4D Printing Architectural Textiles

Programmable Self-Supporting Structures

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Contents

1. Abstract

This research investigates the architectural viability of large-scale FDM 3D printing of thermoplastics directly onto stretched textiles, which retract and warp into 3D structures upon stretch release.

This collection documents the development of an experimental fabrication process specifically for large-scale programmable structural textiles, testing interdependencies in both material, fabrication, and design parameters. Apart from the design development and print variables, this research required the creation of a stable fabrication process; adapting the workflow to different types of 3D printers as well as building and programming both the hardware and software of a 3D printing extruder attachment for an ABB IRB 2400 robot arm.

The results from the early fabrication testing were later used to inform a series of small-scale prototypes. These prototypes were consolidated into a comprehensive design system that accounts for programmable material behaviors, considering the aforementioned material, fabrication, and design parameters.

The project culminates in the design and fabrication of a collection of large-scale prototypes, each featuring pre-programmed structural warping informed by the material behavior design system.

2. Glossary

General

4D printing: 3D printing that changes over time with the introduction of environmental stressors (Tibbits, 2021)

Direct-to-textile printing: Fused Deposition Modeling 3D printing onto a textile

4D printing textiles: Direct-to-textile printing onto stretched textiles, which warp into 3D structures upon release

Textile composite: The 4D printed structures, a composite of plastic and textile

Release from print bed: Unclipping the stretched fabric after it has been printed on to start the warping process

Technical Setup

ABB IRB 2400 Robot Arm: A six-axis industrial high-performance robot (ABB, IRB 2400: ABB Robotics).

Arduino Mini Controllino: Used to set the static values of nozzle temperature and extrusion rate (rpm), and send / receive signals for heating up and extruding / retracting

Micro Swiss Direct Drive extruder: Extruder used to print on the large-scale, with a 0.8 mm nozzle diameter

Print Parameters

Small-scale printing: Printing with a Creality Ender 3 V2

Large-scale printing: Printing with an ABB IRB 2400 robot arm with a Micro Swiss Direct Drive extruder and Arduino Mini Controllino

The frame: The print frame that the textile is stretched over and clipped onto

Extrusion: When the extruder gears are moving counter-clockwise and pushing filament out of the nozzle

Retraction: When the extruder gears are moving clockwise and pulling filament back up into the nozzle

Adhesion: The bond between the plastic and the textile, which affects the print integrity and warping behavior

Nozzle height: The height of the nozzle in relation to the textile. A lower nozzle height results in the filament being pressed deeper into the textile

Equal stretch: A metric to ensure that the textile is stretched equally, to result in uniform warping

Stretch factor: How much a textile material can be stretched from its original size

Weave direction: The weave direction of the textile affects the quality and scale of the warping behavior. Lines parallel to the weave direction will bend, lines perpendicular will lay flat

Nozzle temperature: The temperature of the nozzle attached to the extruder, which affects the viscosity of the melted filament

Extrusion speed / flow rate: The rotations per minute of the gears extruding the filament, translated to millimeters per second of filament extruded. An independent variable from the robot speed

Robot speed: The speed (mm/s) of the robot arm as it moves along a print path

Robot travel speed: The speed (mm/s) of the robot arm as it travels between separate print paths

(Textile) Retraction / (filament) resistance ratio: The balance between the forces of the stretched textile retracting to its original size and the rigid filament resisting the retraction. If the textile retraction is disproportionately stronger than the filament resistance, the composite may lose adhesion. If the textile retraction is disproportionately weaker than the filament resistance, the composite may exhibit little to no warping.

Materials Used

TPU: A soft plastic 3D printing filament
PLA: A hard plastic 3D printing filament
Cotton: A jersey knit 95% cotton textile
Nylon: A circular knit nylon textile
Lycra: A lycra spandex knit textile

Small-scale Print Parameters

(unless stated otherwise)
Material Cotton jersey knit / PLA (white) or TPU (purple/blue)
Nozzle Temperature 215 ° C
Flow 200 %
Printer speed 65 mm/s

Large-scale Print Parameters

(unless stated otherwise)
Material Cotton jersey knit / PLA
Nozzle Temperature 215 ° C
Extruder RPM 30
Robot speed 10 mm/s

3. Introduction

The introduction of additive manufacturing has significantly changed the landscape of technological innovation within the architectural field. Using a myriad of traditional and new materials, 3D printing is used to create full scale structures such as the printing of concrete houses (Figure 3.1) and proposals for bases on the moon (Figure 3.2). 3D printing combined with computational design facilitates the introduction of complexity and iteration without significant increase in material usage and overall cost, making it an innovative and sustainable technology to be further implemented into the Architecture, Engineering and Construction industry in the upcoming years.

4D printing is an emerging development in the research within additive manufacturing that allows for the programming of 3D printed objects to change over time, triggered by various environmental stressors, such as humidity, temperature or tension (Tibbits, 2021). 4D printing has the potential to contribute a new dimension to the additive manufacturing process, and expand the use of 3D printing further and into entirely new fields.

As the concept of 4D printing is relatively new, the research in the field is primarily within an academic context, and the technology has not yet been widely implemented on

Fig 3.1 3D printed concrete House Zero by ICON. (House Zero 2022)

the commercial scale. As the implementation of 3D printing is only in the primary stages of being adopted into the AEC commercial industry, 4D printing will require significantly more research and experimentation before it can become a dependable industry standard.

While the introduction of computational and parametric design has completely redefined architecture, there remains a disconnect in the translation of digital complexity to the physical world in architectural practice. With technologies such as additive manufacturing and the potential to use them in unconventional ways, this gap in translation between digital and physical architecture comes closer to being bridged.

This project is an investigation into the architectural viability of large-scale FDM 3D printing of thermoplastics directly onto stretched textiles, which retract and warp into 3D structures upon release. The research is both an experimental development of a fabrication process, but also an iterative process of research-by-design in order to create a design system of structural-based material behaviors that can be used to create complex and dynamic self-supporting architectural textile composites.

Fig. 3.2 *Lina.* 3D printed lunar structures by AI Spacefactory. (AI Spacefactory, Lina)

4. State-of-the-art

Combining textiles and additive manufacturing has been researched before, but seldom on the architectural scale. In the current sphere of additive manufacturing, it has obvious applications in the context of fashion and small-scale design. Designers such as Iris Van Herpen (Figure 4.4), Nervous System (Figure 4.2), and Chiara Giusti (Figure 4.1) have notably printed or printed on textiles in the fashion and design industry, both using 3D printing and 4D printing techniques. However the number of projects is limited when brought up to the architectural scale, as scalability becomes a significant issue when working with delicate and interdependent material relationships.

MIT's Self Assembly Lab has researched the technology from a more technical rather than aesthetic perspective, however this research is primarily focused on the smaller scale, most notably with their project Active Shoe (Tibbits, 2021). The Active Shoe (Figure 4.3) is created by 3D printing a thin layer of thermoplastic onto a flat surface of stretched fabric, which will warp and turn into a 3D structure upon release, due to the relationship of tension and retraction between the plastic and fabric.

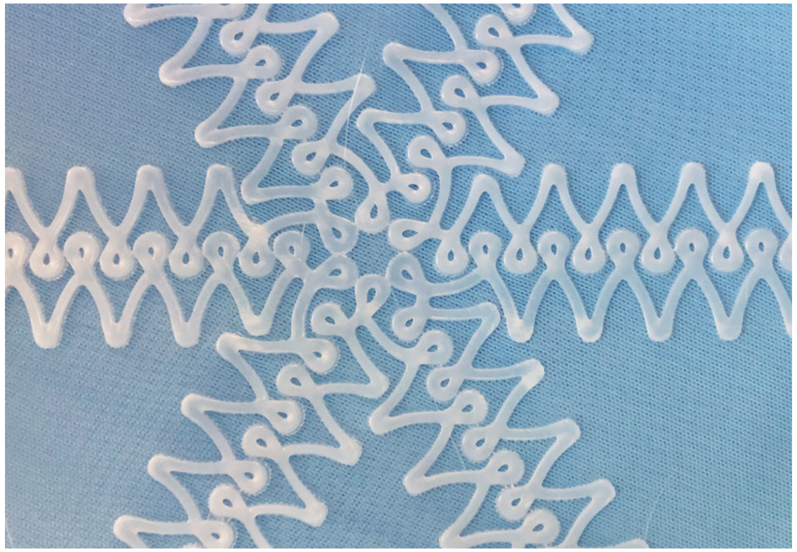
One of the most architecturally significant projects in 4D printed textiles was created for the 2020 Dubai Expo, where a team of designers from NUMEN and Milan Polytechnical University in collaboration with ShapeMode and WASP

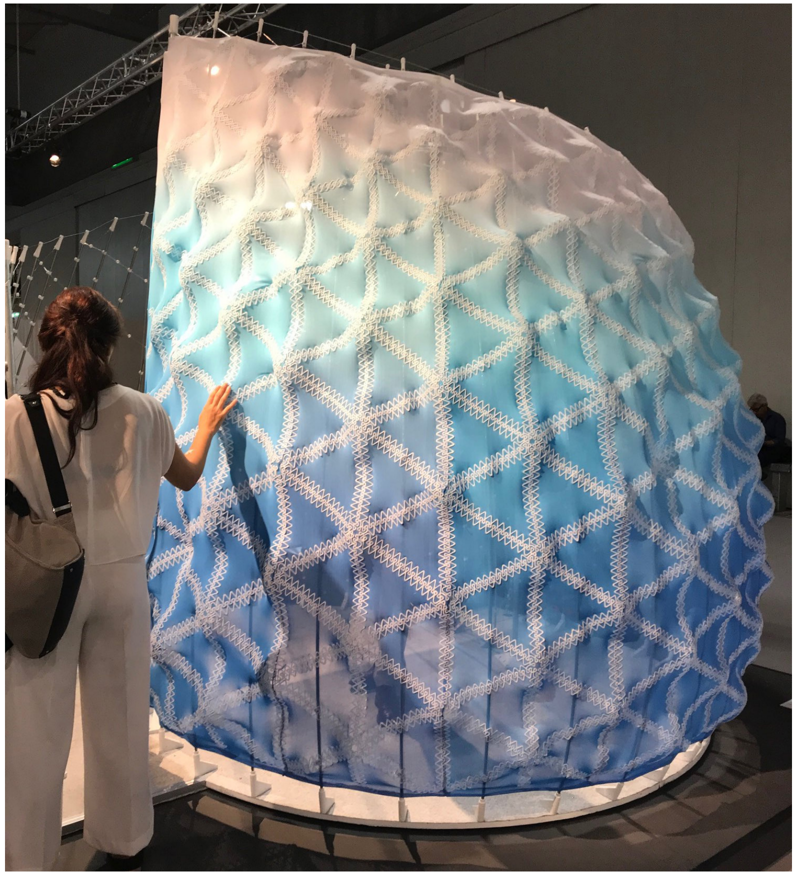
Fig. 4.1 Chiara Giusti's Techne (Teghini, 2021)

Fig. 4.2 Nervous System Self-forming Structures (Fields, 2018)

Fig. 4.3 Self Assembly Lab's Active Shoe (Active shoes-self-assembly lab)

Fig. 4.4 Iris Van Herpen Earthrise Collection (Iris Van Herpen, Earthrise: Collections)





Sikka Project by NUMEN and Milan Polytechnical University in collaboration with ShapeMode and WASP

Fig. 4.5 Looping print geometry (Stampa 3D su tessuto)

Fig. 4.6 4D Textile Cladding (Stampa 3D su tessuto) created a large-scale printed textile (Figures 4.5-7). The digital textile was created using a DeltaWASP FDM pellet extruder on stretched fabric.

Rather than letting the complexity of the fabrication process control the end result, the Active Shoe and Sikka Project utilize the complexity to achieve a specific result that performs in a desired way. This methodology is particularly attractive to architecture and is the primary focus of this research, as it can be used to program extremely complex and lightweight structures that form themselves over time. The Active Shoe and the Sikka Project differ from the other projects in that they are designed with specific pre-programmed behaviors, but there have not yet been projects addressing the issue of structural integrity by creating a self-standing 4D printed textile composite.

Fig. 4.7 4D Textile Curvature (Stampa 3D su tessuto)

5. Literature Review

In his book "Things Fall Together", Tibbits chronicles the Self Assembly Lab's research and prototyping of 4D printing and discusses the necessity of a reframing of the idea around digital vs physical, particularly through the lens of computing. He argues that we no longer associate computers and programs with the physical world, when in fact at their very core they are physical things. If computers that can run programs are simply extremely complex material relationships interacting with each other in a series of positive or negative states, why is it not more common that physical everyday materials are also used to run simple programs? Materials that can sense and respond, fluctuating their physical state due to external stimuli (or "communication") are running programs in their simplest form. In the case of textile 4D printing, the stimulus is somewhat less reversible than moisture or temperature, however the concept remains that the 3D form resulting from textile printing is created via an interaction of forces, pre-programmed into the material.

If we view 4D printing and programmable materials as a way to give physical objects the ability to respond to their environments, we can view the digital to physical translation as bi-directional. Through computational design and additive manufacturing, materials have been given the ability to respond to their environments, imbuing the traits of the computational and programmable world into the physical materials (Sossou et al., 2019). In an ever changing digitized world, perhaps programmable materials can mark a convergence of the seemingly separate physical and digital spheres, making the digital tangible.

Hannah Carlotta Koch, David Schmelzeisen and Thomas Gries authored "4D Textiles Made by Additive Manufacturing on Pre-Stressed Textiles - An Overview", which is a comprehensive analysis of academic research and projects within the 4D printing textiles subject area. In their review, it is noted that the research on real world applications is sparse due to the lack of physical prototypes, citing scale as a significant hurdle between research and fabrication.

4D printing can be classified into three areas: self-assembly, self-adaptability, and self-repair. This research focuses on self-building 4D printing materials which "make it possible to initially manufacture and transport complex 3D products in a planar manner " (Koch et al., 2021). The strength of creating objects with multiple equilibrium states is also considered, and is a technique that could be implemented in multiple categories of 4D printing, depending on the required stimulus, whether it is moisture, heat, light, or force (in the case of this research). An example of a multi state equilibrium print can be seen in the large-scale domes created as part of this research (Figure 5.1).

Fig. 5.1 4D printed textile domes from this research, in multiple stable states

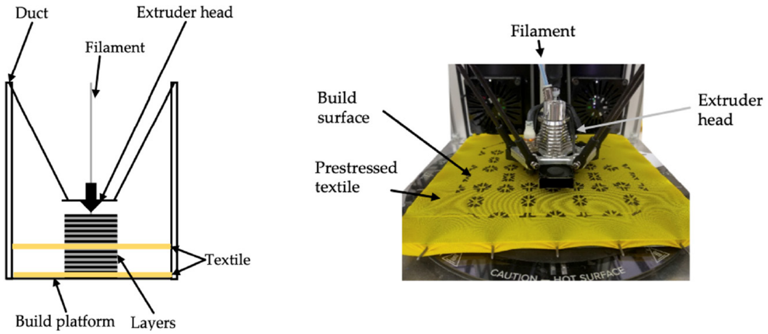


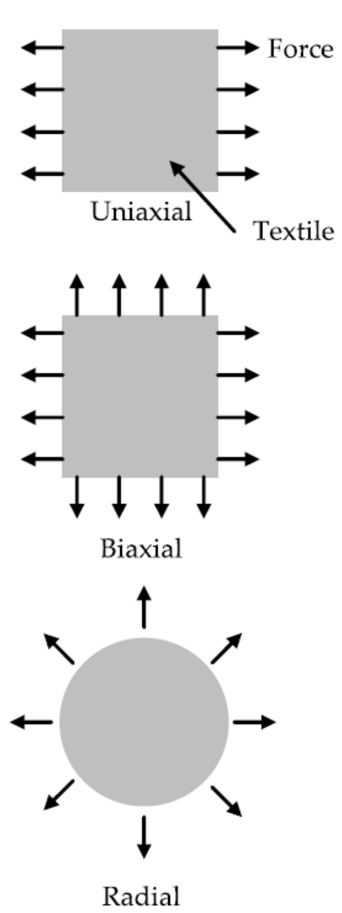
Fig. 5.2 Diagram of 4D textile printing (Koch et al., 2021)

Ultimately Koch, Schmelzeisen and Gries conclude that the most significant issue facing the field of 4D textile printing is scaling, and it is something that must be solved in order for the technology to be viable in the commercial world. The research will attempt to address the problem of scale and real world applications, and contribute to the discourse within the field.

Agata Kycia and Lorenzo Guiducci take a different approach in their study "Self-shaping textiles - a material platform for digitally designed, material-informed surface elements". Their study began as a bottom-up approach, and through initial testing of the material they observed a wrinkling pattern in their results, which morphed the research into the imitation of the wrinkling of lettuce leaves. They exclusively tested open geometries, such as lines and arcs, and experimented with nozzle diameter, distance between curves, and stretching directions. Their results were consistent and reproducible, as seen in their behavior graph (Figure 5.5, Kycia & Guiducci, 2020). They classified the behaviors of printed lines into four categories; coherent wrinkling, independent wrinkling, rolling, and bending. All of these behavior categories were achieved by differing nozzle diameter and spacing between lines by mere millimeters. The study reveals how small changes in print factors can result in vastly different 3D structures, hinting at the immense potential of programmable materials.

The study also addressed the fact that stretching direction can have a significant impact on the 4D textile. They tested biaxial stretching and uniaxial stretching, and came to the conclusion that their line geometries wrinkle most effectively when printed parallel to the stretch direction when stretching uniaxially and overall when stretching biaxially. In the images (Figure 5.4), this can be observed, as the biaxial print has even wrinkling across the entire arc, but the uniaxial stretched print has a high frequency of wrinkles in the areas the arc is parallel to the stretch direction, and a lower frequency in the print areas that are more perpendicular to the stretch direction (Kycia & Guiducci, 2020).

Kycia and Guiducci implemented an FEA (finite element analysis) simulation to attempt to simulate their results.



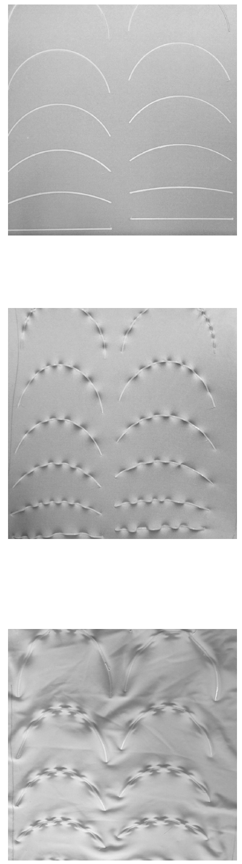


Fig. 5.3 Textile stretching diagram (Koch et al., 2021)

Fig. 5.4 Biaxial and uniaxial printing (Kycia & Guiducci, 2020)

FEA is a simulation often used in engineering contexts to simulate objects in a virtual environment with set conditions (Siemens, FEA / Finite Element Analysis). However when compared with a 3D scan of the printed object, the resulting imagery from the FEA was quite different to the physical print with the same material parameters and environmental conditions, rendering the physical experiments much more informative and valuable to the research.

Ultimately, Kycia and Guiducci discuss the potential applications of their research and the technology of 4D textile printing in general, noting the value of printing lines rather than closed geometries, as it "allows for imagining the out of the roll 3D printing on infinite textiles" (Kycia & Guiducci, 2020). A material with such range will have the potential to be utilized in multiple areas within the field of performative materials and place-specific computational architecture particularly in the interior space, and with further material developments, the building envelope.

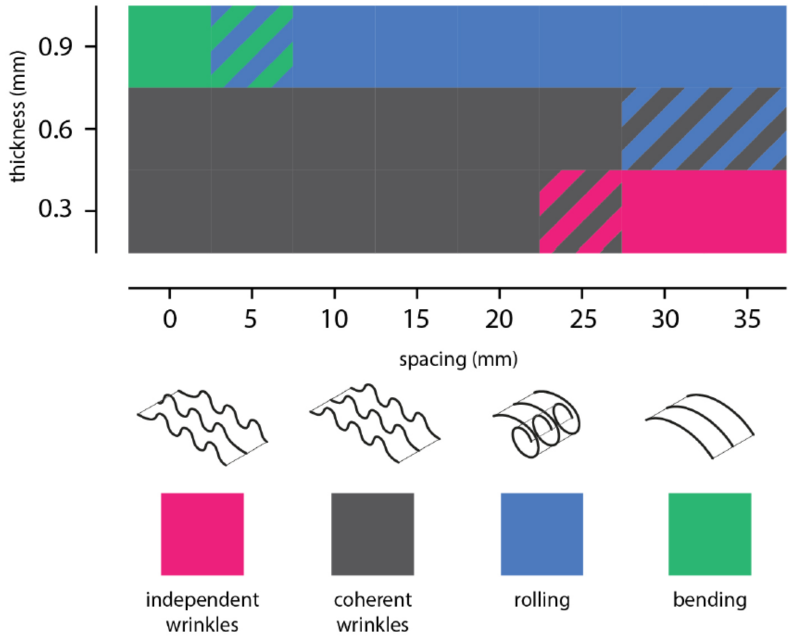


Fig. 5.5 Print behavior graph (Kycia & Guiducci, 2020)

Fig. 5.6 Wrinkling vs bending (Kycia & Guiducci, 2020)

6. Research Questions

The primary goal of this project was to determine if this fabrication method and resulting performative textile composite can be used for full scale architectural applications. The idea was to understand if the unique characteristics presented on the small-scale in the early experiments, such as the composite being lightweight, flat-packable, self-forming, self-supporting and possessing multiple stable states could be accomplished on the larger scale. The research can be divided into the following areas:

Scale

The early stages of this research proved that the fabrication of self-supporting and self-forming 4D printed textiles is possible on the small-scale, and the primary question going into this project was if the same would be true on the larger scale. The shift in scale significantly affects all of the other test variables within the research, such as textile and filament materiality, actual design geometry, connection points, and structural integrity. Increase in scale also required technical developments in the fabrication process, such as building an extruder for an ABB IRB 2400 robot arm, as well as creating a frame solution to effectively stretch the textile on a larger scale.

Structural and Kinetic integrity

The second significant research area was the potential structural and kinetic behaviors and properties of the resulting filament-textile composite. There are multiple intrinsic behaviors of the composite that we essentially get “for free”, such as the aforementioned features of it being lightweight, flat-packable, deployable and reproducible on site, yet two behaviors in particular, the fact that it is self-forming and self-supporting, are what set this fabrication methodology and material apart from other performative and programmable smart materials. The primary question of the research falls into this area, being: is it possible to make a human-scale 4D printed textile structure that is both self-supporting and self-forming?

Materiality

Another question was the issue of materiality when combined with the increase in scale. Not only are there questions about the architectural (transparency, thickness, acoustics) and structural (durability, strength) integrity of the textile material, but the actual filament selection has many variables that are affected when scaling (such as print temperatures, flexibility). As the project is based on the premise of two materials coming together to form a textile composite, the interaction of the textile and plastic is actually as significant as the individual materials themselves. How do they adhere together, how does the balance of tension and retraction withstand a change in scale in some aspects (design, line thickness) but not others (weave size, stretch distance, surface fibers)? How can these factors be controlled and manipulated to garner the best results?

Creating a design system

A crucial question was if it is possible to create a design system that tracks repeatable material behaviors, and if that design system of parts can be leveraged and combined to create specific combinations of programmable behaviors. Is it possible to create a set of design instructions that can be used as a language with which to create new designs that contain all of the desired material behaviors? Upon what framework can the behaviors be judged to conclude the ones best served for the research?

Application

If the answer to the above question is yes, the question of architectural design and application emerges. If this architectural material object proves to be both viable and reproducible, how can the primary and secondary behaviors and properties be utilized to find a place within the architectural discourse? As the fabrication method is expensive and highly technical, in what context or environment is the payoff of these material behaviors greater than the expense of production and fabrication? What further material and fabrication development is required?

