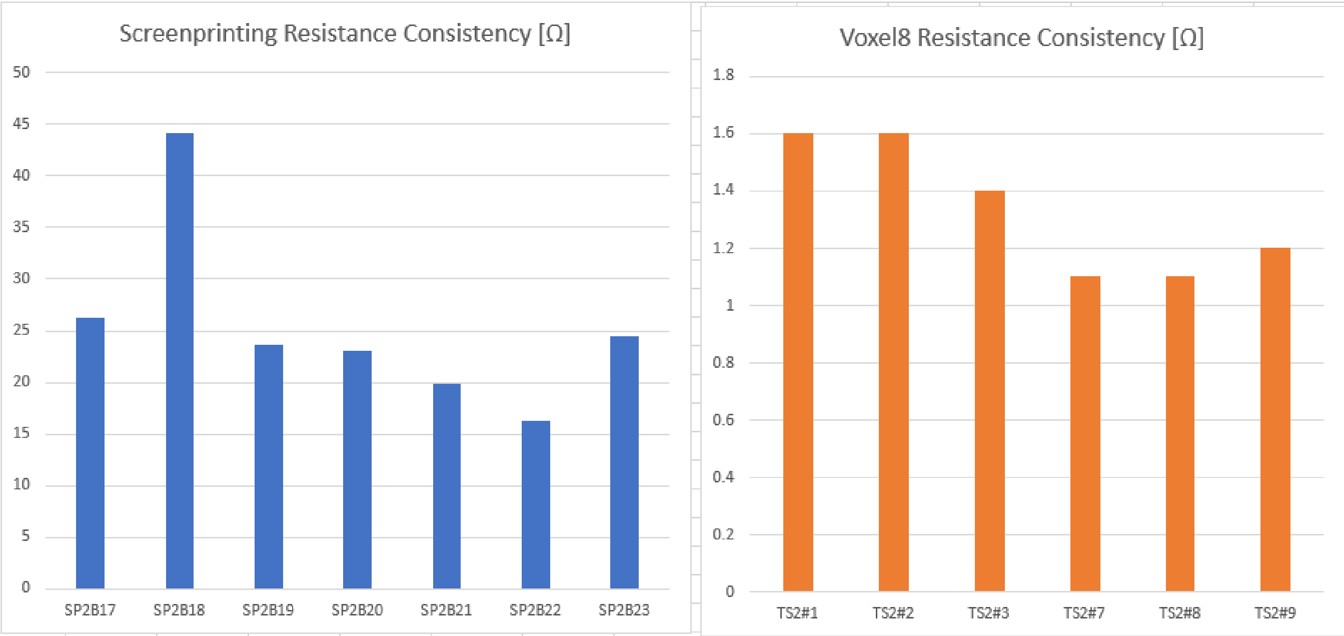
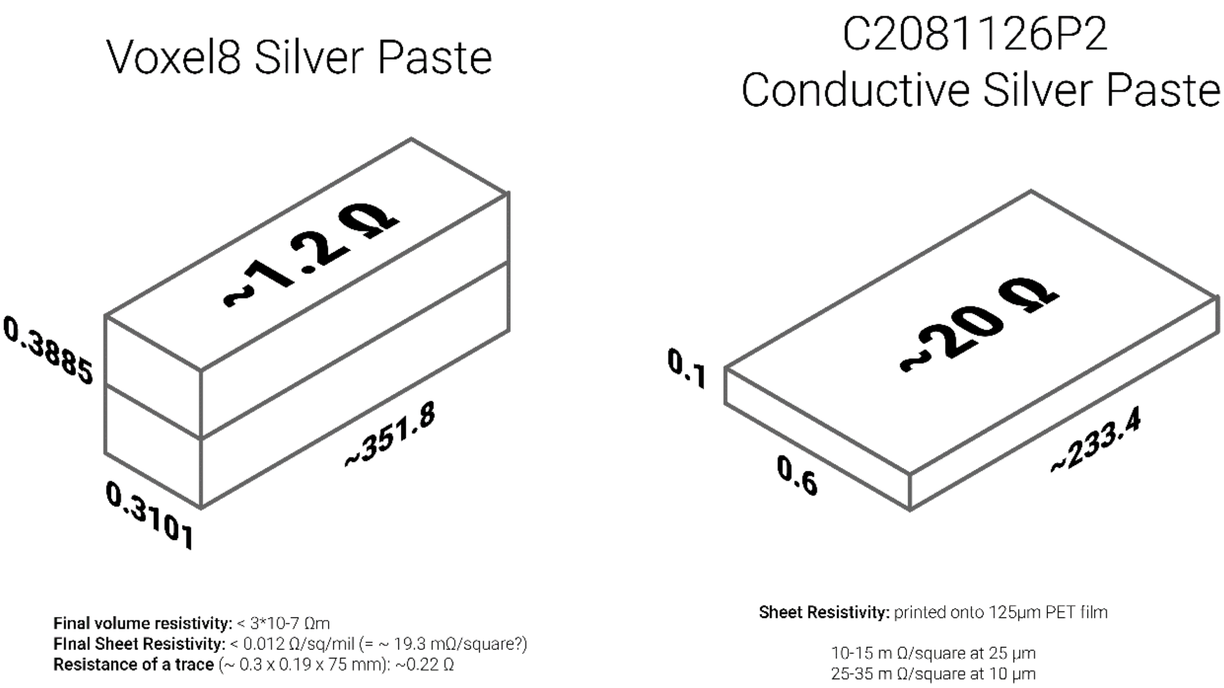


Figure 49: Resistance values for various different samples



F Figure 50: A comparison of trace dimensions and variables of the two conductive pastes used in 3D printing and Screen Printing

3.6) DESIGN BRIEF

When the project first started, the goal was to create a new and improved demonstrator that showed even more unique features than the Turtlebot, with the intent of creating intrigue and interest in FlexTECH technology, specifically among future designers.

The defect of the Voxel8 was a big setback for this goal. By having to switch to the manual screenprinting method, design iterations became more difficult and time-consuming. Ratcheting, the most promising feature, was no longer feasible. Creating a new demonstrator at this point would likely not have been as impressive. Nevertheless, a conductive smart material that offers real-time control has a lot of potential, even well beyond locomotion and robotics.

The ultimate goal of creating interest in FlexTECH technology is for other researchers and designers to pick up FlexTECH actuation and investigate the unexplored potential that is far outside the scope of this project. To facilitate this, we can do more than just another robot demonstration.

A fellow designer might be intrigued by a demonstration, but not have the means available to follow through and participate in the development. Even in this very project, progress was halted when the only available conductive material 3D printer broke down. But, by developing an alternative method like screenprinting, the technology becomes accessible to those without such a 3D printer. Similarly, the many iterations of the 2 concept robots showed that it is difficult to build and experiment with a new technology where many variables are still unknown. Additional quantification of FlexTECH properties would facilitate the design process and encourage designers to consider FlexTECH as a potential option for future design challenges.

What we need is a comprehensive and actionable set of **design guidelines** that provide the necessary tools and knowledge that decreases the barrier to entry. Such guidelines should meet the following demands:

- The guidelines should provide enough information for a designer or researcher to understand the phenomenon and its core principles
- The guidelines should include instructions on how to construct a FlexTECH actuator
- The guidelines should include instructions on how to properly control FlexTECH actuation
- The guidelines should keep into account potential modifications of the technology in case someone wants to experiment with different tools, materials, or design.
- The guidelines should be inspiring and mention relevant subjects for future research
- The guidelines should be presented in a format that is easy to ready and quick to understand, without having to dig through multiple pages.

Design Guidelines are particularly useful to people already interested in the technology, but a demonstration with a physical prototype will always be more effective at capturing that initial interest than a set of guidelines. As such, the final result should still include a new and improved FlexTECH-robot. The purpose of the robot will be as follows:

- To serve as a demonstration of what FlexTECH is capable of
- To validate the Design Guidelines
- To test the effectiveness of actuators produced with the new screen printing method
- To demonstrate a more effective form of locomotion that doesn't rely on friction

The rest of the project will focus on the realisation of this goal.

4) MODELLING

The necessary knowledge for the design guidelines will be modelled through a series of experiments. Quantification by means of a mathematical model is difficult, as the material properties are very unpredictable around its Glass Transition Temperature. In this chapter, three important performance parameters will be quantified by the results of the experiments: Deformation, Temperature, and Force.

Deformation is naturally the desired output of a FlexTECH actuator, or any actuator for that matter. The amount of deformation that can be achieved will ultimately determine the actuator's potential applications. Getting a good overview of the amount of deformation the actuator is capable of will assist in tuning future designs to achieve the amount of deformation they need and allow more accurate estimations of where and when FlexTECH actuators could be useful.

Temperature (specifically the *temperature difference* between the two layers) is the driving force behind the deformation that occurs. Linking the resulting deformation to the acting temperatures is crucial to calculating the system's input so that the actuator can be controlled effectively.

Force produced by the actuation is also relevant when considering applications. Especially in the case of locomotion, where the actuators need to lift themselves, the force-to-weight ratio is essential in the design of the robot.

3 experiments were designed in order to collect useful data on these 3 parameters. The *'DTR-Experiment'* measured deformation, temperature, and resistance simultaneously at various power inputs to link these parameters to each other. The *'Tg-Experiment'* repeats the test within a small power range to pinpoint the exact conditions at which permanent deformation occurs. The *'Force-Experiment'* measures the force produced by the actuator. Various other minor experiments and measurements that were performed during the experimentation phase and contain useful observations will also be discussed.

The following subchapters will briefly explain the most important methods used for each experiment and discuss the results. For a more detailed breakdown of each testing setup, see Appendix B.

4.1) DTR-EXPERIMENT

The DTR-Experiment measured **D**eformation, **T**emperature, and **R**esistance simultaneously. The sample is mounted in a clamp that is mounted sideways to ensure gravity does not influence the deformation. An optical camera records a top-view of the sample , while a thermal camera records the sample from the side (Figure 51). The sample is actuated with varying power inputs. The power input is kept consistent with a PID controller. The video recordings are run through analysing software to produce the final data. Resistance is calculated by reading the voltage supplied by the PSU. The experiment was performed with 2 different screen-printed samples: W3 and W4. The W4 sample was run through the experiment twice.

- Overall results can be seen in Figure 52 and Figure 53
- The results from a pilot test can be found in Appendix C
- If a specific sample is not specified, the value is the average of W3 and W4

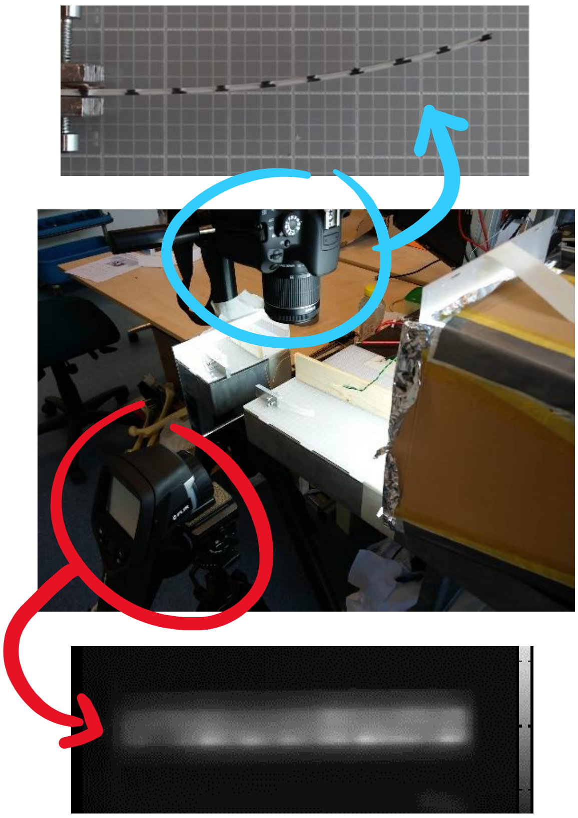


Figure 51: An overview of the test setup, and the corresponding camera views

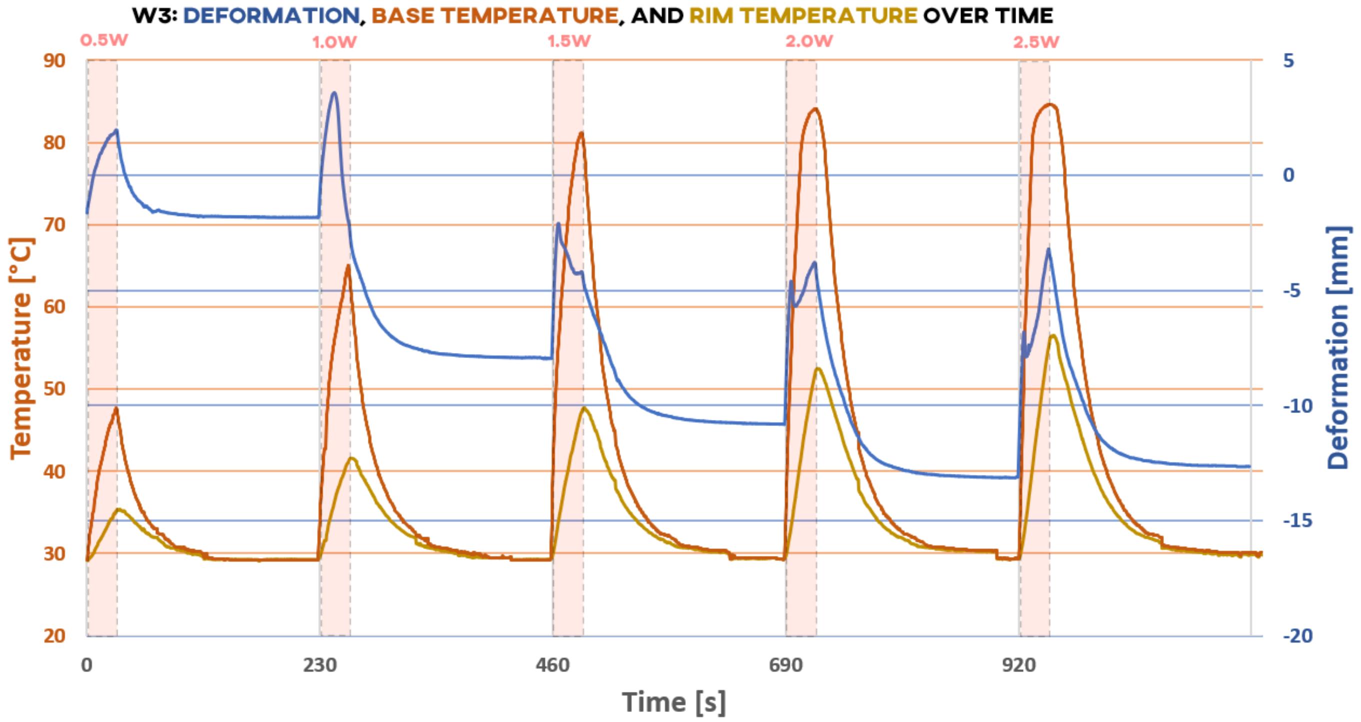


Figure 52

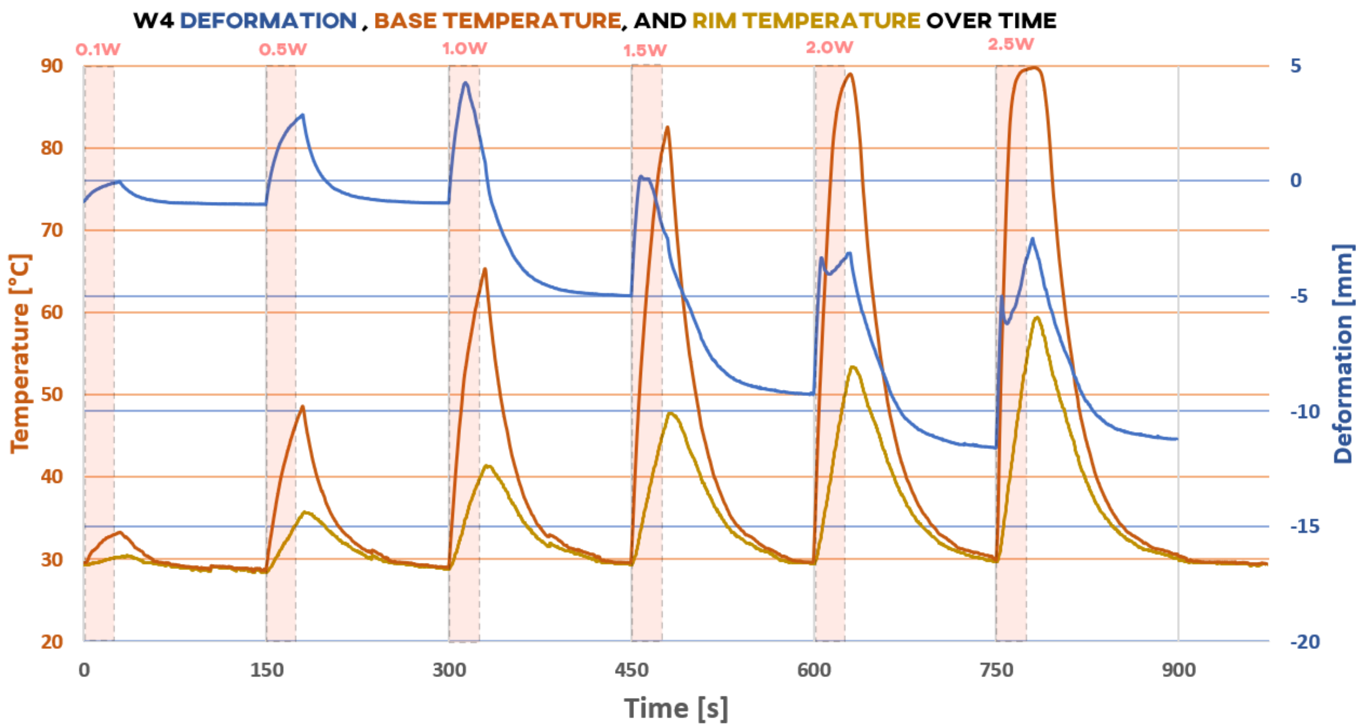


Figure 53

Temperature:

- Figure 54 shows the maximum recorded temperatures for each of the heating cycles.
- Figure 56 shows the average base temperature over time for each cycle.
- Figure 57 shows the average temperature difference between base and rim for each cycle.

The samples first reached their Tg of ~56°C during the 1W cycle, with an average base temperature of 65°C. At 2.5W, even the rim temperature gets to just above Tg.

The recorded temperatures were very consistent between the two samples. The disparity in the high-power cycles is due to the fact that the two experiments had the thermal camera set to a different upper limit (85 °C and 90 °C for W3 and W4, respectively). In both cases, the temperatures turned out higher than expected and the upper limit was not sufficient. This is especially visible in the temperature difference graph. It shows the temperature difference between rim and base decrease during heating for both the 2W and 2.5W cycle. The more likely explanation is that the base reached the thermal camera's upper limit, while the rim temperature continued to climb. In reality, the base temperature will have increased as well, and would have resulted in a smooth curve like the other cycles.

Figure 57 illustrates that a higher power input results in a larger temperature difference. A faster heating rate allows less time for the heat to conduct from base to rim, thereby increasing the relative difference. *Figure 55* shows the heat diffusion in the sample for both a low and high power input. The strong contrast shows that the heat does not have time to diffuse throughout the base layer. When taken to extremes, this could result in very high localised temperatures, inside the trace and in the areas directly attached to it. In earlier tests, going beyond 3 W would occasionally result in a sample short-circuiting by reaching a local temperature so high the PLA started to melt.

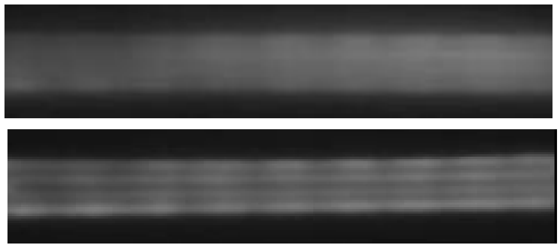
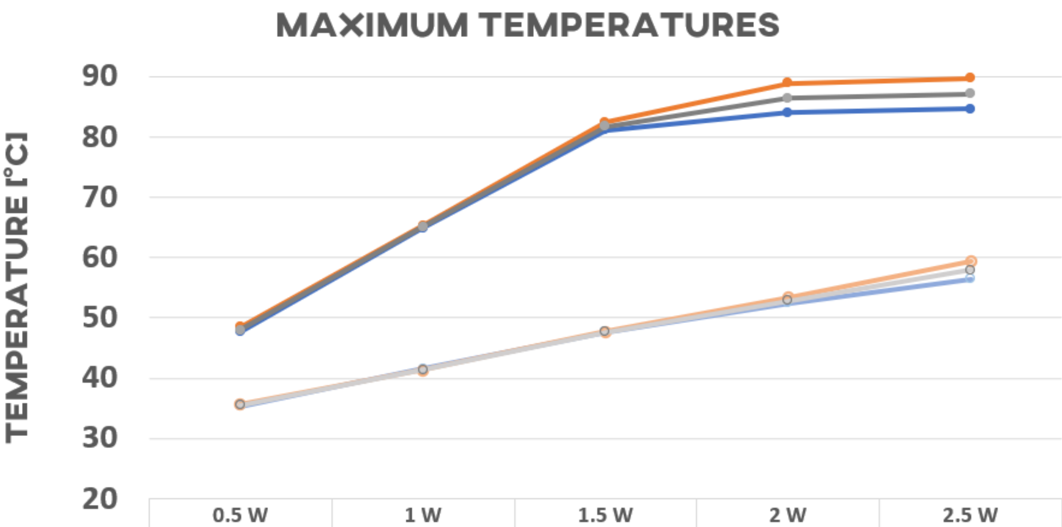


Figure 55: Thermal images of W4, showing the difference in heat diffusion for a sample heated with 0.5W for t = 27 seconds (top) and a sample heated at 2.5W for t = 3.5 seconds (bottom). In both images, the average Base Temperature is ~48°C



	0.5 W	1 W	1.5 W	2 W	2.5 W
W3 Base	47.68	64.99	81.18	84.11	84.66
W4 Base	48.54	65.26	82.51	88.97	89.74
AVG Base	47.96	65.12	81.76	86.49	87.20
W3 Rim	35.33	41.56	47.69	52.49	56.52
W4 Rim	35.72	41.35	47.75	53.39	59.37
AVG Rim	35.52	41.44	47.70	52.89	57.92

Figure 54

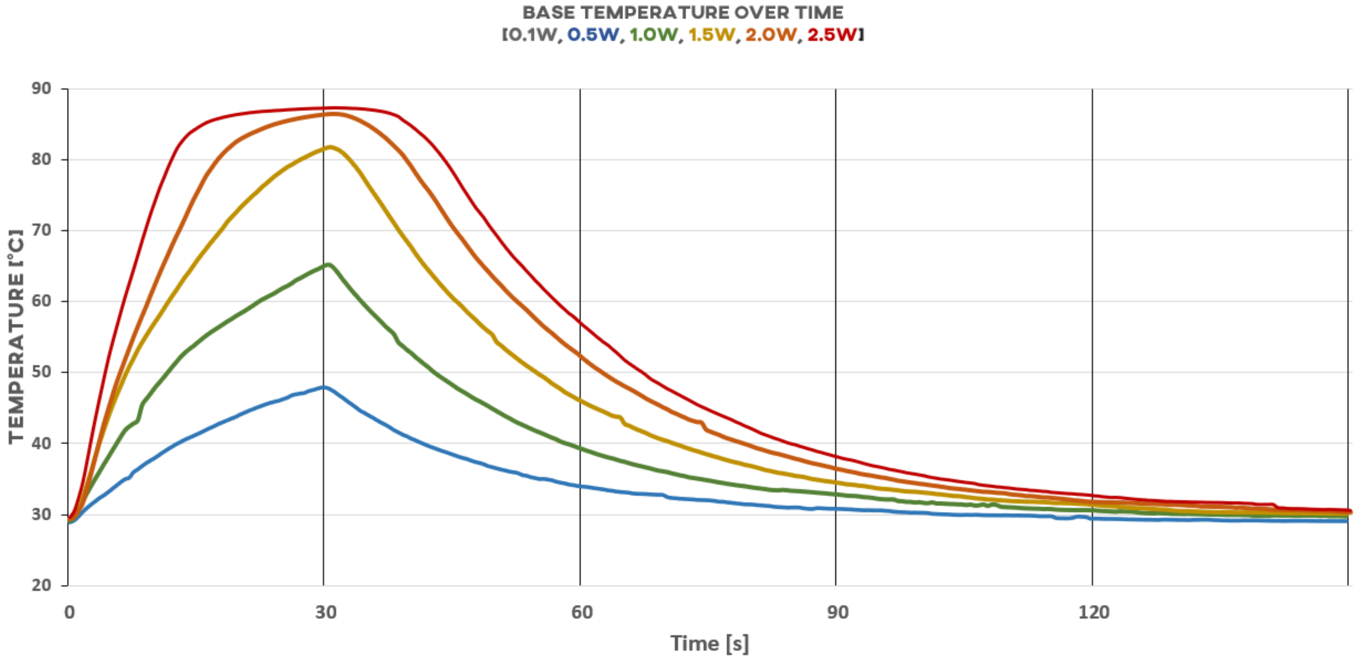


Figure 56

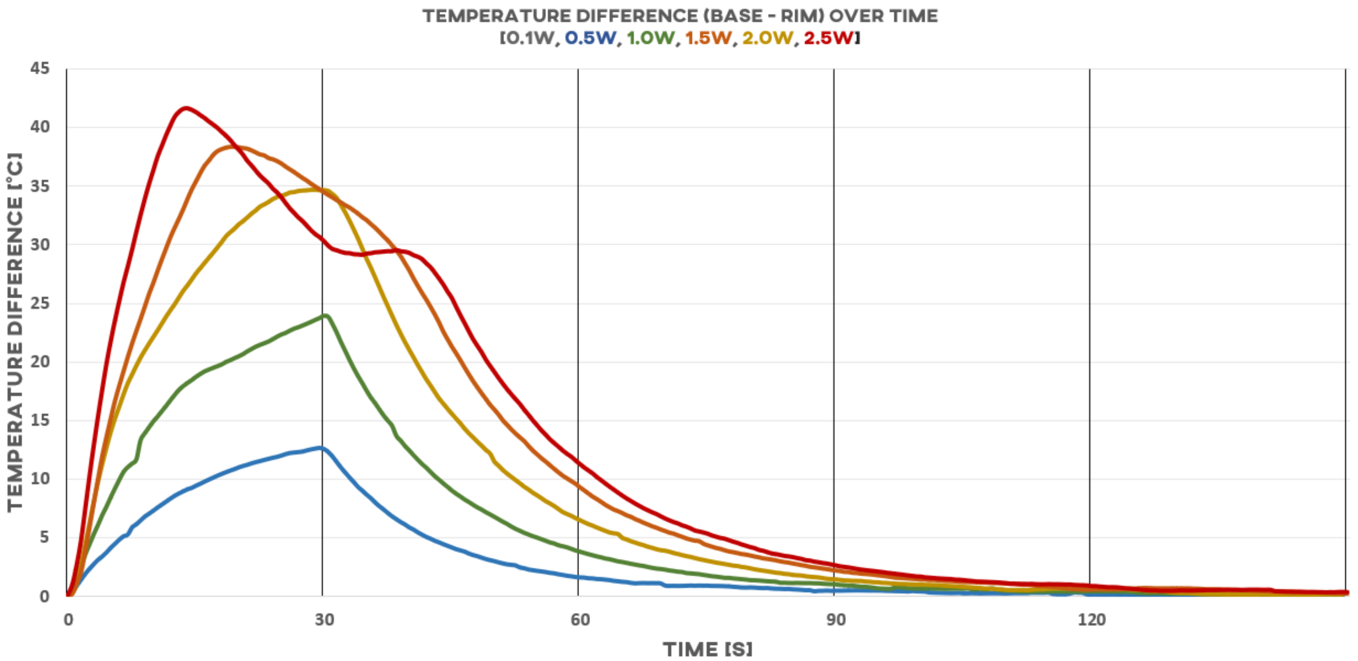


Figure 57

Active deformation

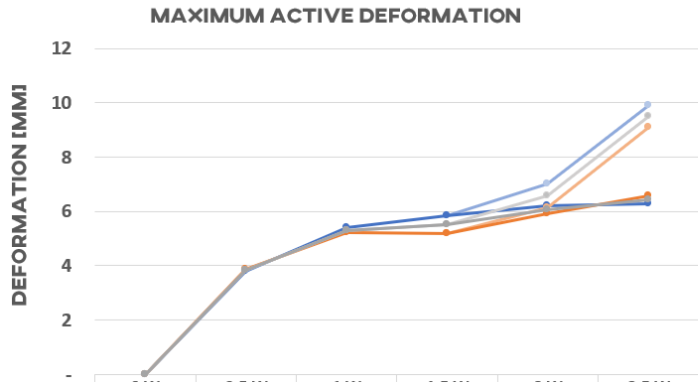
'Active deformation' refers to the deformation that occurs during the heating cycle, while the power input is active.

