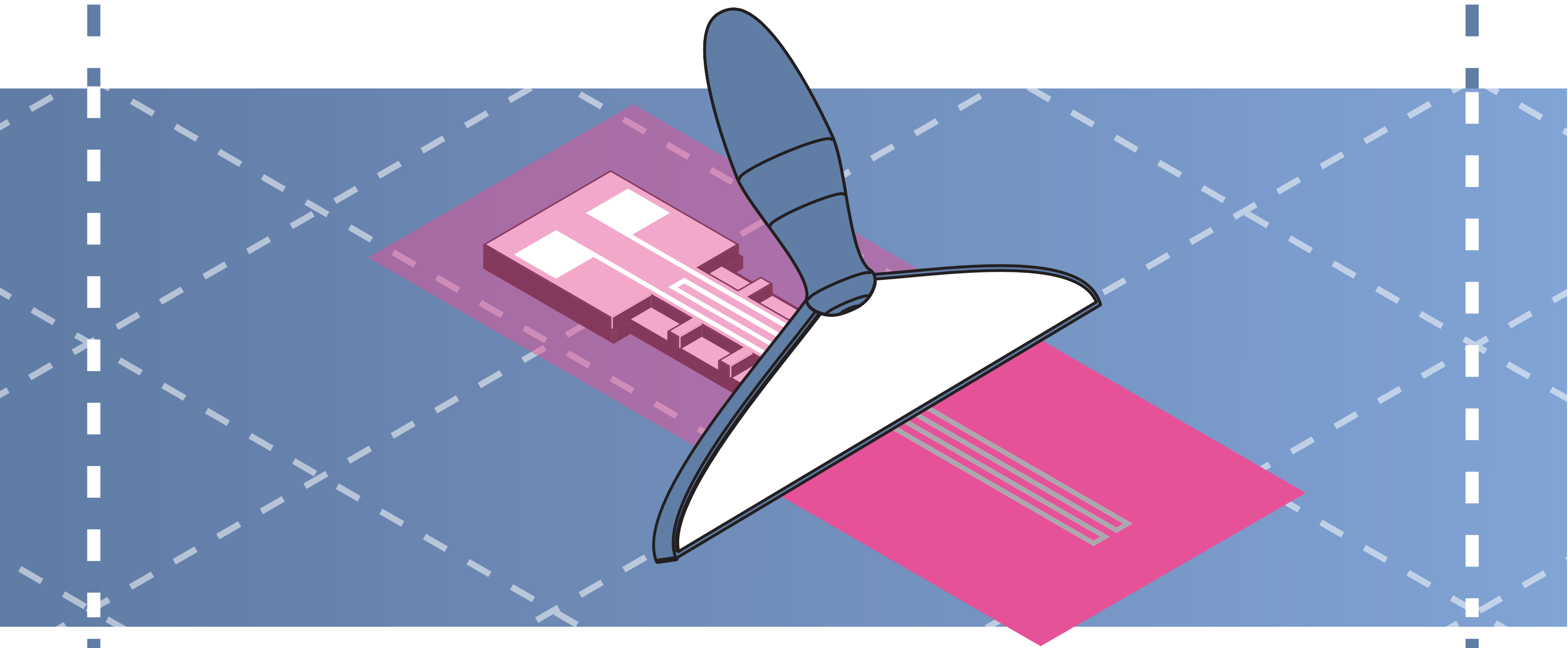
FlexTECH:

Taking the next step with 'Printed Electronics'



SCREENPRINTING SUPPLEMENT

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Delft University of Technology
Industrial Design
Design Engineering
Emerging Materials

Integrated Product Design Master Thesis Supplement
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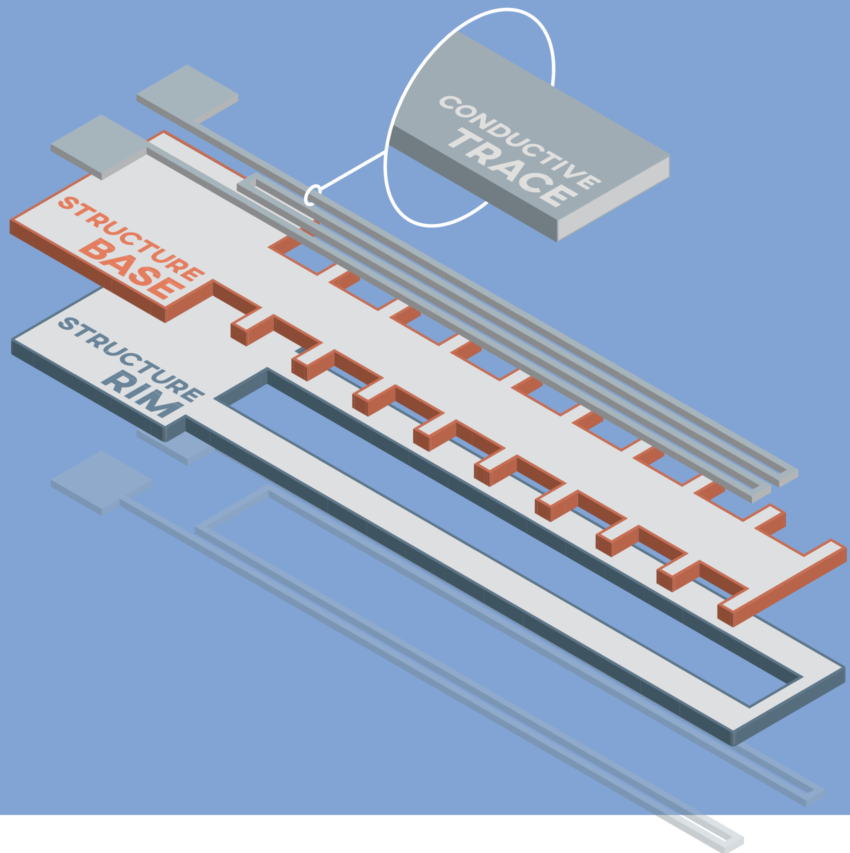


INTRODUCTION

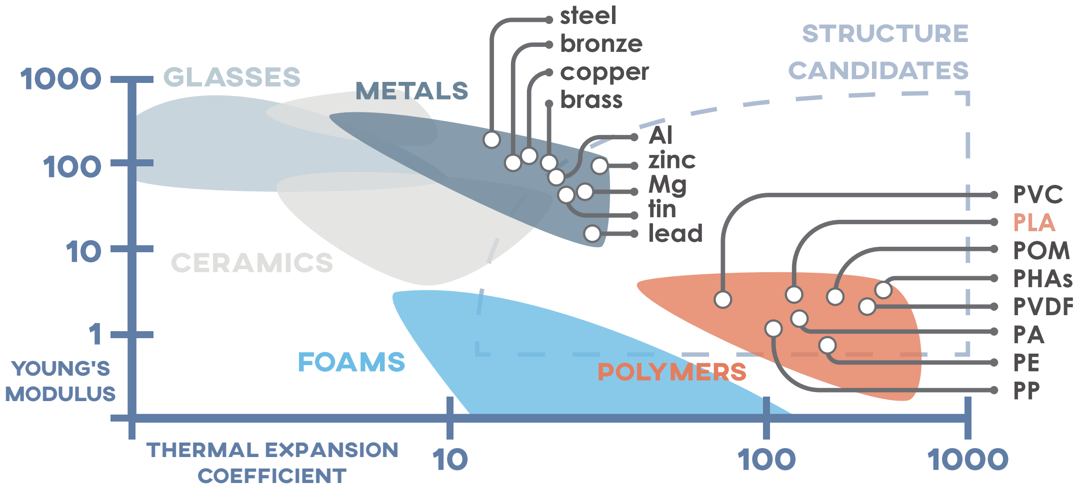
This document is a supplement to the “FlexTECH: Taking the next step with ‘Printed Electronics’ master thesis. It will explain the steps necessary to create a FlexTECH actuator by means of screen printing. This production method serves as an alternative for the multi-material 3D printing method, which became unavailable during the project. The method was realised by exploring several manual production options to ultimately produce an actuator that was equally effective to the 3D printed one.