7. Experimentation

7.1 Early experiments

In preparation for the thesis, early experimentation was completed on the small-scale, which acted as a material study, exploring different combinations of printing material, fabric, and geometric patterns. The results are visualized in a matrix format, and the outcome of the experiments was a better understanding of the relationship between the plastics and textiles, laying a foundation of knowledge to be utilized in the large-scale fabrication and later-stage iterative design cycles. In order to get a broad understanding of how the filaments and fabrics interact, identical geometries were printed using a combination of different fabric and filament pairings. External factors, such as stretching, nozzle height, and flow were controlled up to a point, with some tolerances for human error. The geometries were also input into a simulation that calculated the end result. Factors such as adhesion, durability, warping control, and time were observed.

7.1.1 Simulations

Part of understanding the relationship between textile and filament was attempted via a simulation. The simulation was first attempted in Houdini and later moved to a script in Grasshopper developed by Ronny Haberer using an MIT license. The script was further edited as part of this research to allow for the control of fabric and filament parameters in order to expand the range of the simulation. However, neither of these simulations were able to accurately represent the effects of interdependent material variables such as stretch direction, thickness, knit type, and material weight, proving the Kangaroo Grasshopper simulation to behave on a more general level. The simulation also struggles with complex geometries, particularly offsets. The simulation served as a good starting point to test the 2D geometry before delving into the more intricate physical experimentations of material.

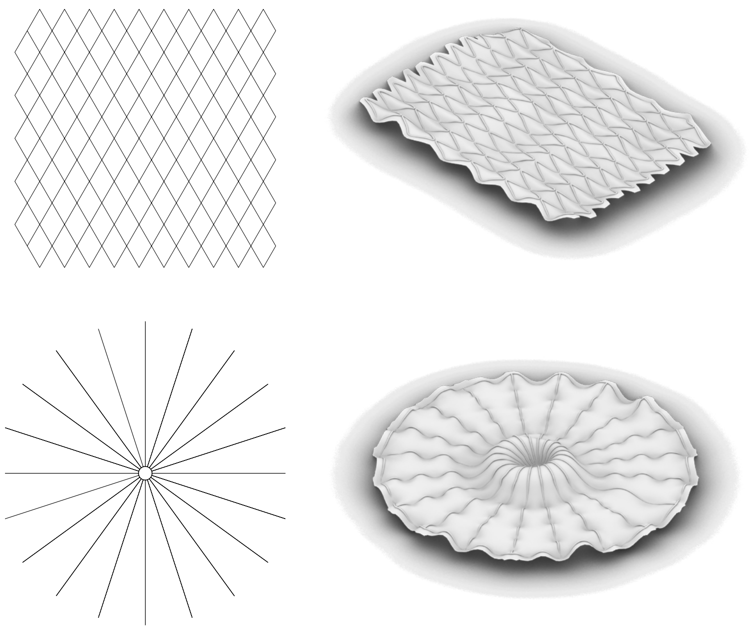


Fig. 7.1.1 4D printing Grasshopper simulation (right) with 2D geometry (left)

7.1.2 Scale

The early experiments were a controlled exploration that resulted in a comprehensive 4D printed textile material library completed on the small-scale, using a desktop 3D printer. Although the research is primarily focused on scaling up the prototype, it was imperative to exhaustively test out multiple forms, structures and variations on the small-scale before bringing it to the robotic scale. Part of this research was focused on the deliverable of a material swatch library, but it was also a crucial period to familiarize and understand the behaviors of the textile composites to bring into the further development of the large-scale designs. To be able to understand and predict on a general level (accurate enough to the Kangaroo simulation) how these designs and material combinations would behave before they were actually printed out in reality was integral to the iterative design process and saved crucial time, allowing for select designs to be taken further into the prototyping.

Fig. 7.1.2 Small-scale printing

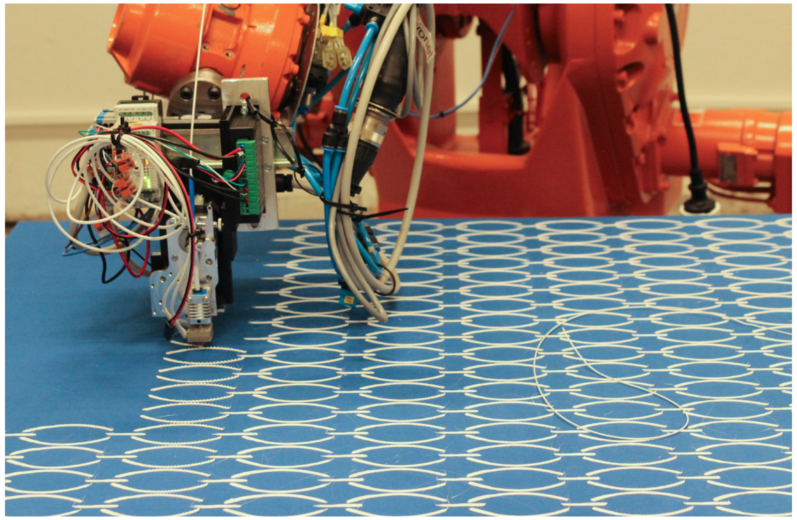
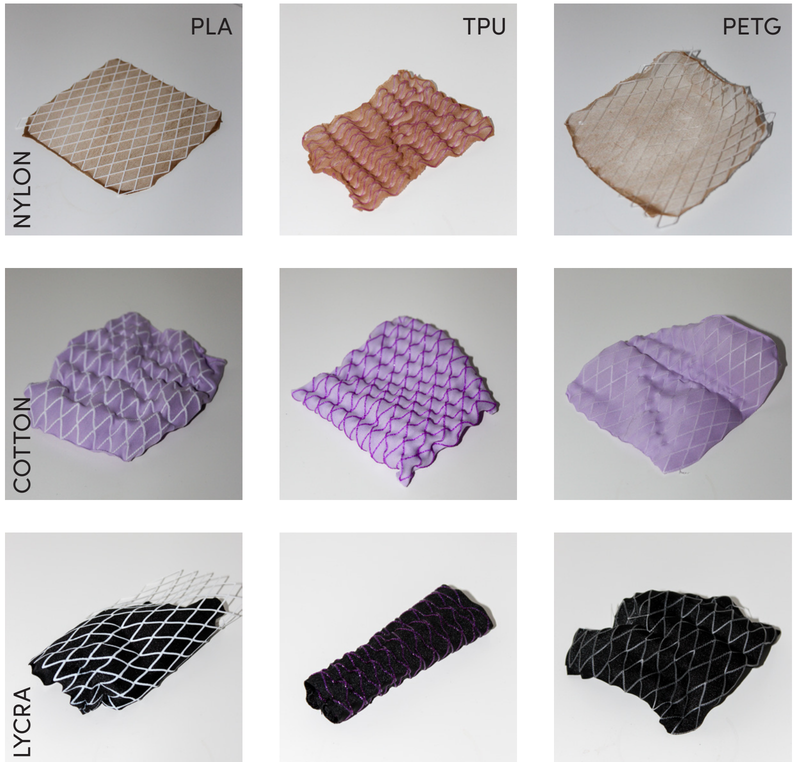


Fig. 7.1.3 Large-scale robotic printing

7.1.3 Test Geometry 1

The first test geometry is made up of a diamond pattern, displayed in a matrix to compare both textile and filament materials. The results conclude that in order for the warping to be significant, there must be a balance between the forces of the filament's resistance to the stretched textile's retraction.



Nylon: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA	No Warping		
TPU		Warping	
PETG	No Warping		

On the Nylon PLA and PETG prints, the filament was too rigid for the weak retraction force of the nylon, resulting in flat composites with no warping and some adhesion loss. The TPU print had strong adhesion and warping. It was uncontrolled in some areas due to unequal stretch.

Cotton: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA		Warping	
TPU		Warping	
PETG		Warping	

PLA/Cotton was the most successful out of the PLA prints, as it had strong adhesion and dramatic warping. However, the warping was not evenly distributed, resulting in an uneven and uncontrolled object. The TPU/Cotton print had strong adhesion and a significant and evenly distributed warping. The PETG exhibited warping, but to a lesser degree than the PLA due to filament rigidity.

Lycra: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA			Warping
TPU		Warping	
PETG		Warping	

The PLA/Lycra print had issues with adhesion, due to an imbalance in the filament rigidity and textile retraction forces, combined with a smooth surface texture. The TPU/Lycra print had good adhesion, but the lycra had more retraction force than the TPU had resistance, causing curling and wrinkling of the entire print.

7.1.4 Test Geometry 2

The second test geometry consists of a star pattern, displayed in a matrix to compare both textile and filament materials. Test Geometry 2 performed better, with four of nine prints displaying strong adhesion, all vastly different warping behavior. The PETG prints exhibited weak adhesion and little to no bend or warping due to the rigidity of the plastic. PETG was not taken further into the research.

Nylon: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA		Warping	
TPU			Warping
PETG	Warping		

PLA/Nylon resulted in a taut rigid dome structure with strong adhesion. TPU/Nylon resulted in a dome that curls outwards on the end, with strong adhesion but weak structural integrity. PETG/Nylon resulted in a structure without bending, due to the brittle nature of the filament.

Cotton: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA	Warping		
TPU			Warping
PETG	Warping		

PLA and PETG/Cotton resulted in a peaked dome, where the textile retraction force was not strong enough to bend the filament. TPU/Cotton resulted in a soft dome, with strong adhesion and moderate structural integrity.

Lycra: Filament Resistance vs Textile Retraction

Filament	FR > TR	FR = TR	FR < TR
PLA			Warping
TPU			Warping
PETG			Warping

PLA and PETG/Lycra resulted in an ellipse shape that curls itself closed, with weak adhesion in some areas. TPU/Lycra resulted in a wrinkled, less structural texture due to the low ridity of the filament in relation to the textile retraction force.

7.2 Robotic 3D Printer Setup

In order to print on the large-scale, a tool for FDM 3D printing of plastic was developed for Lund University's ABB 2400 robot arm. The setup required designing and printing a tool attachment for the robot arm, as well as programming an Arduino Mini Controllino to control the temperature, flow, extrusion, and retraction of the attached filament extruder in sync with the robot movements (print paths). This information was sent to the robot controller via Grasshopper, COMPAS and ROS.

A consequential factor in scaling up the textile is that the actual fibers and weave of the textile are not being scaled, meaning that this needs to be compensated for in other areas, whether it be stretch, design or line weight. One area that can be controlled by the fabrication setup is the line thickness of the print geometry. The desktop printer nozzle has a .4 mm diameter, while the nozzle on the robot has a .8 mm diameter. This requires a higher flow from the extruder, measured in either rotations per minute or meters per second extruded. As the increase in scale of the nozzle is not proportional to the increase in scale of the fabric, printing multiple slightly overlapping adjacent lines allows for the output of thicker solid lines.

A few improvements were added to the robot printing setup after physical testing began. The most significant was the addition of retraction into the Arduino code, allowing for the robot to print multiple separate curves in one file, as opposed to extruding constantly throughout the print file. The retraction code instructs the robot to print a curve, stop extruding, start retracting for a set interval, and return to the home position. The robot then travels to the start point of the next curve, and begins to extrude again.

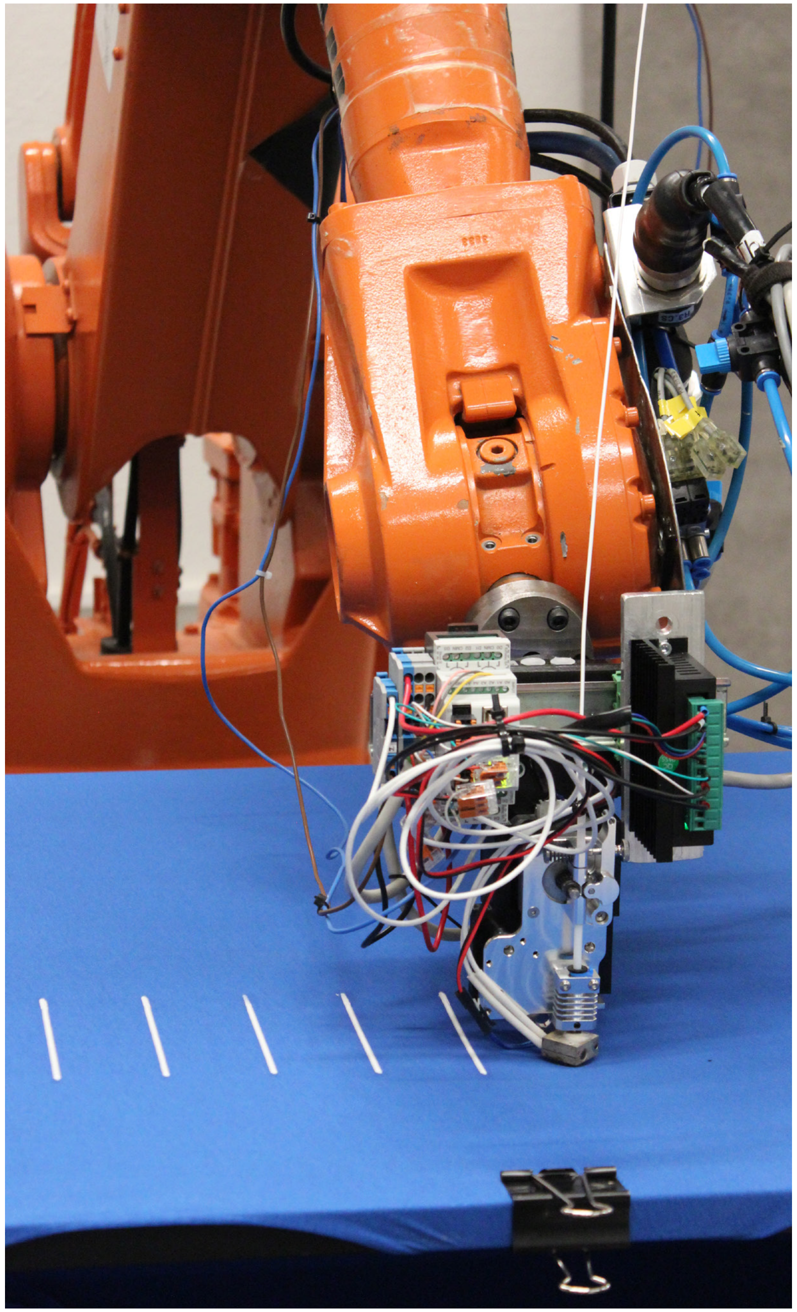


Fig. 7.2.1 ABB IRB 2400 robot arm printing on suspended fabric

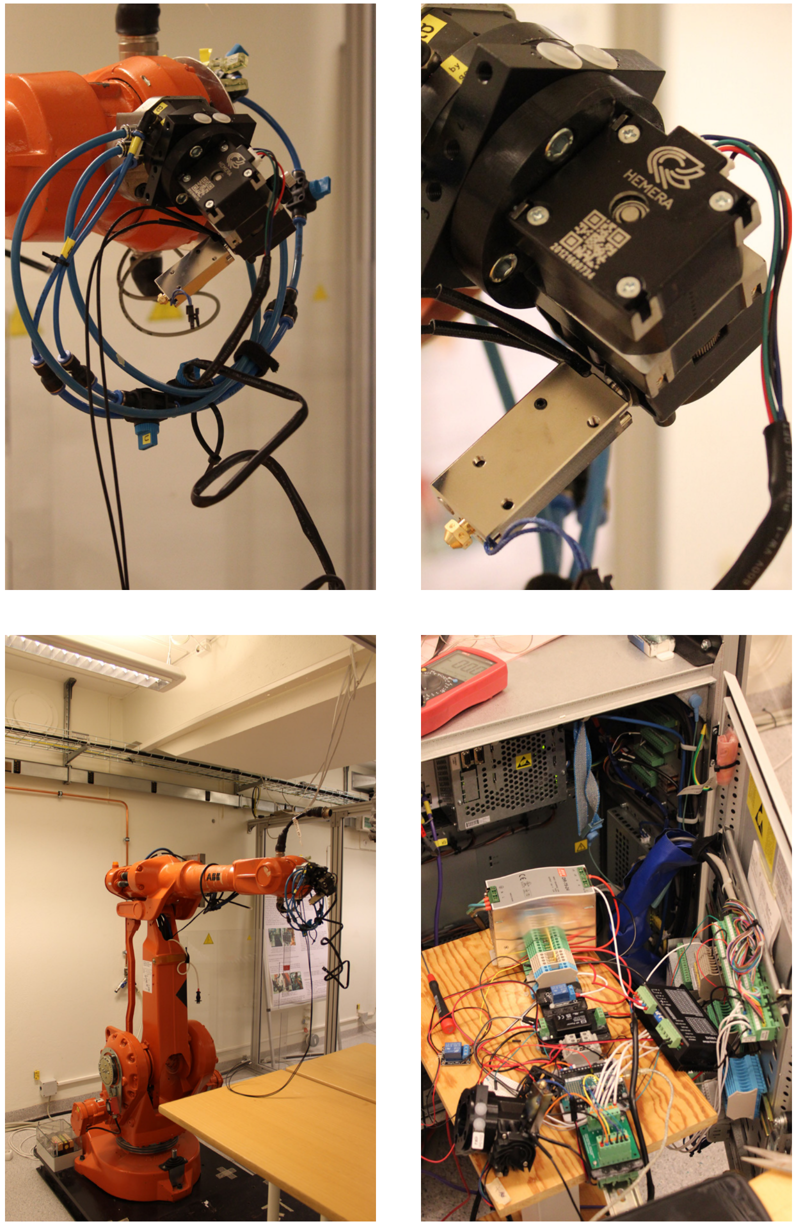


Fig. 7.2.2 Initial setup with Arduino Nano, Hemera Extruder

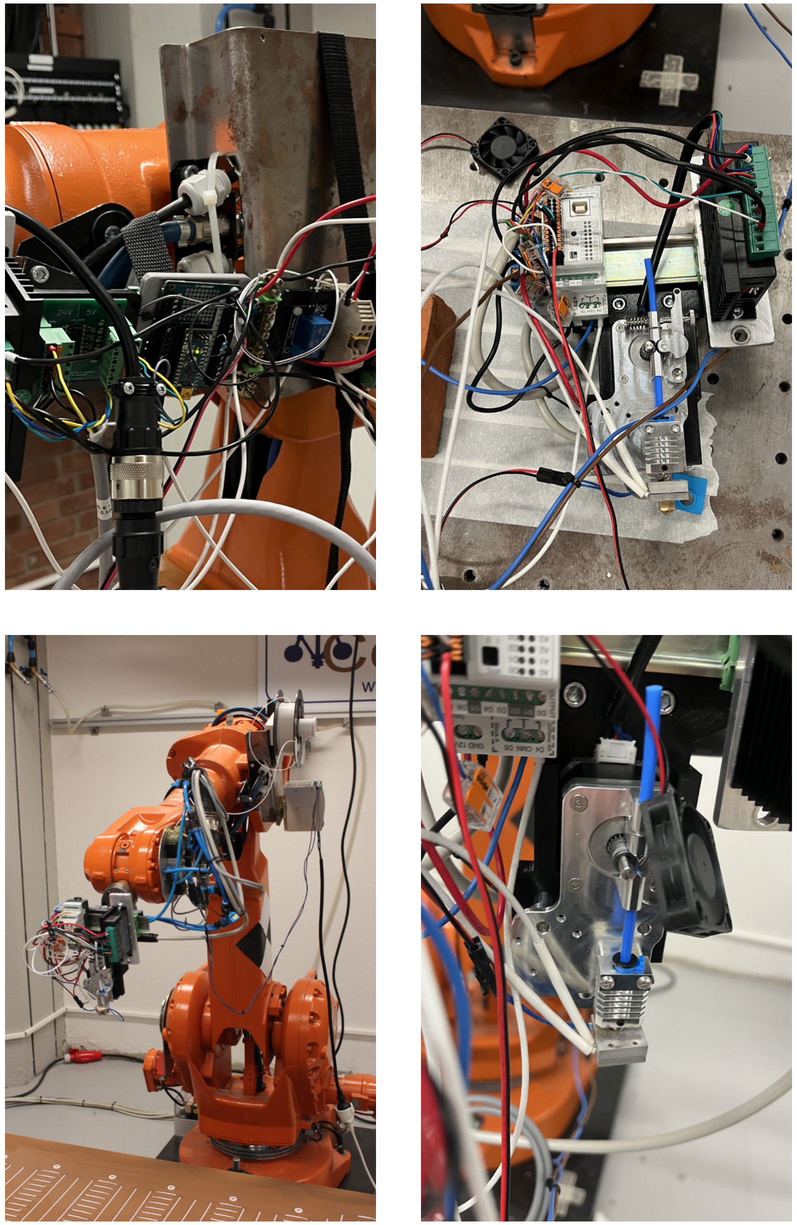


Fig. 7.2.3 Final streamlined setup with Arduino Mini Controllino, Micro Swiss Direct Drive Extruder

7.3 Warping Behavior Classifications

The research takes place on two fabrication scales, but also two classifications of the scale (or degree) of the warping. These two scales of warping result in behavioral properties that can be subjectively classified as structural behavior and textural behavior. This warping classification is not confined by the actual size of the textile, width of the print lines, or even the flexibility and type of the filament.

7.3.1 Structural Warping

Composites printed on the structural warping scale share the quality of significant warping, while also being somewhat self-supporting. This means that the composite object deforms into a shape that is no longer reminiscent of the unaltered textile, and will return to (or pop-up into) this shape even after being stretched or deformed. The leftover tension stored in the fabric from not retracting to its original size interacts with the rigidity of the plastic to create a stable structural state.

7.3.2 Structural Stable States

A further phenomenon of the structural warping is observed with the composite's behavior of having multiple stable states. One geometry in particular, the dome, can be manipulated by pressing down on its center until it flips inside out, and pressure can be applied from the other side to revert it back to its original position. This behavior of multiple stable states is particularly intriguing because it allows for the composite to "pop-up" into different shapes, depending on the location and amount of force exerted upon it. The object can be used in multiple different ways, as the concavity of the object can be adapted to the required function and surroundings at a given time. It can then be hypothesized that the behavior of multiple stable states could be found in other geometries as well.