- Figure 59 shows an overview of the maximum active deformations
- Figure 58 shows the average relative deformation over time for each power input

With the exception of the 0.5W cycle, which did not allow the actuator to reach its deformation potential, the maximum active deformation does not seem to differ all that much, approaching ~ 6 mm. That is, if we ignore the 'second peak' in the 2W and 2.5W cycles. This behaviour was unexpected, but resulted in significant additional active deformation. The second peak is likely a result of the rim entering the glass transition, and losing stiffness. An explanation for the behaviour could go as follows:

First, the base expands. The expansion forces overcome the rim's stiffness and the actuator bends towards the rim. When the base enters the glass transition, its stiffness drops. The rim's stress can now overcome the thermal expansion forces, and pushes the sample back towards its initial state where the rim is at rest. It is at this point that previously stored stresses start to relax in the base, causing permanent deformation if we stop heating. When heating continues, the rim enters the glass transition as well. Now that both the base and rim have lost stiffness, the expansion forces from the base (which has a much higher temperature) take control again, and the deformation continues in its original direction. As the heating continues even more, both layers will lose their stiffness and eventually start to melt.

Although these high temperatures show very large active deformations, the usefulness of this 'second-peak' phenomenon is debatable. The 'second peak' reached a deformation of almost 10 mm and showing no signs of slowing down. However, the base of the sample starts to become so hot that it loses most of its structural integrity and starts to deform transversely as well as laterally. Additionally, as the rim now also starts to enter a glassy state, there is less solid material to hold the sample up. If gravity were to act in either lateral direction, the sample would surely succumb to it.



	0 W	0.5 W	1 W	1.5 W	2 W	2.5 W
W3 (2nd)				5.85	7.01	9.89
W3	-	3.81	5.41	5.85	6.21	6.29
W4 (2nd)				5.18	6.13	9.08
W4	-	3.88	5.21	5.18	5.93	6.58
AVG (2nd)	0.00	3.84	5.28	5.50	6.57	9.49
AVG	-	3.84	5.31	5.52	6.07	6.43

Figure 59

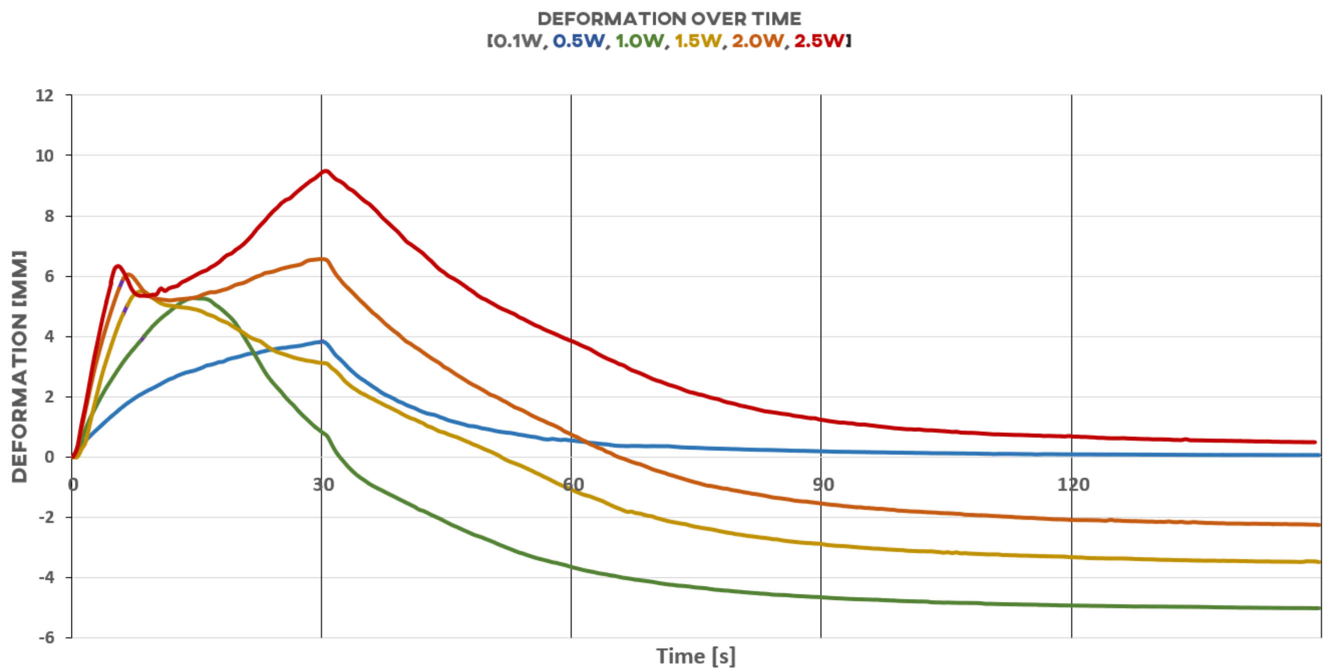


Figure 58

Permanent deformation

'Permanent deformation' refers to the deformation that remains in the sample after reverting to a cold state.

- Figure 60 *shows an overview of the total permanent deformation after each cycle*

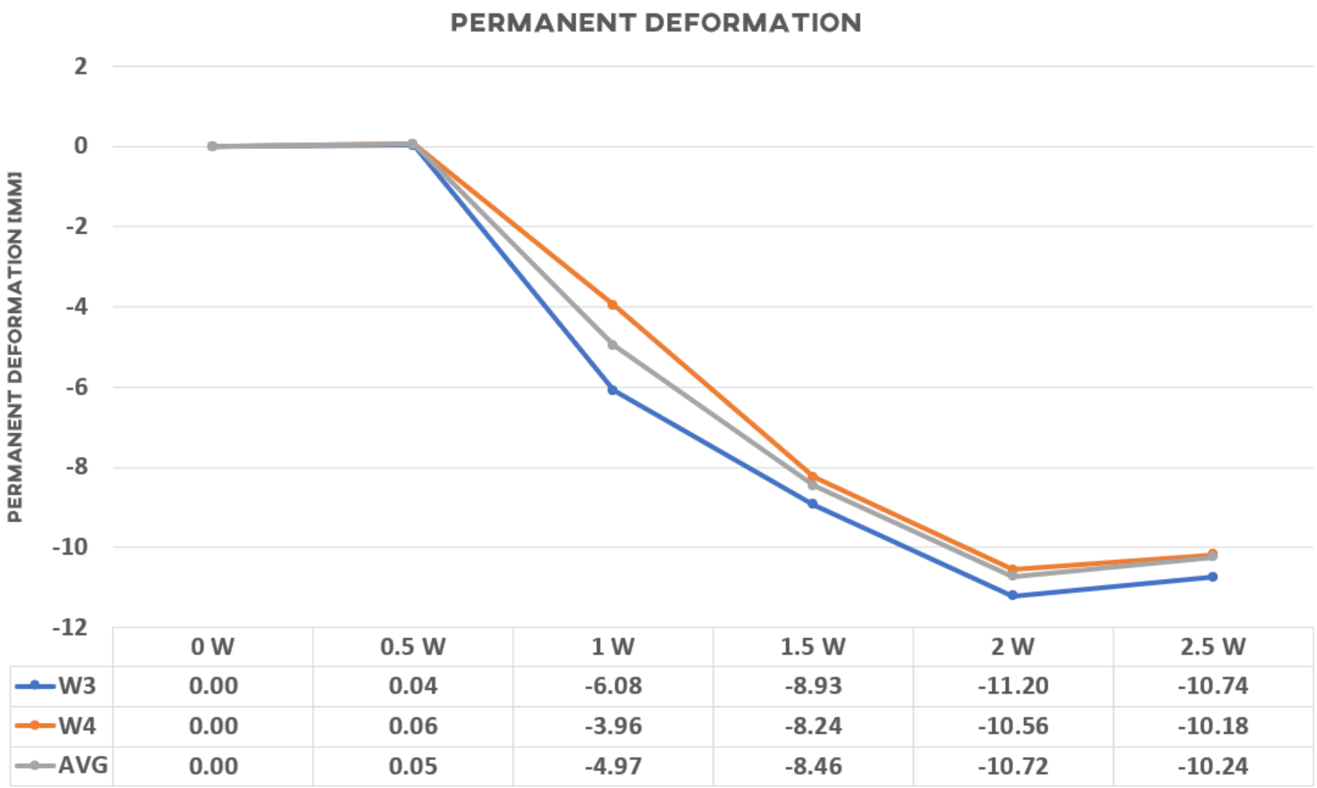
For both samples, permanent deformation starts to occur after the 1W cycle, when the temperatures reach above Tg. The exact point at where permanent deformation starts will lie somewhere between the maximum temperatures of the 0.5W and the 1W cycle; 48°C and 65°C respectively. From the deformation graph, it appears permanent deformation is signified by the sample starting to reverse direction during the heating cycle.

The two samples showed significantly different deformation graphs in the 1W and 1.5W cycle. As discussed in the analysis, a material's behaviour in the glass transition range can depend on the thermal history. It is possible that the micro-scale variables introduced during 3D printing caused these unpredictable results. Interestingly, the differences in these two cycles seem to largely cancel each other out. This could suggest that the thermal history only influences the path taken towards a shared permanent deformation maximum.

The maximum amount of permanent deformation of -10.7 mm is larger than the maximum actuating deformation of 6.5 mm. The effective range of motion can be put anywhere in this range by inducing the correct amount of permanent deformation.

Something interesting happens in the 2.5W cycle. For both samples, some of the permanent deformation appears to be 'undone' as the sample returns closer to its original position. This 'reverse permanent deformation' effect is likely a result of the rim reaching Tg. From the earlier ratcheting experiments, we have seen that heating the rim results in a ratcheting effect in the opposite direction.

This suggests that by keeping the base above Tg long enough (without overheating it) and letting enough heat flow into the rim to reach Tg, the same amount of permanent deformation could be triggered in the rim. The 'permanent deformation stresses' would potentially balance each other out and re-balance the system, returning to its original flat state, on the condition that both layers have the same permanent deformation potential. This reversal would likely only be possible once, after which all stresses imposed by the 3D printing process will have been relaxed. However, it might be possible to reintroduce stresses by applying an external load.



	0 W	0.5 W	1 W	1.5 W	2 W	2.5 W
W3	0.00	0.04	-6.08	-8.93	-11.20	-10.74
W4	0.00	0.06	-3.96	-8.24	-10.56	-10.18
AVG	0.00	0.05	-4.97	-8.46	-10.72	-10.24

Figure 60

Resistance:

Figure 63 shows the resistance values of W4 during each heating cycle. Both samples showed an average resistance increase of 19% during the first 0.5W heating cycle. The following cycle of 1W showed a less significant increase of 10% on average. After that the resistance remained relatively consistent throughout the heating cycles, changing less than 5%. The conductive silver trace seems to react to the high current in some way that causes the resistance to drop significantly at 2.5W, but the exact cause of this remains of unknown.

When sample W4 was run through the experiment again, the drop in resistance remained even at low power (Figure 62). This suggests that something in the trace was permanently changed by the extreme electrical exitance. It is possible that high currents superheat sections in the core of the trace and fused conductive elements together. The exact cause of the phenomenon remains unknown.

The initial rise in resistance could be a result of the paste becoming increasingly dry from the heat of the current. The W4 sample featured an additional cycle of 0.1W that did not seem to induce the same effect. 'Pre-heating' the sample at 0.5W for 30 seconds seems to be a good way of ensuring that the trace has achieved at least a somewhat stable resistance.

Second run:

Apart from the change in resistance, the temperatures and deformation values stayed fairly consistent (Figure 61). This was despite the sample being curved in multiple directions due to the extreme temperatures from the previous test. One thing that is significant is that the amount of permanent deformation appears to increase only very slowly. It seems that most of the stresses have been relaxed and the permanent deformation potential is exhausted. However, it should be noted that even at the last few cycles there were still slight increases in total permanent deformation.

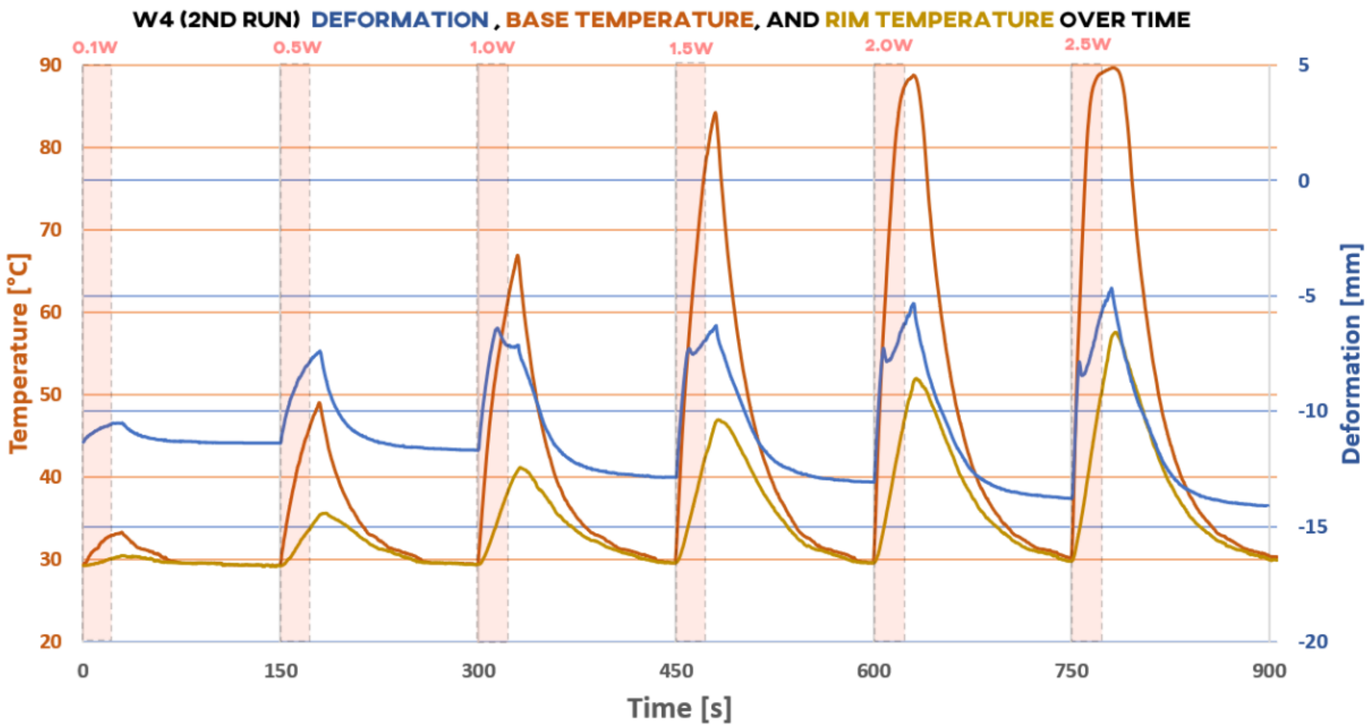


Figure 61

Figure 63

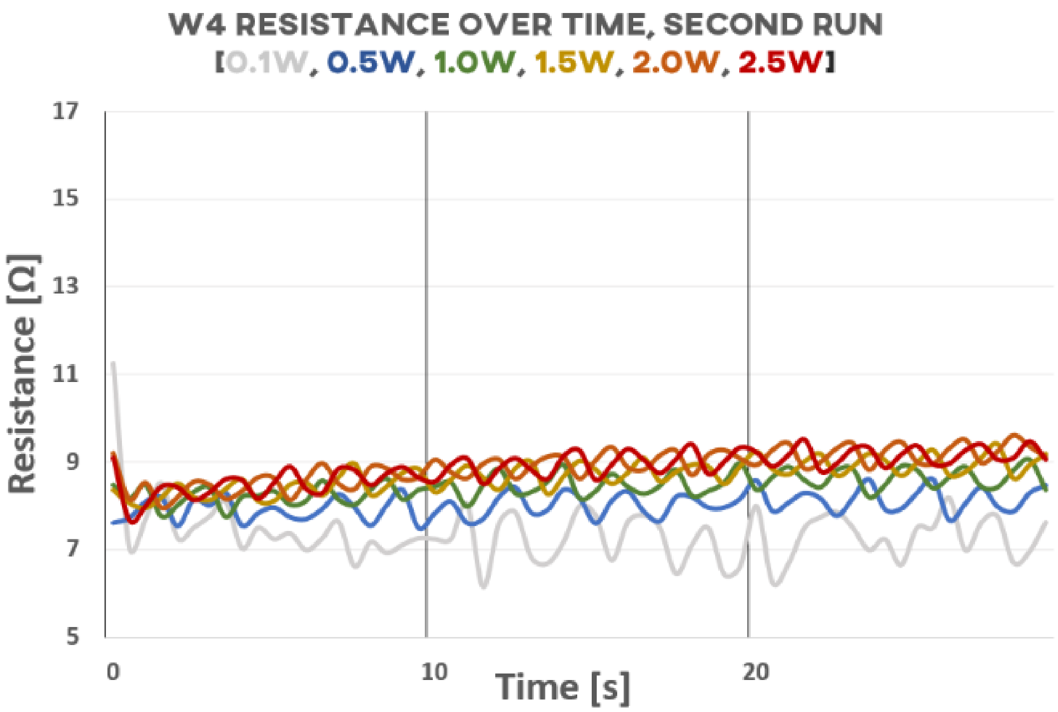


Figure 62

4.2) TG-EXPERIMENT

The Tg-Experiment served to pinpoint the conditions under which permanent deformation started to occur. This information is crucial for defining FlexTECH behaviour, as this point serves as a limit for active deformation

The test setup was identical to the previous DTR-Experiment. This time, however, the experiment featured a much narrower range of power inputs. The pilot experiment had shown permanent deformation occurs when the sample is heated for 30 seconds at somewhere between 0.6 and 0.8 Watts. Each sample was cycled through this range in 5 increments of 0.05W. The experiment was performed 3 times on 3 new samples (W5, W6, and W7) to average out the results.

- Figure 64 shows the complete deformation over time
- Figure 65 shows the relative permanent deformation after each cycle
- Figure 67 shows the maximum base temperatures for each cycle

The results demonstrate clearly that the moment active deformation starts to plateau is the same moment that permanent deformation starts to occur. For each sample it happened at a different cycle: 0.6W, 0.65W, and 0.7W showed the first significant permanent deformation for samples W7, W6, and W5 respectively.

If we average the maximum base temperatures from the first cycle where each sample exhibited permanent deformation, we get 47°C. This temperature will act as the value separating permanent and non-permanent deformation ranges. The average maximum deformation (achieved in this test) from the cycle *before* this point is 4.7 mm. This can be seen as the maximum active deformation that can occur without the risk of permanent deforming the actuator. However, as we have seen in the previous test, faster heating rates can potentially result in larger deformation. And indeed, the W3 sample reached an active deformation of 5.9 mm at 47°C during its 2W cycle.

Second runs:

Each sample was subjected to a second run of the same heating cycles to test for consistency. Now that the samples were not majorly deformed by extreme temperatures such as in the first DTR-Experiment, the results for active deformation and temperature were nearly identical to those in the first run. The exception being permanent deformation, which had largely manifested already in the first run.

The data of the second run does not only prove the consistency of the sample behaviour, it also shows that a PID-controlled Wattage is a reliable instrument to control the actuation. Even when working with increments of 0.05W the active deformation results are on average within 2.2% of the first test.