A “Flexural Thermal Expansion by Conductive Heating”, or ‘FlexTECH’, actuator is a new kind of printed structure that bends when supplied with a current. The technology requires a structure of 2 offset layers (called the rim and base), typically made with a printed polymer, and a conductor circuit on one or both of the layers (called the trace). The screen printing method will show how to manually print the conductor circuit onto the structure substrate by using a conductive paste. For more information on FlexTECH technology, please refer to the thesis.

The screen printing method consists of 5 steps:

1. Material Selection
2. Structure Production
3. Stenciling
4. Screen Printing
5. Drying & Wiring

Each step will feature multiple sections. The **instructions** will state the exact actions to be performed. The **considerations** will provide a more in-depth explanation of what choices were made, as well as general do’s and don'ts. The **benchmarks** will give an estimate on what settings and variables to use, based on what was used for our actuator. The **alternatives** will discuss other possible methods to achieve the same results. Some alternatives have been tested during the project, and some are merely recommendations for future experiments based on theoretical improvements.

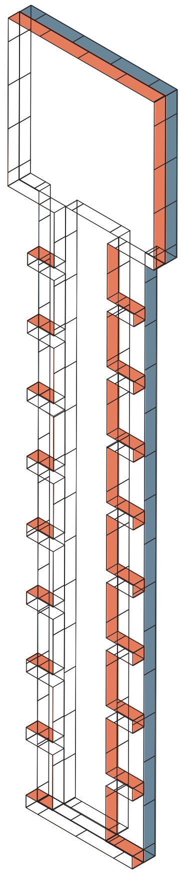


MATERIAL SELECTION

For this project, *3D printed PLA* was used for the structure, and *SunChemical C2081126P2 Silver Paste* was used as for the conductor circuit. This combination performed well, but in theory the phenomenon is applicable to other materials. However, some important factors need to be considered in order for a material to become a candidate.

STRUCTURE CONSIDERATIONS

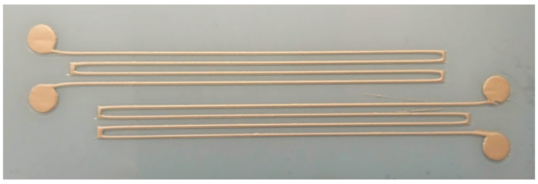
- The material needs to have a large thermal expansion coefficient in order for the actuation to have any effect.
- A good thermal conductivity will assist in spreading heat throughout the material, but too much conductivity will cause the heat to transfer to the other layer. The layers are required to be connected to exert force on each other, but seeing as it is the temperature difference between the 2 layers that drives the actuation, they should be insulated as well as possible.
- The 'cold' part of the actuator (the layer that is not heated) will be forced to bend by the thermal expansion of the other, 'hot' side. As thermal expansion forces are generally low, the material needs to be flexible enough to be deformed by these forces. Too much flexibility, however, will cause the actuator to not be able to support its own weight.
- The material is required to have a glass transition in order to make use of the 'pre-shaping' functionality. This phenomenon is caused by internal stresses from the 3D printing process relaxing when the material is heated above its *Glass Transition Temperature* (Tg). This causes the stresses to relax and the material to become amorphous. The resulting shrinking effect will result in a permanent deformation of the actuator, thus 'pre-shaping' it into a bent state at room temperature.
- A material that can be made to have a smooth surface will greatly assist in the screen printing process.



BENCHMARKS

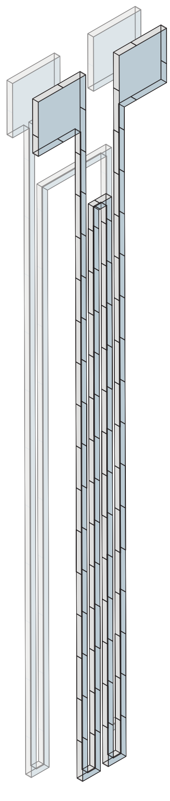
For our actuator, we used ***Ultimaker White PLA 3D printing filament***. PLA has a Tg of ~56 °C, making it easy to heat the actuator into the glass transition from room temperature at relatively low Wattages.

ALTERNATIVES



- PET-G was also tested as a material. The availability of PET-G in flat sheets made the printing process much easier, but did require the two layers to be joined with an adhesive afterwards. The PET-G actuator exhibited the same phenomenon, but to a smaller degree.
- The pre-shaping behaviour is thought to be a result from the internal stresses imposed by the 3D printing process. It's possible that the production of plastic sheets induces similar internal stresses. The pre-shaping functionality of PET-G sheets was not tested.
- In theory, the structure could be made from 2 different materials. The heated layer would have good thermal conductivity, and the cold layer would be an insulator. This would help to increase the temperature differences and increase the actuation. However, adding extra materials adds extra production steps and increases complexity. Additionally, a bidirectional actuator will require a conductor on both sides, and the design should be kept symmetric in order for the actuation in both directions to be equally effective.
- A separate, insulating layer could be imposed between the two layers to increase the temperature differences.

CONDUCTOR CONSIDERATIONS



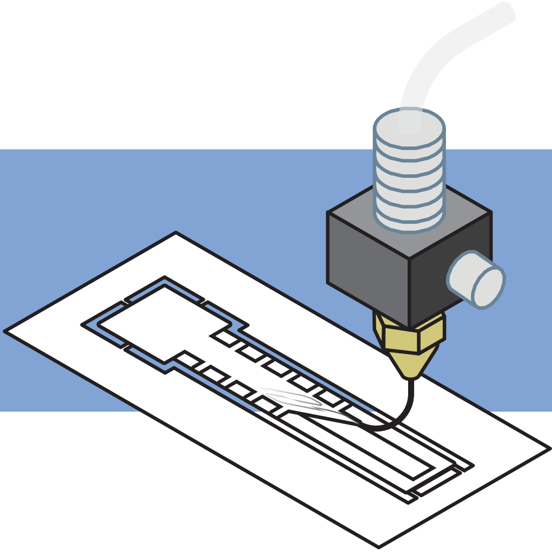
- Conductive pastes are not very common. In order for a conductive material to be printable, a conductive filler is typically combined with a less viscous binder. The material needs to be able to be smeared across a surface, and solidify after drying so that the actuator can be used.
- The viscosity of the paste determines what type of screen meshes can be used. A more viscous paste will need a wider mesh.
- The volumetric resistivity of the material largely determines the final resistance of the conductor circuit. The resistivity should be relatively high, as its purpose is to exhibit resistive heating.
- The material needs proper flexibility to endure the strain from the actuator's flexion without breaking.
- The conductive material should properly adhere to the structure material to avoid disconnection.

BENCHMARKS

For our actuator we used ***SunChemical C2081126P2 Silver Paste***. The material has excellent flexibility and good adhesion to polymeric substrates.

