Investigating the Activation Methods of 4D Printed Structures

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Abstract

Our project tests **how stimuli-responsive materials and 3D printed geometrical structures change** and determine the transformation as well as the result of a 4D print. Our project focuses on analyzing how different stimulus-responsive materials such as polylactic acid (PLA) and thermoplastic polyurethane (TPU) react when an activation substance (heated water) is applied. **Multi-material 3D printing** will be used in order to produce a heterogeneous composition. Additionally, we will analyze how a change in the geometrical shape of a 3D print, affects and determines a 4D transformation.

Introduction

Background:

- An underexplored topic with many potential applications beyond regular 3D printing
- **The "fourth dimension" is time**
- Term of "4D printing" was coined by computer scientist, Skylar Tibbits, in 2013

Goal:

- To analyze different factors that go into changing the structure of a 3D print
- To gain an understanding of the applications of 4D printing and the design specifics that create such predetermined 3D shapes
- To find an ideal combination of materials and geometry in order to transform one 3D print into a mathematically designed structure

What is 4D printing?

4D printing allows structures to have **the ability to transform into something new without human intervention**. 4D printing uses 3D printed components that have been geometrically analyzed and purposefully designed to react in a pre-programmed way when an activation substance, in this case, water, is applied.

Figure 1. Four dimensional print transformation process over time, shown through a 3D printed disc.

"Thermorph – Morphing Matter Lab." *Morphing Matter Lab*, morphingmatter.cs.cmu.edu/thermorph/.

Materials and Methods

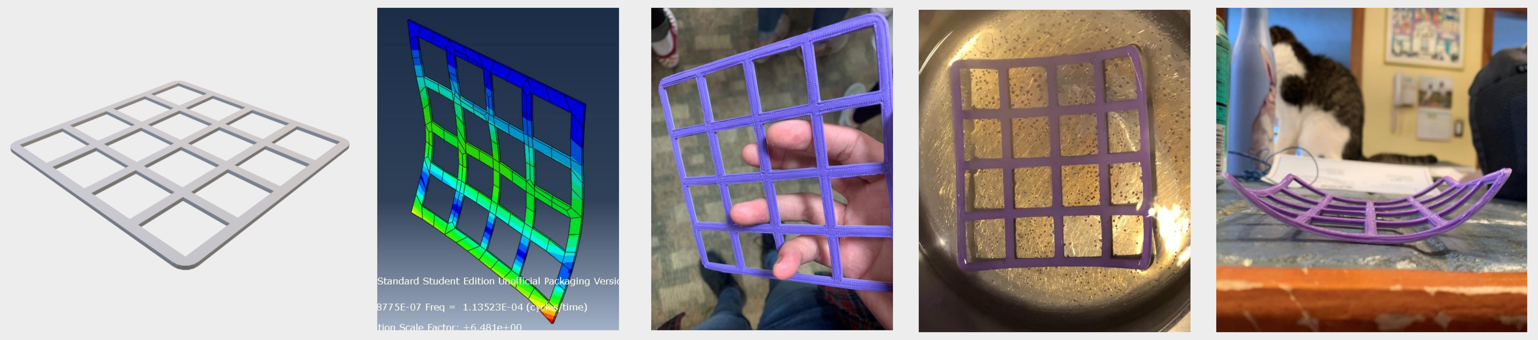
Materials:

- Thermoplastic polyurethane
- Polylactic acid
- Water (100 degrees Celsius)

Software:

- Autodesk Inventor 2019
- Ultimaker Cura
- Abaqus SE (Student Edition)

Design → Simulate → Print → Test → Analyze



Material Properties:

- **Specific Heat Capacity:** the amount of heat energy necessary to raise the temperature of a substance
- **Thermal Conductivity:** a measure of the ability of a substance to conduct heat
- **Density:** a measure of how tightly packed a substance is
- **Elasticity:** ratio of force induced stress to the strain/deformation of the substance

	Polylactic Acid (PLA)	Thermoplastic Polyurethane (TPU)
Specific Heat Capacity	1800 J/kg-K	2 J/g-K
Thermal Conductivity	0.13 W/m-K	0.22 W/m-K
Density	1.3 g/cm^3	1.2 g/cm^3
Elasticity	2,346.5 MPa	26MPa

Flexible polymer + Rigid polymer = Semi-rigid polymer

Real-World Applications

There are many fields in which 4D printing can be applied to. 4D printing allows for more complex problems to be solved because they are not constrained to one solid structure. There is freedom in what can be 4D printed and it is mainly dependent upon the designer. 4D printing can be applied in the following ways:

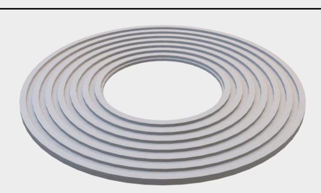
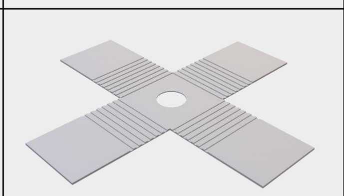
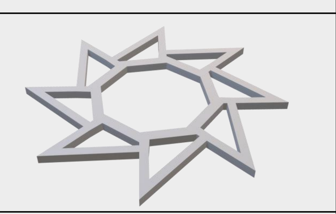
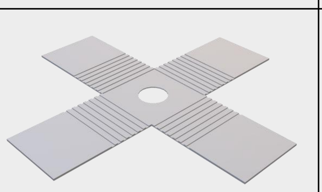
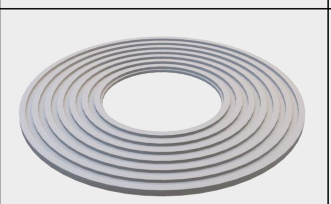
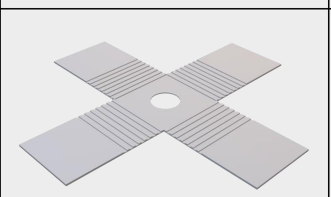
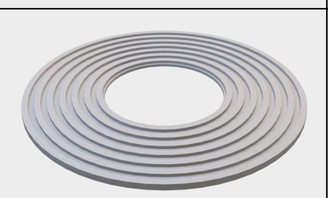
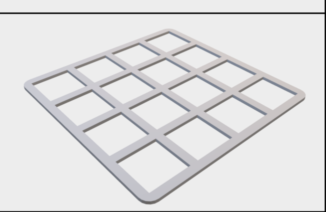
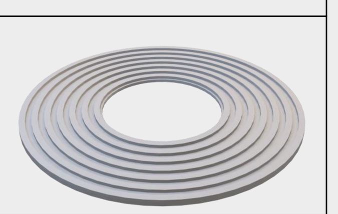
Architecture:
- Joints
- Deployable Housing

Medical:
- Self assembling medicines and medical device implants
- Bio printing organs

Robotics:
- Ocean robots
- Sea Transportation
- Nanobots

Aerospace:
- Post fabrication supplies & structure
- Storage reduction (flat packed cargo)

Results

Model Name	PLA Disc	PLA X	Star	TPU X	TPU Disc	X	Disc 1	Squares	Disc 2
Model Type									
Description	Height: 1mm Width: 78.74mm Shape: circle w/cutout Difference: Yes	Height: .5mm Width: 152.4mm Shape: cross Difference: Yes	Height: 1mm Width: 55.88mm Shape: 8 point star Difference: Yes	Height: .5mm Width: 152.4mm Shape: cross Difference: No	Height: 1mm Width: 88.9mm Shape: circle w/cutout Difference: No	Height: 1mm Width: 152.4mm Shape: cross Difference: Yes	Height: 1mm Width: 78.74mm Shape: circle w/cutout Difference: Yes	Height: 2mm Width: 127mm Shape: rectangle w/square cutouts Difference: Yes	Height: 2mm Width: 86.36mm Shape: circle w/cutout Difference: Yes
Experimental Result	The disc when placed into water, immediately folded into itself and began to stick. The end result was formed by taking it out (human interaction).	PLA X was an unfinished print, with a small amount of TPU on it's surface. It was still tested and the water caused each side to cave in differently.	The star print caved in towards the PLA (purple) side at each corner. The print lifted to a height of approximately 10mm.	The unfinished cross was reversed and started with printing TPU. The PLA didn't stick and left us with a majority TPU cross. No change.	Due to the disc being made out of TPU to begin with, it was predicted that there would be no change. This was a correct prediction.	There were issues with printing the cross with both TPU and PLA and Model X was the best out of all. It curled all the corners in towards the PLA.	Disc 1 was our first print and we predicted that nothing would happen. However, we were shocked to see that it had caved into a shell.	The model Squares, was predicted to cave in slightly. The prediction was correct. It was also less flexible because of the TPU to PLA ratio.	Disc 2 was our second print but with a difference thickness (2mm). The model was more rigid but had nearly the same outcome as Disc 1.
TPU to PLA Ratio	100% PLA	100% PLA	80% PLA 20% TPU	100% TPU	100% TPU	50% PLA 50% TPU	50% PLA 50% TPU	90% PLA 10% TPU	50% PLA 50% TPU

Discussion

Factors that change a 4D print

- Material used
- Material ratio
- Thickness
- Design
- Layering

Who — Who is 4D printing for?

4D printing is for anyone who needs to solve a design problem. 4D prints can change into anything, being dependent upon design and calculation. When done correctly, 4D printing can be very useful. In the future, anyone may be able to manufacture and model structures that can self assemble with a purpose.

Why — Why is 4D printing necessary?

4D printing isn't necessary. In many cases, the semi-rigid structure is an issue because a rigid structure is desired. However, being able to reform materials could increase economic efficiency and economic benefits.

What — What will 4D printing solve?

4D printing can solve storage issues and can be more efficient in some cases. For example, 3D printing is becoming a very useful tool in space by giving astronauts the ability to print the tools they need. What if a tool could be 3D printed and reformed to have a new use? Medical solutions and diagnoses can be more accessible with a transformable device that can access parts of the body that are difficult to access.

How — How do you plan to implement 4D printing at a large scale?

To be able to 4D print at a large scale, you need to be able to 3D print at a large scale. Large scale 3D printers have been developed, however, they are very expensive. Along with a large scale 3D printer, you would also need a significantly large source of hot water, if basing upon our experimentation. But, 4D printing has many applications at a very small scale as well.

Conclusion

By using a unique additive manufacturing technique to produce our structures, we were able to transform several prints into their predicted forms without human interaction. There are many applications of 4D printing, however, with the resources we had, including a single extrusion 3D printer, we were restricted on our design capabilities as well as our 4D transformation capabilities. Due to this minor obstacle of being able to be exact with our materials, we were able to test different material ratios between PLA and TPU. This allowed us to explore more factors that go into transforming a print.

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