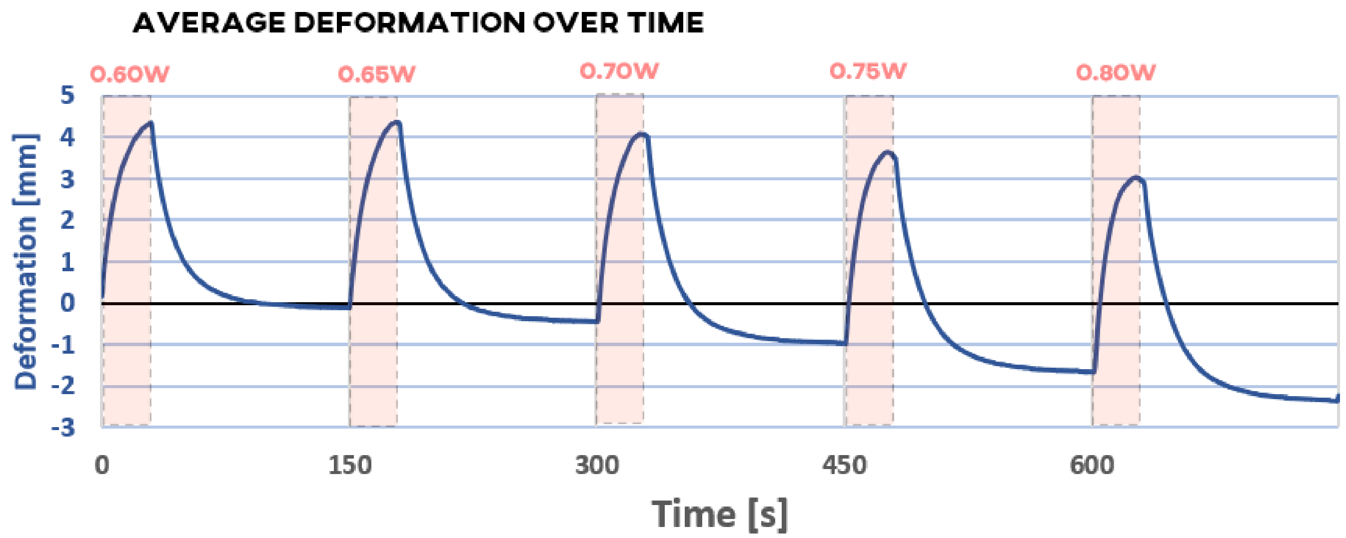
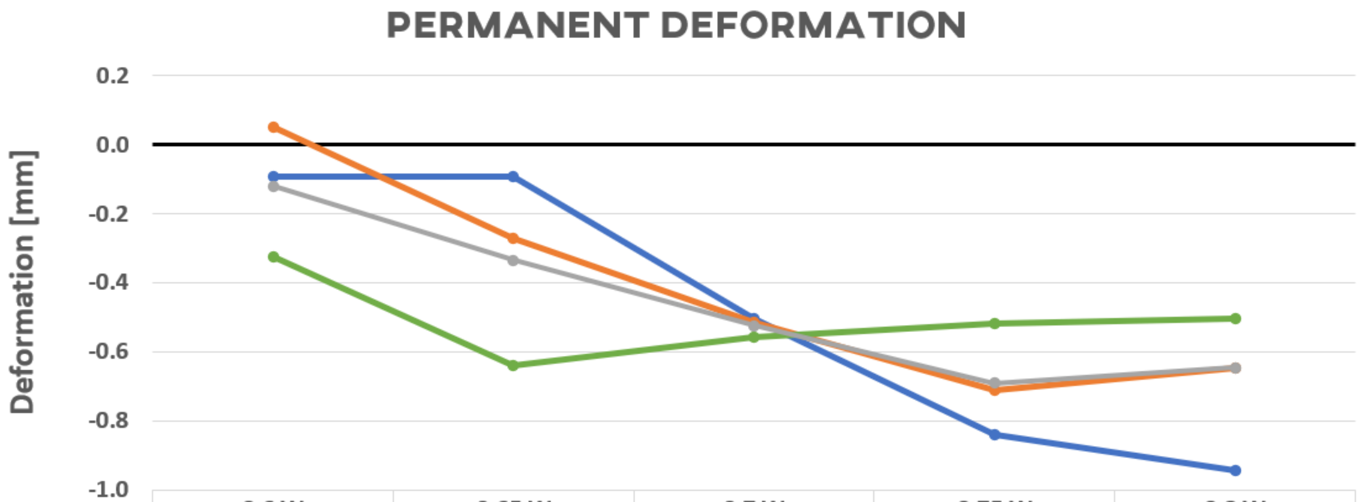
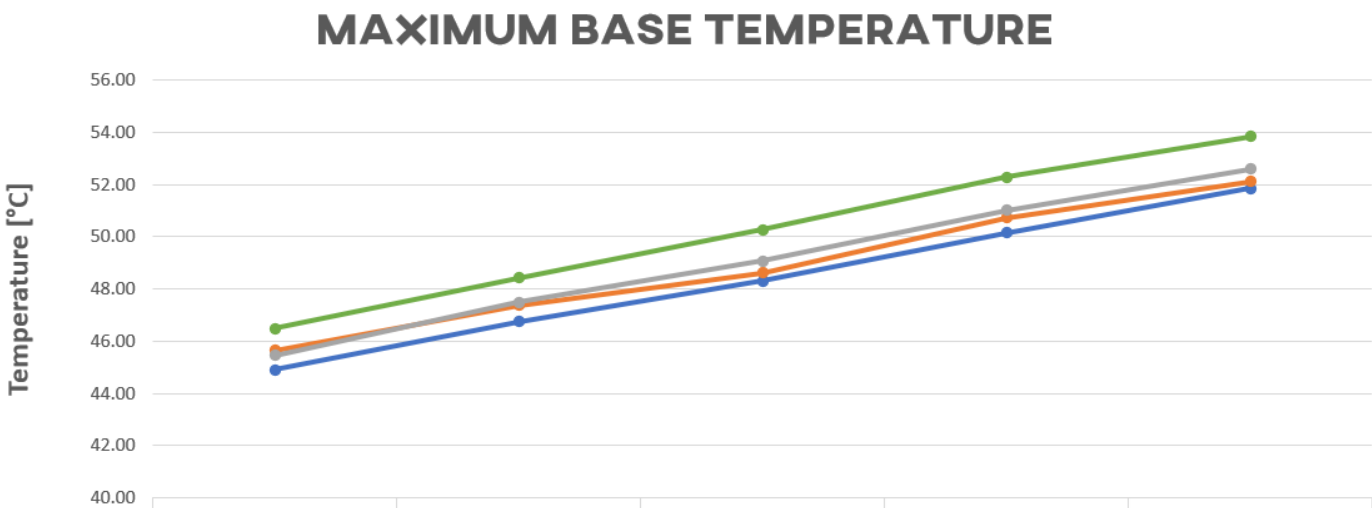


Figure 64



	0.6 W	0.65 W	0.7 W	0.75 W	0.8 W
W5	-0.09	-0.09	-0.50	-0.84	-0.94
W6	0.05	-0.27	-0.52	-0.71	-0.65
W7	-0.33	-0.64	-0.56	-0.52	-0.50
average	-0.12	-0.34	-0.52	-0.69	-0.65

Figure 65



	0.6 W	0.65 W	0.7 W	0.75 W	0.8 W
W5	44.89	46.74	48.29	50.14	51.84
W6	45.64	47.36	48.61	50.71	52.11
W7	46.48	48.41	50.27	52.27	53.85
average	45.44	47.48	49.06	51.01	52.59

Figure 67

4.3) FORCE EXPERIMENT

The actuators deformation needs to be resisted in order to measure its force. Thus, the force was measured in a separate experiment.

Methods:

Because a glassy material turns soft during the Glass Transition, actuations that require force should keep the material below Tg. For this experiment, the power input was kept at 0.65W for 30 seconds as this input was shown to approach the point where the material started to weaken in the previous experiment. The samples used in these tests are the same as in the Tg-Experiment. These samples were already 'pre-shaped' during their experiment, but were not as severely deformed by extreme temperatures as the samples from the first DTR-Experiment. The pre-shaped samples were suspended by a clamp and pressed down onto a scale until they were roughly level. As the samples heated up, the stresses in the sample relax and reduce the force on the scale.

Force:

- Figure 69 shows the force graphs

All 9 cycles averaged to a total produced force of 4.4 grams, or 0.043 Newton. This is 9.2 times the average weight of the sample of 0.48 grams.

Sample W7 exhibited the lowest force of all 3, even though its temperatures in previous tests were higher than W5 and W6. This could be because W7 already showed significantly more deformation post-production as a result form the trace drying process. Because its shape is more curved than the other, forcing the sample level on the scale imposes a greater force on the sample, as is apparent by the fact that the initial force reading for this sample was 11.2 g, where W5 and W6 started with 6.2 g and 4.8 g, respectively.

Furthermore, it seems that even though the samples were restrained during their heating cycle, this did not seem to diminish the produced force in the subsequent heating cycles. Only sample W7 showed slight diminishing results.

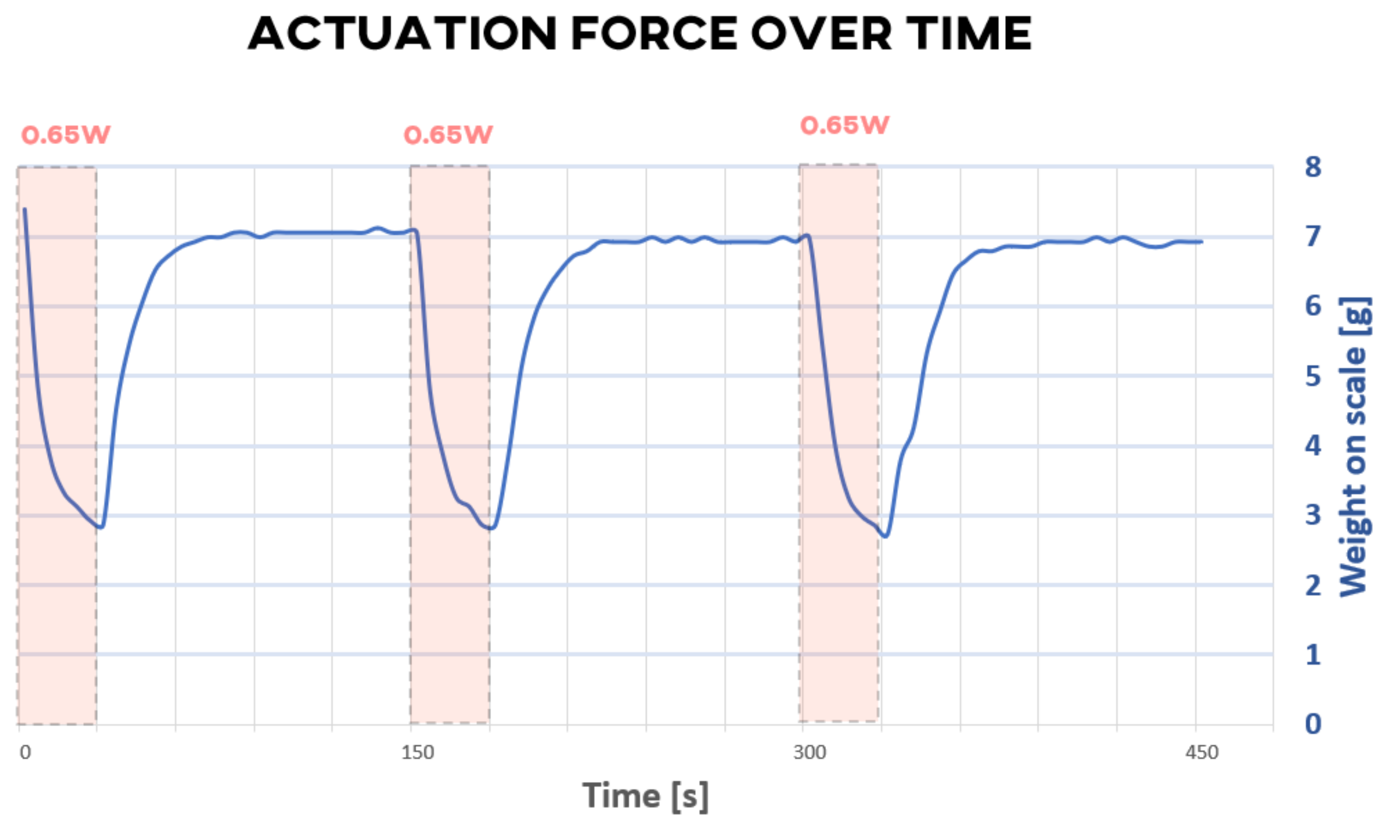


Figure 69

4.4) OTHER OBSERVATIONS

An earlier experiment featured 3 samples of different geometries that had their deformation measured (Figure 70). The data was inconclusive for various reasons (see Appendix B), but the resulting graph shows a glimpse of what effect actuator length and width has on deformation.

Another early experiment recorded the temperatures of a sample where both the rim and base were heated separately (Figure 71). The results show that heating the base (inner layer) resulted in a higher temperature difference than when heating the rim (outer layer). As the inner layer is naturally surrounded by the outer layer, it is less exposed to the movements of the surrounding air which provide convective cooling.

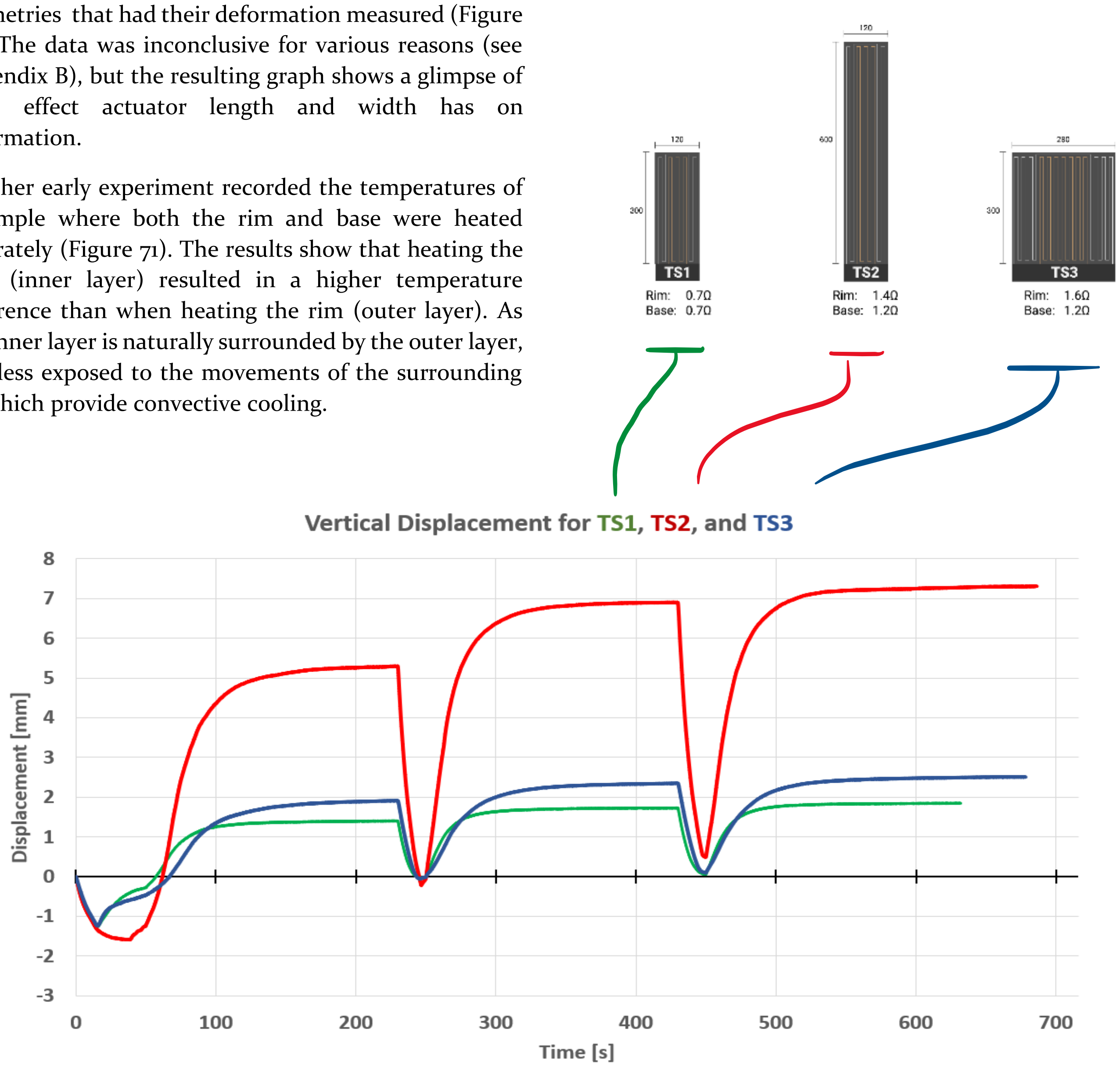


Figure 70

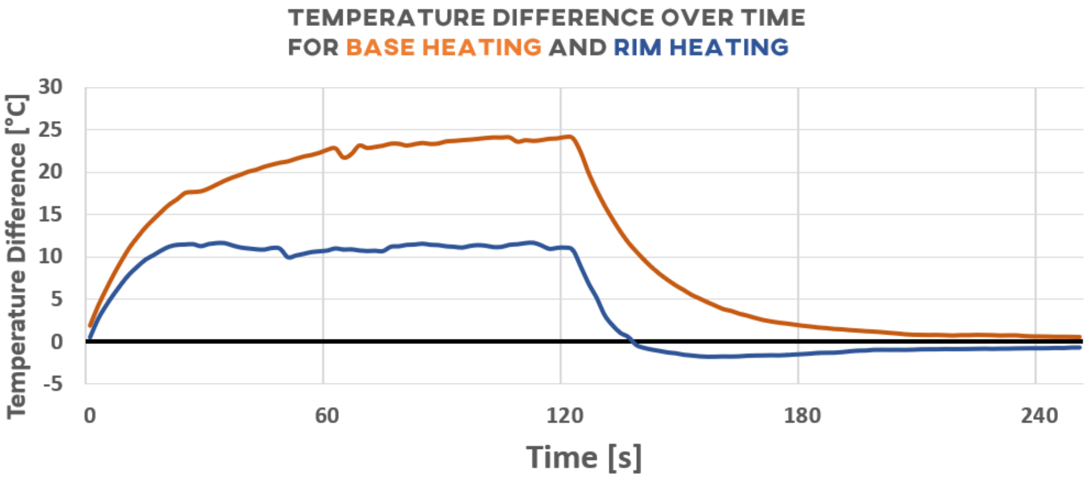


Figure 71

4.5) RECAP:

The experiments performed have provided valuable data for the quantification of the FlexTECH actuator's performance. The behaviour was defined in terms of active and permanent deformation, and linked to corresponding temperature ranges and force values. Additional observations provided insight as to how resistance, geometry, and actuator design influences performance. The tested samples were manufactured with the newly realised screen printing method and produced satisfactory results.

The following important variables were discovered:

- Resistance became stable after heating for 30 seconds at 0.5 W
- Resistance dropped and became even more stable after heating for 30 seconds at 2.5 W
- Maximum temperature without triggering permanent deformation: 47 °C
- Maximum permanent deformation: 10.7 mm
- Maximum achievable temperature difference before reaching permanent-deformation-trigger-temperature at 2.5W heating: 15 °C at ambient temperature of 24 °C
- Maximum active deformation: 5.2 mm
- Maximum active deformation, including second peak:
- Active deformation strain force: 0.43 N
- Preferred actuation heating cycle: 1W for 9.5 seconds
- Preferred actuation cooling cycle: 96.5 seconds

5) DESIGN GUIDELINES

The data by itself, though useful, isn't very actionable and need to be refined further. To be able to communicate the obtained knowledge with proper clarity and ensure it can be applied directly to future endeavours, the relevant knowledge and lessons obtained from exploration and experimentation will be presented in a comprehensive set of design guidelines. The guidelines will be presented in infographic-style pages to make it easy to understand convey the knowledge as clearly as possible.

The complete set of **Design Guidelines** will be divided into 'the 5 A's of FlexTECH':

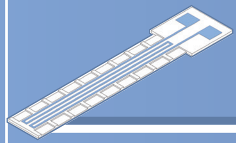
- The *Advantages* section will list the benefits and USPs of FlexTECH to convey the technology's novelty.
- The *Actuator* section will explain the considerations that go into the actuator's design and how design choices affect performance.
- The *Actuation* section will present instructions on how to control the actuation and serve as a performance benchmark.
- The *Adaptation* section will list a set of important considerations for making modifications to the technology.
- The *Applications* section will speculate on the future course of FlexTECH development and provide inspiration for potential applications of FlexTECH actuators in future products.

A new locomoting robot will showcase the current capabilities of FlexTECH actuators and serve as a demonstration of the design guidelines and FlexTECH potential.

Benchmarks:

A lot of the experiments were performed within boundary conditions. Not every single variable could be tested within the scope of this project. In some of the Design Guidelines, a distinction will be made between the general guidelines that will apply to FlexTECH actuators in general, and benchmarks that are specific to the actuator design used in the experiments. The benchmarks will serve as a reference point from which the guidelines can be applied.

The next page provides an overview of the actuator design and variables on which all benchmarks are based.



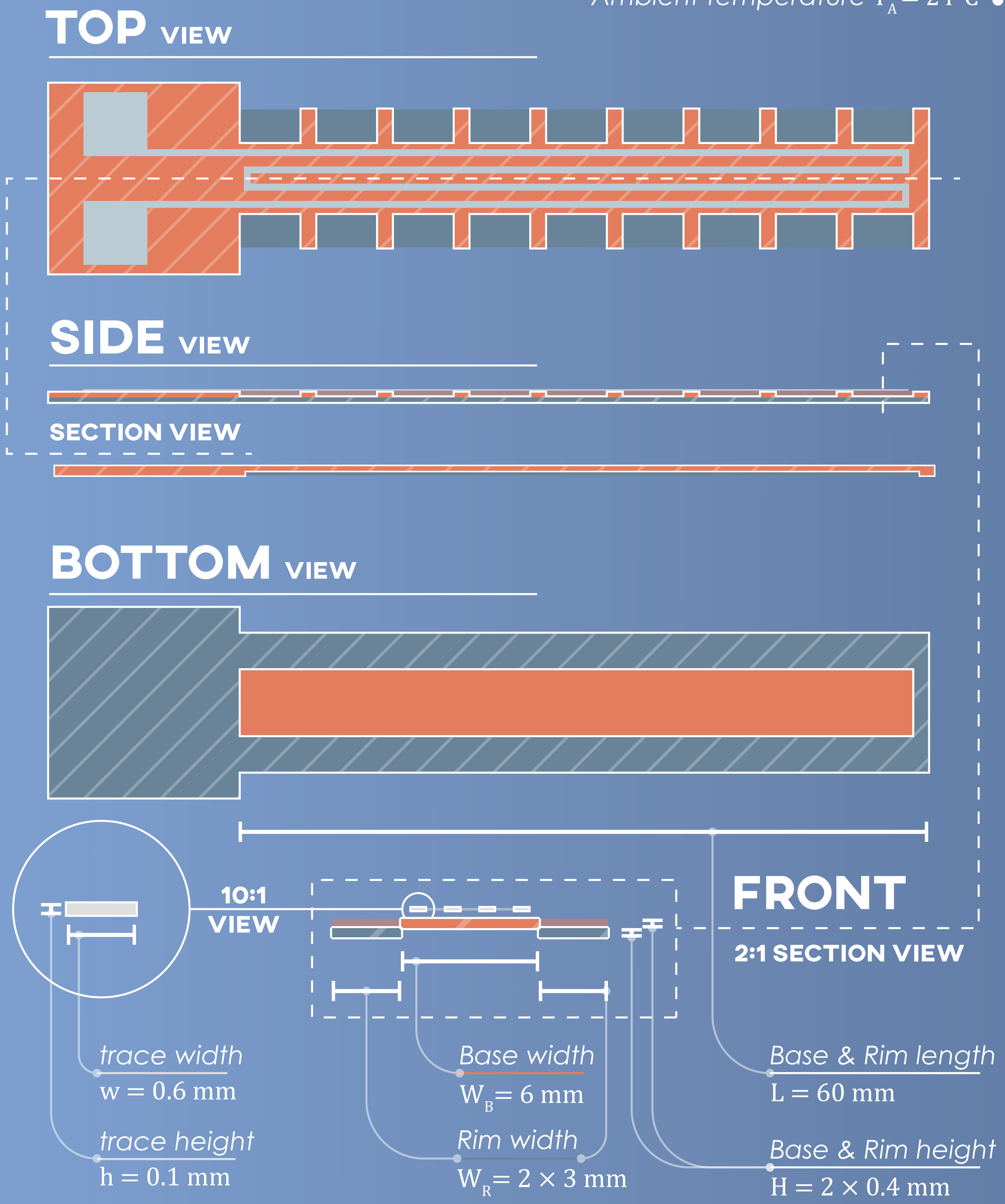
BENCHMARK ACTUATOR

BASE & RIM

- *Polylactic Acid (PLA)*
- *3D printed at 200 °C*
- *0.4 mm nozzle & 0.2 mm layers*

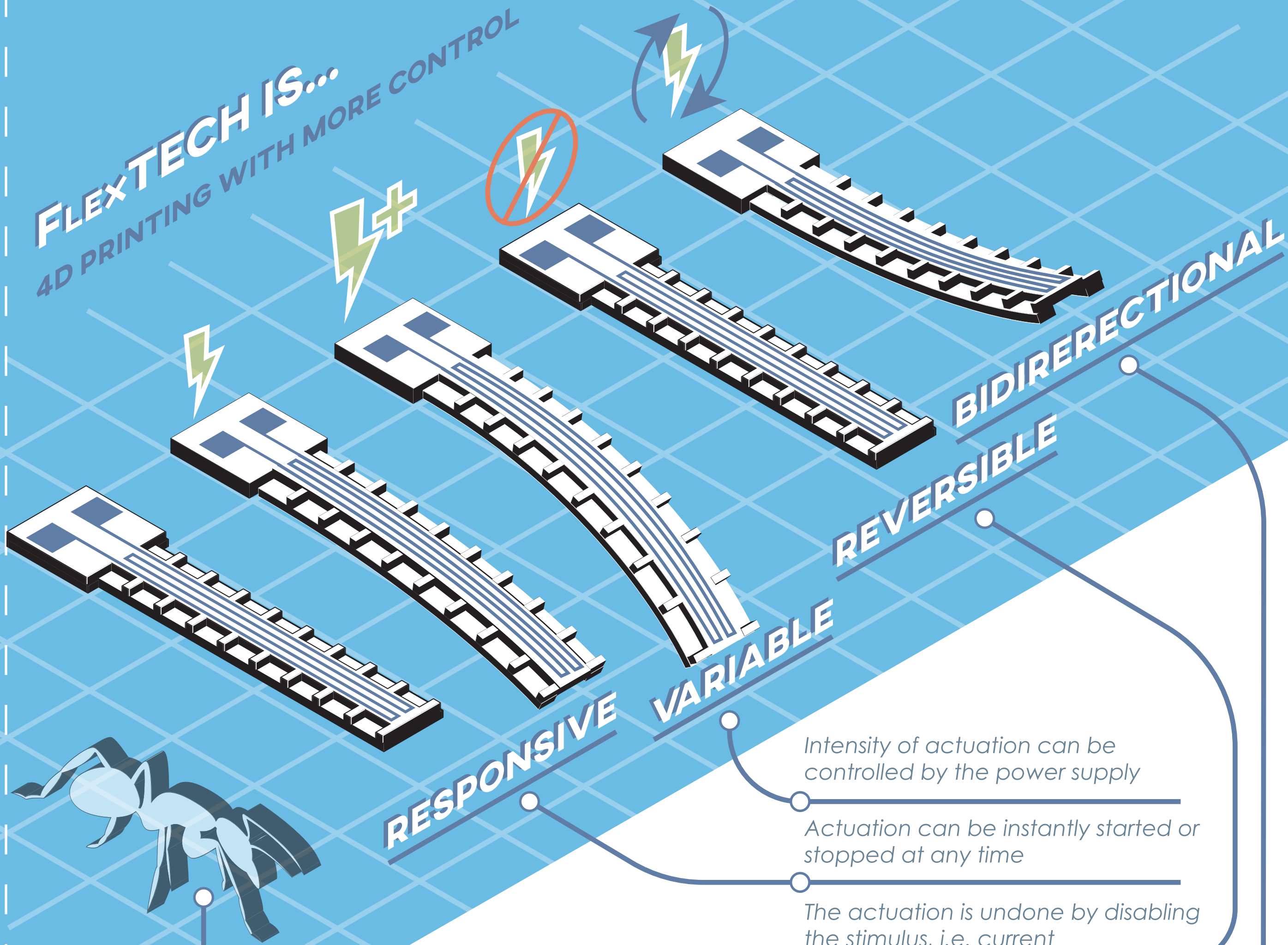
TRACE

- *SunChemical C2081126P2 Silver Paste*
- *Screen printed with 0.1 mm vinyl*
- *Resistance* $R = 15\ \Omega$
- *Ambient temperature* $T_A = 24°C$



FlexTECH ADVANTAGES

DESIGN GUIDELINES



Intensity of actuation can be controlled by the power supply

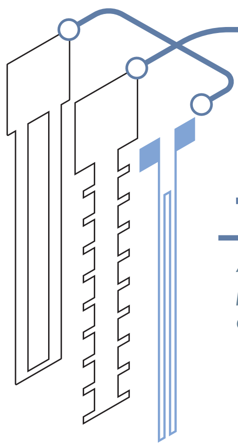
Actuation can be instantly started or stopped at any time

The actuation is undone by disabling the stimulus, i.e. current

The actuator can move in either direction, depending on which side is stimulated

LIGHTWEIGHT

Actuators weigh only a couple grams but have a relatively high force-to-weight ratio

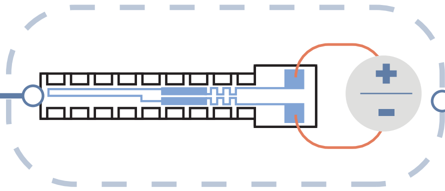


RUDIMENTARY

The actuator is a single component consisting of 3 parts and 2 materials.