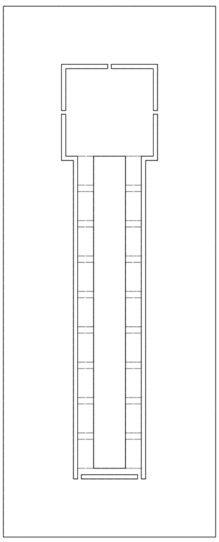
ALTERNATIVES

- Though it is far outside the scope of this project, it would be possible to print conductive materials by other means, such as stereolithography.



STRUCTURE PRODUCTION

Initially, the structure and conductor were printed at the same time with a multi-material 3D printer that featured both a filament extruder and a paste extruder (Voxel8). When the 3D printer went out of service, the lack of an automatic paste extruder meant that the structure now has to be produced separately. 3D printing the structure is preferred, as it causes the actuator to gain a 'pre-shaping' functionality where some degree of permanent deformation can be induced that remains at room temperature. It also means the 3D structure can be printed at once, avoiding the extra step of joining the two layers afterwards.



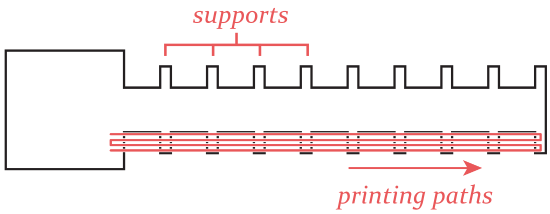
INSTRUCTIONS

1. Model the structure in with CAD software according to the considerations.
2. Model a flat frame around the structure that attaches to the structure at a few points. The frame should be level with the top surface and be modelled as close to the structure as is printable.
3. Prepare the file with slicer software. Make the first layer the one that will be screenprinted. For a double-sided screenprint, use an ironing feature for the top layer if it will also undergo screen printing.
4. 3D print the structure on a heated glass bed. Take the print off when it is finished.
5. Sand the surface if additional smoothness is required.

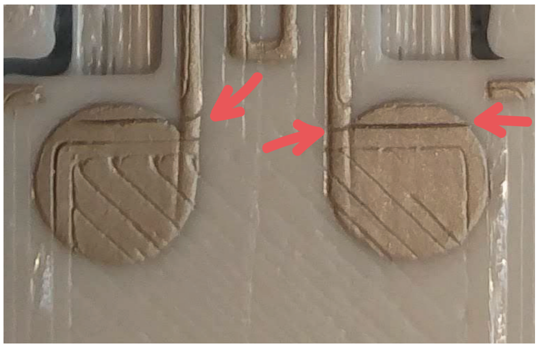
CONSIDERATIONS

- The structure needs to feature two layers. The layers should be offset from the neutral axis, and should be thin to increase flexibility.
- A series of supports are required to print the upper layer. The supports also double as a means of structurally securing the two layers, which is required for the actuation to work.
- The two layers should make as little contact as possible in order to minimise heat transfer.
- Typically, a minimum of 2 printing layers is required to form a properly connected surface.

- The overhangs are printed more easily if they are bridged across the supports in one smooth motion. Modifying the G-Code or slicer settings to ensure the printing paths follows the length of the actuator will have better results.



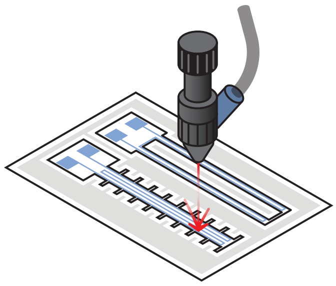
- A smooth surface is required for proper screen printing. The printed paste can sink into the extruder lines and cause high local resistances or even a break in the circuit. Printing the structure on a glass bed ensures a smooth lower surface. The 'ironing' feature of some slicers can help in flattening the upper surface. Additional sanding of the surface can also be performed.
- The frame around the model will assist in keeping the wiper used during screenprinting level with the surface.



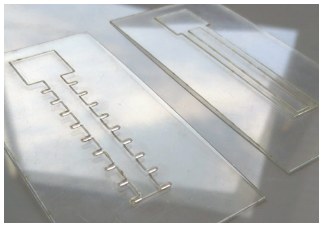
BENCHMARKS

The final page of this document shows a drawing for the structure model used for our printer. The model was printed with an **Ultimaker 3**, on a **heated glass bed**, at **200 °C**, and a **nozzle of 0.4 mm**. For laser cutting (see alternatives), experiments were done with a **0.4 mm PET-G sheet**. By setting the laser at **15 m/s** at **8% power**, the cuts did not go through completely, but were deep enough to be able to be able to push the positive out of the sheet by hand. The laser cuts were wider than expected, on average about **0.25 mm**.

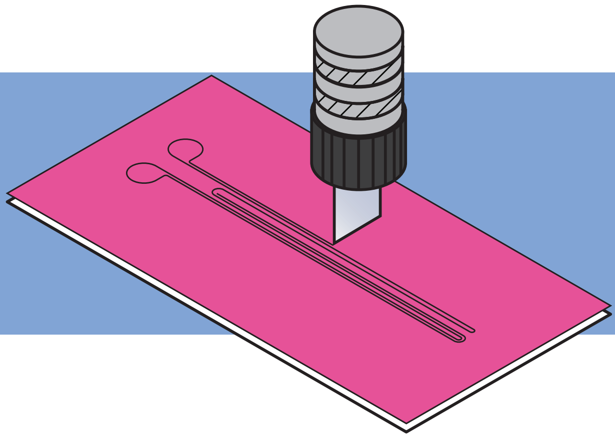
ALTERNATIVES



- It is possible to 3D print the two layers separately. This will enable both sides to be screen-printed at once, and make the surface smoother for a better result. The two layers will have to be joined afterwards with an adhesive or a weld.
- Plastic sheets can also serve as a substrate. This will result in a much easier screen printing process due to the smooth and even surfaces, and the layers can be laser-cut with high dimensional accuracy. This method would also require the layers to be joined afterwards. However, sheet material might not have the same internal stresses as a 3D printed material, so it is possible that this method sacrifices the pre-shaping functionality of the actuator.



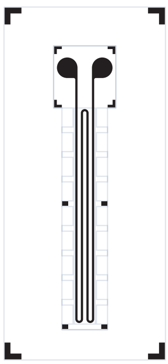
- To properly align the laser cutter with the conductive screen-print, it is recommended to include small reflective indicators in the bounding box of the laser-cutting dimensions in the screen-print. When previewing the laser-cutter alignment, the laser will move around the bounding box. If the laser is seen to move across the reflector, the substrate is lined up properly. Even then, it is difficult to line it up precisely, as it is still done by eye.
- Alternatively, the laser cutting can be done prior to screenprinting. This means the stencil will have to be aligned rather than the laser cutter. When done in this way, it is preferred to cut the material not all the way through and let it sit in a wider frame for easier screen printing. Additionally, the laser-cut produces rough edges that are best smoothed out to avoid the bumps interfering with screen printing.
- If laser engraving can be done accurately, the 3D structure might be able to be produced by engraving the different layers at different heights into a thicker sheet.



STENCILING

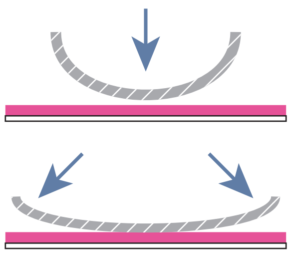
A stencil provides a negative image for the screen that blocks the ink from reaching the substrate so that the print will produce a positive of the final result. Stencils can be made to be reusable, but it requires more effort that is only worth it if a large amount of prints is required. Disposable vinyl stencils were used in the project due to low sample size.