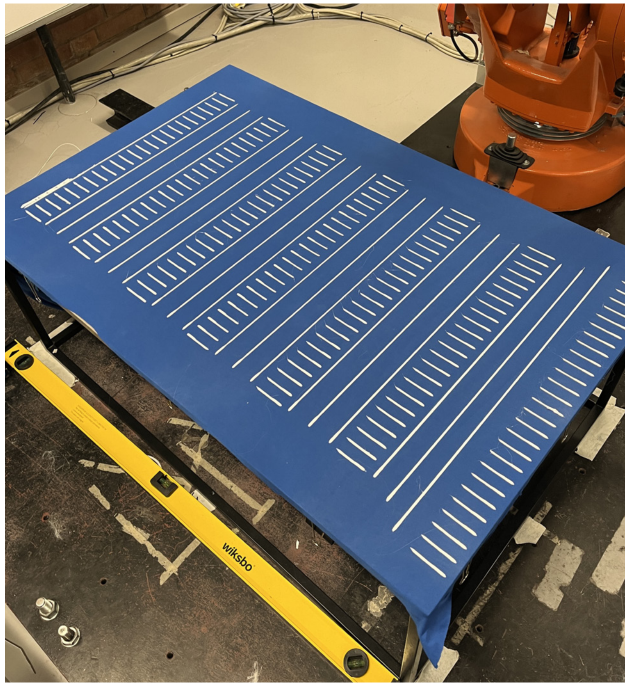


Fig. 7.3.1 Finished tower print before release

Fig. 7.3.2 Tower print after release, structural warping
Material Behavior: Bending

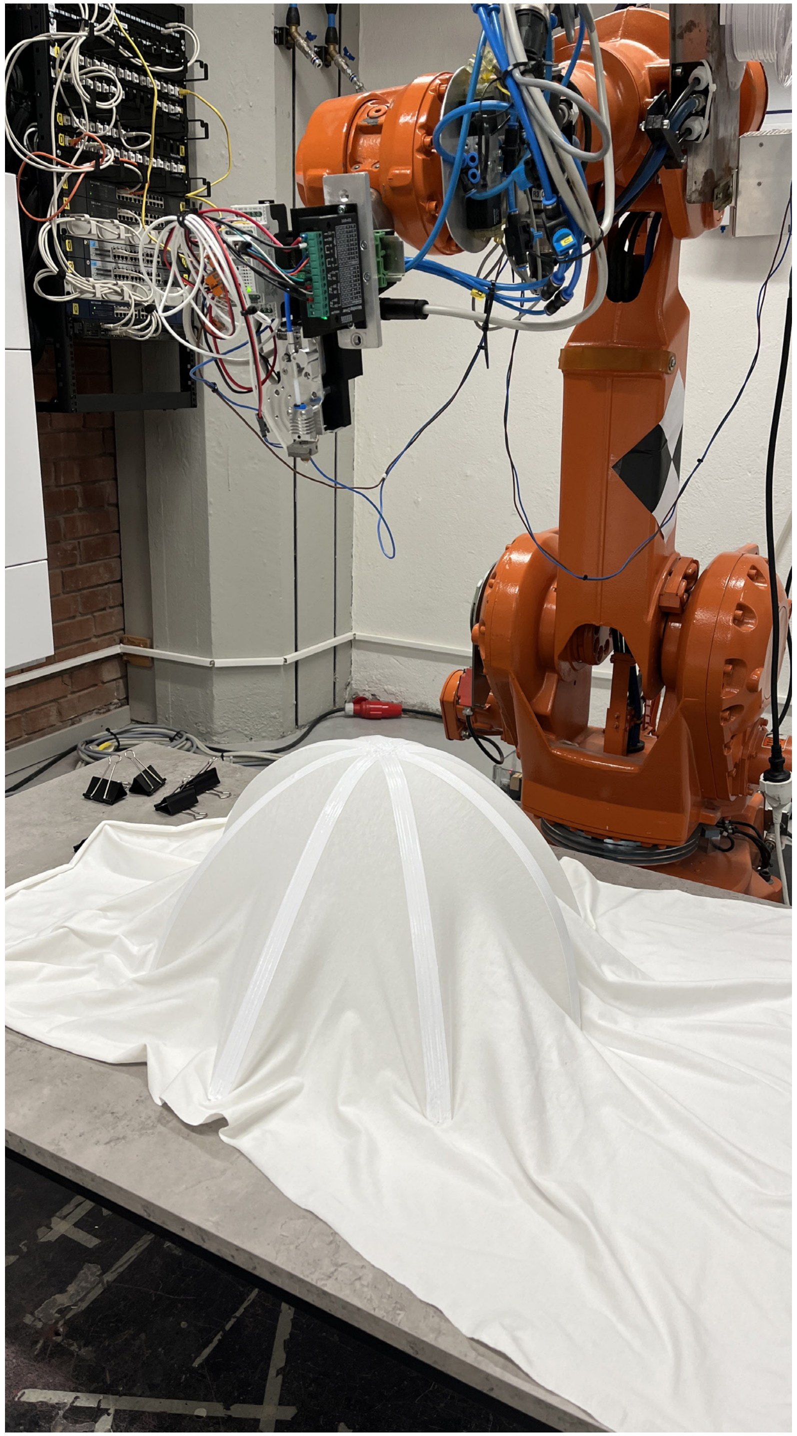


Fig. 7.3.3 Dome after release from print bed, structural warping
Material Behavior: Doming

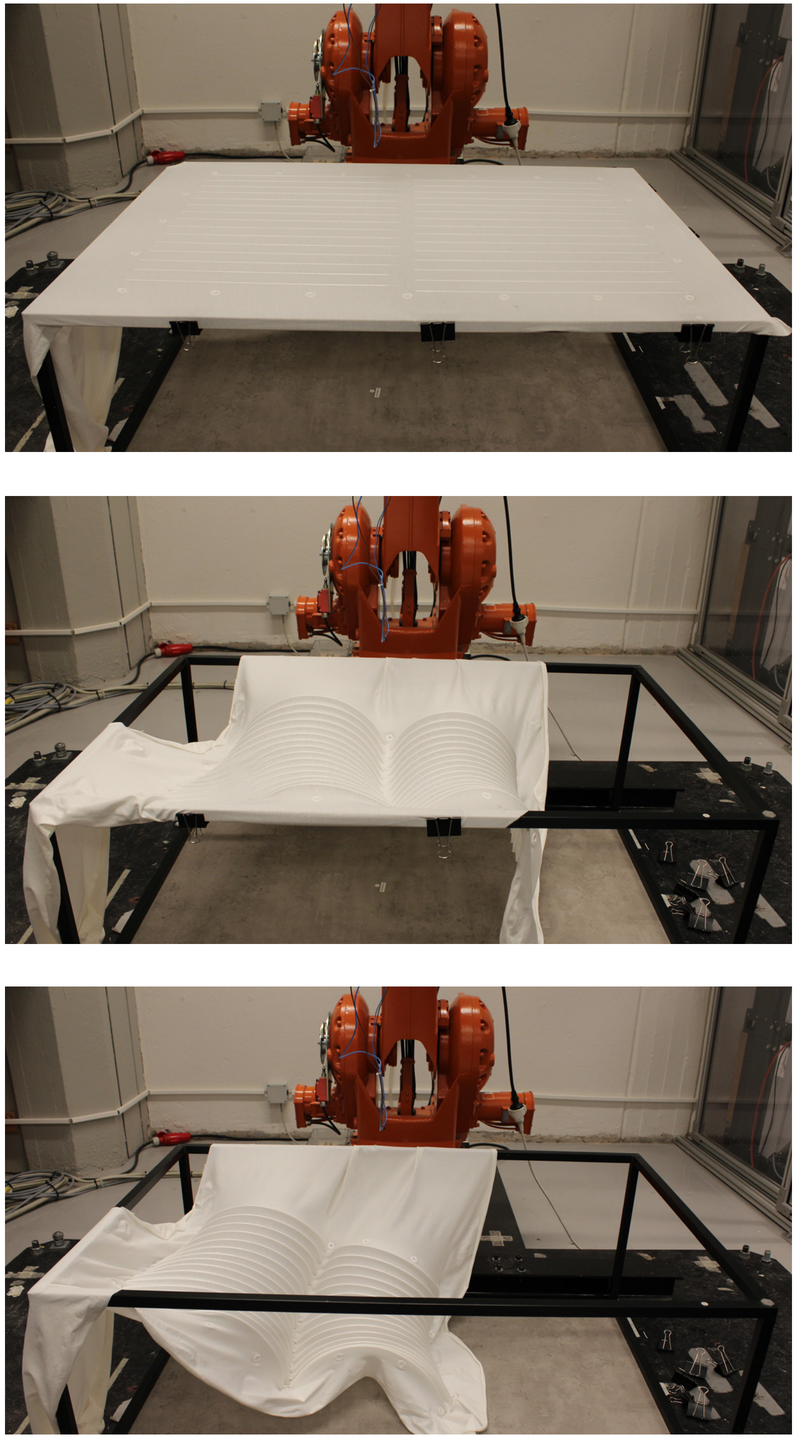
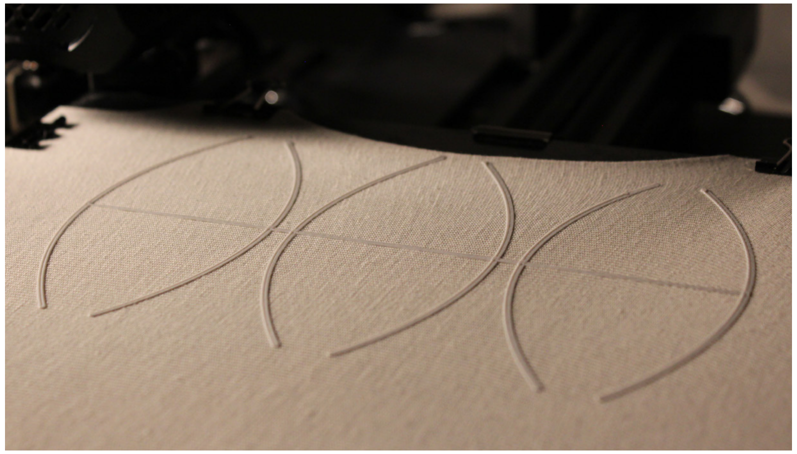
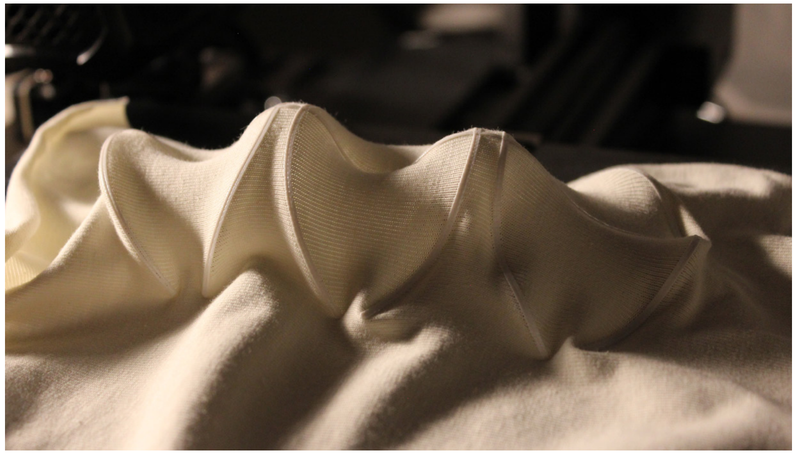


Fig. 7.3.4 Release of dynamic structure, structural warping
Material Behavior: Bending





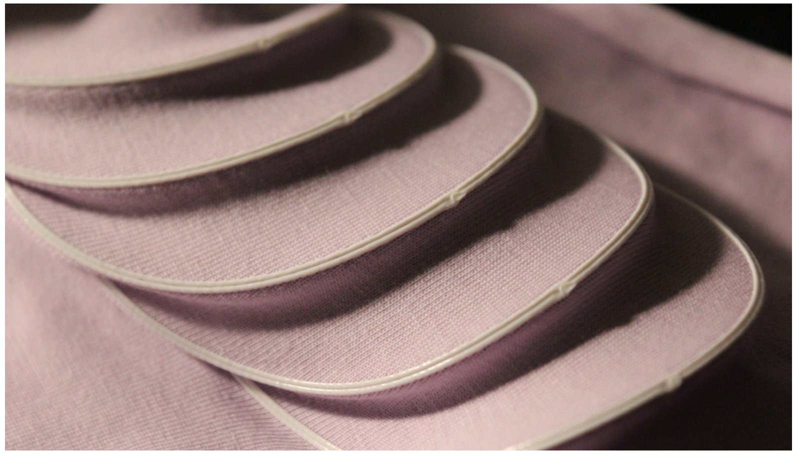
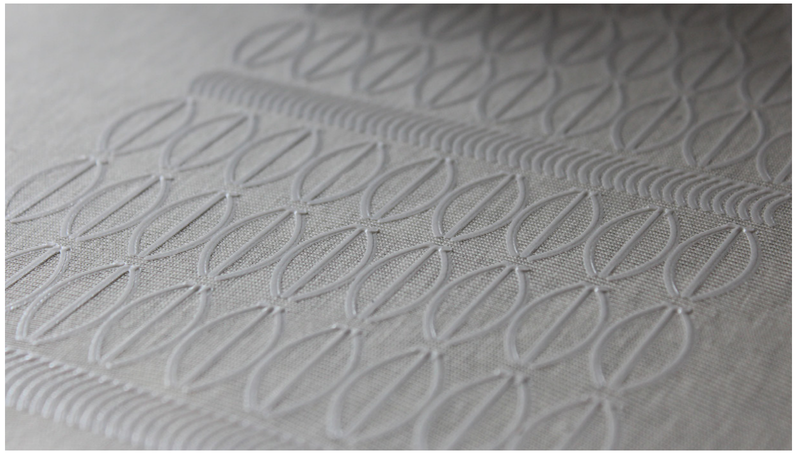


Fig. 7.3.5 Structural material behavior pre-release

Fig. 7.3.6 Structural warping post-release
Material Behavior: Bending

Fig. 7.3.7 Structural warping
Material Behavior: Bending



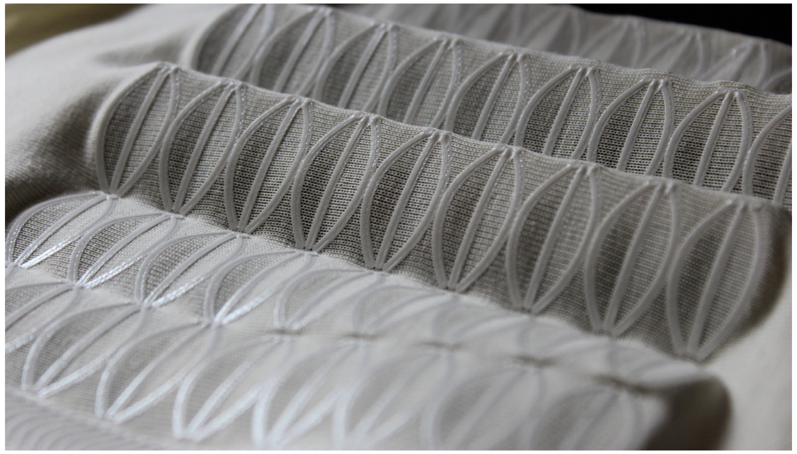


Fig. 7.3.8 Structural material behavior pre-release

Fig. 7.3.9 Structural warping post-release
Material Behavior: Folding + Arching

Fig. 7.3.10 Wall structure post-release
Material Behavior: Folding + Arching

Fig. 7.3.11 TPU parentheses textural tower **Material Behavior:** Wrinkling + Arching + Puckering

Fig. 7.3.12 PLA parentheses textural tower **Material Behavior:** Arching

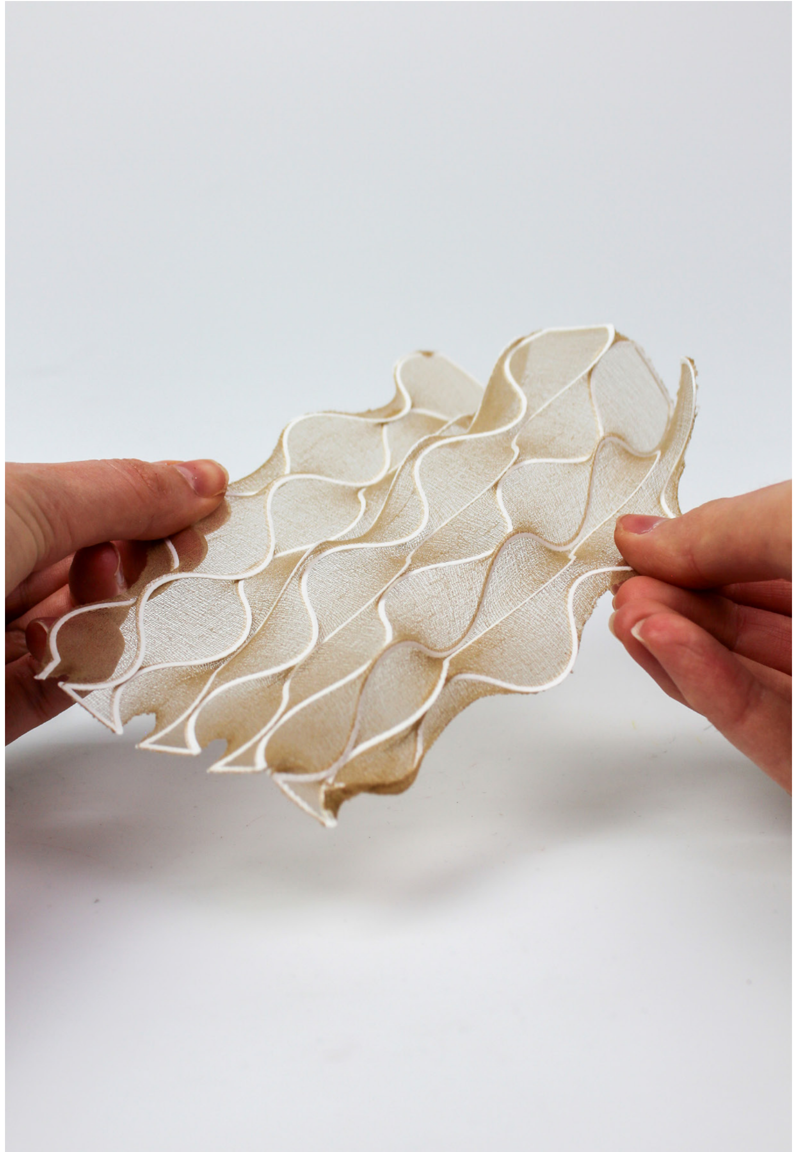
Fig. 7.3.13 Half-circle textural tower with rolled base
Material Behavior: Puckering

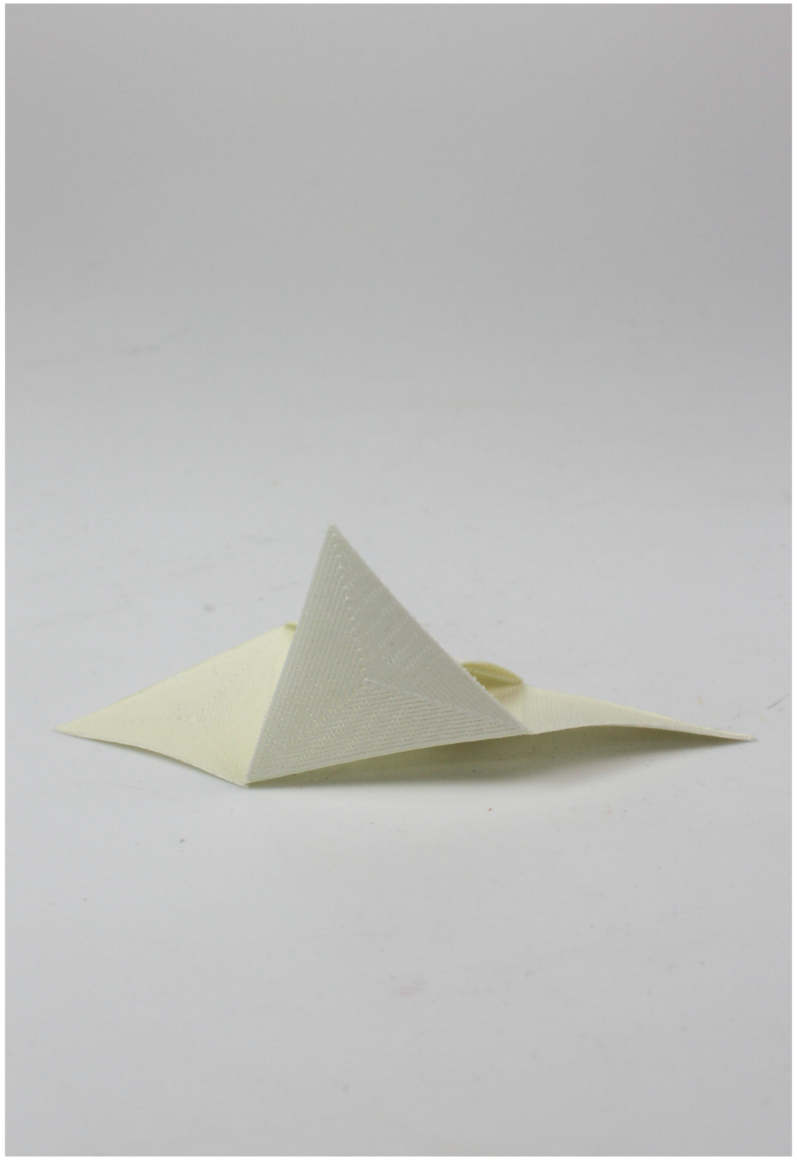
Fig. 7.3.14 Dynamic Structure tower
Material Behavior: Bending + Rolling

Fig. 7.3.15 Diagonal lines experimental tower
Material Behavior: Wrinkling

Fig. 7.3.16 Ribcage rolled base experimental tower
Material Behavior: Wrinkling + Bending