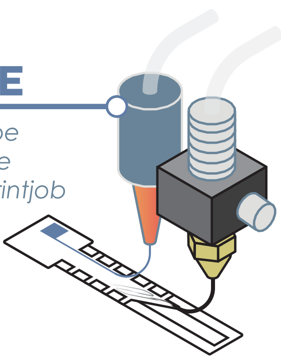
CUSTOMISABLE

Circuit variations can be modelled with CAD to influence behaviour



EASY TO MAKE

Actuators can be produced in one dual-material printjob



INDEPENDENT

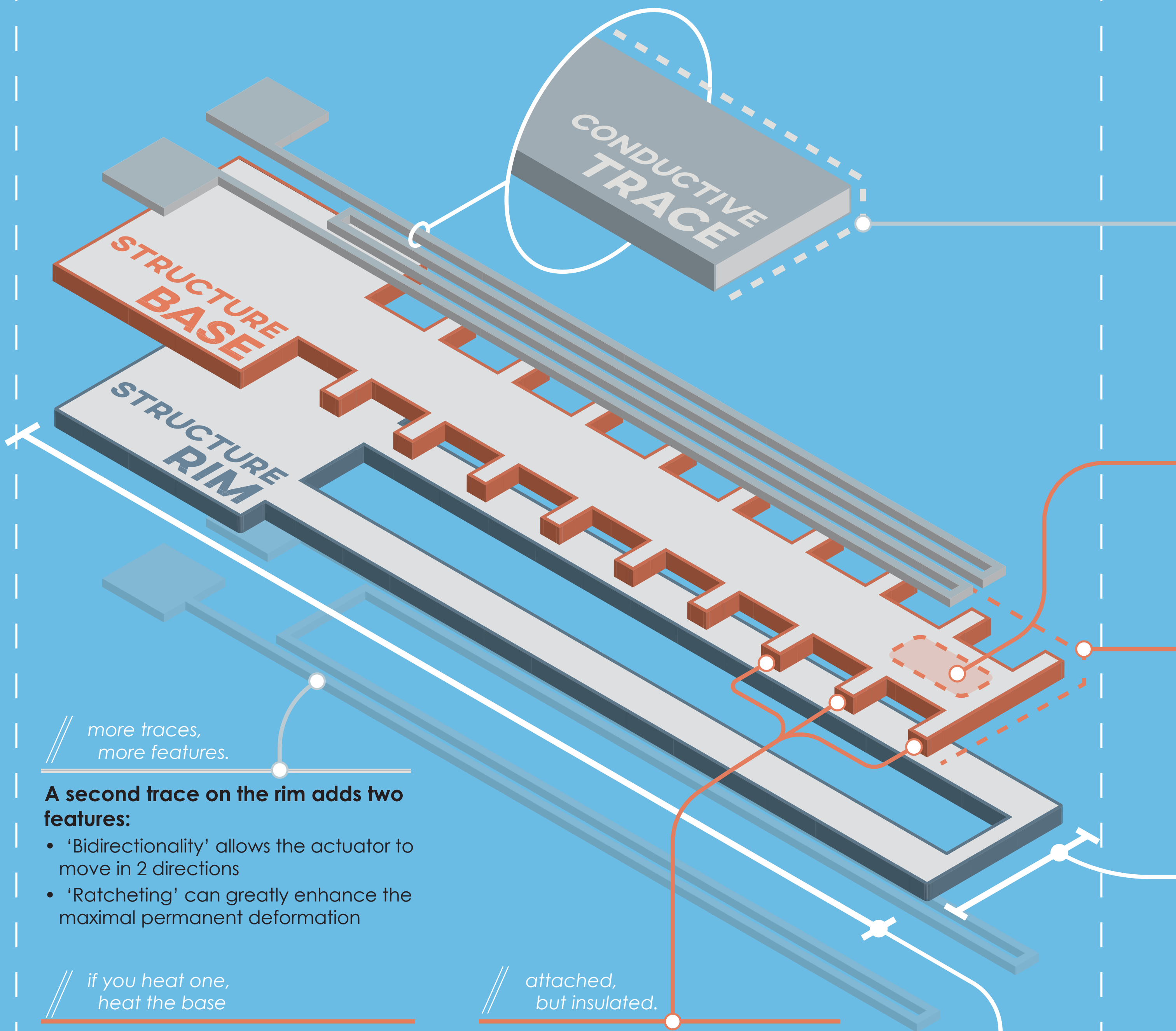
Only a power source is required for the actuator to work. No external load or heat source is necessary

FlexTECH ACTUATOR

DESIGN GUIDELINES

Flexural Thermal Expansion by Conductive Heating

// The material bends...
// due to a temperature difference..
// caused by a resistor circuit.



// *more traces, more features.*

A second trace on the rim adds two features:

- 'Bidirectionality' allows the actuator to move in 2 directions
- 'Ratcheting' can greatly enhance the maximal permanent deformation

// *if you heat one, heat the base*

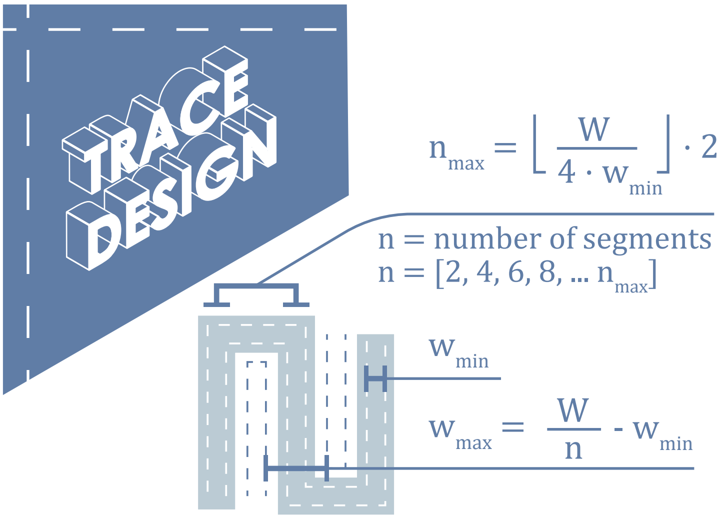
Heating the base is preferred for single-directional actuators

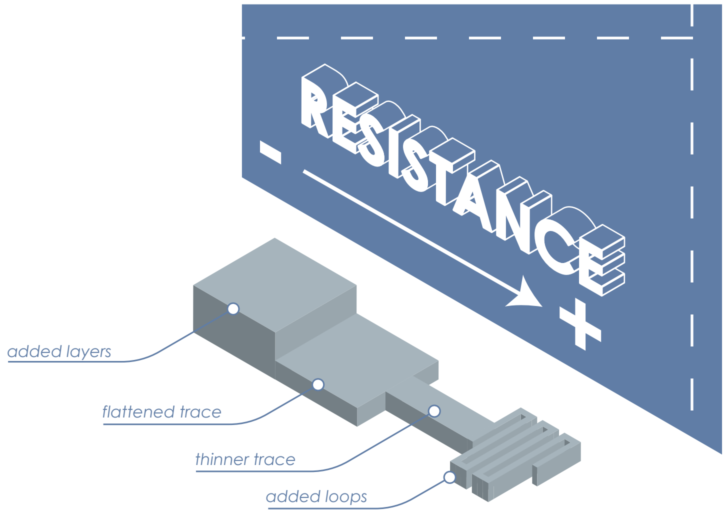
- The inner layer retains more heat, increasing temperature differences
- This also increases cooling time, increasing actuation cycle time

// *attached, but insulated.*

The Base and Rim are printed as 1 part.

- The two layers need to be attached to be able to exert force on each other
- Insulating the two layers as much as possible increases temperature difference and results in larger deformations





$R \propto \frac{1}{w}, \frac{1}{h}$ // *slimmer trace, more resistance.*

$R \propto l$ // *longer trace, more resistance.*

BENCHMARKS

Trace dimensions and pattern can be tweaked to alter resistance

- Local deviations can be used to influence actuation behaviour
- Minimal and maximal trace height and width are determined by the production method
- Total resistance is in large part determined by volumetric resistivity of the conductive material

w_{min} = vinyl cutter limit = 0.6 mm
h = vinyl thickness = 0.1 mm

▸ $1.6 \leq R \leq 15.6\ \Omega$

$A \propto Q$ // *more surface area, faster cooling.*

The amount of surface area can be used to influence cooling time.

- Cooling time is also influenced by heat transfer coefficient, ambient temperature, and volume.
- Surface area also influences the trace pattern.

$A = 2\times 60 \times 6 = 720\ mm^2$
$T = 47\ °C$

▸ Cooling time: 82 sec

$V \propto P$ // *more volume, more power required.*

A larger volume needs more energy with aproper balance between additional heating time and increased power supply.

- Additional heating time can reduce temperature differences, reducing the amount of deformation.
- High power levels can result in local hotspots. A good thermal conductance can assist in dispersing heat throughout the volume.

$V = 60 \times 6 \times 0.4 = 144\ mm^3$
$P = 1$ Watt
$T = 47\ °C$

▸ Heating time: 15 sec

$W \propto F$ // *more width, more strength.*

More expanding or contracting material can sustain more force.

- Additional length would increase torque.
- Additional thickness would decrease flexibility.
- The opposite layer will provide a counter force. An imbalance between the layers can favor force in one direction.

$W = 12$ mm
weight: 0.48 g

▸ $F = 0.043$ Newton

$L \propto D$ // *more length, more bending.*

A longer actuator allows more curvature.

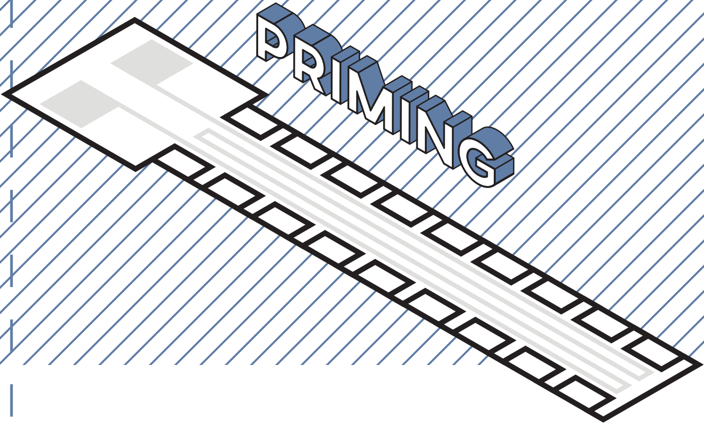
- More curvature increases strain on the trace. Sufficient flexibility of the trace is required.
- Additional length decreases actuation force.

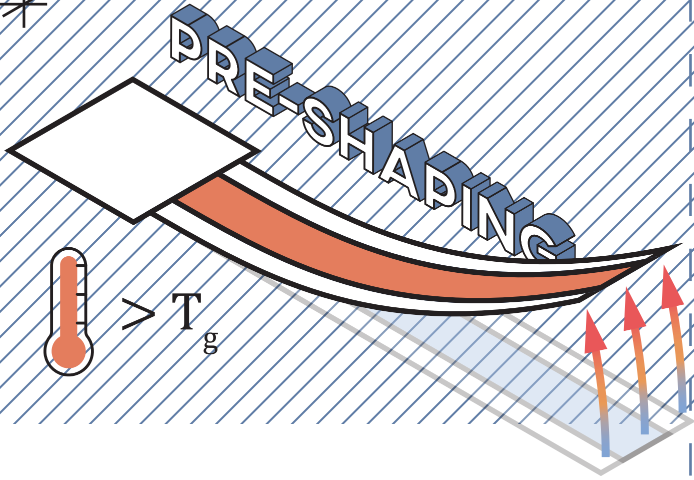
$L = 60$ mm

▸ $D = 6.4$ mm

FlexTECH ACTUATION

DESIGN GUIDELINES





Resistances can vary due to moisture, temperatures, or production inconsistencies

DRYING

The printed trace needs to be dry before resistance is stable

- Inconsistencies in the production process can result in variations of resistance values between actuators.
- As the trace dries, it shrinks slightly and induces a small amount of strain in the sample.
- Airdrying often does not cause the trace to dry comepletely.
- A small current can be used to further dry the trace.
- Large currents can superheat the trace, which lowers resistance even further and increases stability

PID CONTROL

A PID controller can be used to correct for resistance changes and increase accuracy

Both layers have a potential for permanent deformation as a result of 3D printing micro-stresses

SETTING A STARTING POINT

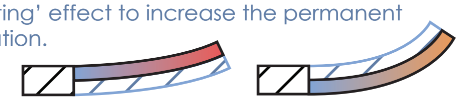
When heated above the glass-transition temperature, stresses are relaxed

- The stress relaxation results in a deformation that remains even at room temperature. This can be used to offset the starting point of the actuation.
- Each pre-shaping cycle increases the permanent deformation, approaching a maximum with diminishing returns.

RATCHETING

- An alternating heating cycle can cause a 'Ratcheting' effect to increase the permanent deformation.

RATCHET CYCLE: BASE > T_G ⟷ RIM < T_G

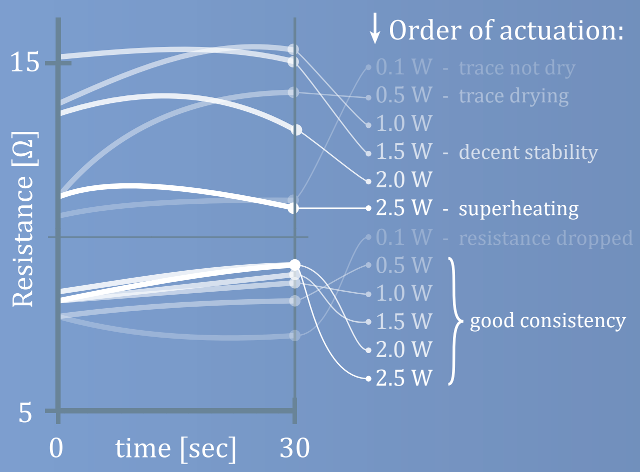


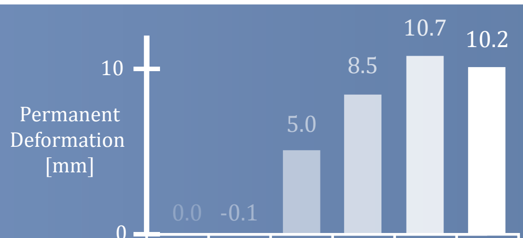
RESETTING

The opposite layer can rebalance the system

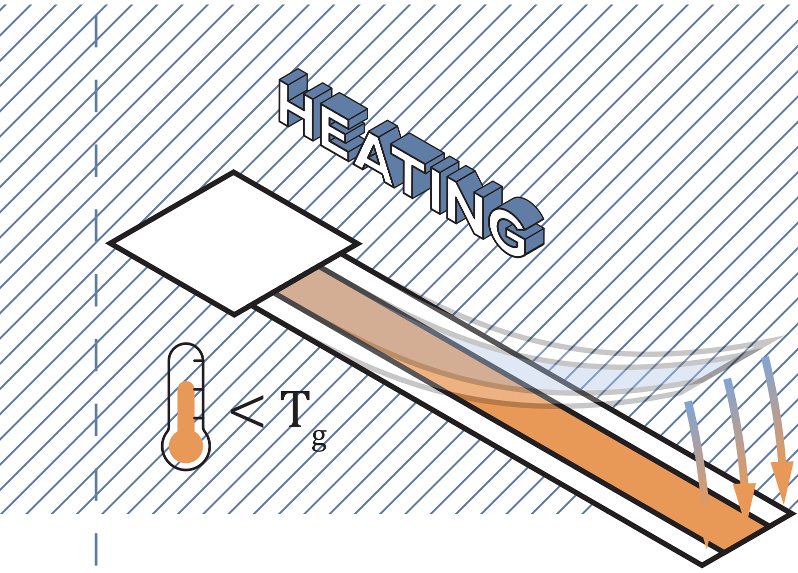
- If the opposite layer enters the same temperature range, it counteracts the first deformation, undoing the effect
- When doing so, temperatures should be kept low to avoid losing structural integrity
- The effect is exhausted once the stresses in both layers are comepletely relaxed. New stresses might be introduced manually.

BENCHMARKS

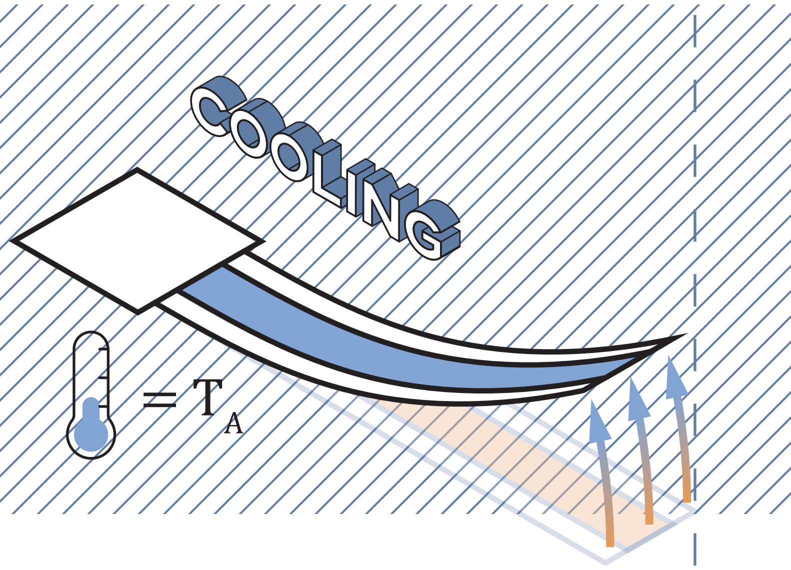




Power [W]	0.1	0.5	1.0	1.5	2.0	2.5
max Rim Temperature [°C]	30	36	41	48	53	59
max Base Temperature [°C]	33	49	65	83	>89	>90



A layer can be heated to cause a bending motion towards the opposite side



Turning off the heat supply will return the actuator to its starting point

REPEATING MOVEMENT

When staying below the glass-transition temperature, the movement can be repeated

- The actuation is temporary due to some heat transfering to the opposite layer. Sustained heating willl either reach the glass transition or equalise the temperatures and cancel the deformation.
- A lower ambient temperature means the material can be heated for longer before reaching the glass transition, increasing the deformation maximum.
- Heating more rapidly increases the temperature difference and deformation, but is more difficult to monitor and can cause local hotspots.

STRAIN-TO-STRESS FORCE

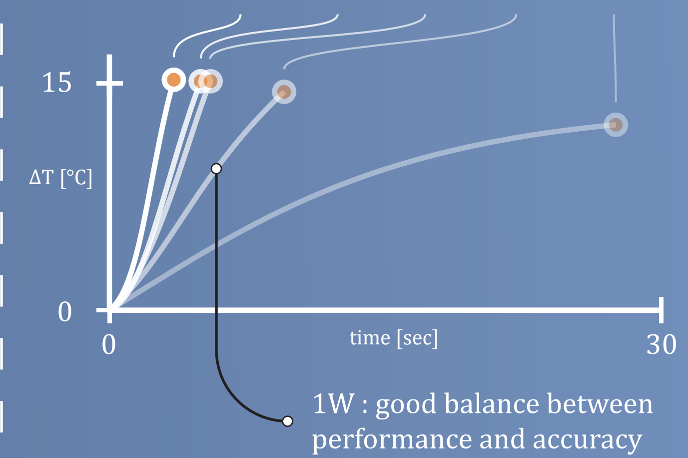
After thermal expansion, the cooling contraction can be used to exert a small force

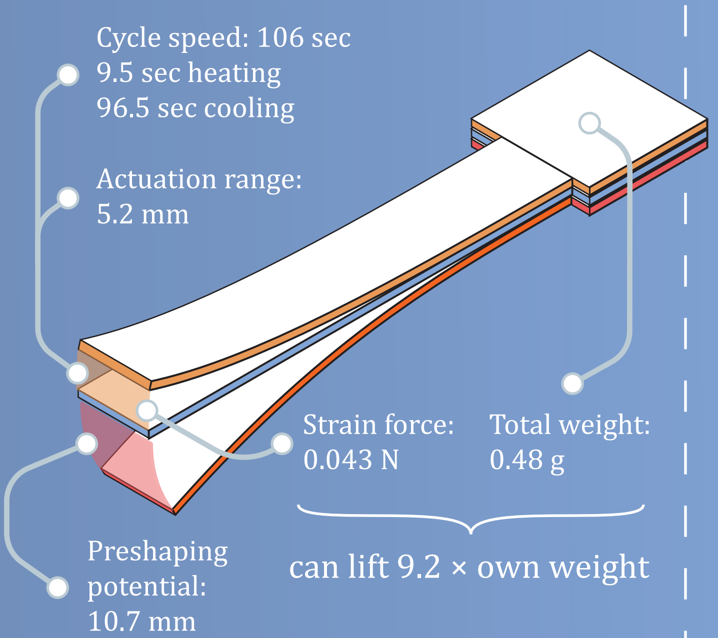
- Heat is dissipated to the surrounding air by passive convection, which takes quite a long time
- The strain from the actuation results in built-up stresses that are released during cooling
- A larger actuation range will induce more strain.
- A pre-shaped actuator is always under stress. Stresses eventually relax over time.
- A FlexTECH actuator can lift many times its own weight.

BENCHMARKS

Temperature Difference ($\Delta T = T_{Base} - T_{Rim}$) over time until $T_{Base} = T_g = 47$ °C

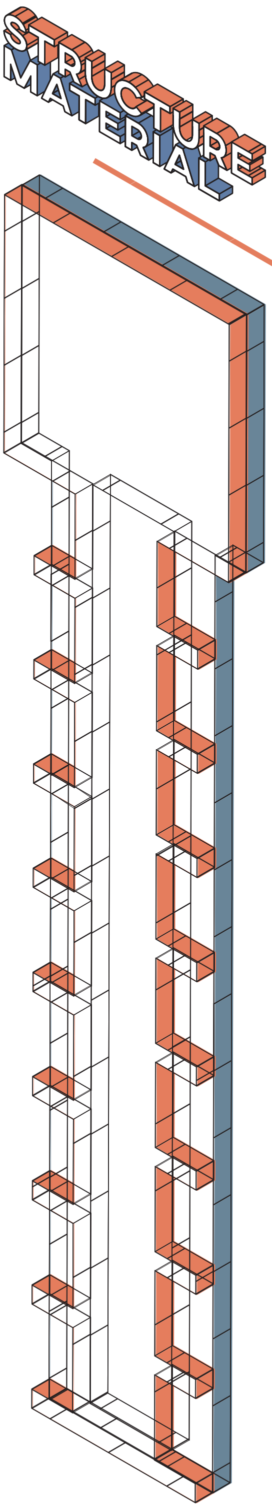
Power [W]	2.5	2.0	1.5	1.0	0.5
max ΔT [°C]	15	15	15	14	12
time until T_g [sec]	3.5	5	5.5	9.5	27.5

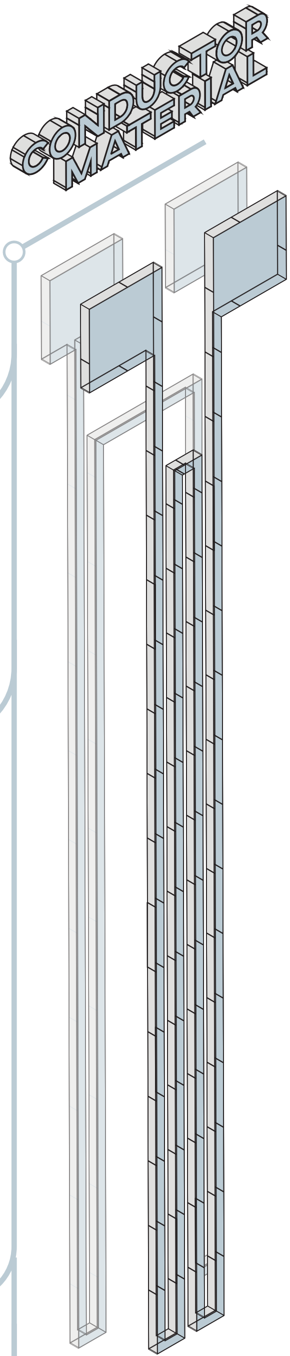




FlexTECH ADAPTATION

DESIGN GUIDELINES





Yield Strength (elastic limit)

The structure's Yield Strength determines the maximum amount of flexion the actuator can take before breaking.