INSTRUCTIONS



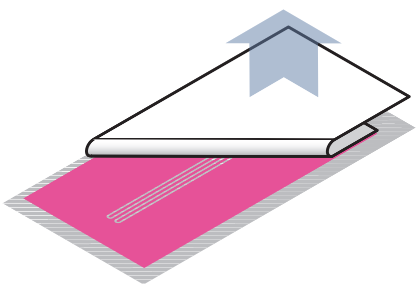
1. Create a line drawing for the stencil outline. A program such as Adobe Illustrator can be used to create the drawing, and is supported by the vinyl cutter software. Include some alignment holes that line up with the corners of the substrate.

2. Load the vinyl onto the vinyl cutter machine, and set the clamps and starting position accordingly. Load the drawing onto the vinyl cutter and start the machine, using the force and speed settings appropriate for the chosen vinyl.



4. When the plot is done, use a small, sharp tool to 'weed' the stencil by lifting and peeling the positive image from the release liner. Then cut a shape around the stencil to remove it from the vinyl roll. Leave some excess to protect the surrounding parts from the ink during screen printing

5. Place a piece of transfer tape on top of the vinyl. Start by flexing the tape downwards, and lower the tip of the curve onto the middle of the stencil, then slowly roll the sides onto the stencil to ensure no air pockets get trapped under the tape. Use a roller to further increase adhesion and remove any air pockets

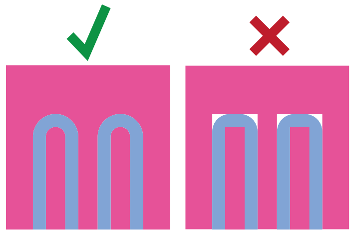


6. Turn the stencil around and remove the release liner. To ensure all the small parts of the stencil stay attached to the transfer tape, peel the liner away very carefully. Peel the liner sideways, diagonally to the lines, while staying close to the surface.

7. Repeat the process to secure the (now exposed) adhesive side of the stencil to the substrate. Drop the stencil onto the substrate, making sure it is properly aligned, force out any air pockets, and peel away the transfer tape.

CONSIDERATIONS

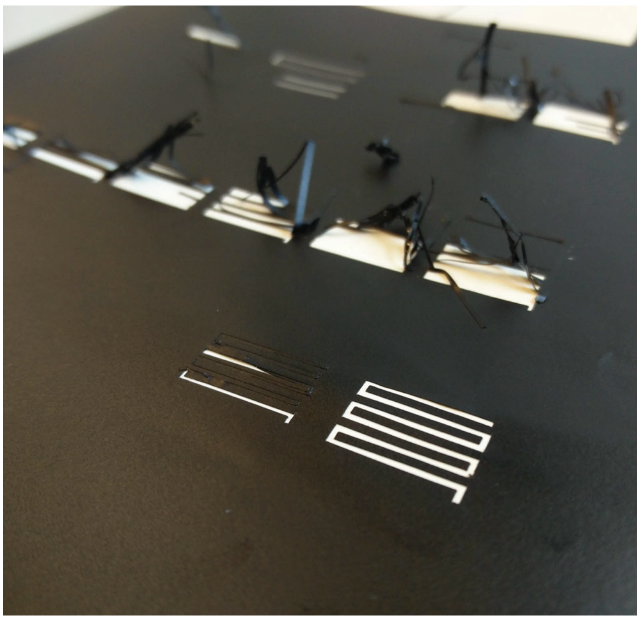
- Since conductive traces typically have a consistent width, it is easiest to use a stroke tool to draw the trace. However, the final line drawing only recognizes the actual lines drawn, so a simple stroke will result in a single cut with no thickness. To convert a stroke to an outline in Adobe Illustrator, use 'Edit > Expand' or 'Edit > Expand Appearance'. Combine the multiple shapes with the Pathfinder tool to avoid multiple cuts for the same sections.

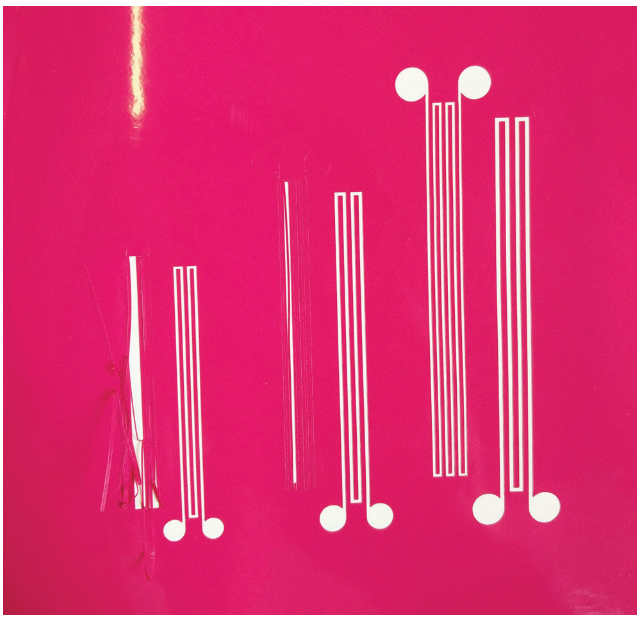


- Sharp corners can sometimes cause the vinyl to be ripped during cutting, especially with multiple sharp corners within a short distance. Smooth corners are also easier to print.
- During testing, it was found that the vinyl cutter performed better if the long lines of the stencil were perpendicular to the vinyl cutter's edge. Cutting long lines parallel to the edge often caused the vinyl strips to become tangled.
- Excess on the side of the stencil can potentially double as a way of securing the substrate to the workbench in the next step.
- To ensure proper alignment of the stencil with the substrate, consider adding a few alignment holes that line up with the corners of the substrate. Since both the stencil and substrate are opaque, it is difficult to see where exactly the middle of the stencil will be placed. Additionally, it is very difficult to remove the stencil once it is attached. These alignment holes will also be printed, so should not cover any important parts
- Wait with peeling off the release liner until just before printing. Any potential dust that gathers on the adhesive stencil will create bumps that interferes with a smooth printing process.

BENCHMARKS

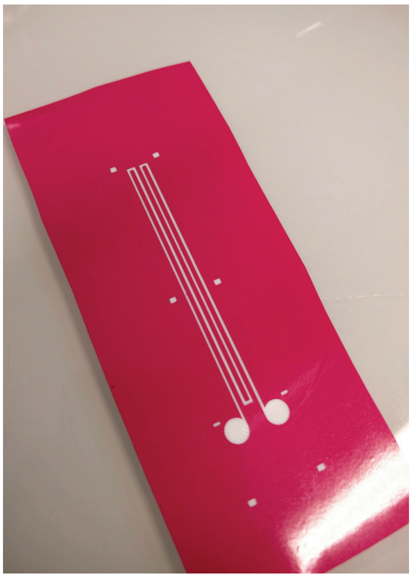
A ***0.1 mm thickness vinyl*** was used as a stencil for the actuator. The thickness and minimum cutting distance determines the dimensions of the final conductive trace. Setting the vinyl cutter force to ***120 grams*** and speed to ***3 m/s*** produced satisfactory results. Not enough force will not properly cut the vinyl, whereas too much force will cut through the release liner. A high speed will sometimes cause cut vinyl strips to come loose and tangle in the cutter, whereas a low speed is time consuming. The minimum cutting distance was measured to be ***0.6 mm***, meaning that each cutting line had to be 0.6 mm removed from another. This causes in the width of the conductive trace to also be 0.6 mm.