Fig. 7.3.17-18 Nylon and PLA, structural warping
Material Behavior: Folding





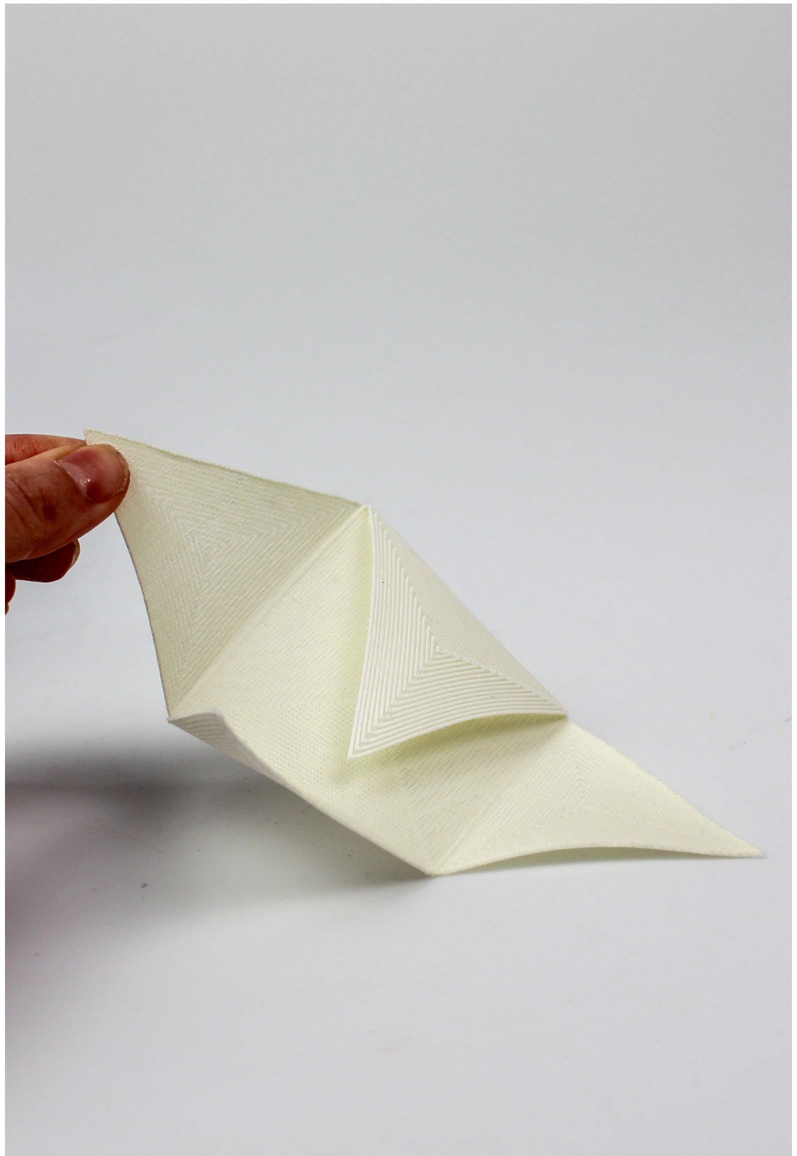


Fig. 7.3.19-20 Cotton and PLA, structural warping
Material Behavior: Folding

Fig. 7.3.21-22 Cotton and PLA, structural warping
Material Behavior: Peaking

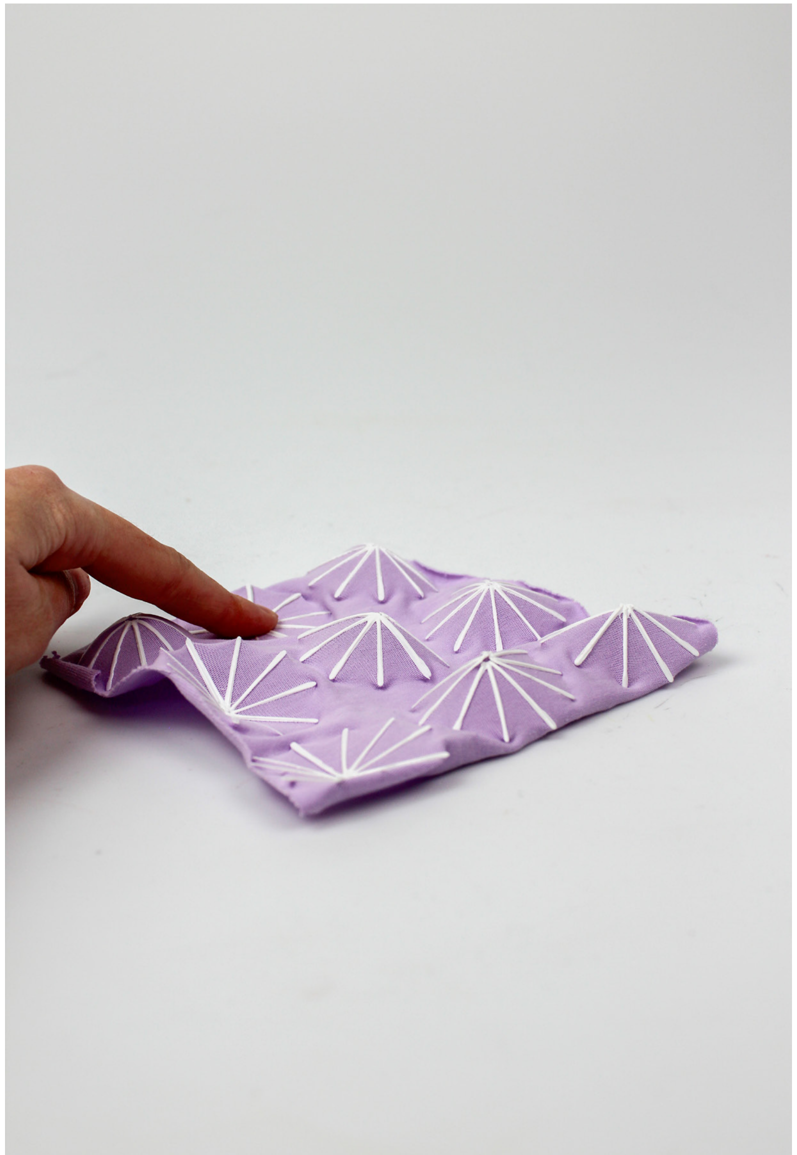
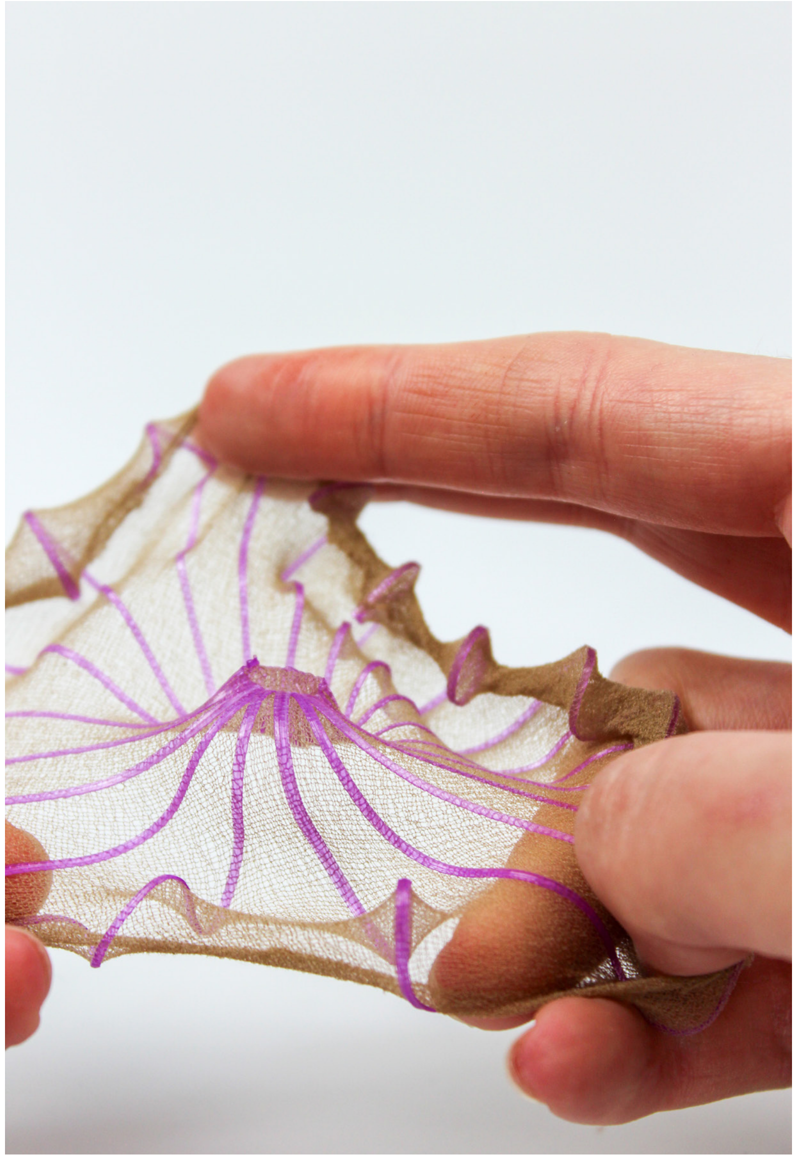


Fig. 7.3.23-24 Nylon and TPU, structural warping
Material Behavior: Curling + Puckering + Wrinkling



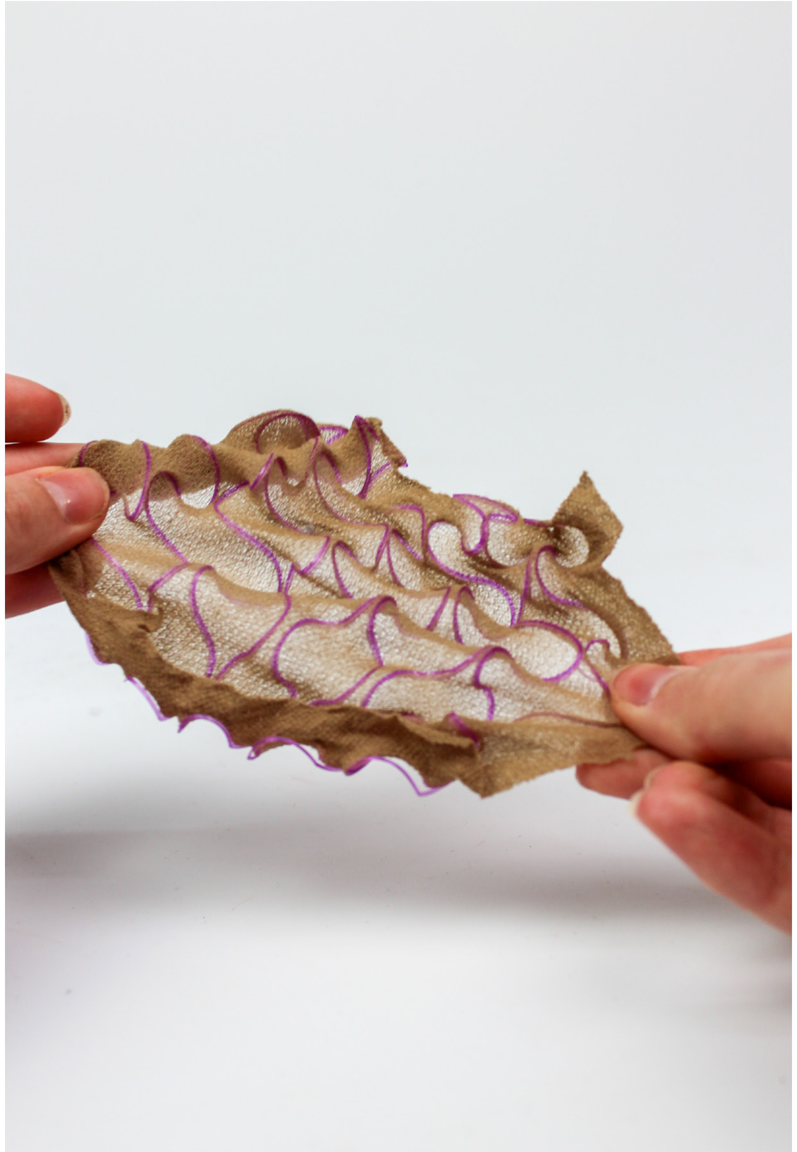


Fig. 7.3.25-26 Nylon and TPU, structural warping
Material Behavior: Puckering + Wrinkling

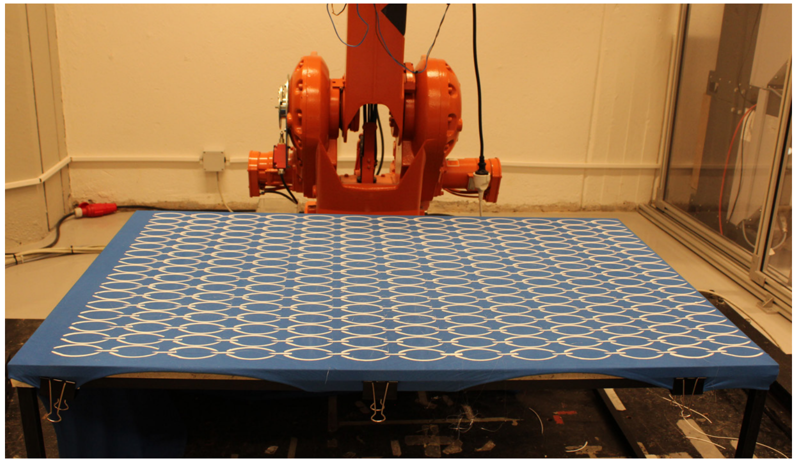
Fig. 7.3.27–28 Nylon and TPU, structural warping
Material Behavior: Curling + Puckering + Wrinkling

7.3.3 Textural Warping

Textural behavior can be achieved primarily through creating an uneven balance of forces between the textile and the plastic, where the textile's retraction force is significantly less than or greater than the resistance of the plastic. Although the line between texture and structure is quite subjective, textural warping generally means that the composite appears to be a textile with plastic forms attached to it, rather than a structural form wrapped in textile. The textural warping can be both intentional (often with TPU) or it can be the result of a "failed" experiment; where the plastic lines were not printed thick enough so that they are weaker than the retraction force of the stretched textile, or they were too thick so the textile was not strong enough to bend them. The scaling up of this research was conducted under the observation from the early experiments that TPU generally results in textural warping, and PLA generally results in structural warping. However, there are many exceptions to this rule. If the difference between structural and textural warping is primarily a balance of forces, it is then possible that TPU could be used to create large-scale structural composites with the right line thickness, textile, and geometry.

7.3.4 Geometry and Warping

The geometry itself also plays a significant role in the structural vs textural behavior of the final textile composite. The early experiments began with a focus on elaborate pattern-making, which resulted in primarily textural swatches. Through iterations, it was observed that the geometries with more open space resulted in greater warping, as the retraction force of the textile was more concentrated on specific areas, resulting in more dramatic bends that were reinforced with thicker lines.



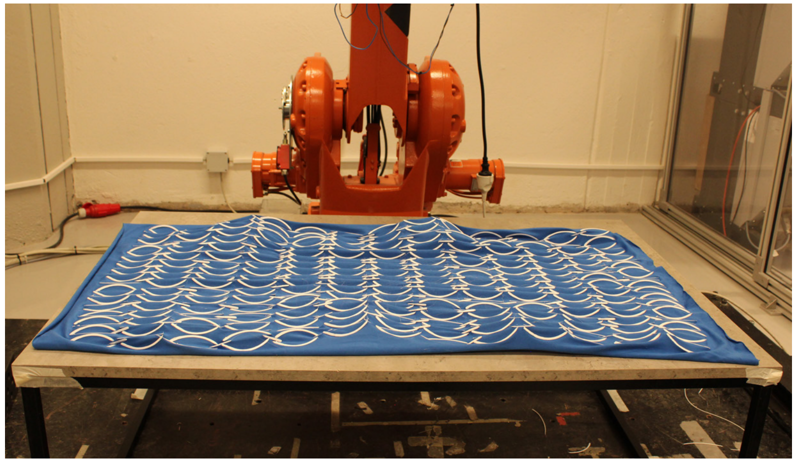
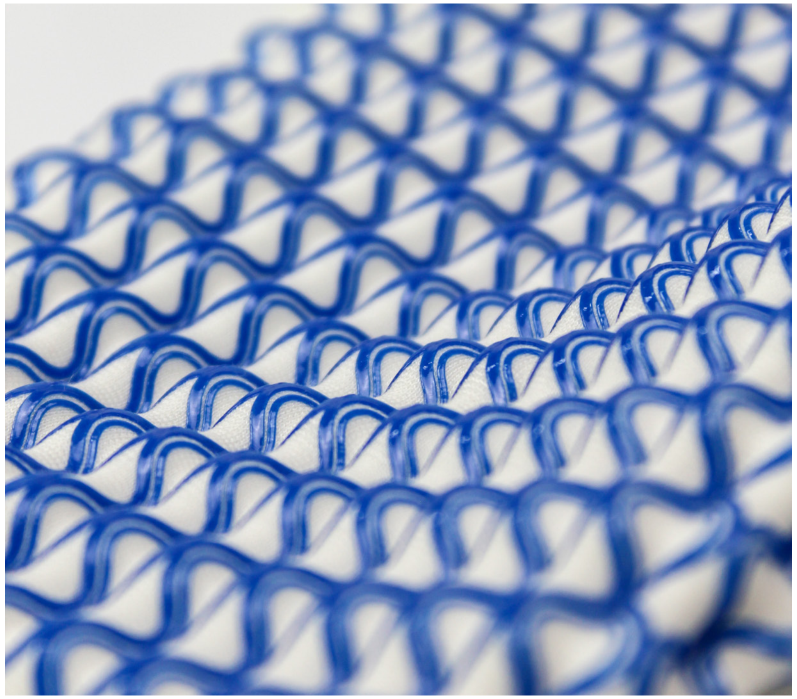


Fig. 7.3.29-30 Large-scale textural warping pre & post-release
Material Behavior: Puckering



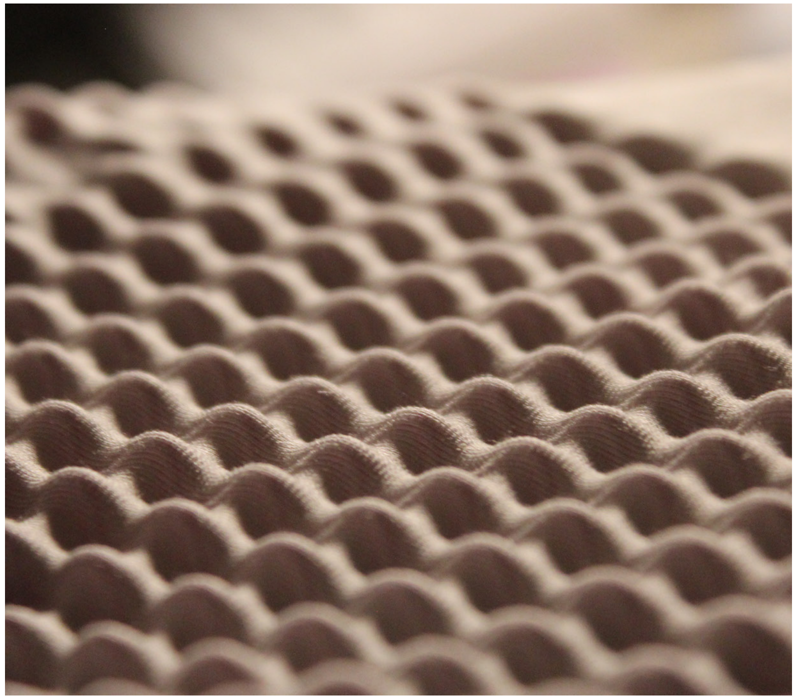
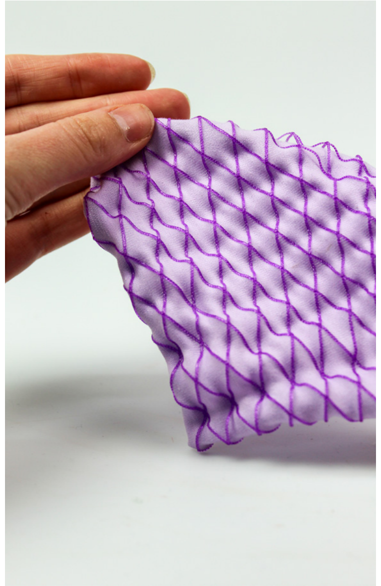


Fig. 7.3.31 Cotton/TPU small-scale textural warping
Material Behavior: Puckering

Fig. 7.3.32 Backside of cotton/TPU small-scale textural warping
Material Behavior: Puckering



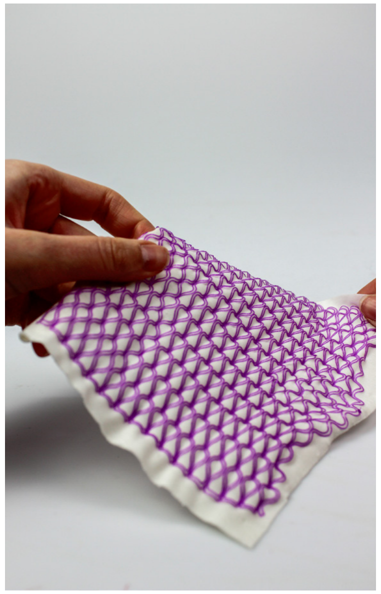


Fig. 7.3.33 PLA/Cotton fabric smocking
Material Behavior: Puckering

Fig. 7.3.34 PLA/Cotton fabric manipulation
Material Behavior: Puckering + Arching

Fig. 7.3.35 TPU/Cotton texture test
Material Behavior: Puckering

Fig. 7.3.36 TPU fabric test, with the testing geometry
Material Behavior: Puckering

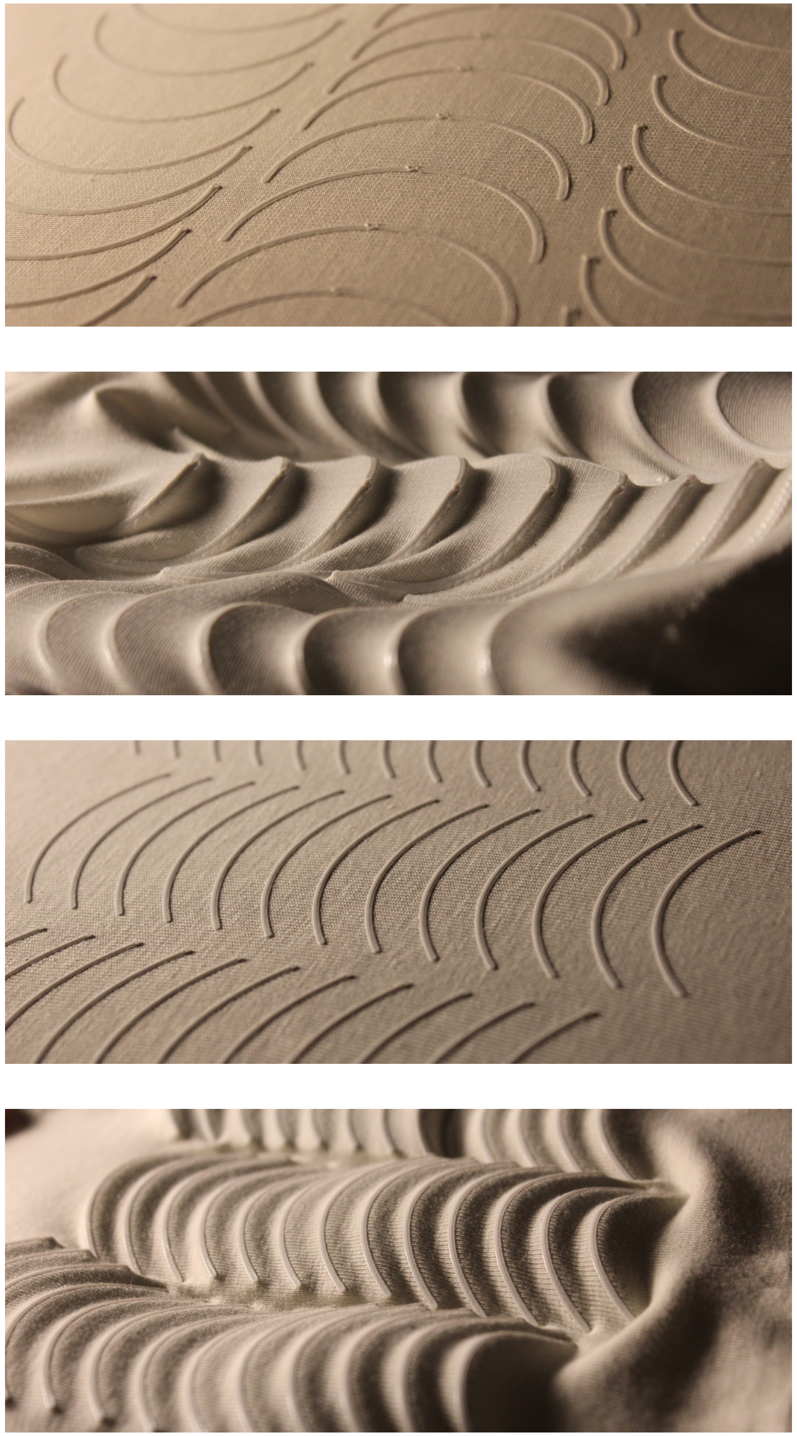


Fig. 7.3.37 Small-scale textural warping pre and post-release **Material Behavior:** Arching

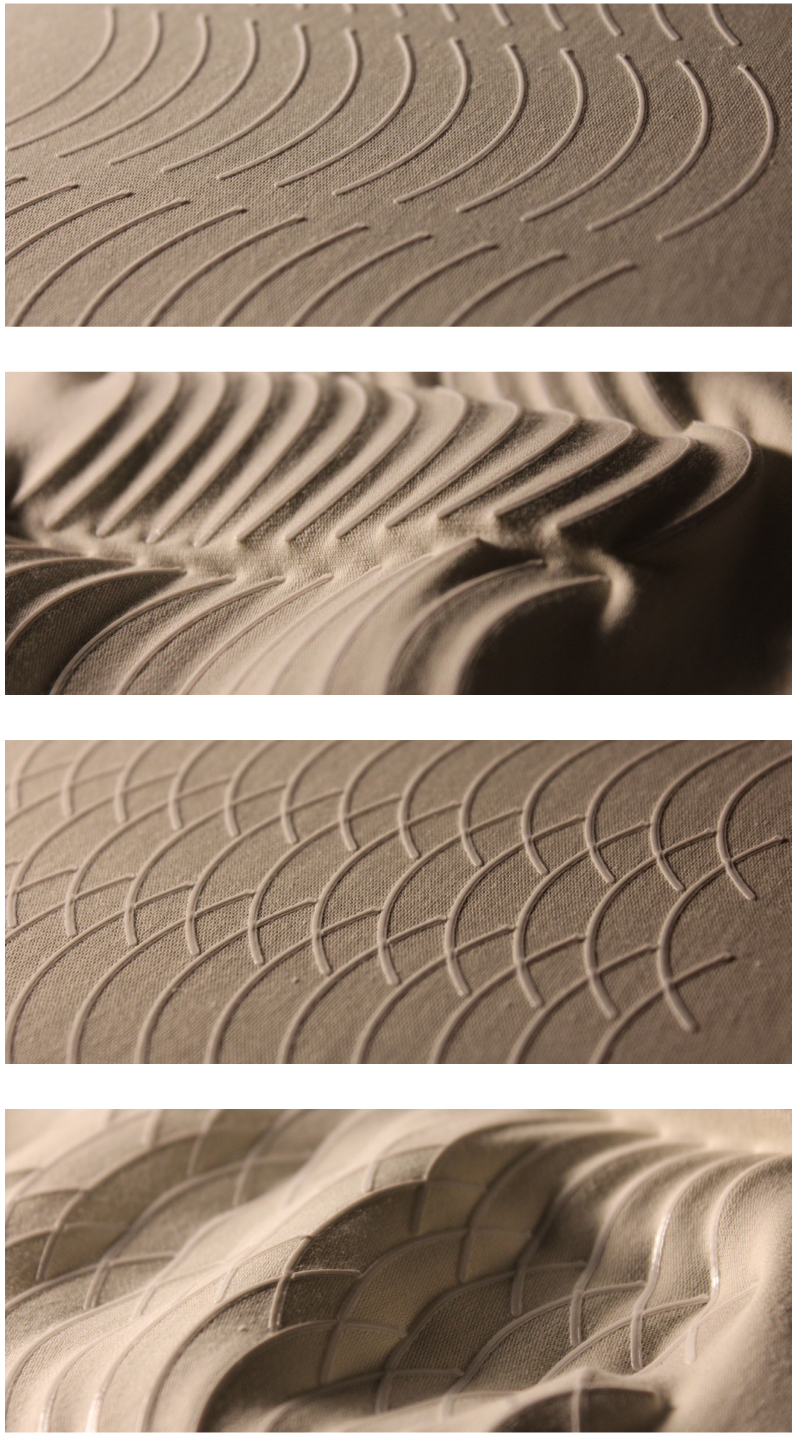


Fig. 7.3.38 Small-scale textural warping pre and post-release **Material Behavior:** Arching

7.4 Adhesion

Adhesion of the filament to the textile has been a constant challenge throughout the project. If the filament does not properly adhere to the textile, the filament will come loose upon release from the print bed or over time. Good adhesion is achieved when the plastic is stuck to the fabric with no edges poking out that can get caught and ripped off, the geometry is printed as one continuous line that bends uniformly, and contains no weak sections wrinkling due to the nozzle being too close and not extruding enough. Many factors affect adhesion quality, such as nozzle height, temperature, resistance / retraction ratio, as well as surface texture of the textile.