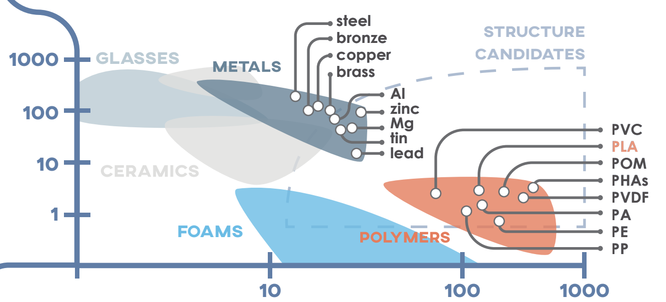
Conductor needs to enough yield strength to be hign enough to avoid breaking under the strain.

Young's Modulus (stiffness)

The stiffness needs to be in a 'sweetspot': low enough to flex from the small thermal expansion forces, but high enough to uphold its own weight at rest.

A typical stretching in 1 direction causes compression in the other 2. Thermal expansion happens in all directions, and thus the Poisson's ratio will be different.

The conductor's stiffness should be low to avoid resisting the deformation.



Thermal Expansion coefficient

Thermal expansion is the driving force of the actuator and should be as high as possible.

Thermal conductivity is also relevant for dispersing heat throughout the material.

Adhesion

The materials need to be properly joined together to avoid disconnecting during flexion.

Volumetric Resistivity

The conductor's volumetric resistivy determines the minimal and maximal total resistance values that can be achieved with different with trace design.

$$R_{min} = \rho_V \cdot \frac{L \cdot 2}{h_{max} \cdot w_{max}}$$

$$R_{max} = \rho_V \cdot \frac{L \cdot n_{max}}{h_{min} \cdot w_{min}}$$

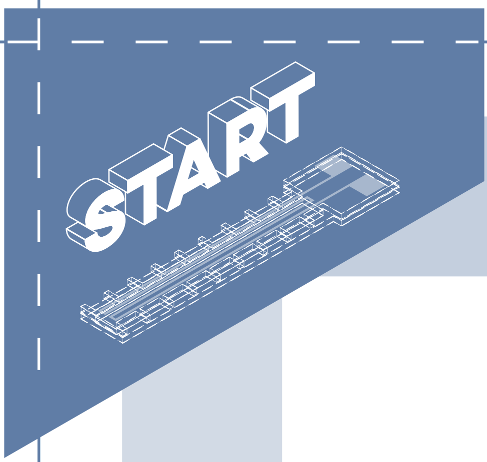
Glass Transition Temperature

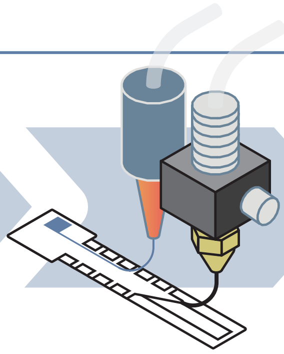
A glass transition is required for pre-shaping.

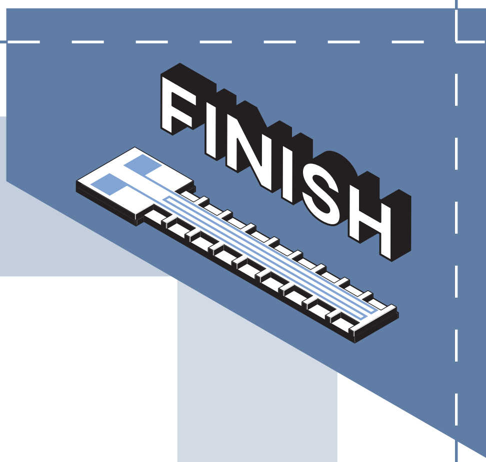
To use the actuator at room temperature, the Glass Transition Temperature needs to be higher than that.

BENCHMARKS

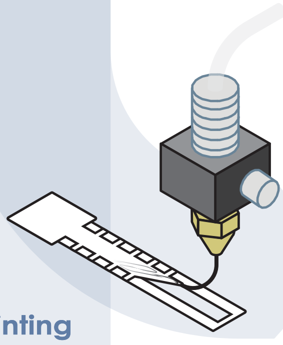
Voltage [V]	Volumetric Resistivity [Ωm]
1.5 [V]	$1 < \rho_V < 27$ $\cdot 10^{-6}$[Ωm]
3 [V]	$4 < \rho_V < 108$ $\cdot 10^{-6}$[Ωm]
5 [V]	$111 < \rho_V < 300$ $\cdot 10^{-6}$[Ωm]
12 [V]	$640 < \rho_V < 1730$ $\cdot 10^{-6}$[Ωm]



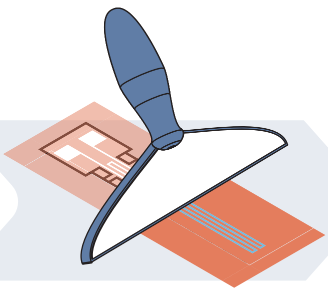




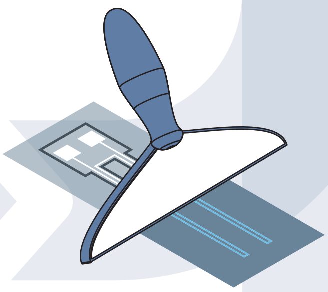
Dual-Material Printing
- The fastest and easiest way to produce actuators
- Greatly enhances form freedom



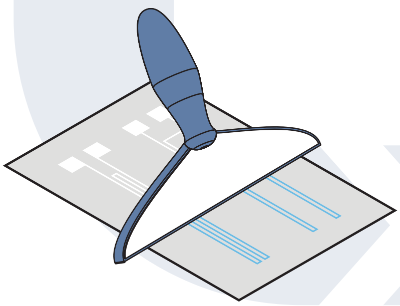
3D Printing
- Both layers can be printed at once.
- Overhangs in the design are more difficult to print
- Surface should be made smooth either with ironing or a glass printbed.



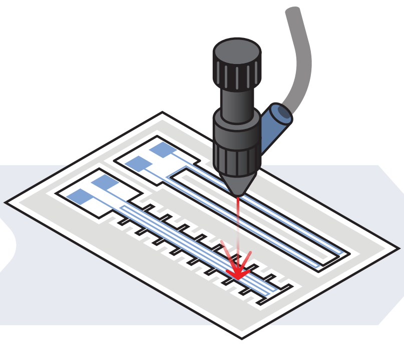
Screen printing
- Stencils can be made with vinyl stickers or photo-emulsion.
- Screen-life of conductive pastes are short.



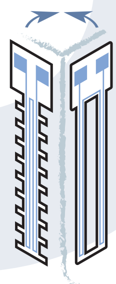
2-Sided printing
- The process needs to be repeated on the opposite side for a bidirectional actuator.
- Beware of damaging the first print.



Double Screen Printing
- Printing on a flat substrate is much easier.



Laser Cutting
- Very high dimensional accuracy
- Proper alignment is crucial to avoid singing the trace



Joining
- Parts will need to be joined with an adhesive
- Adhesive should be a flexible insulator.

Some of the actuator variables are limited by the chosen production method

BENCHMARKS

Production Method	Variable name		Variable		Relation		Value		
Screen Printing	trace minimum width	=	w_{min}	=	minimum vinyl strip	=	0.6	· 10-3	[m]
R_{min} = 1.6	trace height	=	h	=	vinyl thickness	=	0.1	· 10-3	[m]
R_{max} = 15.6	Volumetric Resistivity	=	ρ_V	=	SC Silver Paste	=	3.125	$\cdot 10^{-6}$	[Ωm]
3D Printing	trace minimum width	=	w_{min}	=	nozzle diameter	=	0.4	· 10-3	[m]
R_{min} = 0.3	trace height	=	h	=	2 · layer height	=	0,4	· 10-3	[m]
R_{max} = 7.0	Volumetric Resistivity	=	ρ_V	=	Voxel8 Silver Ink	=	3	$\cdot 10^{-7}$	[Ωm]

FlexTECH APPLICATIONS

DESIGN GUIDELINES

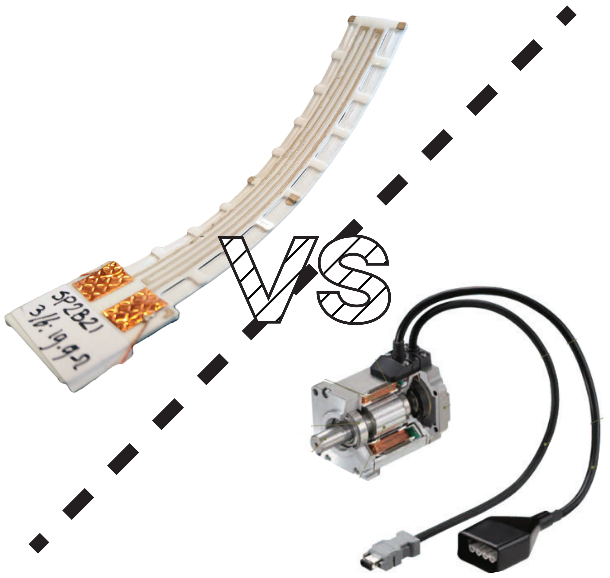
A SINGLE COMPONENT MOTOR

If we let our imagination run wild, we can use this unique piece of technology to change robotics.

Similar to how single-component compliant mechanisms can replace complicated hinges, FlexTECH actuators have the potential to replace complicated motors and other actuators with a single part.

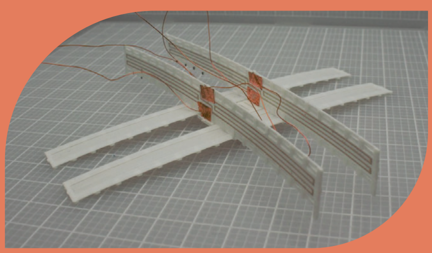
Some quick ideas for potential applications ar presented here to serve as inspiration for future research.

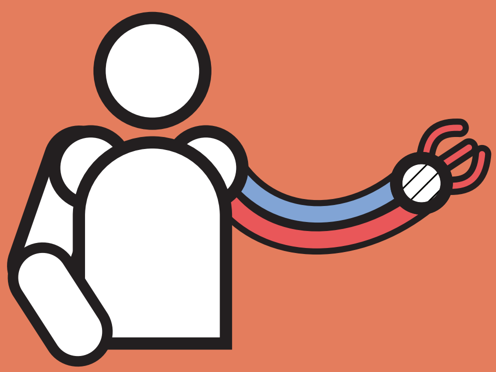
Each section will discuss the most important factors to be considered in the pursuit of the concept.



A FlexTECH actuator....

- ... can pre-shape into a selected starting position.
- ...repeatedly moves in small pulses.
- ...lifts many times its own weight.
- ...can have its behaviour programmed into the material.





A FlexTECH Robot could...

- ...be much more lightweight,
- ...greatly reduce part count,
- ...save on assembly costs,
- ...have a lower fault rate from wear and tear

FlexTECH could greatly improve on robotics by reducing their complexity. The temporary nature of the actuation would work well for robots that feature oscillating movements, such as locomoting robots. The pre-shaping functionality allows a FlexTECH robot to self-assemble.

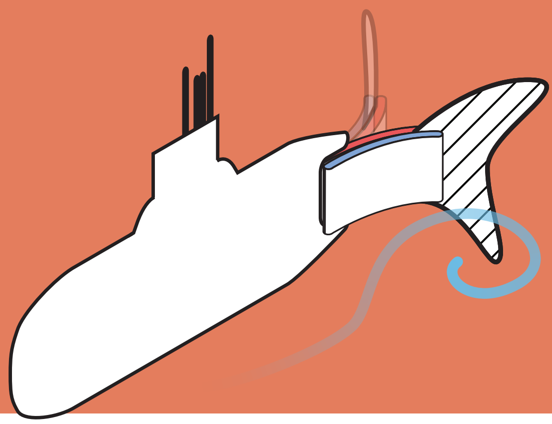
The material could be especially valuable in space exploration, where every gram saved counts. A reduced part count typically results in a lower fault rate, which is crucial in places where repairs can't be performed. It could prove particularly useful on rovers on other planets, where ower ambient temperatures would enhance the actuation. Spacecrafts would likely not benefit as much, as it is difficult to cool the actuator.

A FlexTECH Prosthesis could...

- ...greatly reduce cost
- ...be printed to scale for every patient
- ...save on weight that patient has to carry around

3D printing sees a lot of use in prosthetics already due to its large form freedom and ability to tailor each print to the specific user dimensions. A FlexTECH solution could reduce complexity, cost, and weight of prosthetics. A low weight of the FlexTECH actuators would be a huge advantage for prosthetics, as patients have to constantly carry their weight around.

As these use-cases require the actuator to remain in flexure (for sustained gripping or arm position), a stable active deformation is required. A solution for active cooling of the cold side of the actuator would be necessary to make this a reality. One advantage is that an arm or finger prosthesis would only require movement in one direction, meaning that it is not necessary to implement a heating element as well as a cooling element on the same layer.



A FlexTECH Aircraft could...

- ...offer single-component glider controls
- ...reduce total weight

A FlexTECH Submarine could...

- ...swim like a fish
- ...provide a single-component locomotion solution

The ailerons or 'flaps' of an airplane's wings are tilted up or down to control the pitch of the aircraft. By tilting the ailerons, air resistance on the corresponding side is increased. We can use this increased airflow to our advantage as it increases the cooling rate of the cold side of the FlexTECH actuator. The difference in cooling rate means the hot side can sustain an equal heating rate, thereby achieving stable active deformation.

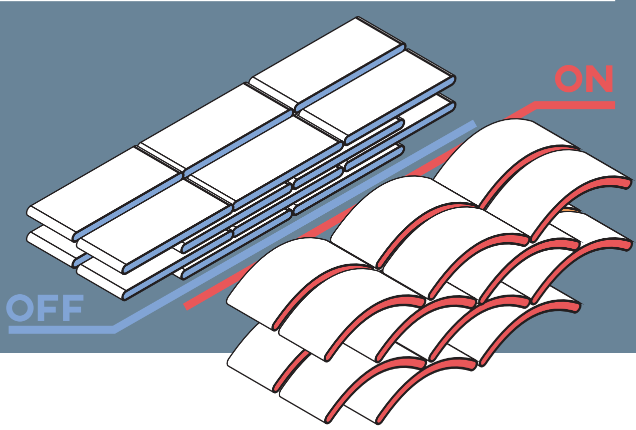
The air flow cause large amounts of torque, which the thermal expansion forces will likely have trouble countering. A FlexTECH solution would likely be more suited for smaller aircraft.

The swimming motions of a fish are a good example of simple oscillating actuation. An underwater FlexTECH robot could use this principle to propel itself forward by imitating a fish tial.

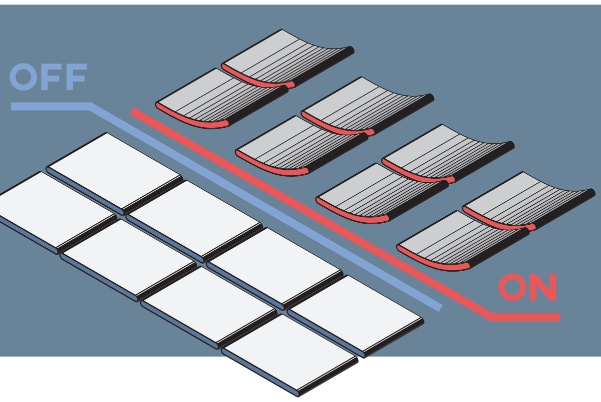
Ambient temperature of most large water bodies is significantly lower than room temperature, meaning we can achieve a much larger active deformation before reaching Tg. Additionally, the convective heat transfer coefficient of water is larger than that of air, meaning the actuator is cooled much more rapidly and will increase the speed of the actuation cycle. As this affects both sides, no stable active can be achieved as with the ailerons, but since the fish-tail motion requires a constant oscillation, this will not be necessary.

FlexTECH actuators have not yet been tested underwater. Water might short the circuit if the resistance is high enough.

META-MATERIAL



SURFACE TOPOLOGY



A FlexTECH Meta-Material could...

- ...inflate the total volume
- ...grow in one direction, and shrink in another.
- ...be able to support additional weight due to the arch structures

...**on command**

A FlexTECH surface could...

- ...increase overal surface roughness
- ...create an anisotropic surface roughness
- ...be able to activate specific areas
- ...lift and even carry objects on the surface

...**on command**

If the technology is made small enough, multiple FlexTECH elements could be joined together to form a lattice of small actuators. The result would be an overal material that can change some of its material properties like roughness, stifness, and volume, when excited with an electrical current. These materials could then go on to be deployed in entirely new applications.

The miniaturisation of FlexTECH would also be interesting for nano-technology. Because the structure is so basic, it might be possible to create microscopic actuators through means of stereolithography or similar techniques. The actuators could be used to trigger circuits or phsyically move small elements.

5.7) ROBOT DEMONSTRATION

In order to properly convey the feasibility of FlexTECH actuators in robotics, a visual demonstration is required. A small locomoting robot was made to show FlexTECH in action, together with the knowledge obtained in the Design Guidelines.

Design

The design of the robot was based on the concepts of chapter 3.4. This time, the weight would be properly divided among all its legs so that there would be no weak points in the design. Each actuator has to account for its own weight, as well as one directly above it.

The robot features a sets of differently orientated arms and legs, creating two planes of motion. Ideally, this extra plane would have been created with self-assembly of the robot through ratcheting. Because ratcheting was not yet possible with the new screen printing production method, the choice was made to print the robot in multiple parts that would connect perpendicularly in order to create multiple planes of motion.

The arms of the robot are mounted at a right angle, so that the vertical displacement of the actuators results in horizontal movement of the robot. The tip of the arm actuators featured small prongs that extend past the leg-body and make contact with the surface. The legs are used to lift the robot, specifically the arms, off the surface so that the arms can move back to their first position without pushing the robot back.

Figure 72 shows the screen-printed parts for the robot, featuring two sets of two arm actuators, and one set of four leg actuators. The circuits of the arms are connected with wires to create one large circuit, so that all arms move at once. The arm sets are then glued onto slots of the leg-body with an epoxy.

The robot's weight was measured as follows:

- Set of 2 arms: 0.95 grams
- Set of 4 legs: 2.19 grams
- Total assembly weight: 5.42 grams
- Weight of robot = 2 x arm weight + leg weight = 4.10 grams
- Weight of wires and attachments = assembly weight – robot weight = 1.32 grams

Actuation

To test the pre-shaping principle, the actuators were all pre-shaped into a bent state (Figure 73), so that actuation would move the actuators flat again. Because the actuators feature larger circuits, the resistance is larger and more power is required to heat the robot. The corrections for the resistance changes turned out to be tricky. Though pre-shaping was effective, the legs were accidentally pre-shaped too far, resulting in the robot not being able to reach the surface with the arm supports. The surface below the arms was raised to correct for this mistake. Alternatively, the arm prongs could have been extended to reach the same effect.

Figure 74 shows the stills from the robot video. Each large square on the surfaces are 10 mm. The most effective test of the robot showed it moving ~20mm forward in 5 strides, resulting in an average stride length of 4 mm. Each stride was an actuation cycle of 90 seconds total, resulting in an overall speed of 0.044 mm per second.

Conclusion

The robot shows that FlexTECH actuators can be used in robotics. The pre-shaping functionality provides means for self-assembly, and the actuation cycles can provide small pulsating movements that can be used for locomotion. Even though thermal expansion forces are relatively small, the robot has no problem lifting its low weight of 5.4 grams. The robot can move both forward and backward by switching the order of the actuation cycle. If sets of arms on the left and right side were to be controlled independently, the robot could even steer itself. The speed of the actuation cycle remains low for now, but could be improved upon e.g. by actively cooling the robot.

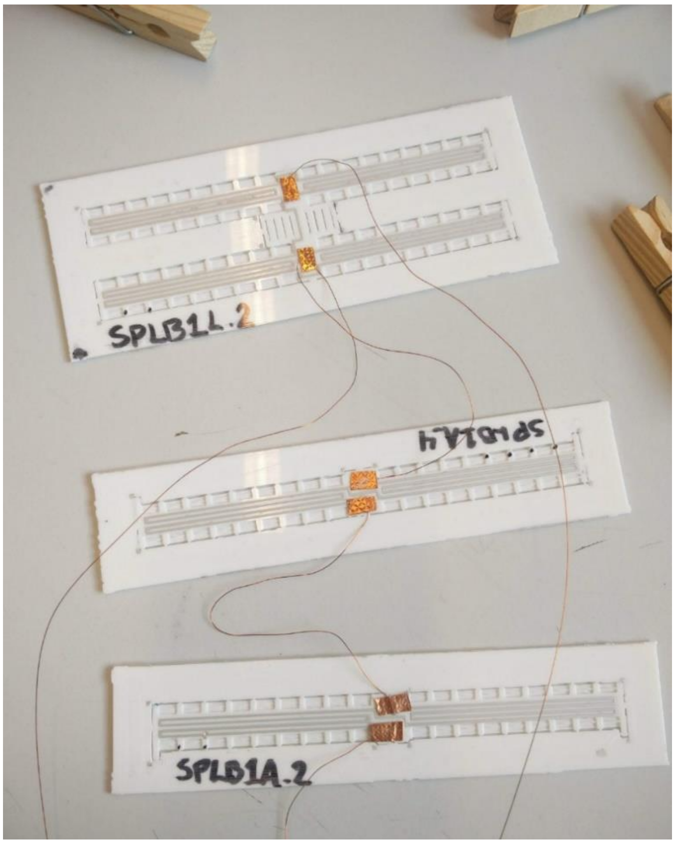
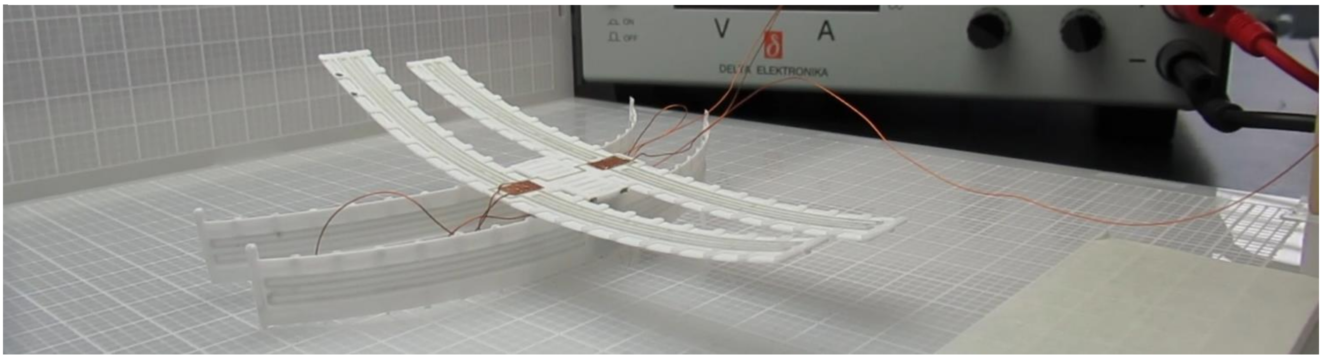


Figure 72: the screen-printed parts of the FlexTECH robot

Figure 73: the preshaping of the robot actuators



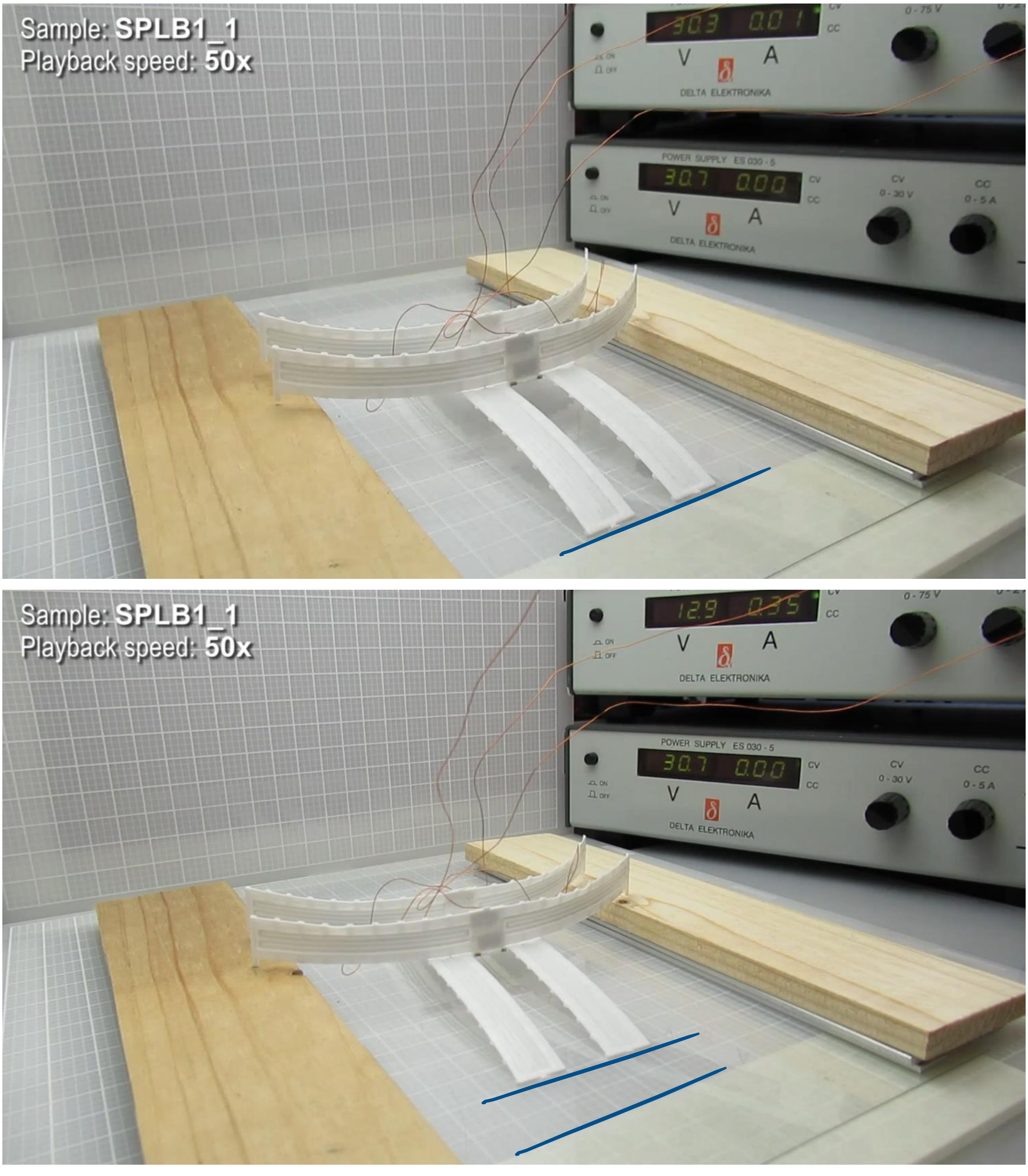


Figure 74: The FlexTECH robot in action. Top: the robot at its starting point. Bottom: the robot after 5 actuation cycles

6) CONCLUSION

The original goal of the project was to make FlexTECH technology more accessible to researchers and designers.