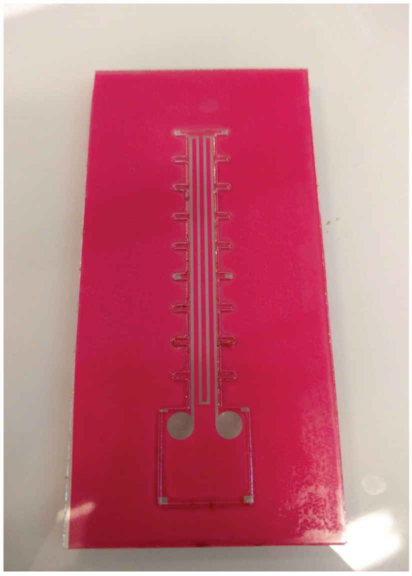


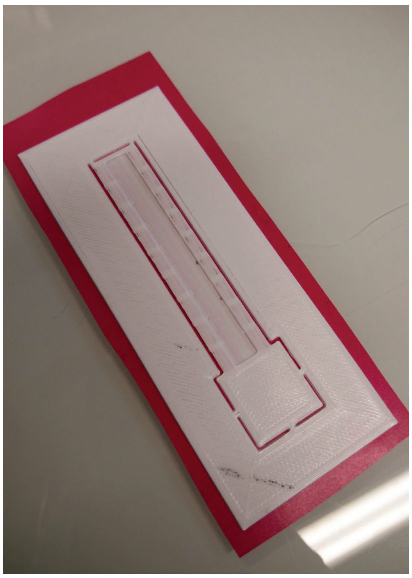


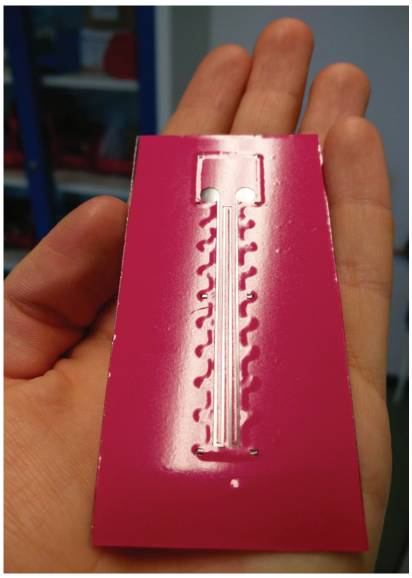
ALTERNATIVES

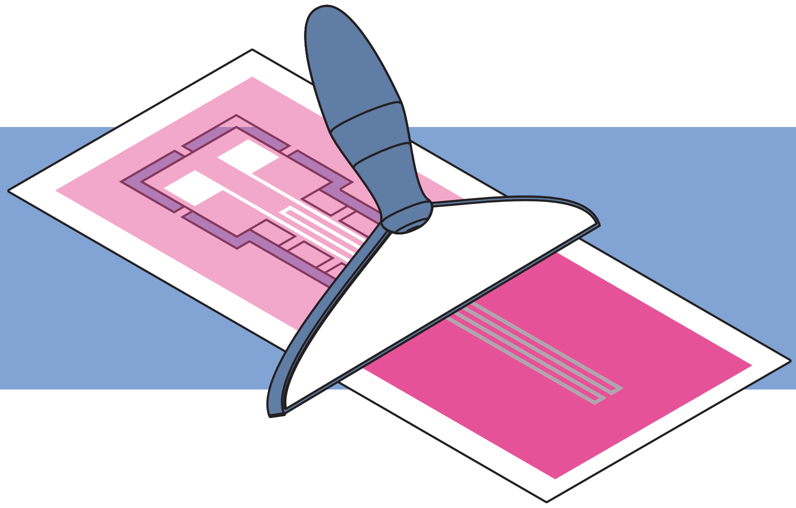
- It is also possible to transfer the stencil onto a screen, as is done with typical screen printing. This will make the stencil able to be reused for a certain amount of prints. It also makes it possible to release the stencil in one motion when the printing is finished. For this project, no screen was used to avoid adding extra resistance to the printing process, and because cleaning the conductive paste out of the screen is troublesome. Thicker pastes will likely require a screen with a low mesh count in order to flow properly. However, using a screen is recommended for larger batches of prints.
- When using a screen, another way of making a stencil is by photo-emulsion. The screen is covered with an emulsion that hardens when exposed to ultra-violet light. By interposing a transparent sheet containing an opaque positive image, only the negative image will be hardened. After the soft emulsion in the positive is washed away, a negative stencil remains. The photo-emulsion is much more permanent than the vinyl stencil, and is only recommended for large batches of prints.
- Instead of lowering the vinyl stencil onto the substrate, it is sometimes easier to lay down the stencil and lower the substrate onto it. Since the stencil is larger than the substrate, aligning from the side of the substrate will provide more vision. When doing so, start with aligning the long edge of the stencil by letting only a single edge of the substrate touch the adhesive vinyl, then carefully lower the substrate until just before the surface will touch. Doing so will allow you to still pull the substrate edge off the adhesive if the surfaces do not line up. This is made even easier with translucent substrates, as can be the case with laser-cut sheets.





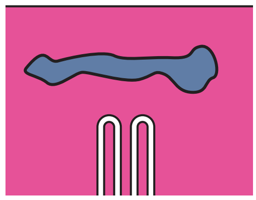






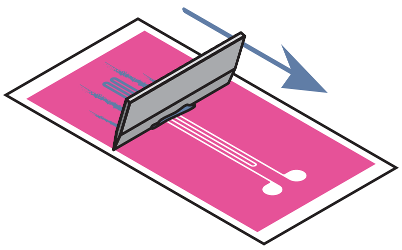
SCREEN PRINTING

Though the method is based on screen printing, the project did not actually use a screen to print the conductive trace. The conductive paste that is used for the print is quite viscous, and printing through a screen would add significant resistance. Instead, stencils are applied directly onto the substrate. Luckily, this also allows for the print smear to be repeated multiple times, filling up any gaps created by the uneven printing surface.

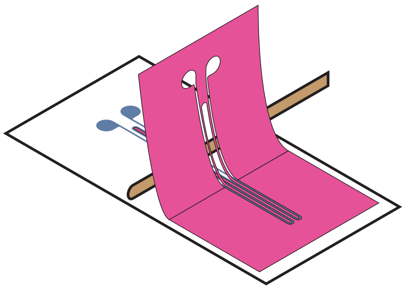


INSTRUCTIONS

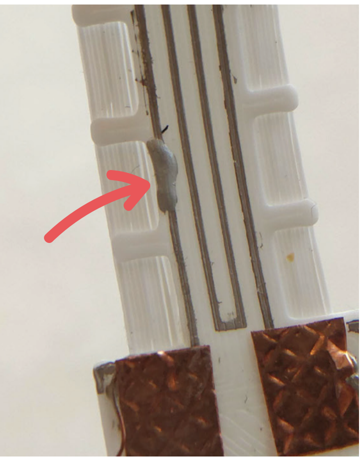
1. Refer to the safety instructions of the print material. Most conductive pastes are hazardous and require a fume hood, nitrile gloves, protective eyewear, and a labcoat to be handled.
2. Secure the substrate with stencil to a workbench with tape.
3. Make sure the conductive paste is properly mixed by stirring it in its container with a tool.
4. Deposit a small amount of conductive paste at the top of the stencil with a small scooping tool.