7.4.1 Nozzle Height

Nozzle height is perhaps the most important factor, as the filament needs to be pressed into the fibers and stretched weave of the textile or else it will come loose from the textile when it retracts. A closer nozzle results in better adhesion, but also has adverse factors such as the lateral spread of the print line due to squeezing and the potential of the nozzle to crash into and skid on the print bed, as the optimal height is just nearly scraping the surface of the bed. Later into the research, another framing method was used to improve adhesion and reduce clogging and skidding where the fabric was stretched and suspended in the air (Figure 7.8.9). This required a much lower nozzle height, as the nozzle would now press significantly down into the fabric as it printed, but resulted in more successful prints overall.

7.4.2 Flow & Speed

Another factor contributing to adhesion is the flow rate in relation to the robot speed. The extrusion rpm (how fast the filament is extruded out of the nozzle) and nozzle temperature are set via a sketch (program) uploaded into the Arduino Mini Controllino, and after finding the ideal settings, were not changed except when switching filament

Fig. 7.4.1 PLA/Lycra, adhesion lost due to too high of a nozzle height during print

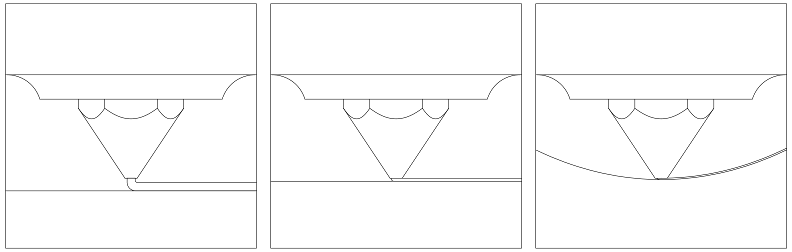
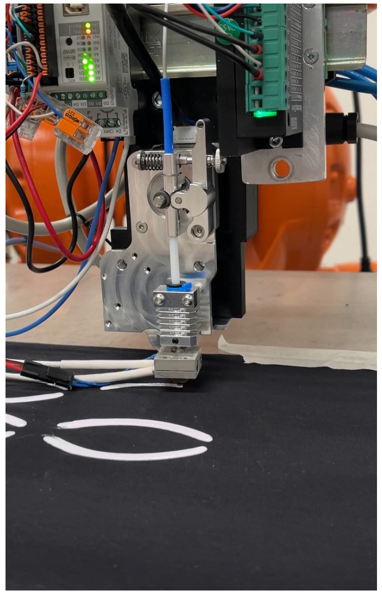
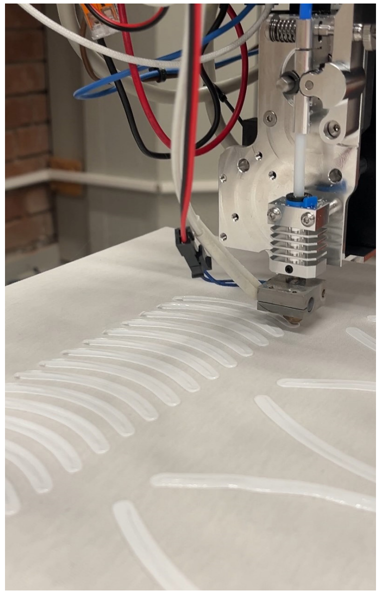


Fig. 7.4.2 Diagram depicting different nozzle heights resulting in bad (nozzle too high), good (nozzle pressing on fabric) and best (nozzle pressing down into textile) adhesion

types or brands (each filament brand has unique optimal temperature ranges). The robot speed is set via the ROS integrated Grasshopper script, and can be tested and updated throughout the whole process. The robot speed controls how fast the robot moves along the print path, so if the robot moves very fast along a path of a straight line, there will be less filament on the line and it will be narrower, as the total length of the extruded filament would be less due to the constant extrusion rate over time (Figure 7.4.9). If the robot moves very slow over the print path, the extruder would output a much greater volume of filament over the same distance, causing the excess to be pushed out both laterally and down into the fabric (Figure 7.4.8). The latter method is optimal for good adhesion, but the temperature is crucial so that the filamenthas a low enough viscosity to "spill" out laterally and not push back against the nozzle, causing skidding or a clog in the gears of the extruder.

Fig. 7.4.3 Hemera extruder with a nozzle height too high





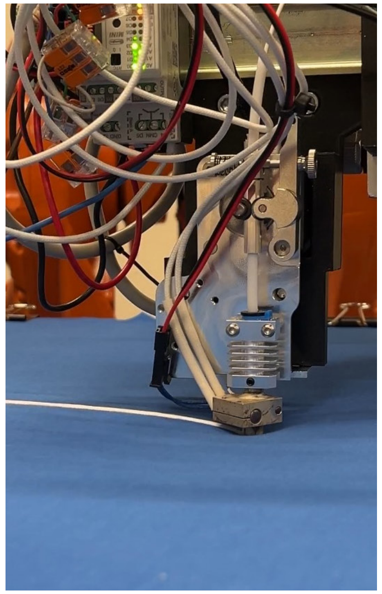


Fig. 7.4.4 Sanding the surface of the fabric to increase surface fibers for the filament to adhere to

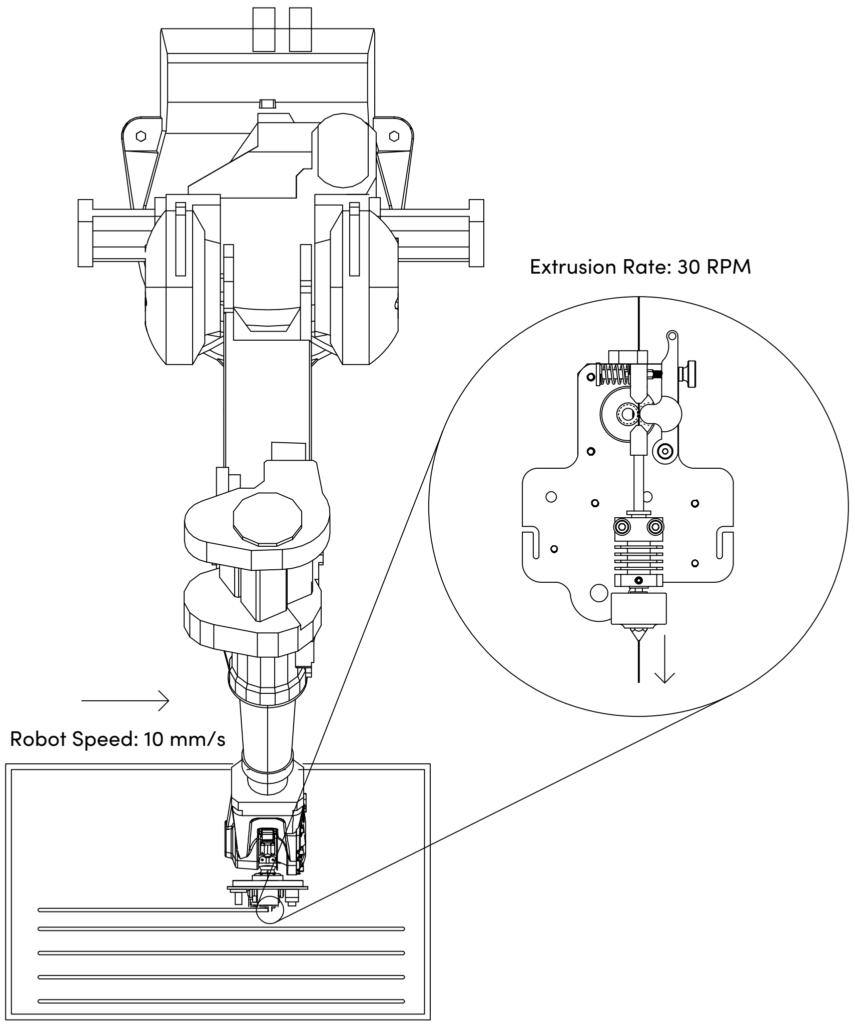
Fig. 7.4.5 First test with Micro Swiss Direct Drive Extruder

Fig. 7.4.6 Decreased nozzle height to push filament into white fabric

Fig. 7.4.7 Printing on the suspended (blue fabric frame, with a nozzle height of -20mm below the frame

Wide Print Lines, Better Adhesion

Constant extrustion and slower robot speed



Narrow Print Lines, Worse Adhesion

Constant extrustion and faster robot speed

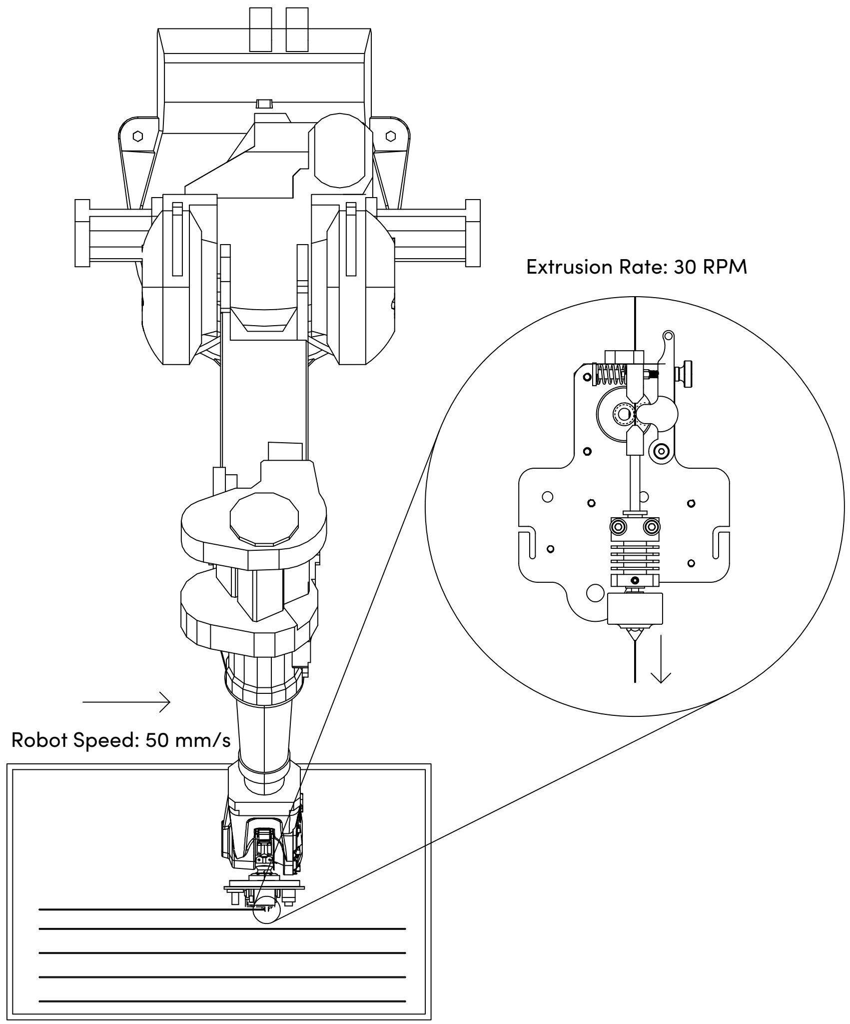


Fig. 7.4.8-9 Effect of robot speed on print line width and ahesion

7.5 Material: Filament

Two types of thermoplastics are primarily used in the research, PLA and TPU. PLA, or polylactic acid, is a polymer filament derived from starches. It is a hard plastic, but somewhat flexible in thin layers. TPU or thermoplastic polyurethane is a soft plastic that behaves like a hard rubber (Stampomatica, 2023).

7.5.1 Filament Behavior

When used in 4D textile printing, PLA maintains a rigid structure with varying degrees of bending. In some cases the structure of the plastic is stronger than the retraction forces of the fabric, resulting in little to no warping. TPU is much more flexible and much less structural, allowing the fabric to warp significantly. With TPU, the 4D warping can be too dramatic if paired with an extremely stretchy textile (such as nylon) and result in a small compressed piece of fabric.

7.5.2 Structures vs textures

Different filaments play a significant role in transforming the fabrics into structures versus maintaining them as textiles. The best example of this is seen in Figure 7.5.1-2, where the Cotton/PLA combination results in a structural object that no longer behaves as a textile, while the Cotton/TPU combination results in a deformation similar to smocking, a traditional fabric manipulation. Both transformations are significant when compared to the previous state of the textile, but the ability to output textures vs structures by simply altering the filament reveals how each parameter plays a crucial role in creating programmable behaviors.

Fig. 7.5.1 PLA/Cotton structural warping
Material Behavior: Puckering + Arching

Fig. 7.5.2 TPU/Cotton textural warping
Material Behavior: Puckering

Fig. 7.5.3 PLA vs TPU on Nylon, with identical print geometries
Material Behavior: Arching + Bending vs Curling + Puckering + Wrinkling

7.6 Material: Textile

When the fabrication scale is increased, the printing nozzle diameter can also be increased to create stronger print lines. However, as the fabric may increase in width and length, the thickness remains constant, meaning that the fabric strength does not increase proportionally. This significantly affects the balance of the retraction and resistance that was established at the smaller scale.

7.6.1 Small-scale

At the small-scale, the most successful prints were made using cotton and TPU / PLA. Cotton's stretch factor is in the middle of lycra and nylon, as the lycra provided too much retraction and the nylon provided too little. When paired with the correct filament, the results could be controlled with lycra and nylon, however cotton performed best overall across the various filaments. These tension and structure ratios change significantly when introduced onto a larger scale, however techniques such as creating an offset print path or using looped geometries (as seen in the SIKKA project, Figure 4.5) can be implemented to mitigate those effects.

7.6.2 Large-scale

Heading into the large-scale experimentation, it was decided to test a variety of thicker fabrics, but ultimately the same cotton that was optimal on the smaller scale performed the best on the larger scale as well. In an effort to simplify as many variables as possible, the cotton fabric was the primary textile used in the large-scale testing, and nearly all of the prototypes are printed on it. One significant difference was observed when using the same fabric on the larger scale; the weave direction of the fabric needed to run parallel to the long printed lines in order for them to bend. It was also crucial to stretch the fabric much more than was necessary on the smaller scale in order to achieve similar results.

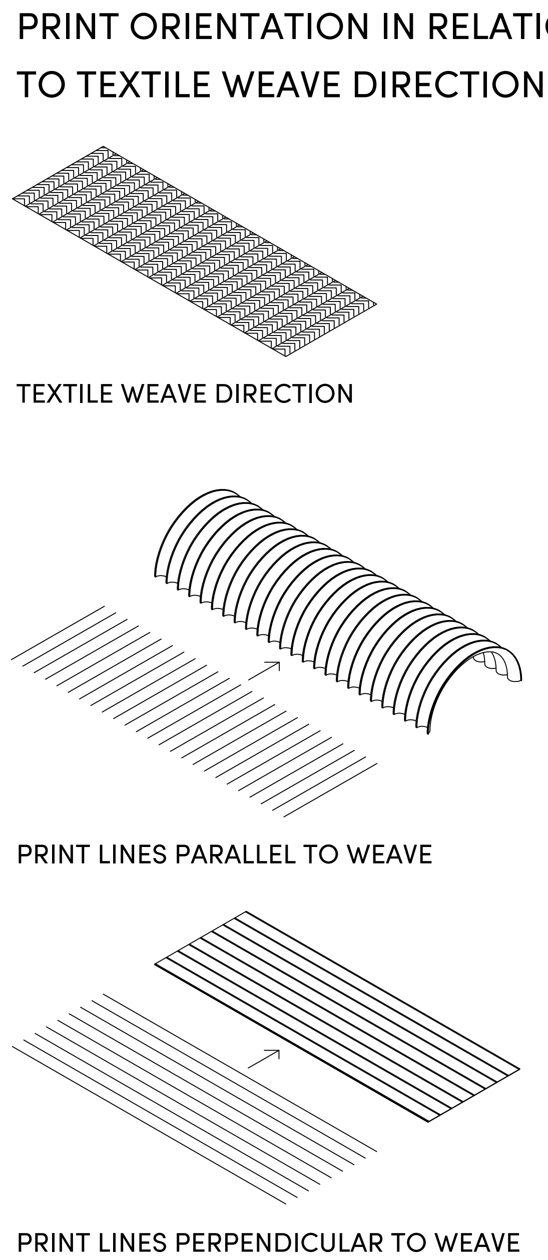


Fig. 7.6.1 Printing in relation to weave direction

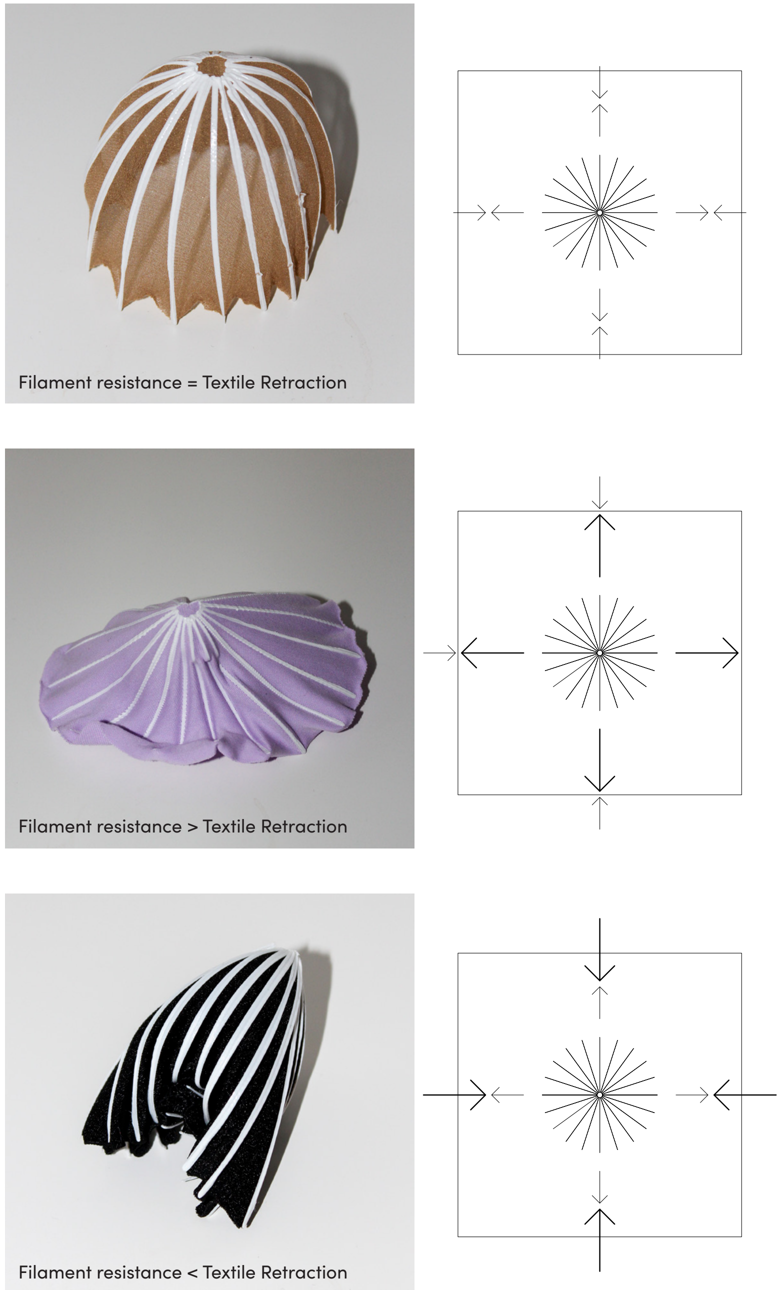


Fig. 7.6.2 Diagrams depicting the balance between the forces of filament resistance and textile retraction in Test Geometry 2

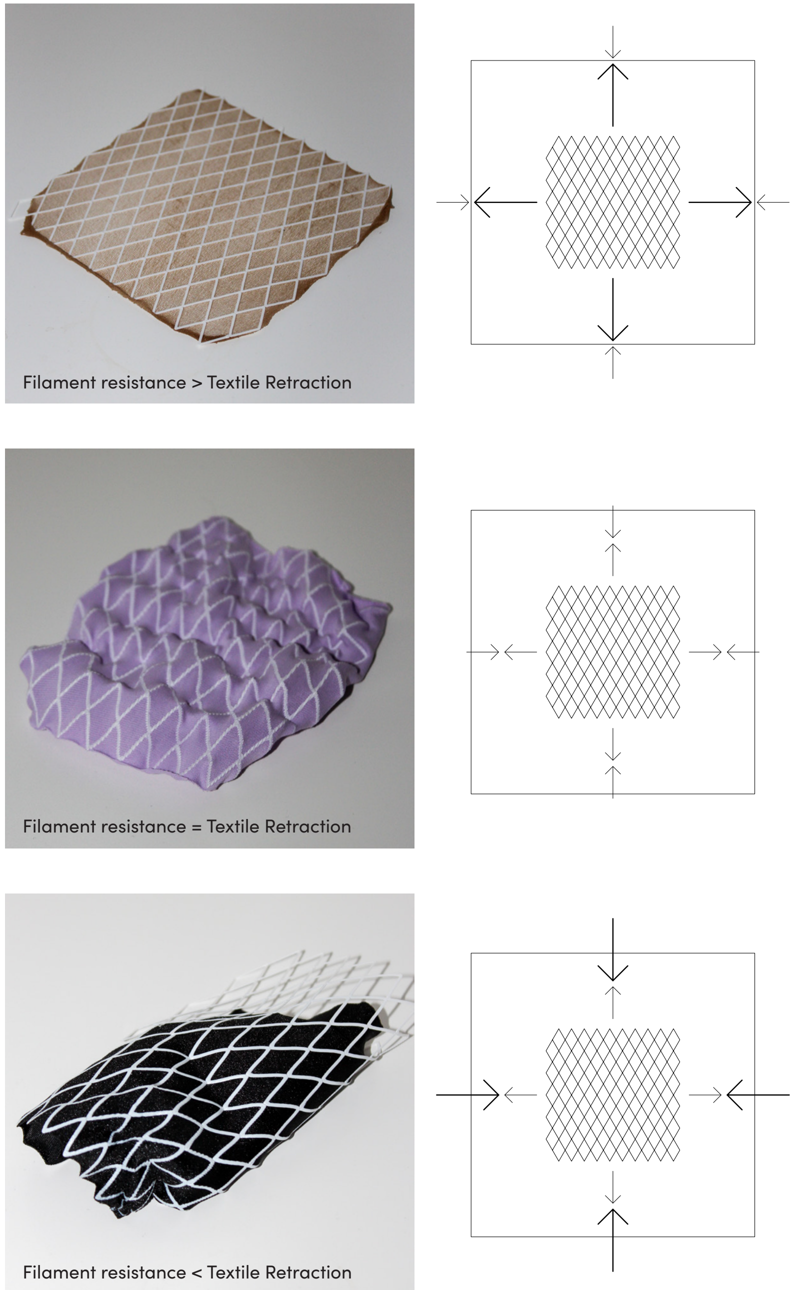


Fig. 7.6.3 Diagrams depicting the balance between the forces of filament resistance and textile retraction in Test Geometry 1

7.6.3 Material Stiffness

A significant factor in the material behavior upon release is dependent upon its stiffness and rigidity. Throughout the early experiment matrices, the ratio of fabric stretching and the rigidity of filament was documented. Materials with a high stretch factor and high tension release force, such as Lycra, do not interact successfully with rigid materials such as PLA, resulting in poor adhesion due to too great of a retraction force in the fabric, however the same material achieves good results with TPU. Materials with a medium stretch factor and a moderate retraction force, such as cotton, achieve good results with both TPU and PLA. Materials with a high stretch factor and low tension release force, such as nylon, can perform both well and poorly with both filament types, depending on the geometry.