The analysis provided the necessary context and theory required for the understanding of the phenomenon and the significance of its discovery.

The exploration phase explored ideas for other types of functionality for FlexTECH, such as ratcheting and intrinsic oscillation, and experimented with concept robots to test its feasibility.

The modelling phase quantified the performance of a FlexTECH actuator, to link the different variables and provide valuable data to serve as a starting point for future designs.

The Design Guidelines present all the gathered knowledge in an easy to read format to lower the barrier of learning about FlexTECH. It showcases the overall advantages of FlexTECH, as well as the most important considerations for FlexTECH actuator design, actuation control, and potential material & production adaptations. On top of that, it showcases potential applications to inspire future research.

The FlexTECH robot demonstration provides a proof-of-concept, and showcases the technology's feasibility. It also serves as an 'eye-catcher' to pique interest in other researchers and designers.

By developing an alternative production method based on screen printing, the construction of FlexTECH actuators is no longer limited by the availability of conductive-material 3D printers.

The project shows that FlexTECH has potential as a 4D printing material by utilising the unique mechanics of Printed Electronics. By offering real-time control over actuation, the material is arguably 'smarter' than most smart materials. The actuators are very basic and easy to produce, which opens up the potential for further application. A printable, single-component actuator could greatly reduce on complexity, material & assembly cost, weight, maintenance, and fault rates.

6.1) IMPROVEMENTS & FUTURE RESEARCH

The applications section of the Design Guidelines highlight a few possible directions for further development of FlexTECH actuators in their current form. However, more significant changes to the technology could expand the scope even farther. The following examples pose suggestions for modifications of the current design, while still utilising the core principles of FlexTECH.

Trace modifications

The development of a better conductive print material could enhance form freedom in actuator design, and facilitate the design of additional conductive-material 3D printers. Due to the limitations imposed on the trace dimensions by various production methods, the volumetric resistivity is of great importance. As the Design Guidelines have shown, a printable conductive material with a Volumetric Resistivity between 4 and 108 Ωm could effectively actuate our actuator design with a voltage of 3 V, which is the voltage supplied by most small cell-batteries. These batteries are small enough to be carried by a FlexTECH robot, and would eliminate the tether restriction currently brought by the wires and power supply. Furthermore, the development of printed battery and microcontroller contacts could make the robot completely autonomous.

Structure modifications

Different shape variations of the actuator structure could be used to influence the actuation, enhance performance, or provide additional features.

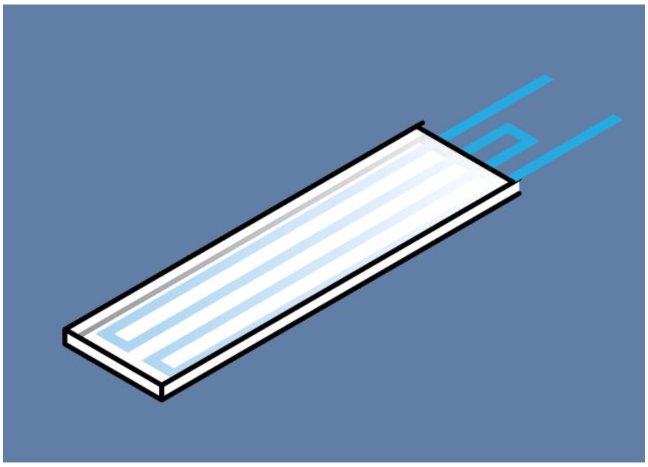


Figure 75: A trace embedded in a structure

Figure 75 shows an example of a hollow structure that has a trace embedded within. A dual-material 3D print could print both the trace and structure simultaneously to achieve this result. Embedding a trace would result in better heat dispersion, and protect the more delicate trace from damage or potentially even from liquids in underwater applications.

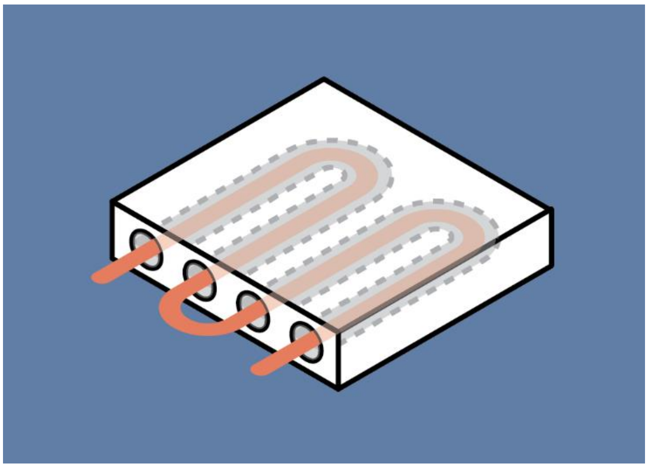


Figure 76: A structure with hollow channels that can fit a trace inside

Alternatively, a structure with hollow channels could be printed by itself (Figure 76). A conductive paste material could then be cast into the channels to create an embedded circuit. Drying the paste would be difficult if the structure is not made permeable so that the moisture can escape. The structure channels could also be threaded with a solid resistive wire, to avoid using printable conductors altogether.

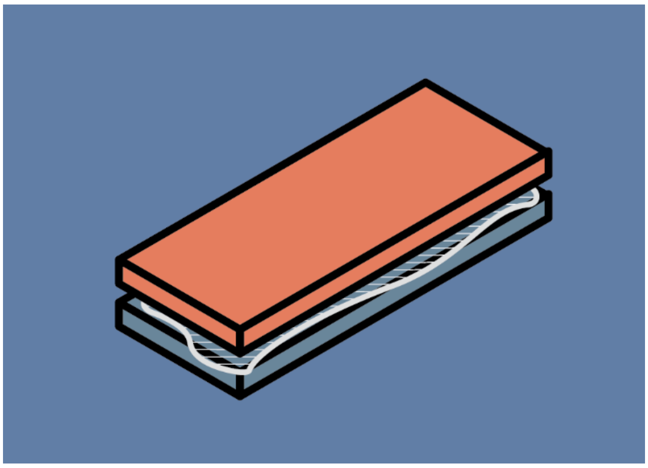


Figure 77: An adhesive joins two symmetric structures together

If an adhesive were to be found or developed that is sufficiently flexible and has good insulation properties, the structure could do away with its offset layer design. A structure made of two flat pieces that are joined with such an adhesive (Figure 77) would be a good step toward miniaturisation of technology, for implementations such as the meta-material and surface topology applications as seen in the Design Guidelines.

Research into different structure materials could also prove useful. PLA was used because it was readily available, and while it does seem a good candidate for FlexTECH actuation, materials with similar properties could fulfil the same function. Specifically polymers with a higher glass transition temperature could likely reach much greater active deformation. Alternatively, polymers with a low glass transition temperature could be tested at low ambient temperatures.

The adaptation section of the design guidelines show that aside from other polymers, even some metals could be considered as candidates. These metal actuators would not feature any pre-shaping due to a lack of a glass transition, but could potentially have other benefits. Thermal conductance of metals is much higher than that of polymers, which would probably make the actuator more energy efficient. However, the two layers would need to be insulated extremely well, as the conductance would also affect heat transfer between them.

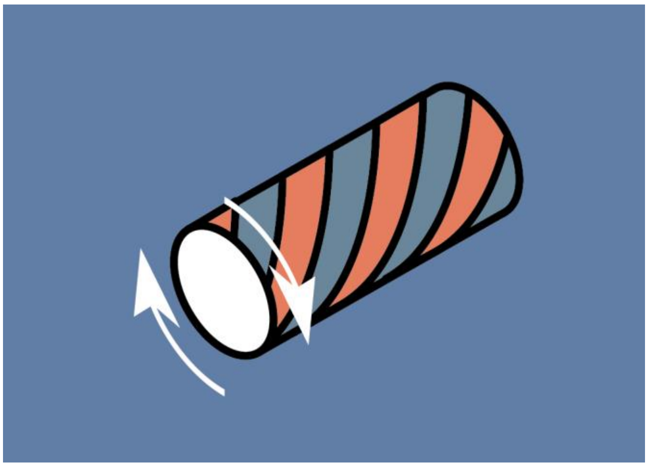


Figure 78: An idea for a twisting actuator

Torsion was briefly considered during the exploration phase, and remains an interesting subject. A complete redesign of the rim and base structure could potentially cause the expanding sections to twist the material, rather than bend, causing a 'TwistTECH' actuator if you will (Figure 78). The different movement of the actuator could be used to create additional planes of motion and add a new dimension to locomotion solutions.

Sensor feedback

One major drawback of FlexTECH actuation is that there is no feedback from the actuator, meaning the system does not know exactly how far has deformed. It is not easy to regulate the temperatures in the material which ultimately determine the actuation. Feedback from sensors that could relay information about the actuation are crucial for greater control.

A conductive material of which the resistance strongly varies with temperature, called a thermistor, could be used to monitor the temperature in both layers. A printable version of such a material could double as the heating element.

Alternatively, a material with a piezoelectric effect could be used to act as a flex-sensor and monitor the amount of deformation. A downside would be that the amount of deformation is only an indication of the relative temperature difference between the two layers, and not the absolute temperatures. The approach towards the glass transition will have to be estimated by the change in actuation direction when the material loses its stiffness.

Active cooling

A solution for active cooling would greatly enhance actuator performance. Currently, actuation is very slow as passive cooling takes several minutes to complete. An active cooling method could drastically speed up this process.

Additionally, selectively cooling one of the layers would result in an actuation effect similar to the current thermal expansion approach. If these were to be combined, with one layer actively heated, and one layer actively cooled, we could achieve a stable temperature difference. This means that the actuator can remain in its position during active deformation.

Printed Relay

As mentioned in the exploration phase, printed oscillation remains an interesting subject for further research due to its potential to replace the microcontroller used to start and stop the power supply.

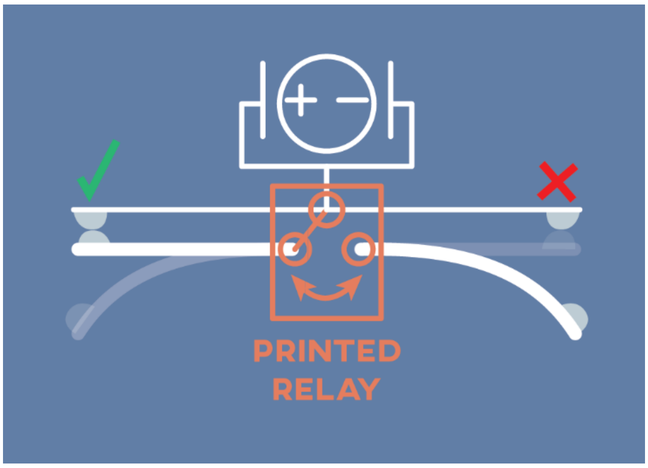


Figure 79: A schematic for an intrinsic oscillation concept

Figure 79 shows a concept for a FlexTECH design that uses an actuator to trigger a different actuator, which then repeats the process. The central part of the design is a relay switch that switches the power supply between the two actuators. If this relay switch could be replicated with printed electronics, a FlexTECH robot could incorporate it into its design.

Compliance-controlled composite

The dual-material printing of conductors and polymers could be used in a different way. Rather than designing a flexing structure, a digital material variant could be made to achieve different functions. As we know, thermal expansion is not the only side effect from the heat supplied by the conductor, as heating a polymer through its glass transition drastically affects many material properties, the most notable of which is its stiffness. A digital material that carefully weaves the conductor and polymer together could create a solid block of material that heats up when supplied with a current. When doing so, the stiffness would drop significantly, resulting in reduced compliance of the material. In essence, the compliance of this composite could be controlled with an electrical current. It might not be an actuator, but it could very well have interesting applications beyond the scope of FlexTECH.

6.2) REFLECTION

Working with a new material such as FlexTECH at such an early stage of its development was challenging, and quite a change from the typical way of developing production-ready products in *Integrated Product Design*. That said, the project has taught me a lot about material science, and I would love to pursue a career in this field. The diversity of the ideas and epxlorations have shown that new materials are at the core of most new innovations, and a new material discovery could go in endless different directions. I personally think 3D printing and smart materials have a promising future, by cutting down on material waste, assembly, and providing decentral manufacturing.

The breakdown of the Voxel8 3D printer was a big setback for the project, but in hindsight opened up the way for a more accessible means of production to continue research into the phenomenon. If I had more time, I would have loved to test all the additional features mentioned in the exploration and recommendations, as well as validate the experiment through a proper mathematical model and simulation. I hope my work has inspired others to do so as well.

REFERENCES

Alsop, T. (2021, February 25). *Most used 3D printing technologies in 2020*. Retrieved from Statista website: https://www.statista.com/statistics/560304/worldwide-survey-3d-printing-top-technologies/

Ansys. (2020). GRANTA EduPack Software. Cambridge, UK.

Ge, Q., Qi, J. H., & Dunn, M. L. (2013). Active materials by four-dimension printing. *Applied Physics Letters*.

Hou, T., Elkhuizen, W. S., Wang, C. C., Jiang, J., Geraedts, J. M., & Song, Y. (2019). Design of 3D Wireless Power Transfer System Based on 3D Printed Electronics. *IEEE Access*, 94793-94805.

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*, 35-54.

Leigh, S. J., Bradley, R. J., Purssell, C. P., Billson, D. R., & Hutchins, D. A. (2012). A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLoS ONE*, 1-6.

Maas, M. (2017). *A Robot out of a 3D Printer - an exploration of 3D printed thermal actuators.* Delft: Delft University of Technology.

Momeni, F., Hassani.N, S. M., Liu, X., & Ni, J. (2017). A review of 4D printing. *Materials and Design*, 42-79.

Must, I., Kaasik, F., Põldsalu, I., Mihkels, L., Johanson, U., Punning, A., & Aabloo, A. (2015). Ionic and Capacitive Artificial Muscle for Biomimetic Soft Robotics. *Advanced Engineering Materials*, 84-94.

Osswald, T. A., & Menges, G. (2012). *Material science of polymers for engineers.* Carl Hanser Verlag GmbH Co KG.

Sturm, K. G. (2017). *Microscopic-Phenomenological Model of Glass Transition I. Foundations of the model.* ResearchGate.

Tibbits, S. (2013). The emergence of "4D Printing". *TED Conference.*

Wu, J., Zhen Ding, C., Isakov, M., Mao, Y., Wang, T., Dunn, M. L., & Qi, H. J. (2016). Multi-shape active composites by 3D printing of digital shape memory polymers. *Scientific Reports*.

Zhang, Q., Zhang, K., & Hu, G. (2016). Smart three-dimensional lighteight structure triggered from a thin composite sheet via 3D printing technique. *Scientific Reports*.

Zhao, S.-C., Maas, M., Jansen, K., & van Hecke, M. (2019). 3D Printed Actuators: Reversibility, Relaxation, and Ratcheting. *Advanced Functional Materials*.

APPENDIX

APPENDIX A: LOCOMOTION

SCOPE & CATEGORISATION

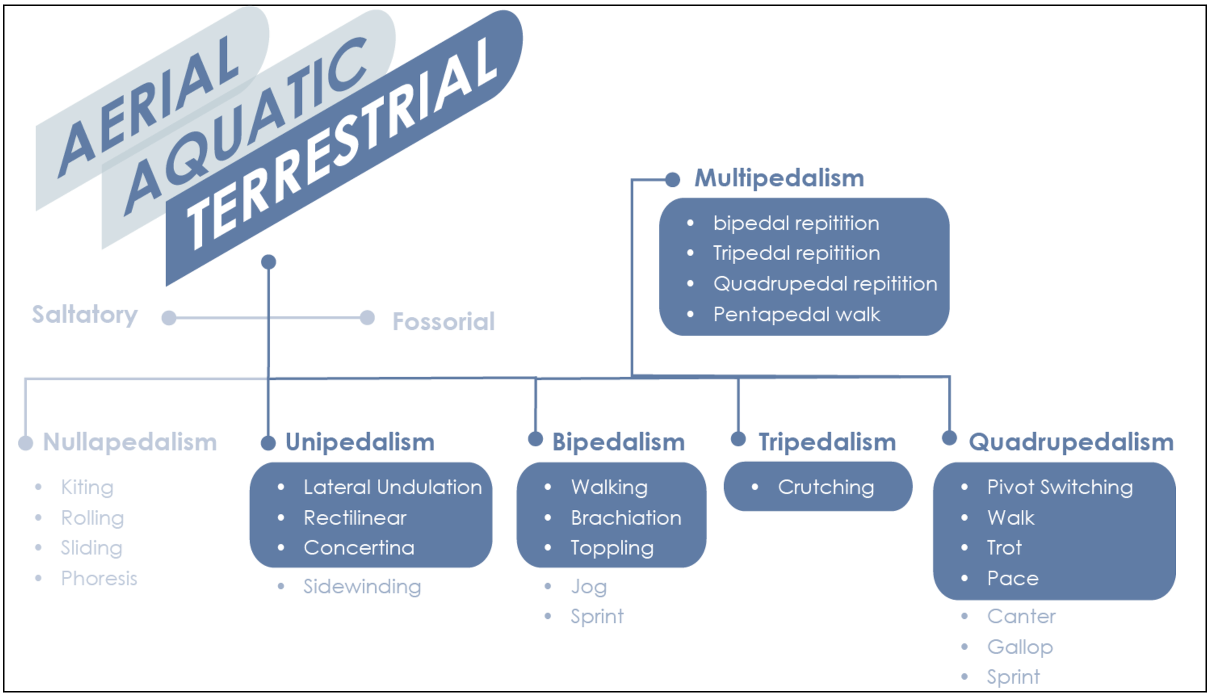
To find inspiration for locomotion, we need not look far. Through the course of evolution, nature has optimised the process of locomotion in a variety of different ways. Each family of organisms has evolved a unique method of locomotion by adapting to their environments and utilising the biological mechanisms at their disposal. As a result, there is an immense amount of different variations of locomotion.

All types of locomotion can be roughly put into three main categories. Aquatic, for movement in water (or any fluid with a density roughly equal to the locomoting body), Aerial, for moving through the air (or a fluid significantly less dense than the locomoting body) which requires the generation of lift, and Terrestrial, for moving across solid surfaces.

Because FlexTECH actuators not yet been tested in water (and the use of electric currents is sure to pose some problems) and are not fast or strong enough to generate any kind of lift, we will limit our scope to terrestrial locomotion only. There are some aquatic and aerial types of locomotion that would potentially be possible, especially passive types of locomotion like sailing and kiting performed by jellyfish, tumbleweeds, and spiders, that are based on riding a current flow. However, since the ultimate goal is to show the capabilities of an actuator, passive locomotion is also not of any interest.

Within the category of Terrestrial locomotion, there are a few subgroups that we can already exclude, specifically 'Fossorial' and 'Saltatory' types of locomotion. Fossorial locomotion includes any kind of burrowing through loose solids (performed by e.g. moles and some lizards) and falls outside of the scope as PTAs lack the force required to displace terrain. Saltatory locomotion describes 'hopping' motions performed by animals like kangaroos, hopping mice, frogs, and many insects, among others, and requires explosive force unable to be generated by current PTAs.

Within our chosen scope, the clearest denominator for different types of locomotion among different species is probably the number of locomotory organs, or limbs, they use to perform said locomotion. Therefore, number of limbs has been chosen to distinguish further subgroups.

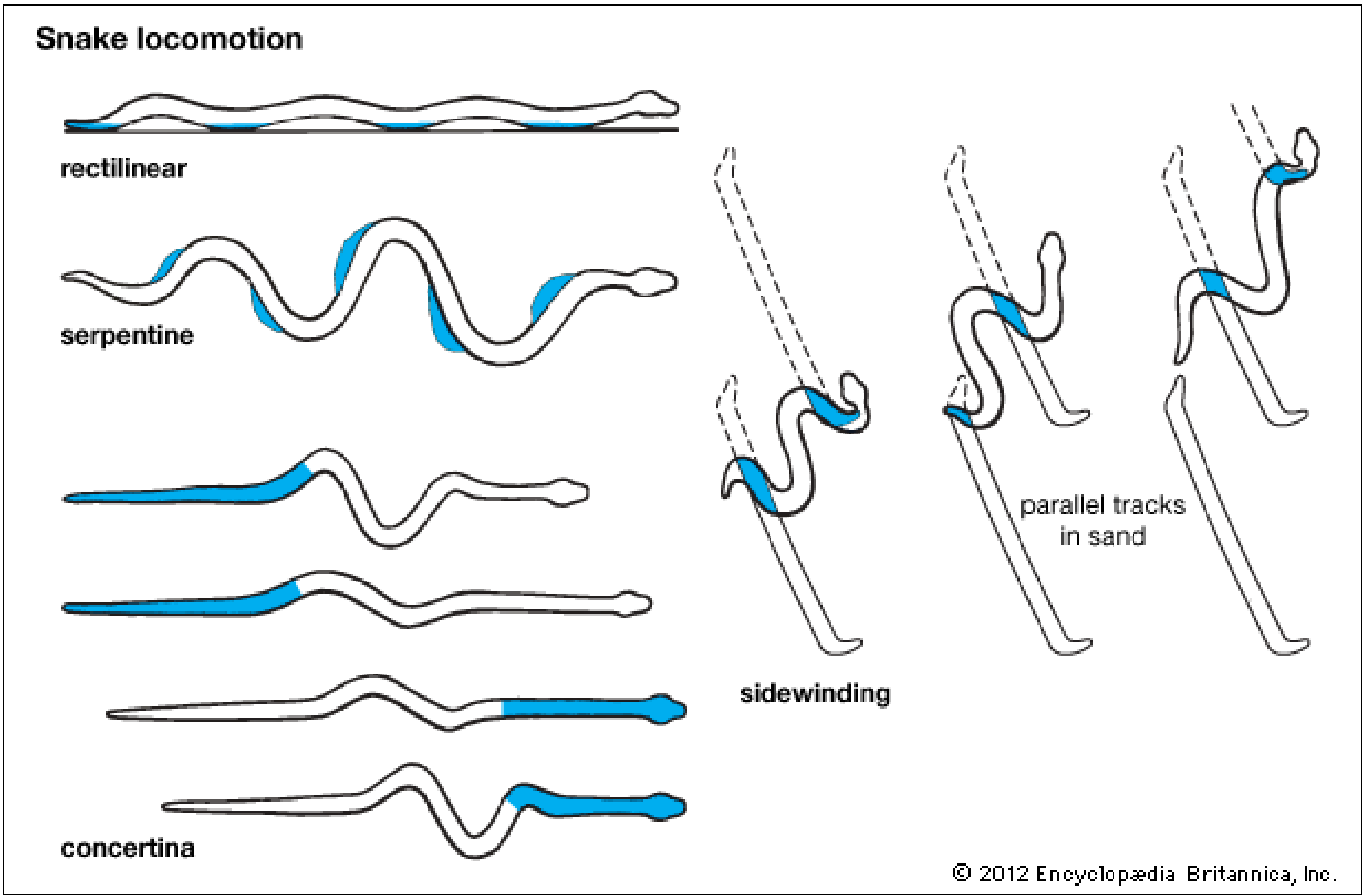


NULLAPEDALISM (PASSIVE LOCOMOTION)

It might seem difficult to perform any kind of locomotion without any limbs. Yet, there are examples in nature of limbless animals moving around. Because of this lack of actuating limbs, these forms of locomotion are mostly passive. 'Nullapedalism' is a made-up term to make it fit with the rest of the categories, as the types of locomotion within this category are more often referred to as '**passive locomotion**'. Even limbed animals can often use this type of locomotion to save energy, and thus *nullapedalism* refers more so to the fact that these types of locomotion do not *require* any limbs, rather than suggesting only limbless animals perform it.

Kiting refers to catching and riding a draft of wind, and is performed even by non-aerial animals like spiders, or even plants such as the tumbleweed. Some species of beetle let gravity do the work by ***Rolling*** down inclines, or one could ***slide*** across slippery surfaces as penguins do. Lastly, ***Phoresis*** refers to catching a ride on other moving animals.

Regardless, passive locomotion is not of any interest to this project, as the entire goal is for our actuator to show its potential.