5. Using a blade or squeegee, press down firmly on the substrate and smear the paste across the stencil in one smooth motion. Divide pressure equally across the wiper, and angle it slightly towards the printing direction.
6. To fill up small corners, the smear can be repeated in the opposite direction
7. Collect any excess paste from the wiper and stencil that can be reused and deposit it back into the container.



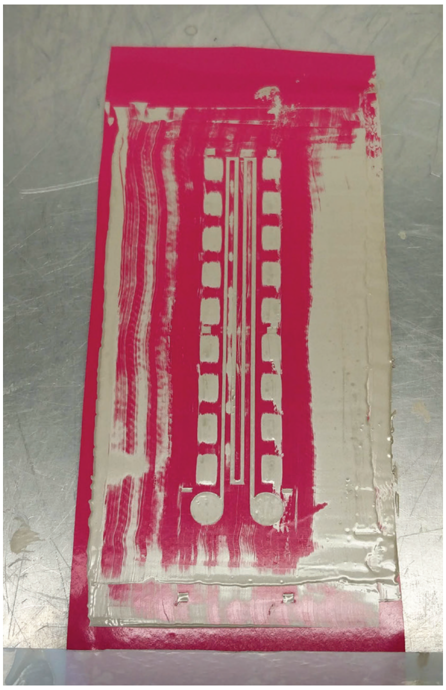
8. Before the paste dries, peel off the stencil from the substrate. Peel away from the substrate so that it does not damage the print. To avoid small strands of the stencil damaging the print after they come loose, use a small tool to lift these parts away from the substrate. A stencil with strands in two directions will have to be peeled off in two steps.



9. If the trace has small defects, patch the defect by depositing a small droplet of paste onto it before the paste has dried. This can be done using a small, sharp tool.
10. Clean all of the used tools and any other areas that were exposed to the conductive paste. Most pastes are cleaned with acetone.
11. Dispose of the stencil, nitrile gloves, and all cleaning material by putting it in the bin for hazardous materials.
12. Some functionality of the actuator requires a conductive print to be featured on both sides of the substrate. In that case, the printing process has to be repeated on the opposite side after the first one has dried.

CONSIDERATIONS

- Do not secure the substrate with tape in areas where the blade or squeegee will move. The thickness of the tape will raise the level of the wiper and interfere with the printing process.
- Small substrates that leave no room for tape outside of the printing area can be secured by putting double-sided tape at the underside of the substrate.



- Because the structure is not completely flat, there will be bumps and irregularities on the printing surface. This is very unfavorable for the printing process, but can not really be avoided unless flat substrates like sheets are used, and joined together later to create the 3D structure.
- Repeating the smear can typically not be done when using screens. Screens are lifted from the substrate during the smear. A repeated smear would press down on the previously printed paste and spread damage it.
- If the stencil has a complex pattern, peeling it off the substrate by hand will be impossible without damaging the print. A screen can be used to avoid this issue.
- When performing a second print on the opposite side of the structure, measures will have to be taken to avoid damaging the first print, e.g. placing a piece of filt between the substrate and workbench.

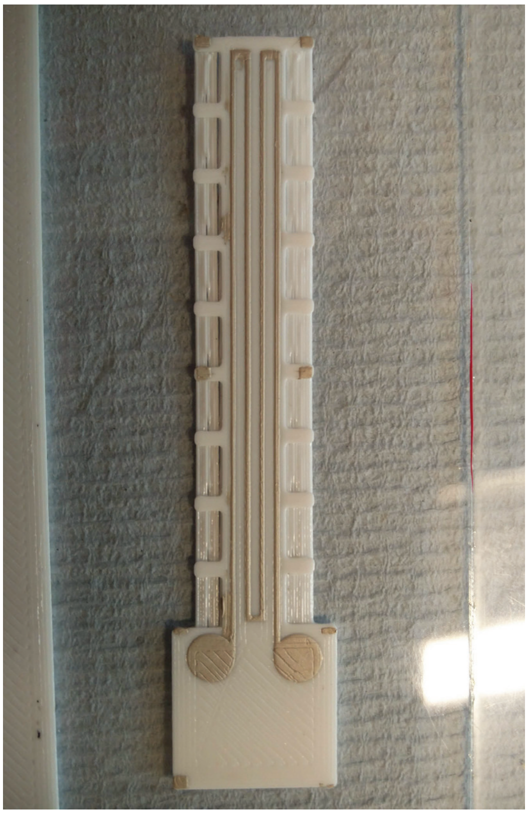
ALTERNATIVES

- The use of a screen would be recommended for larger batches, as this will enable a single stencil (on the screen) to be used for prints on multiple substrates, rather than the current method of applying a stencil to each individual substrate.
- Stencils placed on the screen are still temporary, as the stencil needs to be disposed of when the paste dries. A properly reusable stencil can be performed with a photo-emulsion on the screen, but this was considered to be too great of an investment for the limited time of the project. A screen with a photo-emulsion can be washed and reused, and is recommended when repeatedly producing large batches of prints.

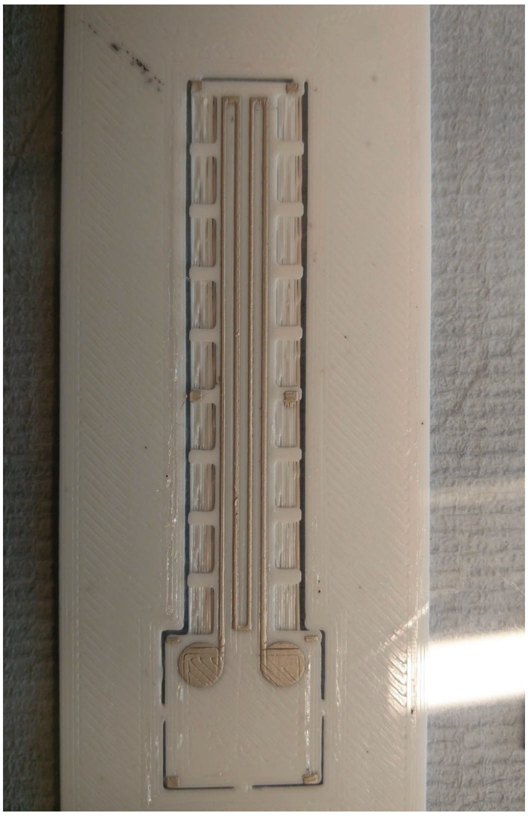
BENCHMARKS

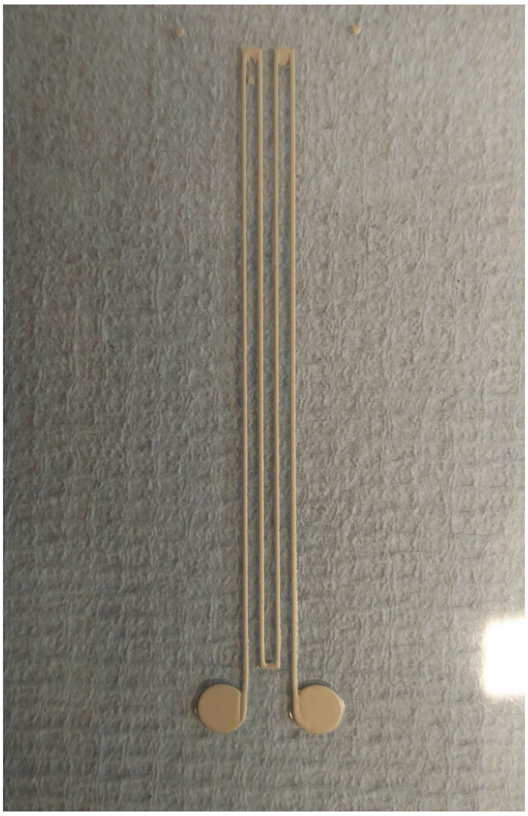
SunChemical C2081126P2 Silver Paste was used as the conductive paste. The material has excellent flexibility and adheres well to polyester substrates. It is cleaned with acetone. The blade of a box cutter, or ***Stanley knife***, was used as a wiper to perform the smear.