Fig. 7.6.4-5 Identical PLA geometries printed on Nylon and Cotton, displaying different warping behaviors
Material Behavior: Arching vs Puckering + Wrinkling

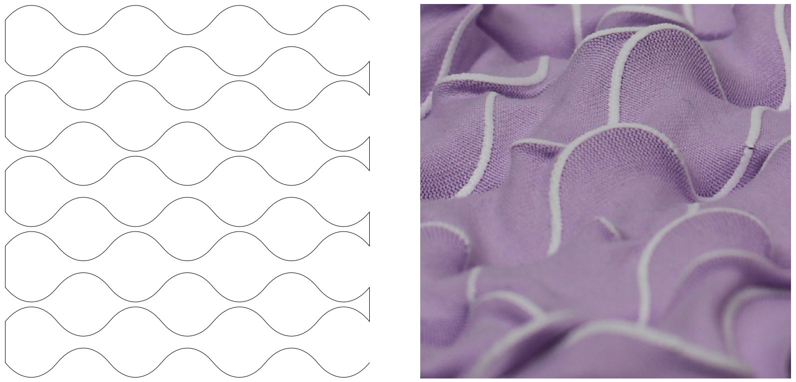
Fig. 7.6.6-7 Identical PLA geometries printed on Nylon and Cotton, displaying different warping behaviors
Material Behavior: Folding vs Folding + Arching

7.7 Print Geometry Design

When the research transitioned from a general experimentation in fabrication process to a focus on creating a self-supporting structure, it was imperative to simplify and control certain variables. This was achieved in part by narrowing to one material for both the filament and the textile, but also through simplifying the design curves from a framework of pattern thinking and evaluating warping behavior as a whole, to a set of isolated geometrical parts, each evaluated on its individual warping behavior.

7.6.1 Geometry as a print variable

The print geometry itself must be considered when interpreting the material interactions, as the early physical experiments display how crucial the print geometry is when predicting the warping behaviors of the composite textiles. The success of material combinations was not consistent across geometries, best seen in the case of the Nylon/PLA combination on the small-scale, one of the most successful prints using the star geometry (Figure 7.6.2), and one of the least successful in the diamond pattern geometry (Figure 7.6.3). In another experiment, offsetting a print geometry (Figures 7.7.1 & 7.7.2) completely altered the structure of the resulting object, adding stability and consistency into the print. Therefore, the print geometry itself must be considered as a direct factor in determining the success or failure of a material combination.



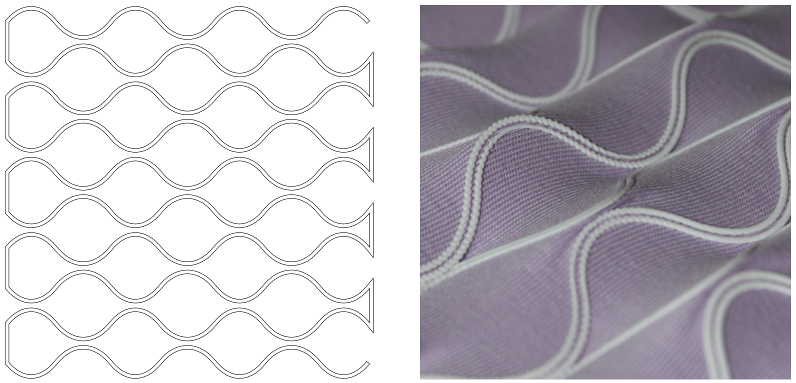


Fig. 7.7.1 PLA/Cotton single line geometry
Material Behavior: Puckering + Arching

Fig. 7.7.2 PLA/Cotton double line geometry
Material Behavior: Folding + Arching

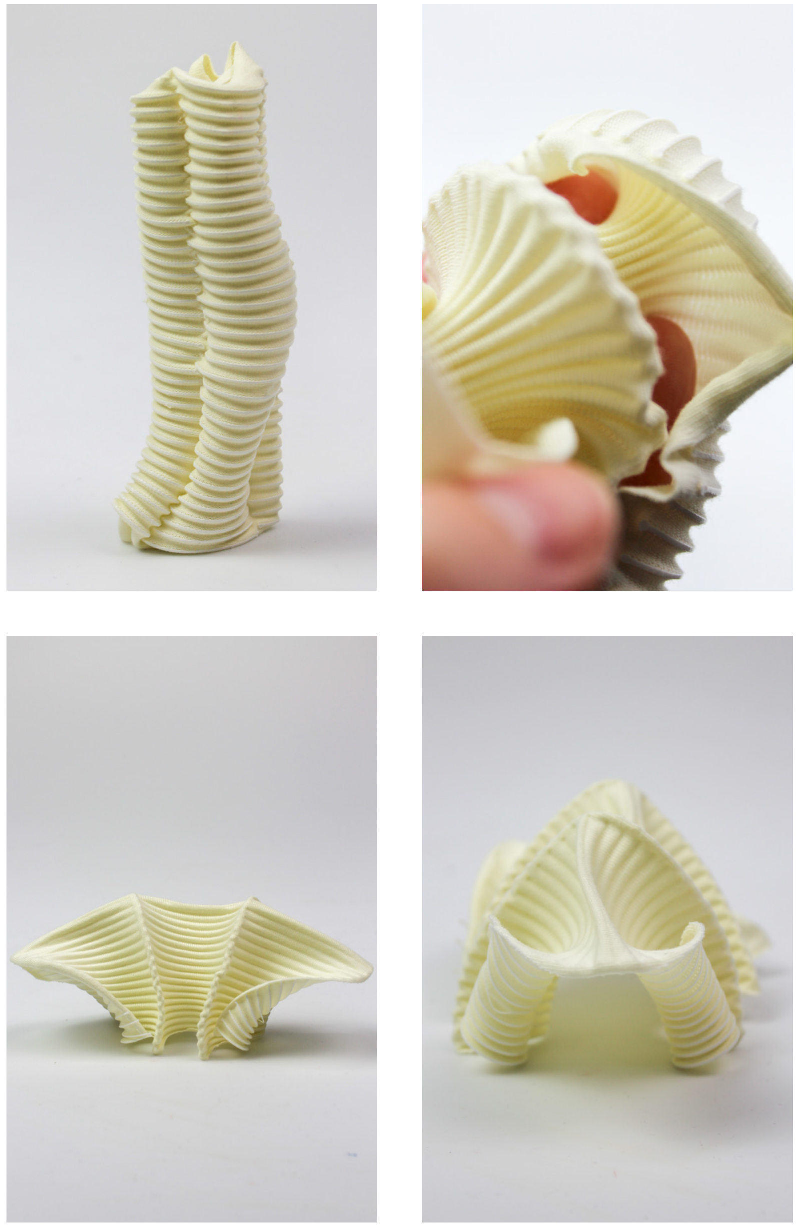


Fig. 7.7.3 Various configurations of an early iteration of the Dynamic Structure prototype

Fig. 7.7.4 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

Fig. 7.7.5 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

Fig. 7.7.6 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

Fig. 7.7.7 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

Fig. 7.7.8 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

Fig. 7.7.9 Early iterations of the tower prototypes, in neutral and compressed states, showcasing the geometry's effect on structural integrity

7.8 The Frame

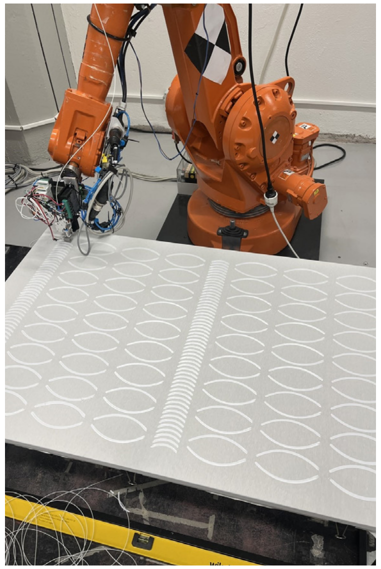
The frame is arguably the most difficult technical question to solve, as it affects multiple other factors in the printing process. The IRB 2400 has a build volume of approximately 1.5m³, and this project had a planar printing bed of around .8m², which is significantly larger than the .0625m² bed of the desktop printer, but does not fully equate to a human or architectural scale. Thus the question of achieving a larger scale without switching to a larger robot was to be solved with a smarter frame.

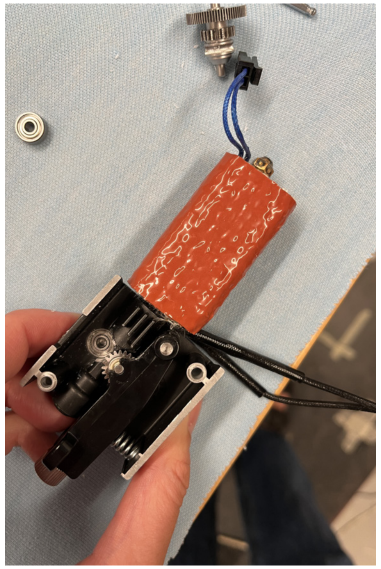
The Equal Stretch Problem

As with 3D printing, 4D printing on textiles does come with challenges, as it leaves a vast amount of room for human error. Because there are so many variables that can affect the plastic and the fabric, let alone their adhesion, it can be difficult to achieve identical warping on duplicate prints. The tension of the textile is one of the greatest areas of difficulty in terms of consistency, as the warping behavior is created by the ratio of the tension of the fabric to the rigidity of the plastic. If the fabric is universally stretched and the tension is equal, the potential energy (retraction force) stored in the fabric will interact with the resistance of the plastic equally across the entire fabric. However, if the fabric is pulled tighter in one direction and the tension is not equal, the tighter direction will retract with greater force, resulting in irregular warping (Figure 7.8.5).

The Frame Problem

The simplest solution would be to create a massive frame and rotate it to print in quadrants, however the robot is housed inside of a glass cage, which also limits the size that the frame can actually be. Another option would be to stretch sections of fabric onto the print bed one at a time, but this will result in uneven stretching, which will create uneven warping. Equal stretching is crucial to a successful print, as the warping behavior will not be distributed equally if the retraction force is not also distributed equally. This





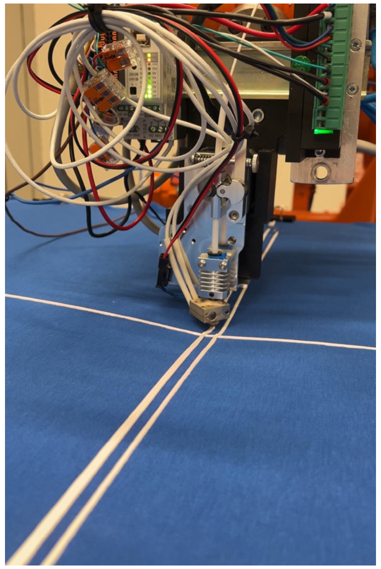


Fig. 7.8.1 Printing on a frame with tabletop attached

Fig. 7.8.2 Early frame prototype proposal

Fig. 7.8.3 Clog in the extruder gears due to heat leak and nozzle height from the bed

Fig. 7.8.4 First test with suspended fabric frame will significantly affect the panels' alignment and behavior, creating uneven prints that lack structural integrity.

A Nozzle Height Solution

Another technical problem to be considered in the construction of the frame is the issue of the nozzle height. As the filament needs to be pressed into the textile to achieve a good adhesion between textile and plastic, there was often an issue of the nozzle skidding on the bed if the bed was not completely planar. This was solved by removing the print bed from the frame, and instead stretching the fabric across the frame, suspending it taut in the air. This allowed for the nozzle to press down into and stretch the fabric while printing, creating good adhesion while also accommodating variations in both fabric resistance and the frame itself. This resulted in an improvement of overall print quality and time required to make a single print, reducing from an average duration of eight hours per print down to one.

The Cube Frame

Towards the end of the project, it was tested to wrap and stretch the textile around the cube of the frame, and print on it in sections. This allowed for the print area to significantly increase from 1.1 x .75 m to 1.1. x 2.5 m, but did create a significant gap due to the inability to print on the fabric that was wrapping around the metal pipes of the frame. Further research is required to understand the viability of this method.

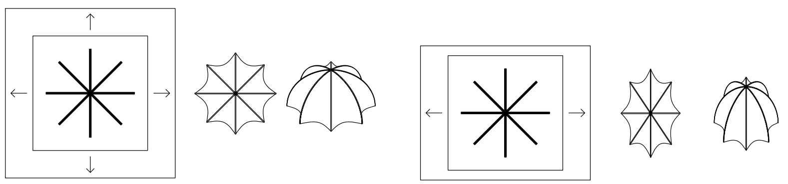
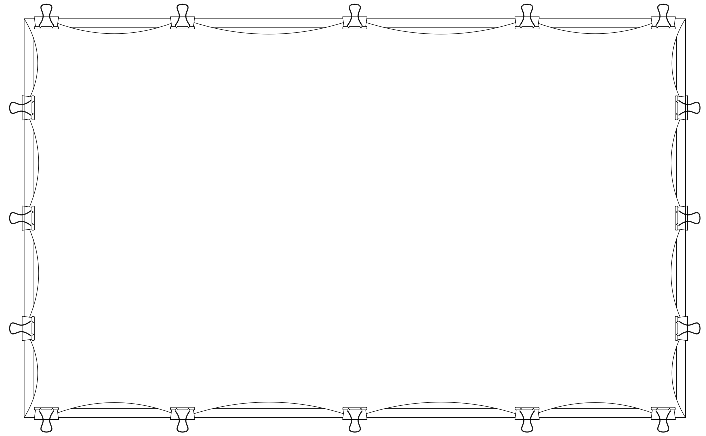
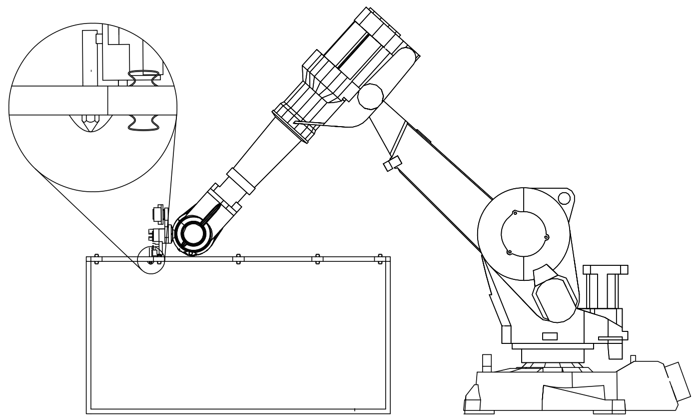


Fig. 7.8.5 Unequal stretch resulting in uneven composite warping





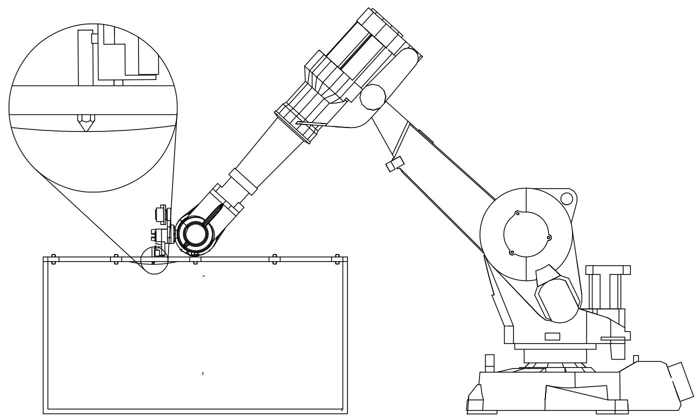
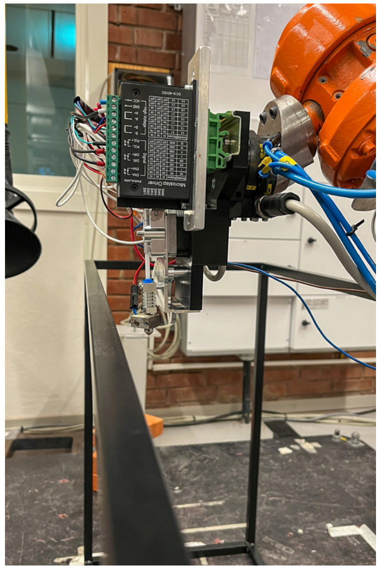
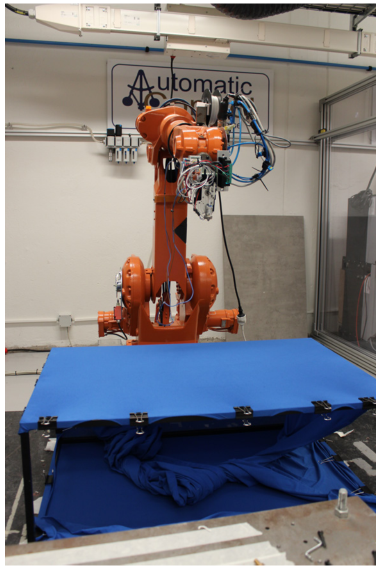


Fig. 7.8.6 Diagram of fabric fastened to frame at points, resulting in different levels of tautness depending on proximity to attachment point

Fig. 7.8.7 Printing close to an attachment point, where the nozzle has more resistance and results in a better adhesion

Fig. 7.8.8 Printing farther from an attachment point, where the nozzle has less resistance and results in a worse adhesion





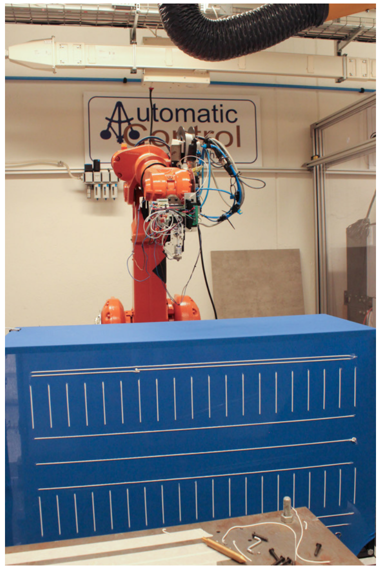


Fig. 7.8.9 The "cube frame", where fabric is wrapped around multiple faces of the frame