UNIPEDALISM

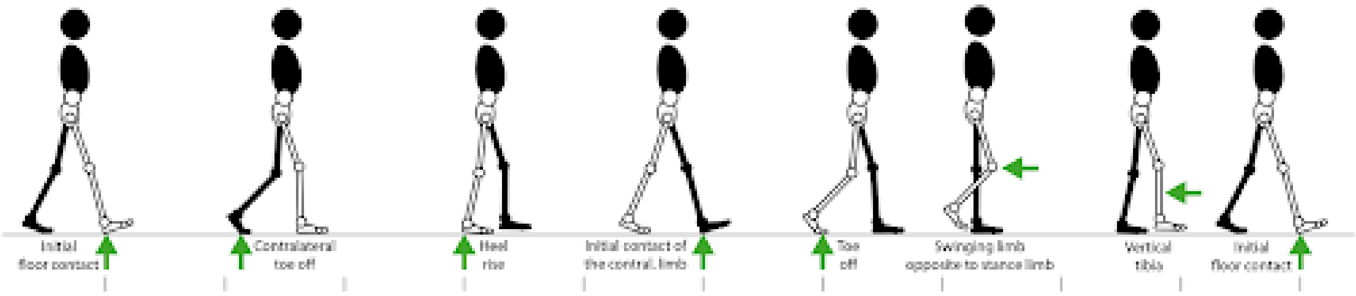
The difference between nullapedalism and unipedalism is slightly vague. Animals that have only a single locomotory organ, like snakes, snails, and worms, wouldn't be considered 'limbed'. Furthermore, the body with which they perform said locomotion is often a complex system of many muscles and vertebrae. Yet, while limited to a single locomotory organ, **unipedal** animals have developed quite a diversity in their locomotion methods. Snakes alone use at least 5 different locomotion types to get around, all of them quite distinct. They could be considered 'gaits', but which locomotion method a snake uses is more often determined by the type of terrain and the obstacles a snake has to manoeuvre around rather than the desired speed, which is typically the case with bipedal and quadrupedal gaits.

The most common type of locomotion is **lateral undulation**, sometimes also called *serpentine* motion. As the name suggests, the snake moves its body in lateral waves, pushing each bend outwards. These bends push against the surface, or objects like rocks and sticks, and the multiple inward vectors from each bend cancel each other out to create a net forward movement. Because it relies pretty heavily on irregularities in the surface to push against, lateral undulation is not effective on flat, slippery surfaces.

In **rectilinear** locomotion, a snake keeps its body relatively straight. Small elements of the body are extended to propel the body forward, while alternating segments in between are lifted slightly from the ground and contracted to repeat the motion. If you were to follow an individual body segment, it would appear to make small circular motions, very similar to how a millipede's legs would move if they were all connected to each other. This type of locomotion is often employed by heavy snakes.

With **concertina locomotion** the centre of the snake's body acts like a spring, contracting and extending, while the ends of the body act as alternating anchor points. Activating entire muscle groups at once instead of more continuously like with the other types of locomotion results in a very slow and strenuous movement. Typically, snakes use concertina locomotion when space is limited. When crawling through tight tunnels, they use a variant of this motion called **tunnel concertina**, where, instead of anchoring parts of the body by pushing them vertically against the ground, the body is anchored by curling up, essentially making their body expand, to wedge themselves in the small space of the tunnel. Snakes can even climb using this method.

Sidewinding is the fastest type of snake locomotion, equivalent to a horse's gallop. It is similar to lateral undulation, but has some major differences. The initial movement is created by the snake throwing the front of its body through the air. The rest of its body then follows and 'rolls' along the surface, meaning there is only static friction and no sliding movement. Because of this, sidewinding is very efficient on loose and shifting surfaces like sand.



BIPEDALISM

With only 2 points of contact with the surface, bipedal locomotion is relatively unstable. When one of those anchor points needs to move, only a single anchor point remains. This creates a labile equilibrium much like an inverted pendulum, and thus good motor control and sense of balance is necessary to achieve efficient bipedal motion and avoid the risk of falling over. In a sense, bipedal **walking** uses this lability to its advantage by pushing off and 'falling' the rest of the way forward. Each step uses gravity and momentum to preserve energy.

Although one thing that is interesting about types of locomotion with a labile equilibrium (e.g. bipedal walking), as well as some passive types of locomotion like rolling, is that the effect that it uses gravity itself to do the heavy lifting and create a forward momentum by 'falling forward'. With such designs, only a small threshold needs to be overcome by actuation, after which gravity will carry it the rest of the way. If the object in question has some rotational symmetry, e.g. a cube, the process can then be repeated until it ultimately rotates back to the original position. This type of locomotion will be dubbed '**toppling**'.

Different gaits are determined by the speed of the motion cycle, as well as the amount of contact points with the surface during the cycle. However, as discussed earlier, both speed and airborne phases are of little interest for slow-moving actuators.

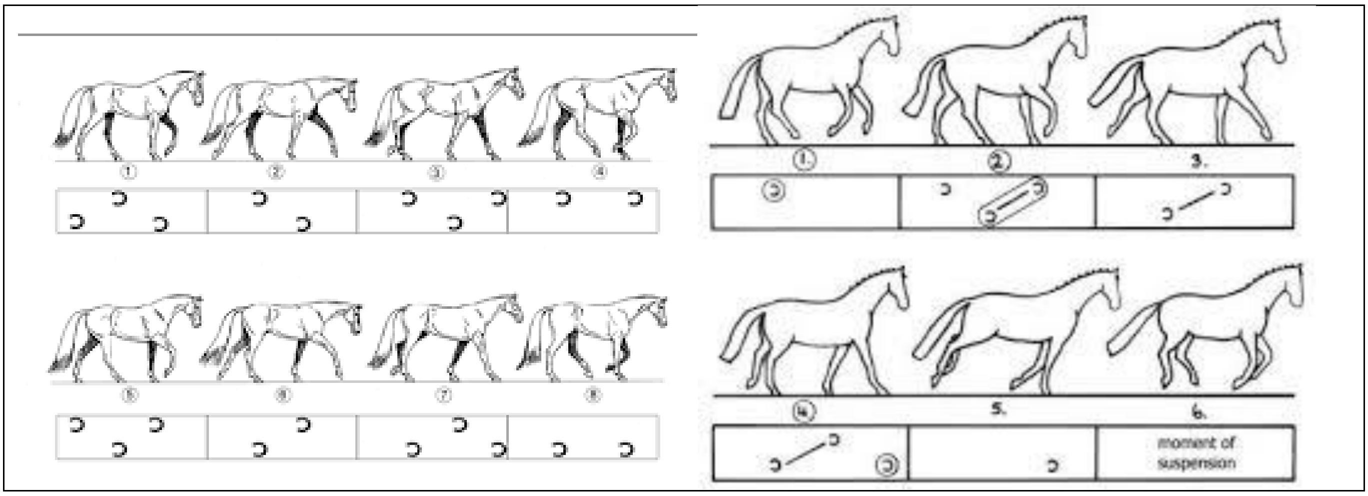
Notable examples are of course humans and many bird species.

TRIPEDALISM

Not many examples of tripedalism are found in the wild. Most examples include quadrupedal animals that turn tripedal through injury, or when one limb is unavailable, such as when carrying something. Humans, though bipedal, can also become tripedal when they use crutches to allow their arms to make up for a missing leg. The swinging motion they perform is very similar to bipedal walking, but with an extra contact point.

Similarly, some animals circumvent the lability of bipedal walking by resting on a third large contact surface in between motions. However, this creates a lot of resistance that needs to be overcome when that body needs to be lifted or dragged across said surface in a **crawling** or **crutching** motion. An example of this is the mudskipper fish when on dry land, virtually rotating their fins to drag their bodies across the surface.

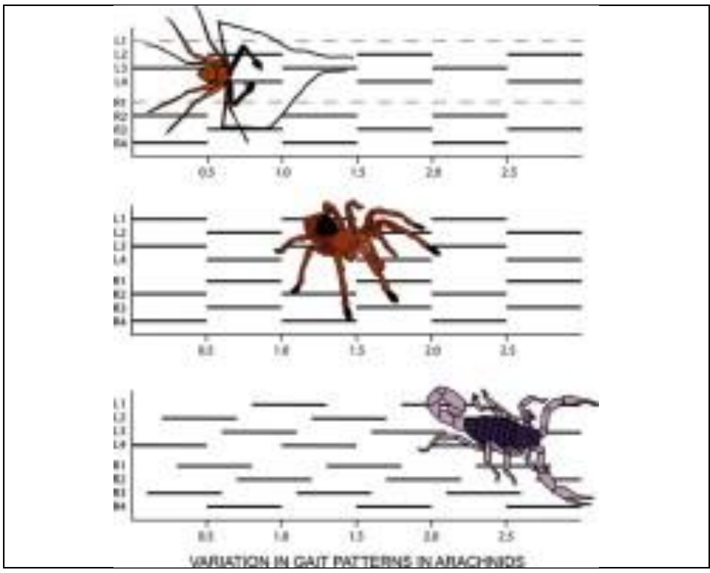
It can be argued that most climbing birds, e.g. parrots, that heavily utilise their beak as well as their legs exhibit tripedal locomotion, though it has not officially classified as such. Nevertheless, the benefits of tripedalism in climbing is clear, as there will always be two anchor points to remain a stable balance while the third one can move to a new position. However, to maintain balance when leaning on two contact points and leaning over for the third one to anchor itself, the anchor points need to have a firm grip on the surface (or make use of a counterweight), as is the case with a bird's beak and claws (and tail). Lastly, some macropods like kangaroos can alternate between resting on their muscular tail as well as their two legs, and even do so to slowly hop around.

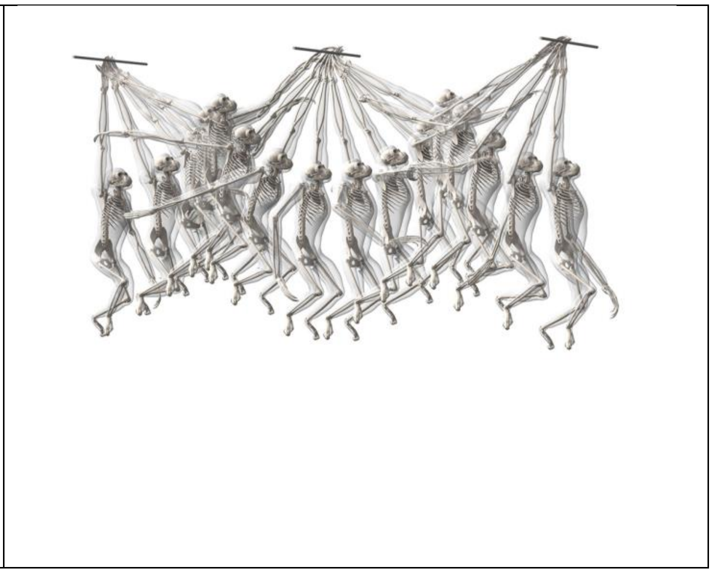


QUADRUPEDALISM

Quadrupedalism is the most common type of locomotion among mammals. The extra pair of locomoting limbs allows for more gaits than compared to bipedalism. In fact, quadrupedalism knows 6 different gaits, all used for different speeds. The slowest of them being the quadrupedal **walk**, which moves all 4 limbs one by one in 4 different beats, ensuring there are always 2 or 3 feet touching the ground. After that follows the **trot**, which has only 2 beats where each diagonal leg pair moves in the same motion, always keeping one pair in contact with the surface. In contrast, a **pace** has alternating leg pairs on the same flank. This locomotion type needs to be faster, as leaning on the pair of legs on the same flank would cause the animal to fall over to the opposite side, and paces often include a moment where no feet touch the ground at all. The other 3 gaits: **canter**, **gallop**, and **sprint**, are all even faster gaits with more airtime, but with different beats (3, 4, and 2 beats, respectively). But as mentioned before, locomotion that utilises momentum or airborne phases are not of any interest for this research.

A unique thing happens in the locomotion of many quadrupedal reptiles like lizards and crocodiles. Often, their hips are positioned more parallel to the surface, with also their legs extending from their body parallel to the ground. This limits their range of motion. To compensate for this, these animals bend their spine in order to pivot their body mass around the two current contact points. By alternating the set of legs they pivot around, the left-to-right bending of the spine can make the animal move forward, even without the legs themselves performing any kind of forward push. We call this type of movement **pivot switching.**





MULTIPEDALISM

Most examples of locomotion with more than four legs, including hexapedalism and octopedalism, are simply repeating sets of the same bi-, tri-, or quadrupedal motion. Multiple sets of legs have more contact points with the surface at any given time and thus are very stable, but require a lot of energy and motor skills to operate. Each set of legs adds significant weight and inertia for the body to move. *This is probably why multipedalism is most common in lightweight animals such as insects and arachnids that can support many times their own weight.*

ARBOREAL & BRACHIATION

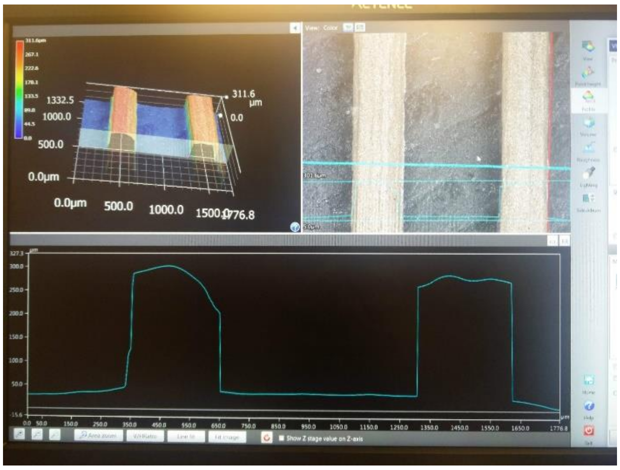
Even though arboreal locomotion falls outside of the scope, there are 2 interesting phenomena in this area that are worth discussing. Firstly, there is another type of concertina movement called '**arboreal concertina**', which describes the way snakes move across tree branches. The movement isn't very different from regular concertina, but it does demonstrate how diverse and stable the concertina movement is.

Another interesting and common type of arboreal locomotion is '**brachiation**'. This type of locomotion shows that it is not always the 'legs' of a creature that perform the locomotory movement. Sometimes other locomotory organs are used. Primates like gibbons and siamangs use their arms and tails to perform *brachiation*, i.e. swinging from branch to branch. Much like with regular bipedal walking, the pull of gravity is being used to 'fall forward' and create momentum. However, in the case of brachiation the anchor point is situated *above* the centre of mass, which causes the motion to have a much stable equilibrium. The locomoting body swings around like a pendulum, during which it can grab a new anchor point to either anchor itself or to continue swinging. While a stable equilibrium has some advantages, the use of momentum still seems a difficult task to apply to the incredibly slow actuation of PTAs. Additionally, a disadvantage of a stable equilibrium is that it is hard to get the momentum going again once you fall into the equilibrium point.

APPENDIX B: METHODS

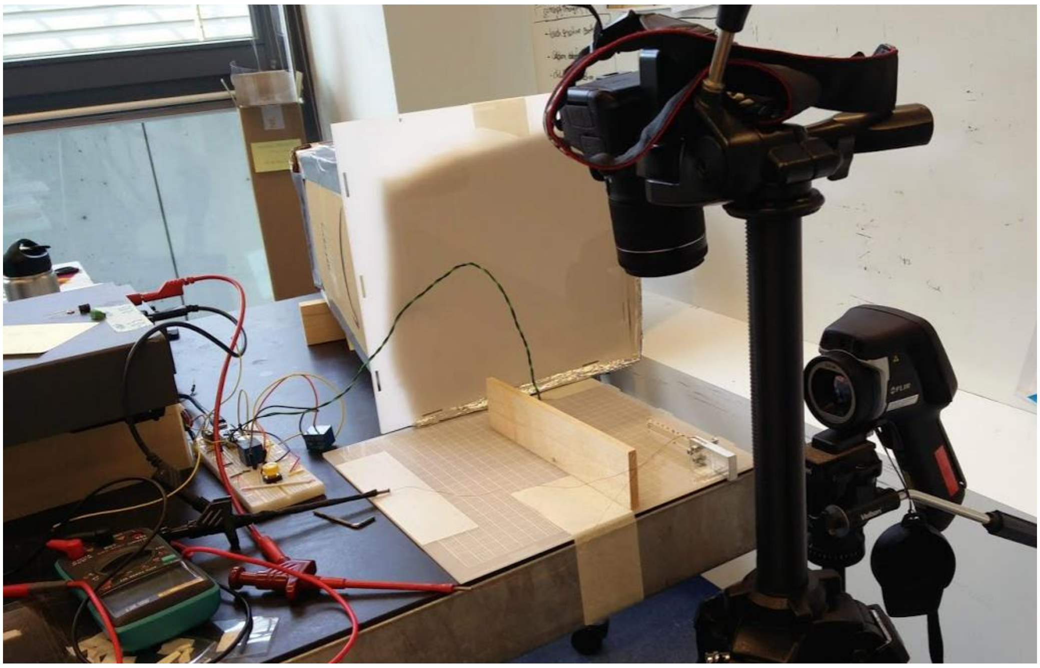
Trace dimensions

A KEYENCE microscope was used to ascertain the trace dimensions of the samples printed with the Voxel8. The microscope was only available for a limited amount of time, and thus no extra measurements were performed. The rectangular approximations of both depicted traces were averaged.



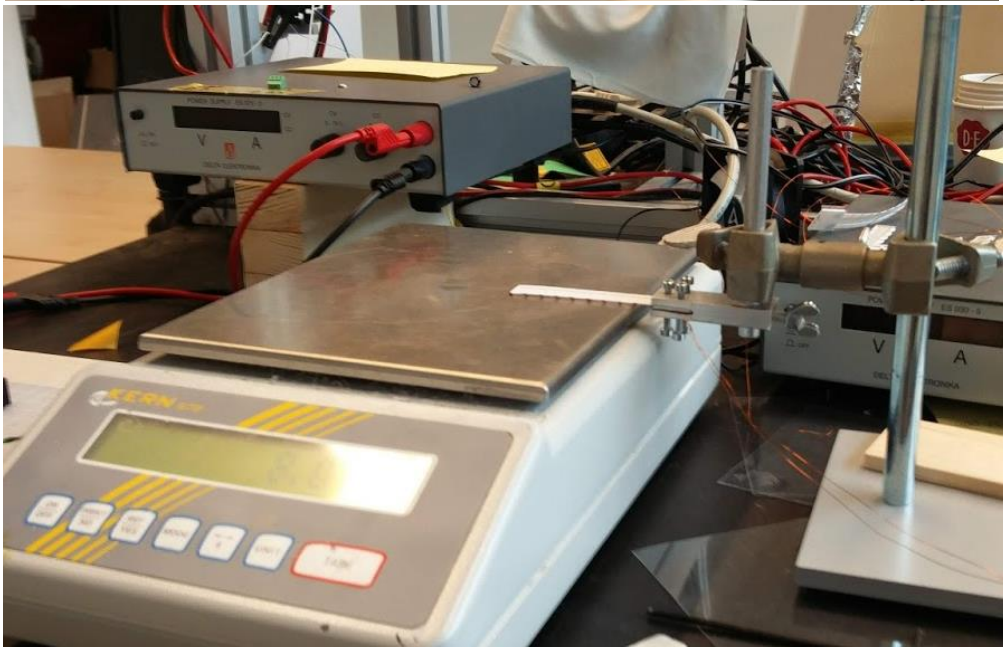
DTR-Experiment Setup

The sample was mounted in an aluminium clamp that was fixed to a desk. In between the desk and the clamp was a piece of acrylic that had 10 mm major gridlines and 2 mm minor gridlines engraved int it by a laser cutter. A camera was mounted on a tripod and positioned directly above the sample, pointing down. A thermal camera was mounted on a different tripod and was positioned to the side, level with the sample. A LED was mounted to a wooden backdrop (to avoid any thermal reflection) and would light up when the actuator switched on to synchronise the two video feeds. The LED was controlled by the same microcontroller that controlled the actuator. The microcontroller was placed on a breadboard and connected to 2 relay switches, for both the base and the rim. The relay switches were connected to two separate power supplies. Lastly, a lightbulb in a softbox was positioned on the other end to provide enough light for the video camera. A mirror was placed behind the sample to ensure even lighting conditions. All values were logged every 0.5 seconds.



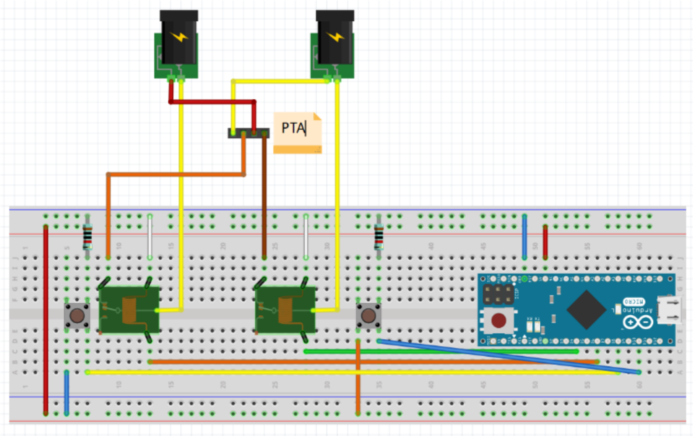
Force-Experiment Setup

For the force experiment, the sample was mounted on a clamp that was suspended by a pole. The clamp was carefully positioned so that the actuator would be level with the surface of a scale. The sample was angled ever so slightly upwards so that only the tip would touch the scale. This was briefly tested by lifting the tip of the actuator a minimal amount and checking if the scale read 0.0 grams. The most accurate scale available had a resolution of 0.2 grams. Other, more accurate scales had a large time delay that could not provide real-time data. Unfortunately, there was no interface to digitally read the data from. Therefore, the scale display was recorded with a camera during the experiment. The data was input manually by analysing the video and typing the value displayed on the scale into a spreadsheet. As this process was very time-consuming, readings were only taken every 5 seconds, with an exception being made for points where the actuation started and stopped, so that maximum values would not be overlooked.



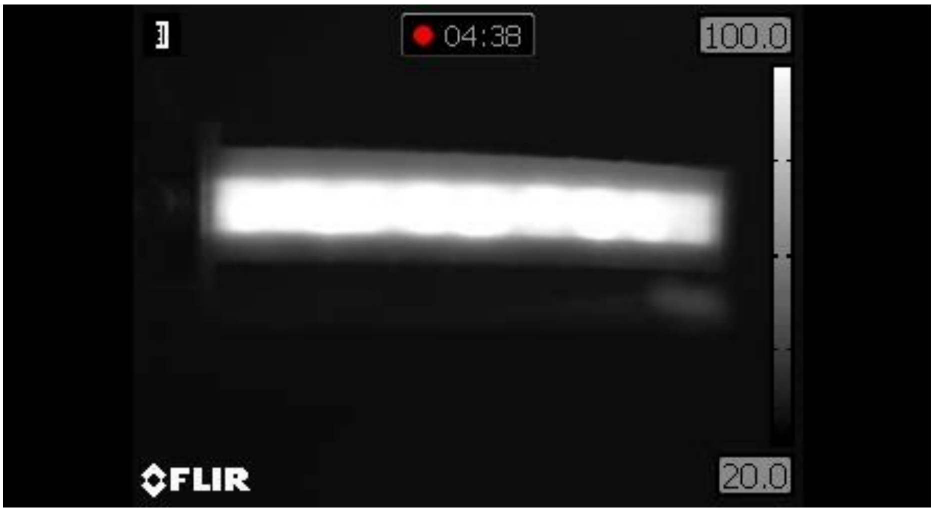
Electronics control

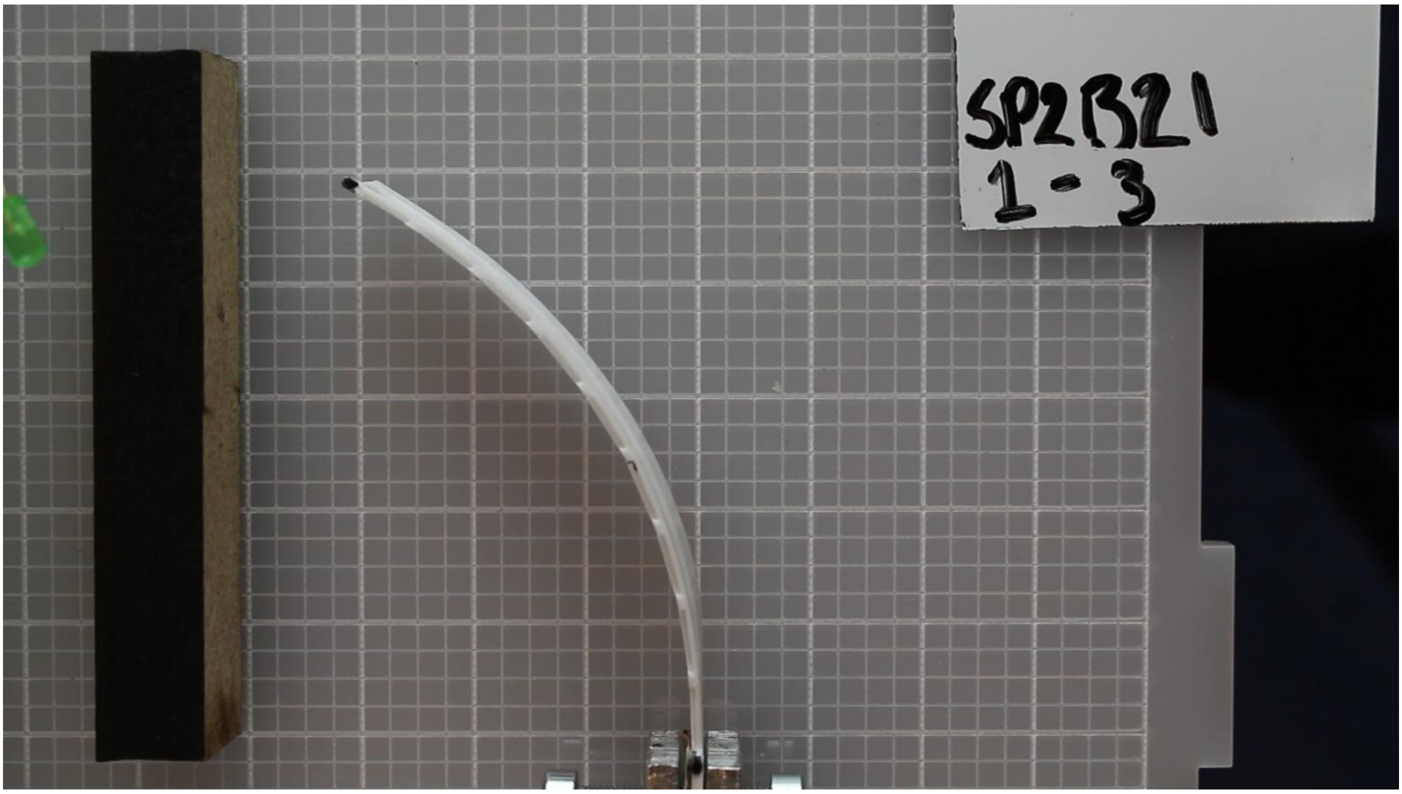
A script on the microcontroller controlled whether the relay would close or open the circuit. The time values for heating and cooling were coded into the script. To provide a stable power input, the power supply was also hooked up to the microcontroller with a data cable. The microcontroller would write the value a value on a digital pin, which corresponds to a specific current that would then be supplied by the power supply. The microcontroller would then read the resulting voltage from the power supply through a different pin. With both the current and voltage known, the script would then calculate the power output and run it through a PID controller to compare it against a target. The PID controller then output the next desired power value that the microcontroller could write to the power supply in order to approach the power target value. (P = 1, I = 1, D = 0)



Thermal data extraction

The thermal camera recorded the side of the actuator that did not have the trace on it. This means the temperatures observed are minimum temperatures, when the heat has travelled through the thickness of the sample. This method was chosen because the trace itself was expected to be much hotter than the material below, and would influence temperature readings if recorded directly. The videofeed of the thermal camera was recorded in greyscale. The video was cropped to feature only the actuator surface. The tip of the actuator that curved away and would expose the background was also cropped and these temperatures were excluded. This was not expected to influence results as temperatures are generally evenly divided across the length of the actuator. A python script provided by Dr. Song analysed each frame of the video, and divided it into a 4 by 8 grid. The 4 rows lined up with the 4 sections of the actuator. The top and bottom row covered the two rim sections, and the middle two rows covered the base. The script took the grayscale values from each pixel of a grid cell and returned an average value. These values were then imported to Excel, where they were mapped from grayscale to temperature values according to the scaling bar seen on the thermal camera video. The values for each section were averaged to achieve an average value of the temperature for both the rim and the base.