PLA STRUCTURE



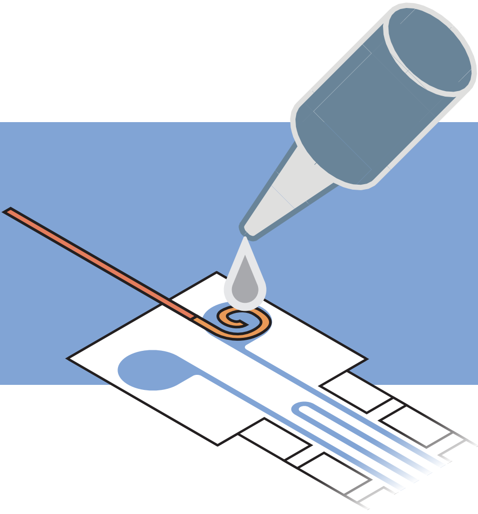
PLA STRUCTURE + FRAME





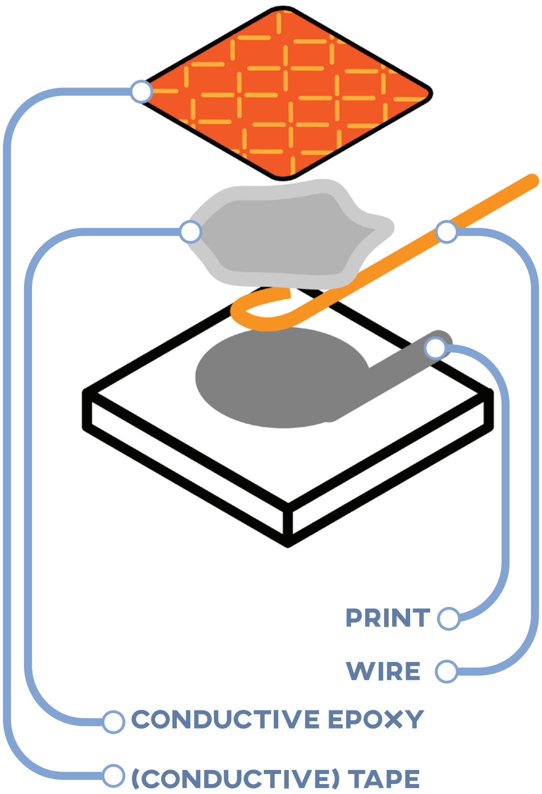
PETG SHEET

PETG LASERCUT SHEET



DRYING & WIRING

After the print, the paste will need to dry before it can be used. The conductive print will eventually have to be connected to other electronics. To accommodate this, it is preferred to attach a set of wires immediately after the print. Electronics can then be connected and disconnected repeatedly from the connections on these wires, instead from directly onto the printed trace, which is susceptible to damage.

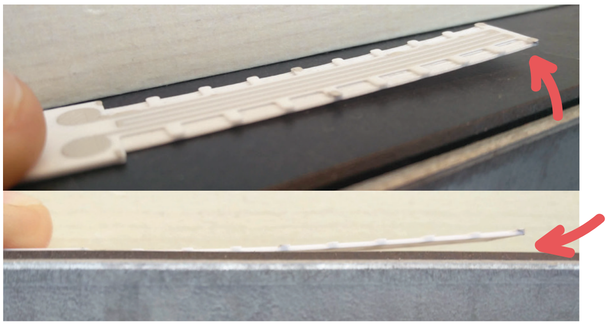


INSTRUCTIONS

1. Let the print air-dry until it is fully dry.
2. Prepare a pair of wires to be connected, e.g. by scraping off the protective coating at the tips with a piece of sandpaper. Twist the end of the wire for a better connection.
3. When the print is dry, It can be removed from the frame by severing the small connection points.
4. Mix a small amount of conductive epoxy to attach the wires with. Place a drop of the epoxy on the part of the trace that is to be connected to the wire, and push the uninsulated part of the wire inside the epoxy.
5. Put a small piece of tape over the epoxy, and place a clamp, such as a clothes peg, to hold the wire in place and avoid glueing the peg.
6. Crimp a connector to the other end of the wire
7. Repeat the process for the other wire.
8. Wait until the epoxy is dry to remove the peg
9. Further dry the conductive print by supplying a small current

CONSIDERATIONS

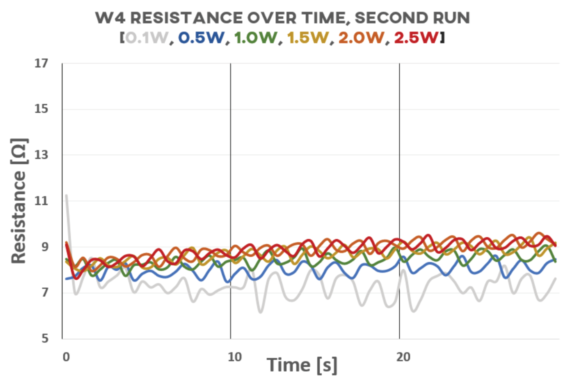
- Drying the trace with high temperatures, such as with an oven, will relax the stresses that are used for pre-shaping if the temperature is above Tg. This is why air-drying is preferred. The point of the conductive print is to selectively heat parts of the material. Heating the entire material would defeat the purpose.
- The drying process will cause the paste to shrink, causing a small amount of curvature in the final result.



- The actuator is very lightweight. It is best to use very thin wires that will impose minimal strain on the actuator.

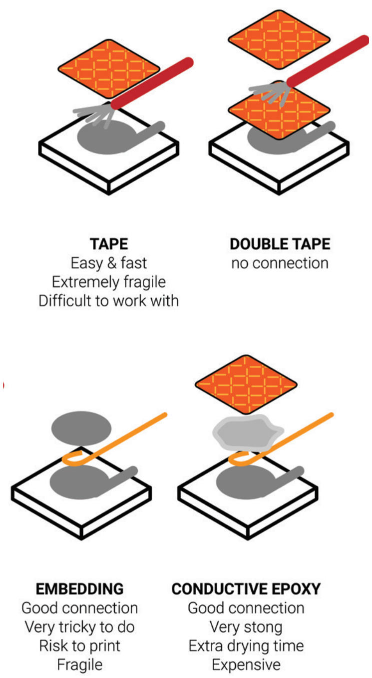
BENCHMARKS

The ***SunChemical C2081126P2 Silver Paste*** was dry enough to be handled after about ***½ to 1 day*** of airdrying. C***ircuitWorks Conductive Epoxy CW2400*** was used as the epoxy and provides good conductivity and adhesion, and dries in roughly ***1 hour***. After exiting the conductive trace with ***1 Watt for 30 seconds***, the resistance increased and became more stable at the end, possibly due to additional drying through resistive heating. After heating the trace at ***2.5 Watt for 30 seconds***, the resistance dropped significantly by almost ***50%***, and became much more stable. This is thought to be the result of conductive elements within the conductive trace fusing together.