Fig. 7.8.10 A dry run to test the -20mm nozzle height and print path

Fig. 7.8.11 Printing the first plane / face of the cube frame

Fig. 7.8.12 Printing the second plane / face of the cube frame

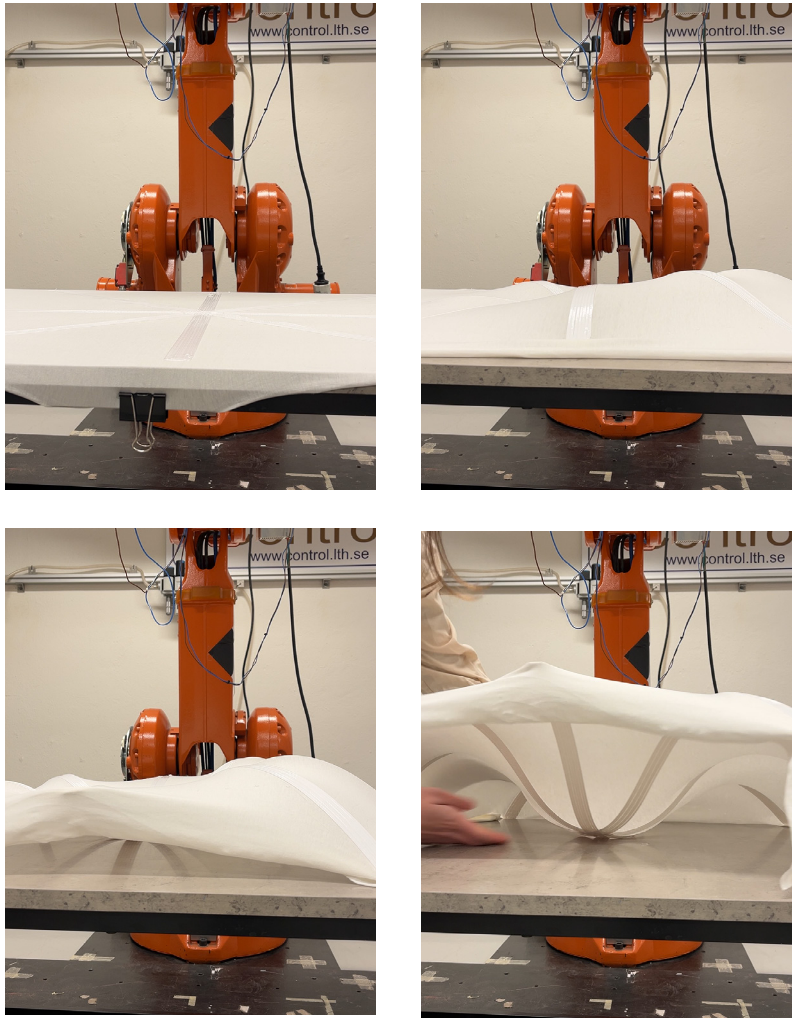


Fig. 7.8.13 Time-lapse images of releasing a dome print from the bed

Fig. 7.8.14 Time-lapse images of releasing print from the bed / frame

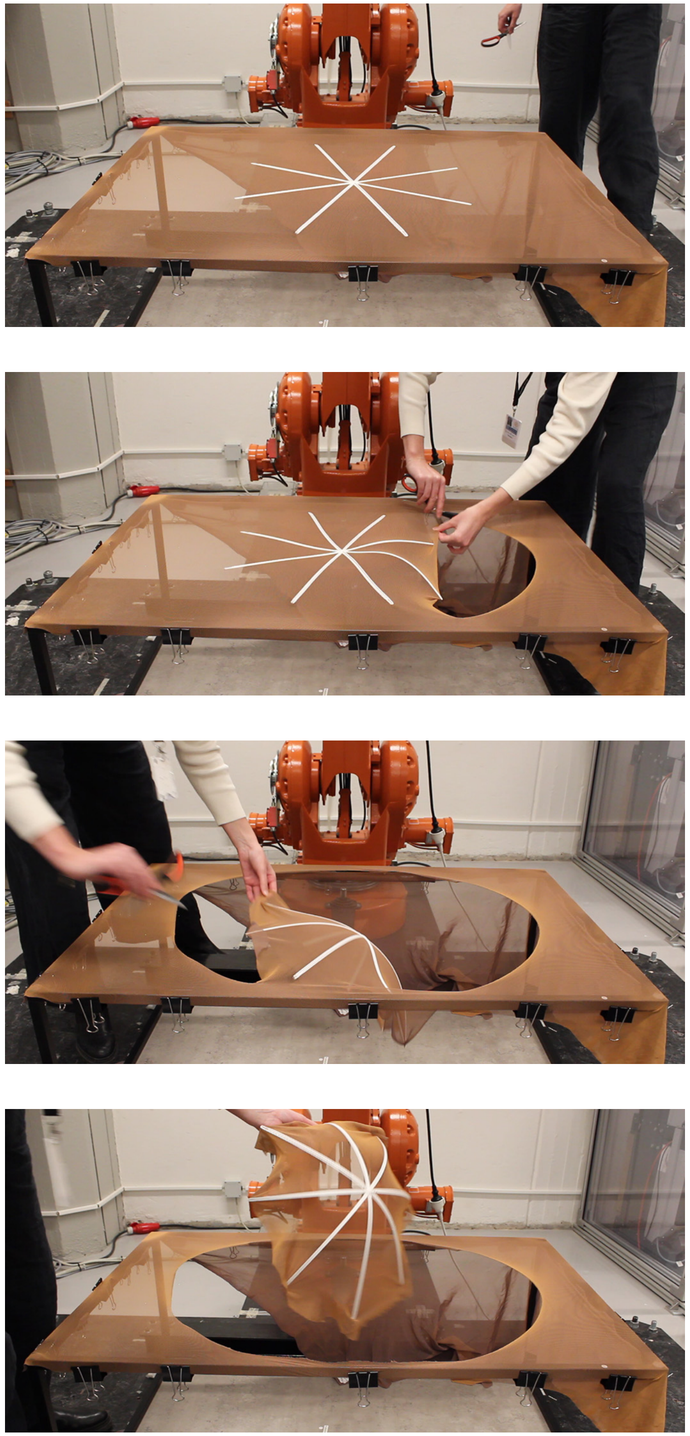


Fig. 7.8.15 Time-lapse images of releasing print from the bed / frame

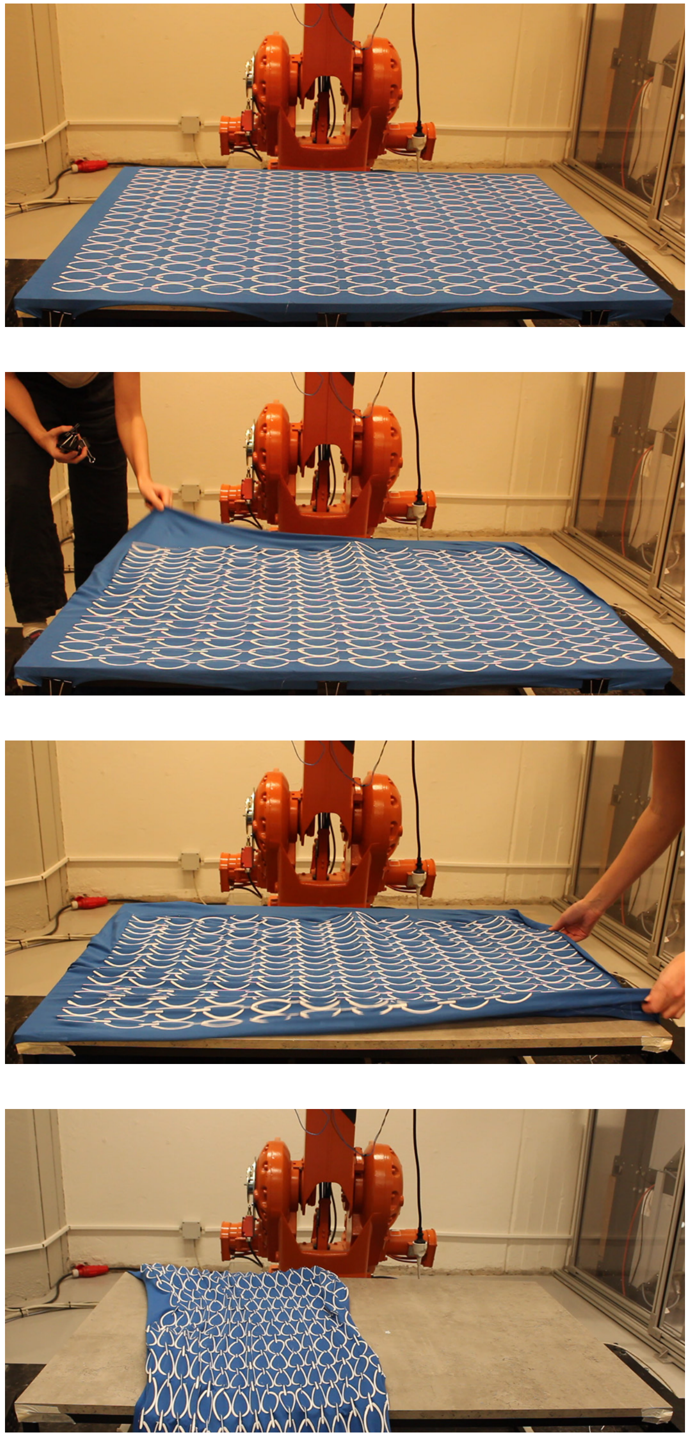


Fig. 7.8.16 Time-lapse images of releasing print from the bed / frame

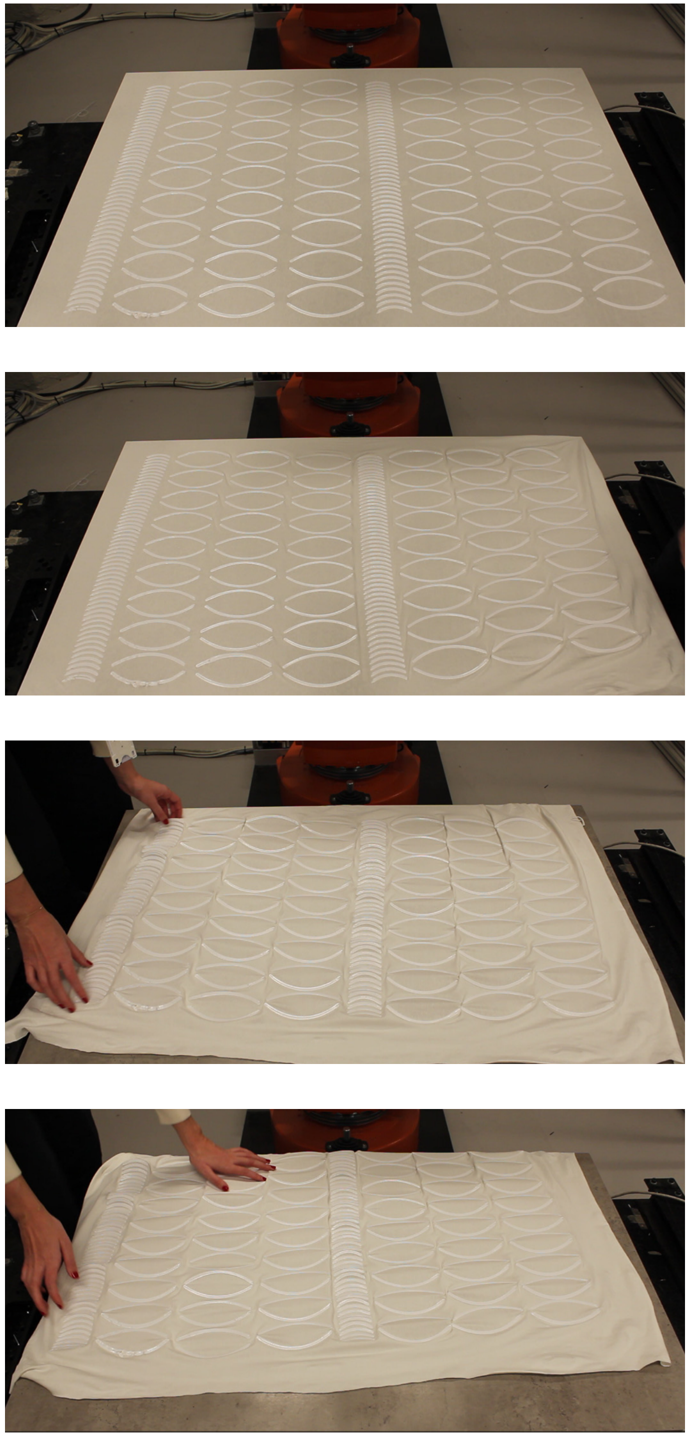


Fig. 7.8.17 Time-lapse images of releasing print from the bed / frame

7.9 Connections

A significant part of the research focused on answering the design question of how the forms will connect and close, and how these connections can allow a single textile composite to have multiple design forms. Regardless of the warping behavior, the textile will always have a seam. For this to be considered a viable structure, it was important to find an elegant way to allow the user to interact with the structure to create varying degrees of privacy by being able to open and close the seam.

Sewing

The first method explored was sewing the seam shut by hand or with a sewing machine, but this was quickly rejected in search of a more dynamic solution- as once the seams were sewn shut, they could not be simply re-opened, limiting both the use of the final object and the possibility of multiple configurations and functions out of one textile composite.

Snaps

The next method explored was the creation of a snapping mechanism that could be printed directly onto the fabric in tandem with the warping pattern. This method was beneficial in that it allowed for a much simpler fabrication process, and required no further handling and fabrication after it was released from the print bed. It also allowed for increased precision, as any irregularities in the stretching of the textile would be reflected in both the warping and the connection points. However the integrity of the closure was quite vulnerable, depending on the adhesion of the connector to the textile, as well as the durability and tolerances of the actual connecting pieces themselves.

Fig. 7.9.1 No seam connection

Fig. 7.9.2 Sewn seam

Fig. 7.9.3 Direct-to-textile 3D printed snaps

Fig. 7.9.4 Printed assembly instructions: taut printed circles with fabric cut out and a piece of plastic slid through them

Mixed Material Snaps

As the plastic can always be removed from the textile if enough force is applied, it was a fine balance between finding a connection that snapped together and held fast, that did not also rip one of the connectors off of the textile when separating them to open the seam. To combat this, TPU as the connection filament was explored. The rubber-like texture of TPU allows for more tolerance and friction in the connections, as well as a bit of bend in the connector itself, allowing for the removal force to be transmitted into the other connector rather than the adhesion point between plastic and fabric. However with TPU, the surface adhesion is not as strong as with PLA, particularly when printing solid 3D objects onto a textile that will significantly warp and move. The ideal connection was found using a mix of PLA and TPU, with a TPU cylindrical ring that stretches around a solid PLA cylinder. This allowed for a sufficient textile adhesion on the PLA connector (the solid objects are first to separate from the textile, the rings of TPU allow the pliant filament to bend and warp along with the textile). This connection functions, however it is also not ideal as it requires a filament change, still presents a risk of separating, and would require a different printing method on the larger scale due to the robot tolerance and frame setup. It is also worth noting that although these connectors are also printed and made of the same material, they do not act as coherent parts of the textile composite. From a design standpoint, they are separated from the rest of the textile composite, and lack any inherent intelligence or benefits of the complex fabrication method of 4D printing.

Snap Tape

Even though they are printed alongside the warping geometry, the connectors feel and behave as foreign objects that were attached afterwards, and if post-print attached connections are the goal, there are far better connectors to be used. In this line of thinking, “snap tape” used in clothing manufacturing was explored as a connection method. This requires the sewing of a small line of fabric with snaps attached along the seams after removal of the

Fig. 7.9.5 Sewn snap tape

Fig. 7.9.6 Collection of various connector prototypes textile composite from the print bed. This solved the issue of the permanence of the sewing as well as the adhesion of the printed connectors, but was still not contributing to off-the-bed deployability, one of the more interesting material benefits of the textile composite.

Printed Assembly Instructions

The next development looked further into the previous observation that creating closed curve shapes resulted in an area of the textile that remained taut after release from the print bed. The taut fabric can then be cut out, resulting in reinforced holes that can be attached through multiple methods, whether a pole is stuck through them, they are used for sewing, or they are snapped together with external hardware. Regardless of the actual assembly tool, this connection method allows for the programming of assembly instructions into the actual manufacturing process of the material. These connection holes are printed using the same method as the rest of the printed geometry, allowing both the designed geometry and the connection geometry to be printed at the same time. These inherent, built-in assembly instructions grant the end user a balance of control and customization over the textile composite, while also appearing native to it. The end user can decide the appropriate connection mechanism based on their unique environment and requirements, as well as the specific function.

Printed Assembly Instructions + Magnets

The final connection iteration consisted of attaching magnets via superglue onto the printed assembly points. This allowed ease of access by the user, as well as informing assembly instructions through fabrication.

Reusability

Another benefit of this fabrication method is the ability to disassemble and reuse all of the material found in the structures. Depending on the level of adhesion, the textile and plastic can be separated from each other by applying a stretching force that is greater than the print stretching. The plastic can be melted back into filament and the fabric can be reused and printed on again. This allows for multiple different objects and structures to be created from the same material over time, allowing the user to adapt the composite's form and function as their needs and environment changes, another aspect ultimately contributing to the overall functional adaptability of these artifacts as architectural pieces.

7.10 Malmö in the Making Workshop

During the time period of the thesis, a workshop was held teaching the 4D printing textiles workflow developed through this research. This workshop took place in September 2023 as part of Malmö in the Making, an architectural festival hosted by Malmö City. The workshop consisted of a presentation of 3D printing in an architectural context and the current state of the art of 4D printing on textiles, as well as an overview of all the research and knowledge resulting from the experiments documented here. The participants were shown physical examples of the textile experiments to better understand how the fabric, filament, and design geometry interact to create different structures and textures. The participants were instructed how to draw their own designs in Rhino 3D, with the goal of creating textural pieces with TPU. Each participant was able to print at least one design. This workshop contributed to the thesis research through the exploration of more textural patterns, as well as the testing of the workflow in different contexts.

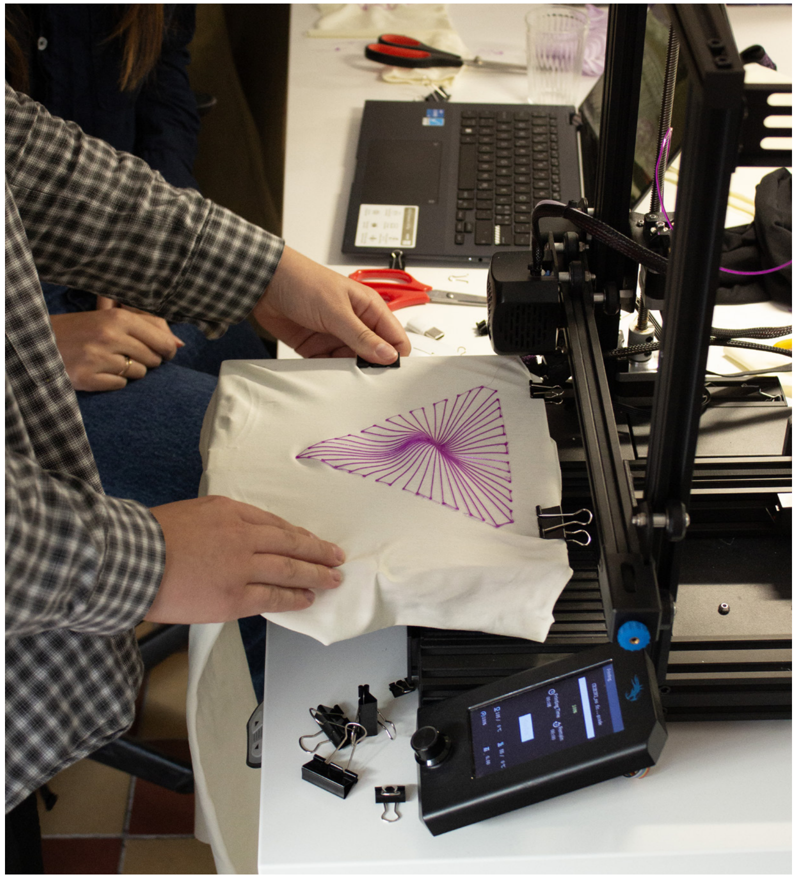


Fig. 7.10.1 Demoing releasing and cutting a complete print

Fig. 7.10.2 Participant releasing print from bed

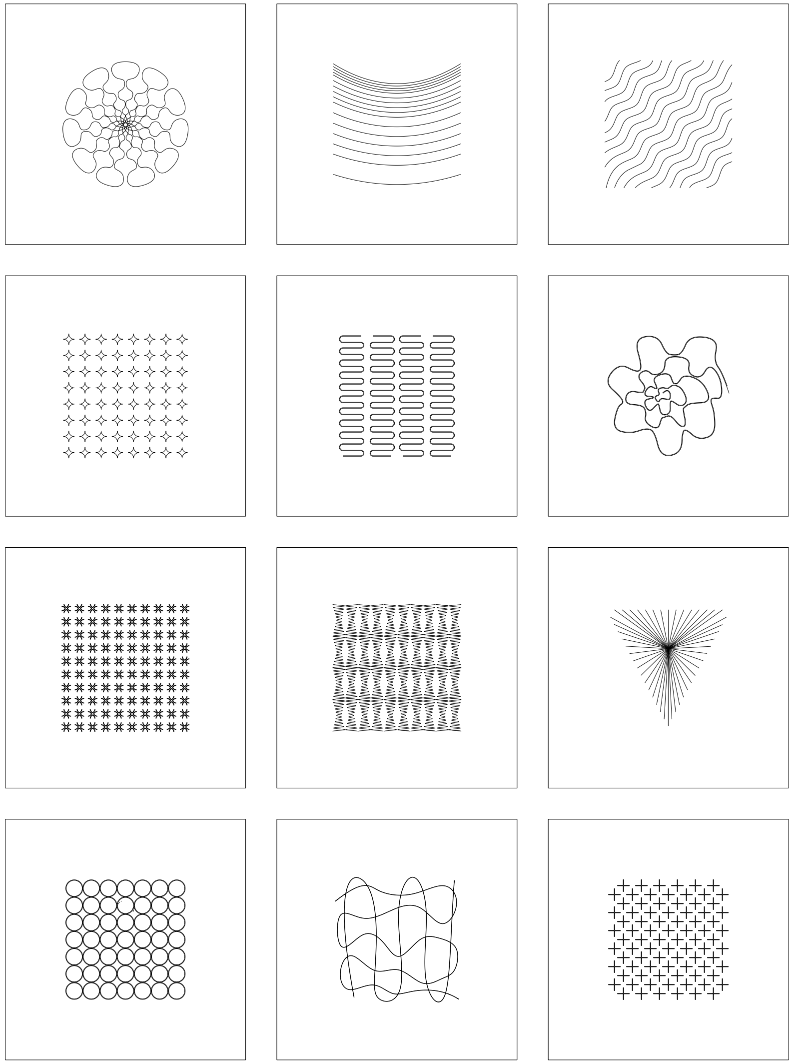


Fig. 7.10.3 Participant 2D geometries

Fig. 7.10.4 Sample of participants' prints

8. Results

Final Prototypes

The results of this research conclude in the form of a set of 4D-printed programmable textile structure prototypes. Each prototype is the result of designs tested iteratively on multiple scales. The prototype collection serves as affirmative evidence for the hypothesis that it is possible to make self-supporting 4D-printed textile structures across multiple scales.

8.1 The Dome

The Dome is a classic building block of architectural typology, and it made sense to test this shape early on. This is a material behavior that can be reproduced at multiple scales by simply increasing the line width and count. The most interesting behavior observed in the dome is the presence of multiple stable states, meaning that the dome can transition between convex and concave states through the application of light force to the center.

Fig. 8.1.1 Dome prototype

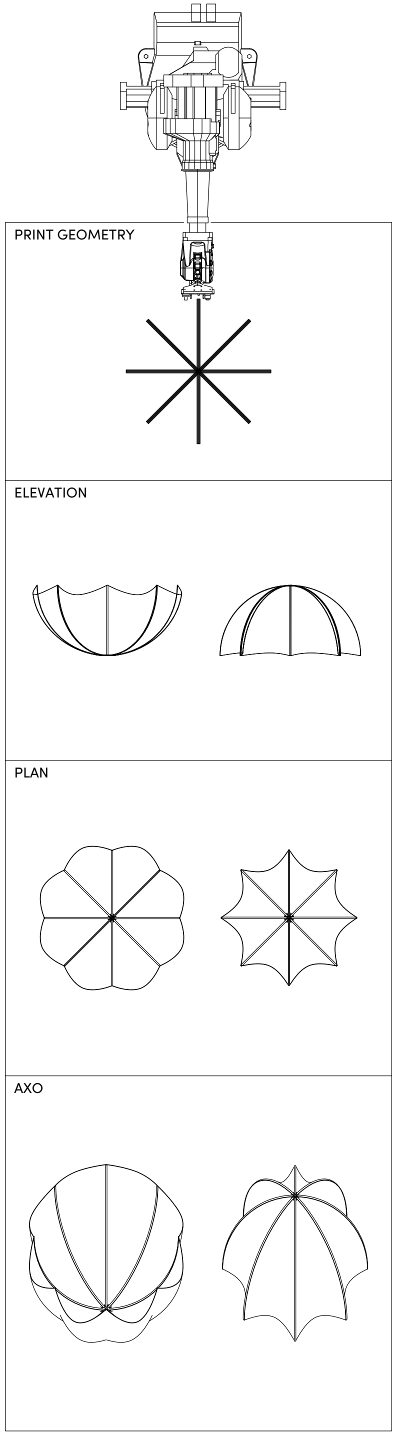


Fig. 8.1.2 Dome 2D geometry and 3D drawings

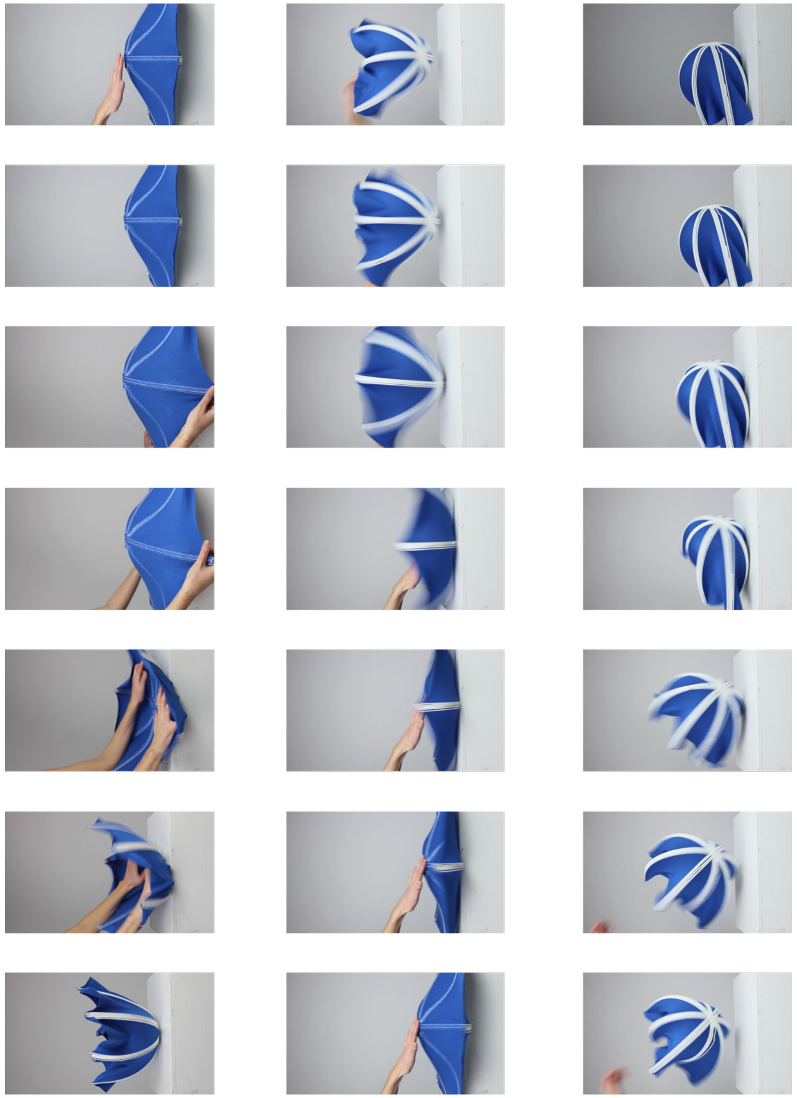


Fig. 8.1.3 Time-lapse of dome flipping between stable states of concavity

Fig. 8.1.4 Domes in various stable states of concavity

Fig. 8.1.5 Dome in convex stable state

8.2 The Tower

The first tower prototype resulted from a highly iterative design process, initially inspired by the concept of a rib cage. The fabric weave direction is crucial in this design, as the long curved lines must run parallel to the weave in order to achieve the desired bending material behavior. This prototype rests in a compressed state, and can be stretched and elongated by the user as needed. The Tower is the strongest prototype to confirm the theory of self supporting structures, as it can withstand a significant application of force and interaction before it tips over. If the tower is dropped from a shoulder-height to the floor, it lands standing upright.