Deformation data extraction

The tip of the sample was marked with a black dot using a permanent marker. The video feed was imported into a video tracking software called 'Tracker'. The neutral axis for the zero-value were lined up with the clamp direction. A scale was given by the software by measuring the largest distance between two points on the acrylic grid, of which the dimensions were known. The Tracker software then tracked the black dot for each frame of the video and returned a value for the distance from the neutral axis. This means that all deformation values purely measure vertical displacement.

Excel data extraction

All data was imported into Microsoft Excel to be further analysed. Because of some small synchronisation issues discovered after the experiment, some small corrections were made to synchronise the temperature and deformation graphs. The data was split into sections for each heating cycle, after which most of the data of different samples was averaged. Further data like minimum and maximum values were extracted by means of excel formulas.

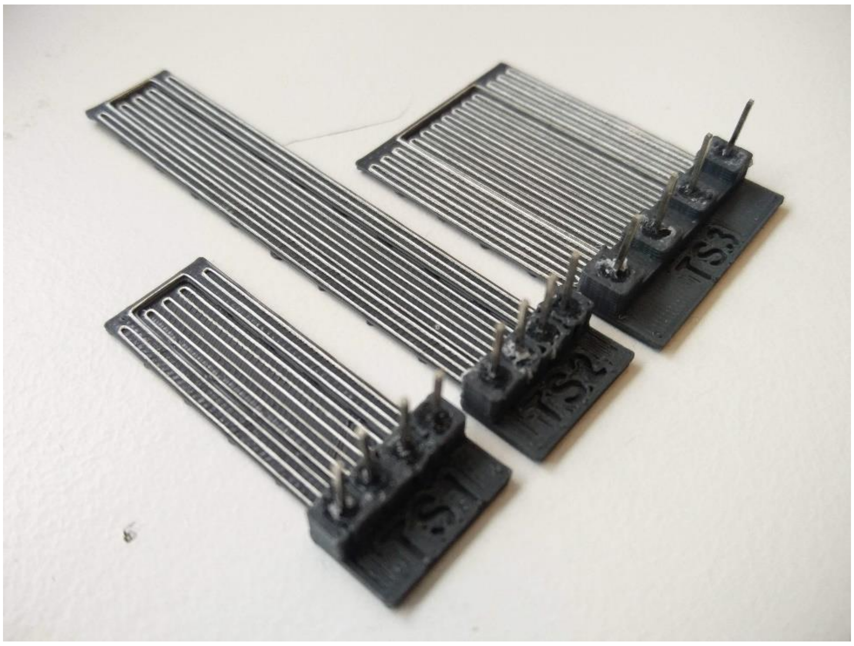
DMA-Experiment setup

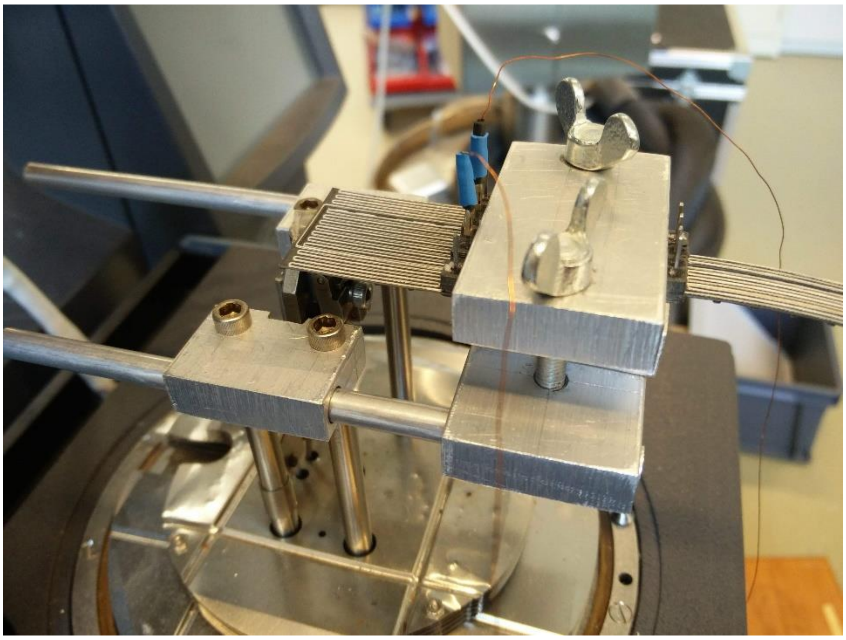
One of the first deformation experiments made use of the DMA Q800. The machine features a small piston that can exact a small force, and the displacement of which can be measured by the machine. A special clamp was made to fit the samples onto the machine, with the tip resting in the middle of the piston. The piston was set to exert a small force of 0.001 Newton to stay connected to the sample without influencing the deformation too much. Later, a second test attempted to test the load bearing capability of the sample, and upped the force to 0.1 Newton halfway through the test.

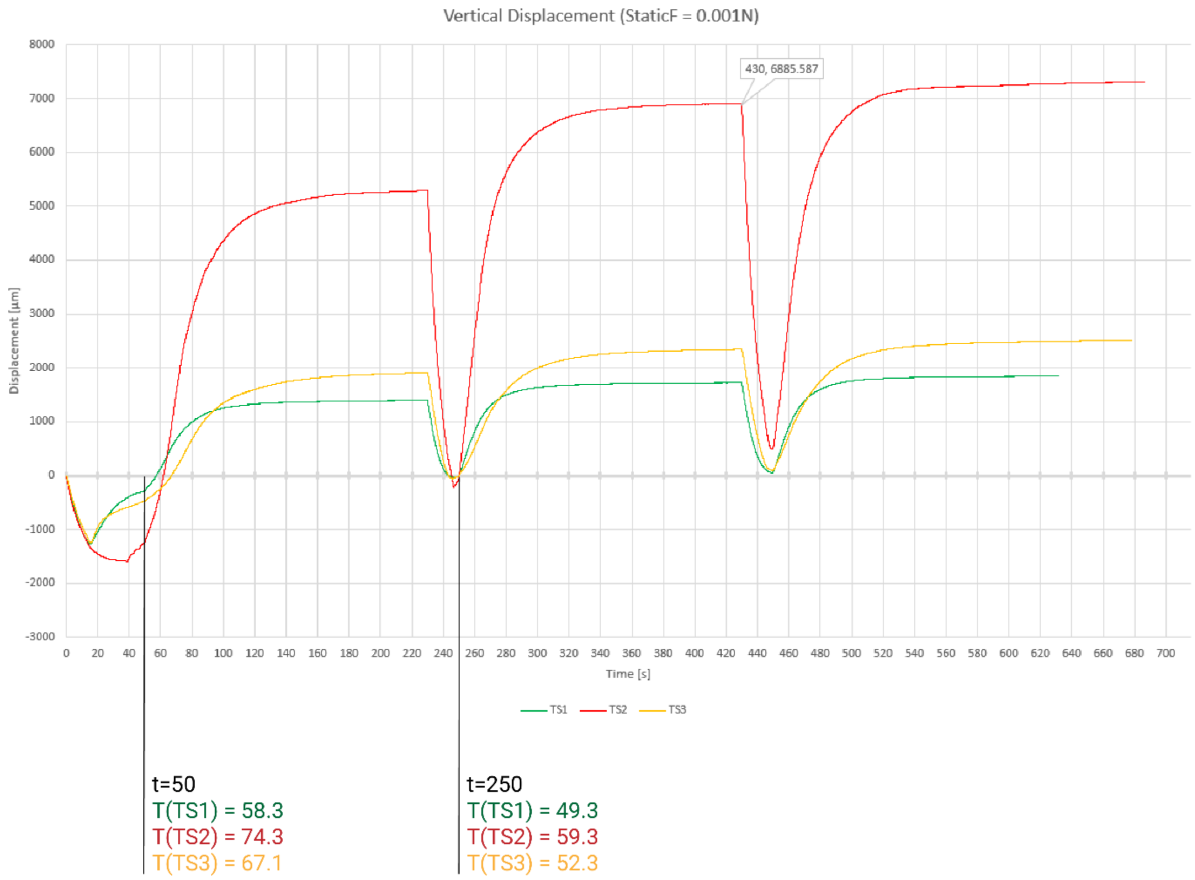
During this test, no PID control was available yet, and thus a constant current of 0.8 A was used instead. Three different samples of different geometry were tested. As the different geometry influenced the resistance, the temperatures curves were different for each sample.

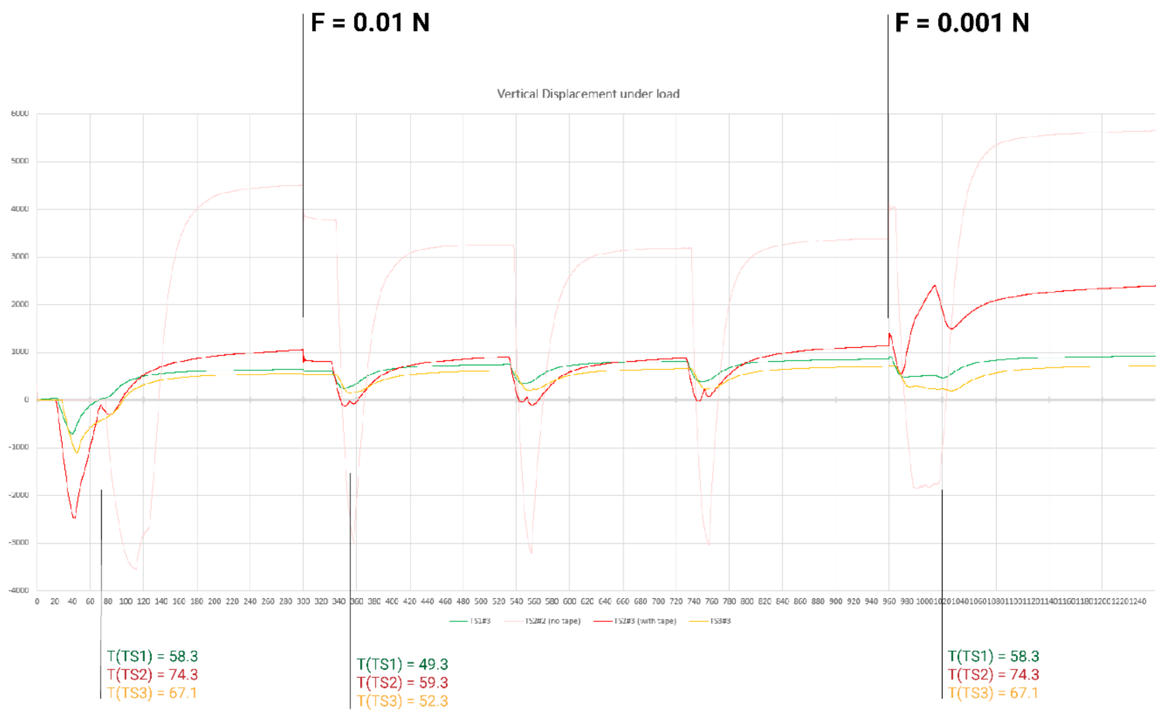
Unfortunately, the machine seemed to have trouble staying in contact with the sample. At several occasions, the piston was seen to disconnect from the sample during the test. Later, the test was attempted again with an added piece of double-sided tape to fix the sample to the piston. However, this resulted in wildly different results, and sometimes would cause the machine to start pushing the sample beyond its starting point.

Ultimately, while the exact nature of the errors was unknown, the data from the experiment was deemed inconclusive and unreliable.



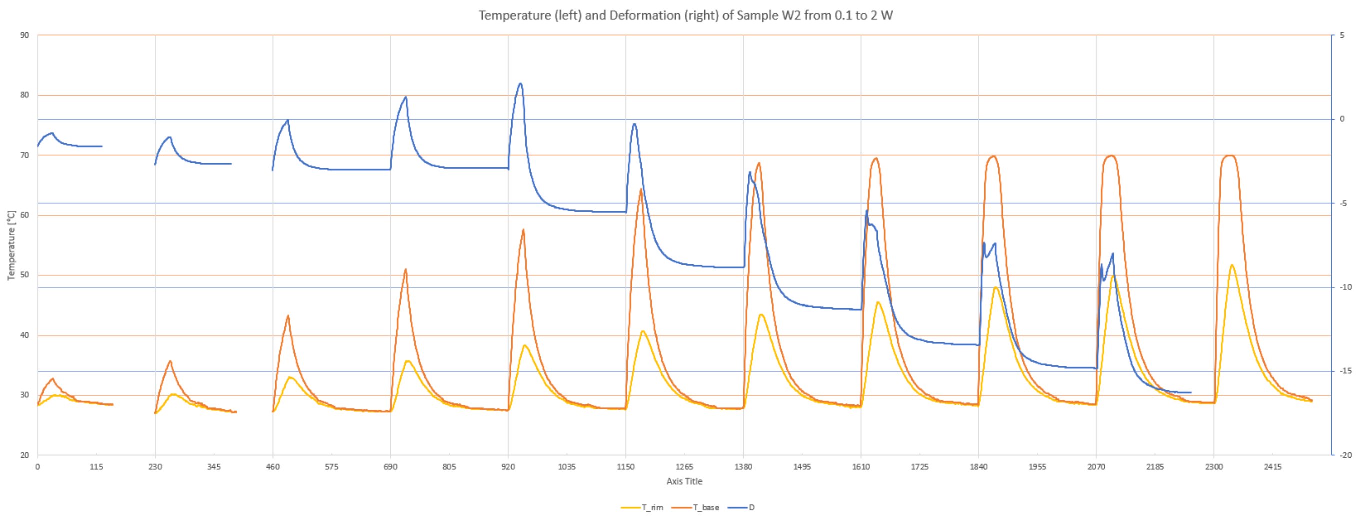



Vertical Displacement (StaticF = 0.001N)
430, 6885.587
Displacement [µm]
Time [s]
TS1
TS2
TS3
t=50
T(TS1) = 58.3
T(TS2) = 74.3
T(TS3) = 67.1
t=250
T(TS1) = 49.3
T(TS2) = 59.3
T(TS3) = 52.3


F = 0.01 N
F = 0.001 N
Vertical Displacement under load
TS1#3
TS2#2 (no tape)
TS2#3 (with tape)
TS3#3
T(TS1) = 58.3
T(TS2) = 74.3
T(TS3) = 67.1
T(TS1) = 49.3
T(TS2) = 59.3
T(TS3) = 52.3
T(TS1) = 58.3
T(TS2) = 74.3
T(TS3) = 67.1

APPENDIX C: PILOT EXPERIMENT

The first experiment was a pilot tests of sorts, where W2 was subjected through 10 wattages ranging from 0.2 to 2 W in 0.2 W increments, as well as an initial 0.1 W. Each time the sample would be heated for 30 seconds, and then left to cool for 200 seconds. Values were collected every half-second.



Deformation data loss: During the first two cycles (0.1W & 0.2W), as well as the last cycle (2W), the optical camera encountered some problems and some of the data was lost. In the first 2 cycles this was due to it reaching a recording limit and during the last cycle it was due to a depleted battery. In future tests, the cooling time and number of heating cycles were reduced to avoid this issue.

Temperature data loss: The maximum temperature on the thermal camera was set to 70 °C. This turned out to be insufficient as this temperature was reached in the 1.4W cycle. Thus, any temperature above this value was lost. The maximum temperature on the thermal camera was raised for future tests. Additionally, the tip of the sample would be cropped out of the recording in order to avoid any data artefacts caused by the (cold) background being revealed by the sample deforming away from the camera. As the heating pattern is evenly dispersed across the sample's surface, this is not expected to cause significant change in the temperature reading. Even a sample's local 'hotspots' that might occur in the cropped area are unlikely to impact the total deformation of the sample.

Because we observed the backside of the sample (the opposite side of where the heated trace is), the recorded temperatures are minimum temperatures as the heat has travelled through the material. Material on the other side will have slightly higher temperatures. However, as we can still clearly see the 'lines' of the trace through this side, it suggests the heat spreads pretty quickly.

Synchronisation issues: The LED did not heat up fast enough to pinpoint the start of the heating cycle on the thermal camera recording. Additionally, the cycles seemed to run slightly out of sync the longer the experiment ran. This could be due to a difference in the internal clock in both cameras, or perhaps due to the difference in framerate followed by an imperfect conversion in the video editing software. This error was only discovered during data extraction, after all experiments were completed, so no correction could be made. Some small liberties were taken to synchronise the two data streams by manually aligning the first significant shift in value for both deformation and temperature. Even so, because values were extracted every 0.5 seconds, the two data streams could not be synchronised to an accuracy below this value.

Data: Even though this test was a pilot, the dataset showed a lot of interesting things. Because it was opted to decrease the number of cycles for future tests, the pilot result is also the most complete dataset with 11 different wattages ranging from 0.1 to 2 Watt.

Looking at the graph, we can immediately identify the first occurrence of permanent deformation at the 0.8 Watt cycle, suggesting that the permanent deformation point lies somewhere between 0.6 and 0.8 Watt, or rather the corresponding maximum temperatures: 51 and 58 °C. The total permanent deformation after the 10th cycle was also more than expected, for a total of 13.2 mm from its starting point, and 16.3 mm from the neutral axis. The actuation itself seemed to perform a deformation of roughly 4 to 5 mm without inducing permanent deformation. Higher Wattages resulted in an even bigger actuation of up to 6.8 mm. Interestingly, these large actuations in the higher temperatures seemed to introduce some unexpected behaviour where the sample would switch direction twice, resulting in a 'double peak' in the deformation graph.

APPENDIX D: ORIGINAL ASSIGNMENT BRIEF

Introduction

3D printing is a rapidly developing field of research. Although the core principle has been around since the 80's, the technology has recently developed to a point where 3D printing machines have established a solid consumer market, and have become a valuable asset in the field of prototyping and product design. The recent spike in interest has triggered research in many different kinds of printing methods, materials, applications and other technologies.

One of such fields of research is 4D printing. 4D printing adds an extra dimension to 3D printed samples by having the samples be able to move over time, typically triggered by an external stimulus like moisture or heat.

The Voxel8 multi-material 3D printer, introduced in 2016, has made it possible to print with conductive materials like silver onto plastic samples, thus integrating simple circuits into a single print. Applying power to this printed circuit will make it generate heat, and, if designed correctly, cause the sample to bend. The printed sample essentially serves as an actuator, and an example of 4D printing. This piece of technology is called a 3D Printed Thermal Actuator (PTA).

What is unique about these PTAs is that once the power is cut off, the sample cools and is returned to its original state. This is unlike most 4D printing technologies, where deformations are either permanent or require a 'programming step' to define the desired shape (Momeni, Hassani, Liu, & Ni, 2017)*.

3D printed thermal actuation has not yet been observed outside the Applied Labs of the Industrial Design faculty of Delft University of Technology. These PTAs are exploration of 'adaptive materials' (i.e. materials that can change shape and adapt to the user or its environment) by the Emerging Materials group at the faculty. Research into its unique behaviour and properties could trigger curiosity in the academic world and reveal the technology's potential in robotics and consumer electronics.

Problem definition:

Research into this subject from a previous graduation project by M. Maas in 2017 has produced a first sample that uses a PTA to perform locomotion. This sample, while an interesting first step, is a fairly simple demonstrative piece that utilises linear actuation. There are a lot of potential features of PTAs still left unexplored (e.g. torsion, intrinsic oscillation, anisotropic materials, extreme (permanent) deformation, bidirectional actuation, etc.), and others perhaps yet entirely undiscovered. Additionally, the sample requires an external power source and a microcontroller to perform its function. These could be replaced by integrating batteries and intrinsic oscillation into the design.

'Intrinsic Oscillation' is a phenomenon observed in the previous graduation project on this topic. It refers to the circuit on the PTA being broken by the bending motion, causing it to no longer conduct the electricity and thus cool off and bend back, after which the circuit is connected again and the cycle repeats

As part of an upcoming publication being worked on by other researchers of the Design Engineering department, it would be useful if these potential features were made into functional samples to serve as demonstrational pieces, showing the full potential of PTAs and triggering curiosity.

Assignment:

The main goal of this research will be to explore and demonstrate new features, properties, and possibilities of the PTA technology. This project will focus on integrating as many features as possible into the material and print itself, in an attempt to make a printed sample perform locomotion with the addition of only a single battery. The assignment includes:

- Studying the intrinsic oscillation phenomenon of PTAs
- Analysing and mapping different types of locomotion that would suit the demonstration
- Studying and testing other features that would be necessary or possible to demonstrate with such locomotion (e.g. torsion, anisotropic materials, extreme (permanent) deformation, bidirectional actuation, etc.) and note their influence on the actuation.
- Designing and creating demonstrative 3D printed samples for each of the observed features
- Designing and creating a final 3D printed sample that is able to perform locomotion using PTAs with only the addition of a battery and minimising assembly steps

- Optimising the design of the sample to be eye-catching to the academic world and trigger interest and curiosity about PTAs

Approach

The project will have four phases.

The **Analysis** phase will start with getting familiar with existing literature and the Voxel8 3D printer. Some small test prints will be done to explore the machine, material, and PTA technology. It will continue to focus on studying and mapping different types of locomotion, as well as the material properties. This time will also be used to study the intrinsic oscillation phenomenon in particular, conducting some small tests. The end of this phase will produce a design brief detailing the most suitable types of locomotion and a list of features and material properties to explore in the next phase.

The **Synthesis** phase will be used to design and create several test samples that showcase the previously identified features and properties. This phase will teach what exactly is possible or feasible with the technology. During this phase the project will move through many different cycles of the Basic Design Cycle. The tinkering and experimentation will be combined with ideation to generate ideas for a final design. The phase will end with a number of concepts and a final choice regarding the type of locomotion and which features are to be integrated into the design.

The **Embodiment** phase will be used to design and build a functional prototype that combines all the selected features into a single sample, with the objective of having it perform the selected type of locomotion and minimising assembly steps or need for external support. Once the design is functional, the focus will shift towards optimising its efficiency and appeal, iterating on the aesthetic and experiential qualities of the sample as a demonstration.

The **Finalisation** phase will start after the report has been delivered, and will focus on getting the prototype ready for demonstration and creating a presentation and video of the final design that details all the different features and possibilities of the technology.

Graduation project results

The expected outcome of this project is a 3D printed sample that, with the addition of a battery, is able to move autonomously. The sample is intended to demonstrate unique features of PTAs and will use them to perform locomotion.

This sample will serve as an example of how PTA technology is able to integrate actuators and circuitry into a single 3D print, and perform a task without the addition of wires or electronics. As PTA technology is still unique to the TU Delft research lab, it is expected to generate some interest and attention to this new technology, and perhaps open up new possibilities in the field of robotics and 4D printing or be used in further research.

Relation and relevance to the domain of Industrial Design Engineering, the chosen master direction, and the IDE pillars

The project will include a lot of prototyping, testing, and tinkering, which should definitely fit an **IPD** student.

The subject is very inclined towards the **technology** pillar, with its focus on exploring and testing a new smart material, utilising a fairly new production technique of 3D printing.

Human interaction will be taken into account mainly during the Embodiment phase. The project is not purely a scientific study of the material and technology. Instead, the final design is meant to be a demonstration. One that grabs peoples' attention and inspires them. The demonstration should leave an as positive-as-possible impression, therefore aesthetics and experience of the final design will have to be considered as well.

The **business** side of this project is not very pronounced, as the technology is brand new and has no real applications yet. However, the final demonstrational sample will serve as a first look into potential applications, and is meant to create interest among researchers and businesses alike.