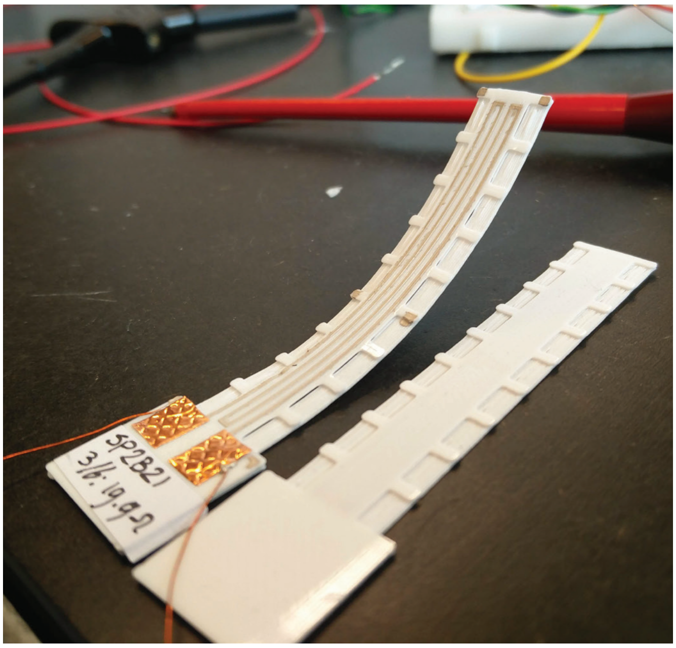
ALTERNATIVES

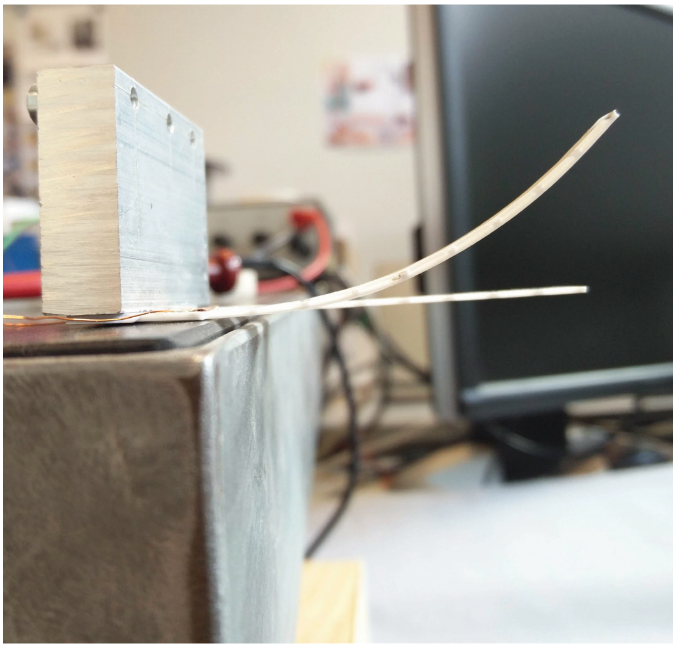
- Taping the wire directly onto the conductive print with a conductive tape was tested, but did not form a proper connection. Especially with thicker wires, the adhesion of the tape was not enough to keep it secured.
- To avoid the extra step of adding the epoxy, the wires can be embedded in the conductive print by placing them into the paste when it is still wet. However, it is very difficult to ensure the wire is placed correctly, and clamping the wire with a peg will damage the wet print. After the paste has dried, the connection with the wire is quite brittle, and is prone to breaking if too much strain is put on the wire. Securing the connection with some extra tape or glue can assist with this, but the epoxy remains a much stronger connection. Still, this method might be preferred as the conductive epoxy is quite expensive.

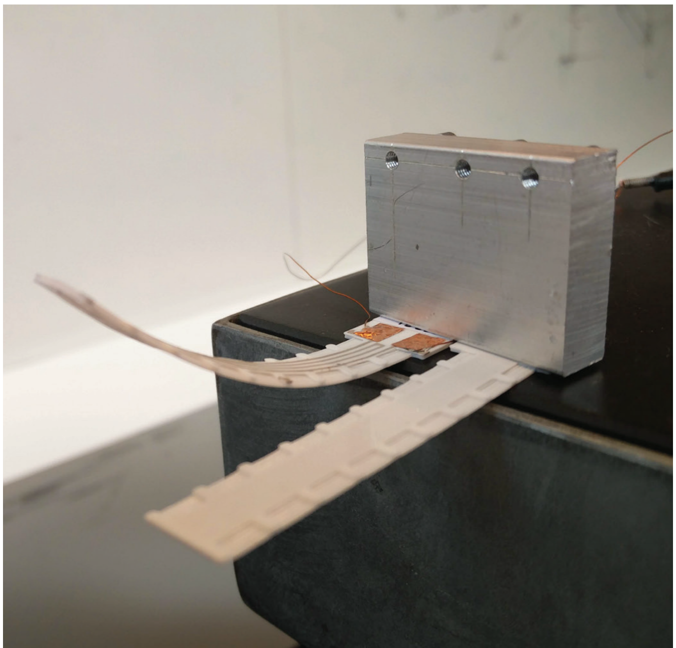


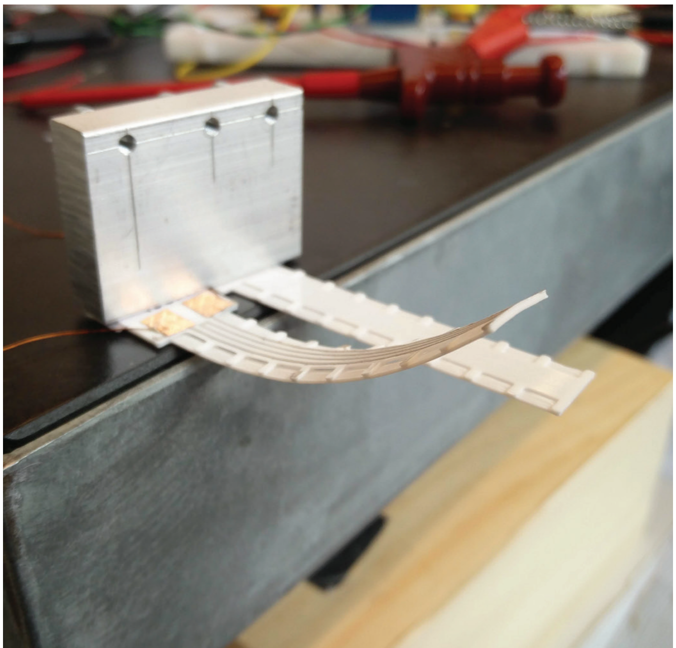
FINISH

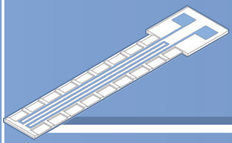
Congratulations, the screen-printed FlexTECH actuator is finished! By smearing a conductive paste onto a 3D structure, a flat strip of plastic was transformed into a smart material that can bend on command!
For more information on how to control the actuation, as well as FlexTECH actuators in general, please refer to the “FlexTECH: Taking the next step with ‘Printed Electronics’” master thesis.











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* $T_A = 24°C$