Fig. 8.2.1 Large scale iteration next to final small scale iteration

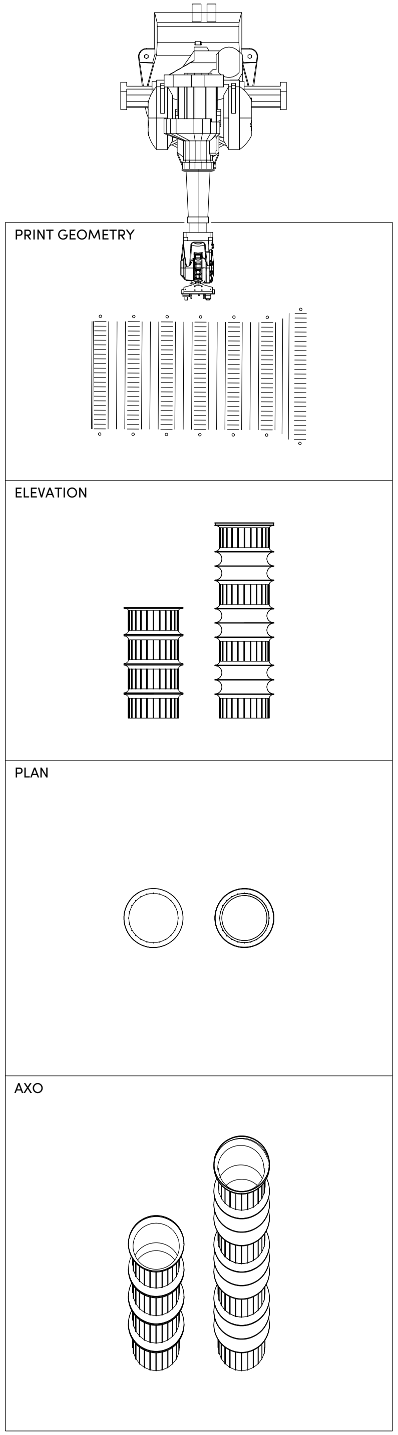


Fig. 8.2.2 Tower 2D geometry and 3D drawings

Fig. 8.2.3 Tower surface details

Fig. 8.2.4 Base of tower folded over for stability

Fig. 8.2.5-6 Surface details of the white tower, in states of resting and compressed

Fig. 8.2.7–8 Tower prototype in rest (compressed) vs expanded

Fig. 8.2.9–10 Tower prototype in rest (compressed) vs expanded

Fig. 8.2.11–12 Both tower prototypes in rest (compressed) vs expanded

8.3 The Dynamic Structure

The third prototype took inspiration from the idea of flexible spaces, creating a structure that could be formed and molded into multiple different shapes, depending on how it was assembled and where it was attached. This structure also worked with the idea of being scalable in both floor area as well as height, allowing the user to significantly change the area of the enclosed space by wrapping the structure around itself.

Fig. 8.3.1 Dynamic structure details

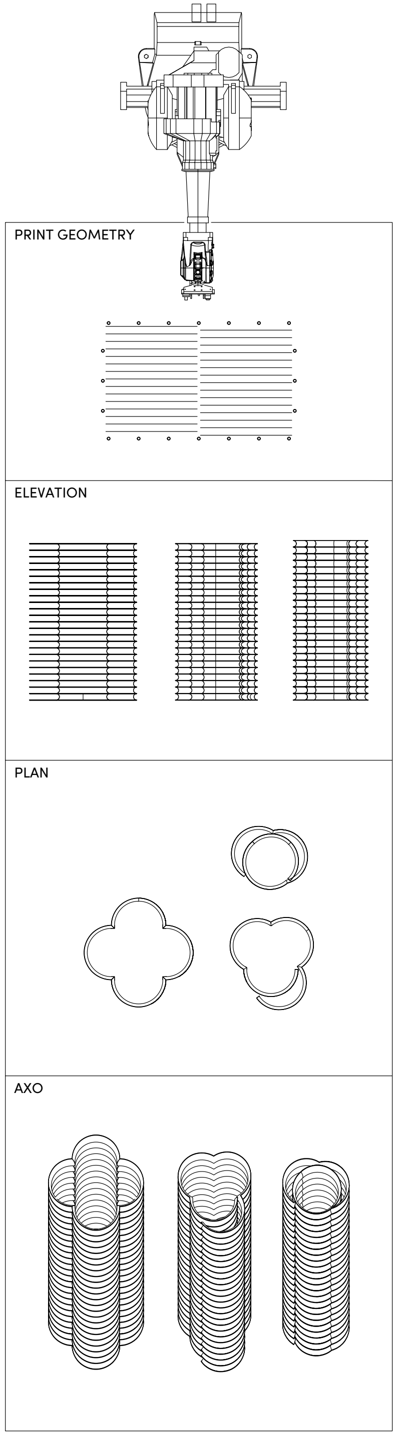


Fig. 8.3.2 Tower 2D geometry and 3D drawings

Fig. 8.3.3-4 Details of dynamic structure

Fig. 8.3.5-6 Dynamic structure in various configurations

Fig. 8.3.7–8 Folded single column configuration of the dynamic structure, compressed and expanded

Fig. 8.3.9–10 Folded double column configuration of the dynamic structure, compressed and expanded

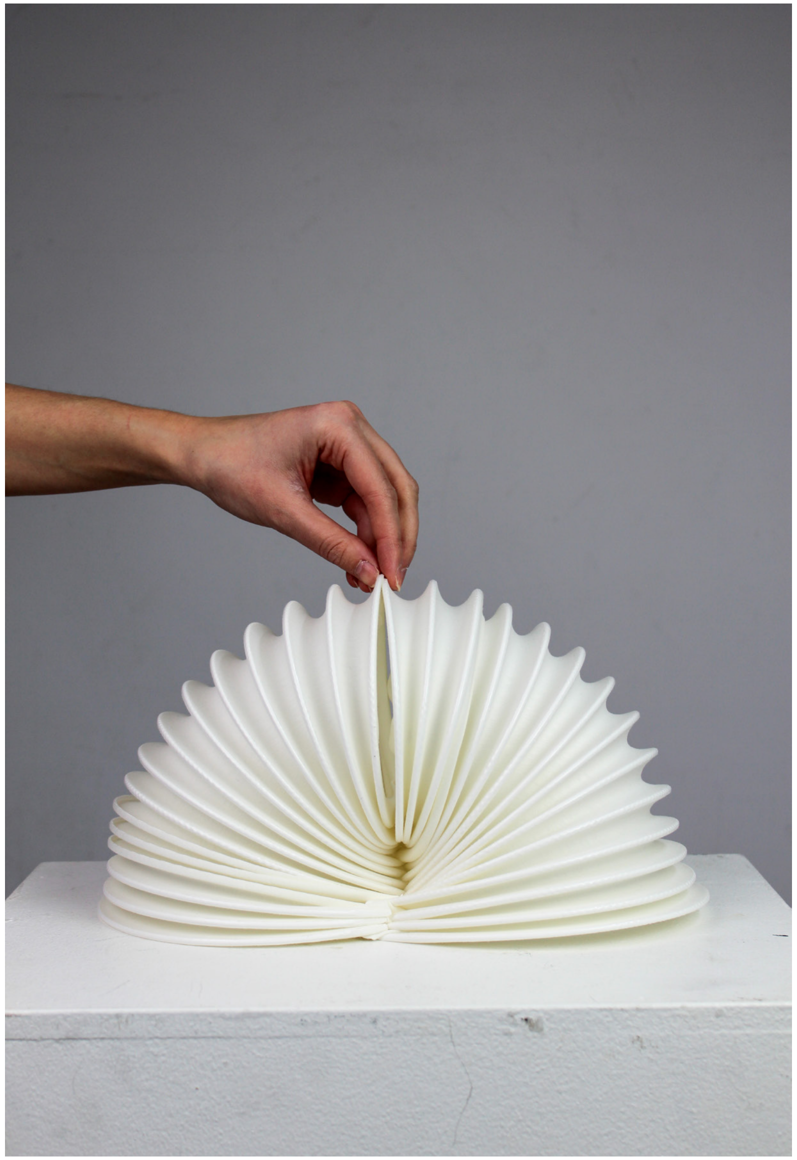


Fig. 8.3.11–12 Dynamic structure in various configurations

8.4 Textural Pieces

Many of the designs did not successfully scale in terms of structure, instead becoming textural pieces. These pieces present an imbalance of the resistance and retraction forces, as the filament resistance is much stronger than the retraction force of the textile, resulting in little to no warping. It is important to note that these textural pieces are reinforced by the filament, meaning that they may have the potential to be turned into structural pieces by bending or folding them and attaching connectors, as seen in Figure 8.4.8.

Fig. 8.4.1 Large-scale textural prototype

Fig. 8.4.2 Detail of large-scale textural prototype

Fig. 8.4.3-4 Large-scale textural prototype

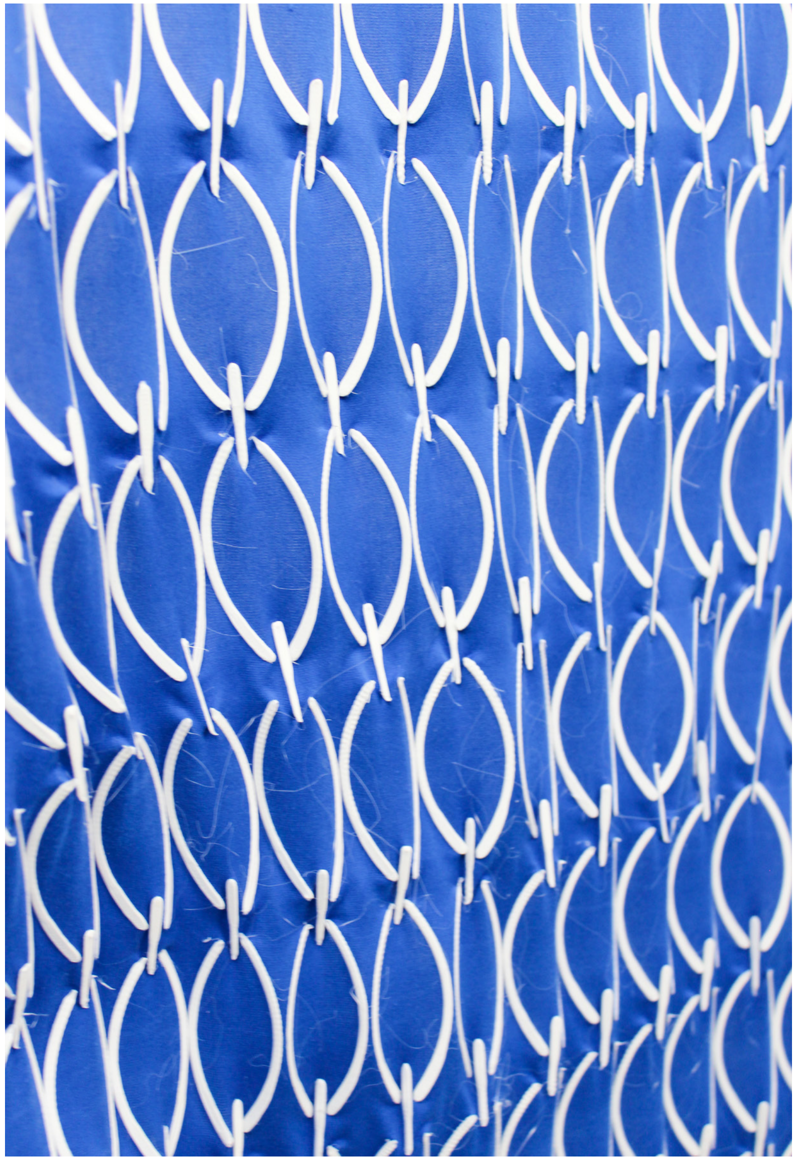


Fig. 8.4.5-6 Large-scale textural prototype

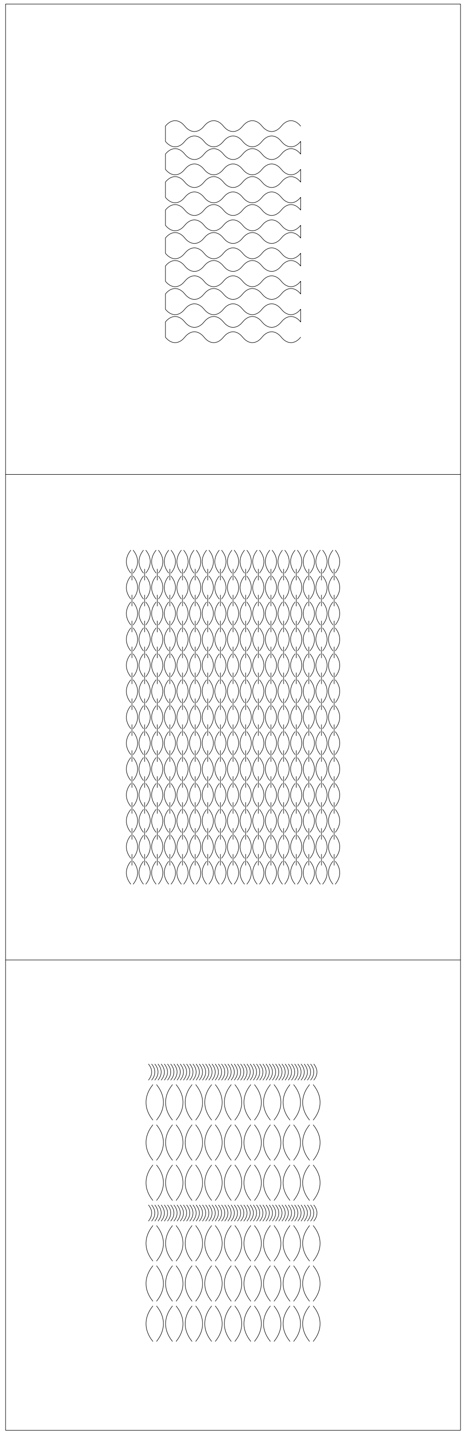


Fig. 8.4.7 Textural pieces 2D geometry

Fig. 8.4.8 Textural piece connected to create a structure

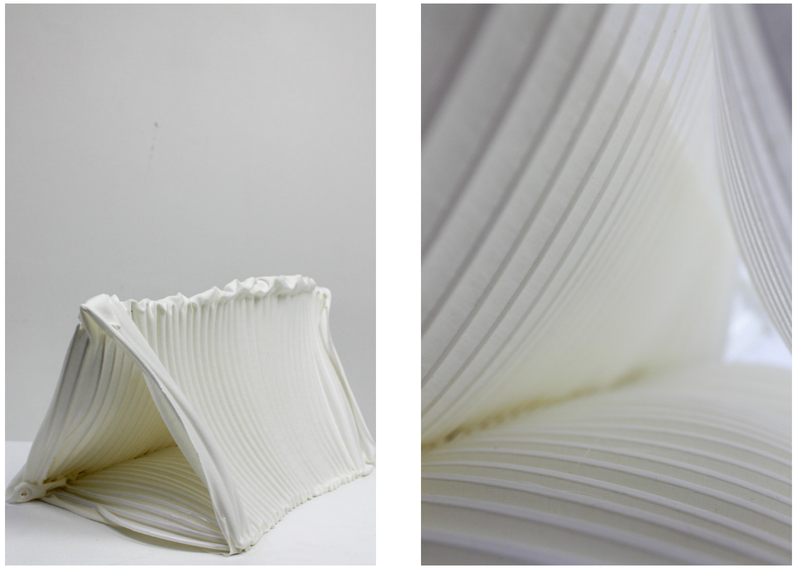


Fig. 8.4.9 Dynamic structure that was printed the wrong weave direction, resulting in no bending. However, by folding it, the structure becomes a triangular tunnel

8.5 Key Parameters: A Stable Workflow

A less tangible result of this research is the creation of a best practice workflow to use when 4D printing architectural structures, as well as the physical fabrication setup. For every design iteration, there were even more fabrication and setup tests, as a significant question of this research was not only to make a structural textile composite through design, but to see if it was possible to make something self-supporting and structural at all. Arguably one of the most significant outputs of this research is a breadth of both failed and successful experimentation, resulting in knowledge to guide future construction of fabrication setups and key parameter solutions for 4D printed textiles.

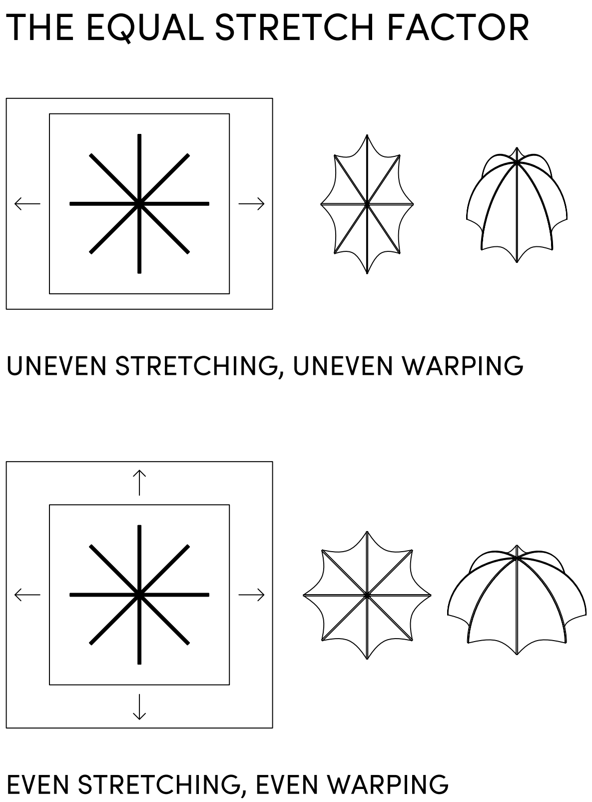


Fig. 8.5.1 Equal stretch factor's affect on print warping

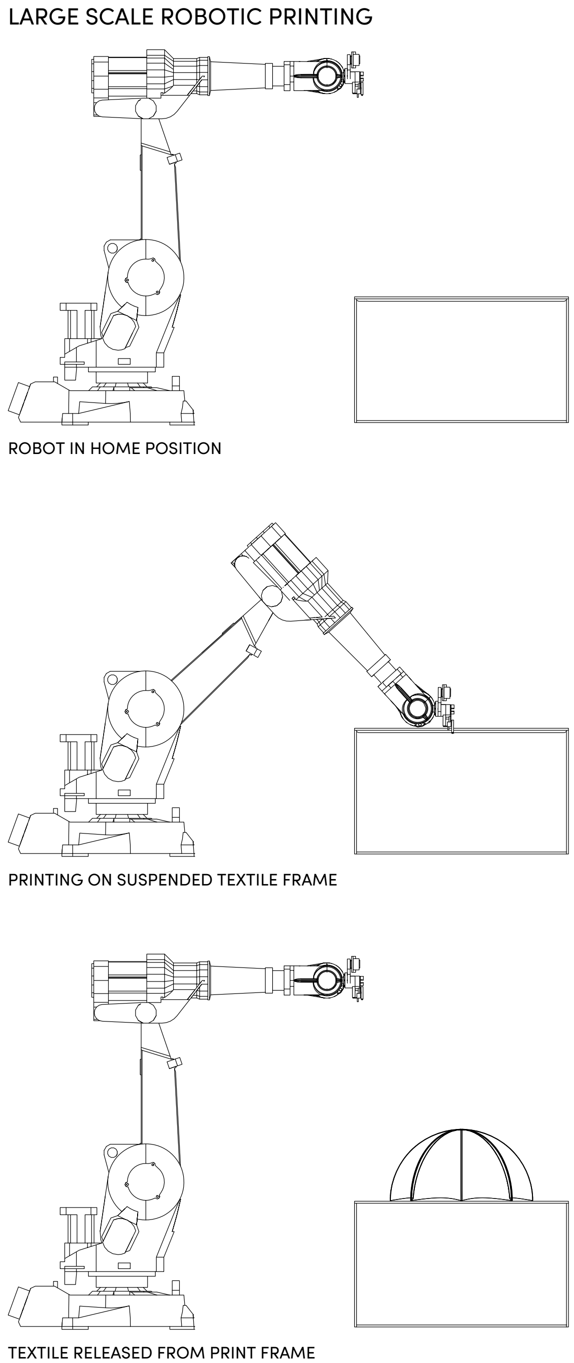


Fig. 8.5.2 4D Printing Textiles process

8.6 The Material Behaviors Design System

Creating a design system

The Design System of Material Behaviors both formed and was informed by the design iteration process. In the early experiments, the design iteration process was extremely broad, in order to get a wide understanding of the potential types of material behavior. As this behavior was observed and documented, it allowed for the design focus to narrow, isolating the iterations to one specific behavior and attempting to "perfect" it. This process resulted in the documentation of geometrical building blocks of material behavior that can be combined to create complex and repeatable structural behaviors across a textile composite.

Implementing the design system

By simplifying the testing geometries, it is possible to map the behavior of each one and subsequently "program" certain behaviors into specific areas of the textile by combining these building blocks. This bottom-up approach allows for a deeper understanding of the behavioral properties of the fabric in an early stage of design, allowing the designer to imagine a complex final structure, break it down into behaviors (rolling, arching, folding) and then select from a library of material behavior building blocks, placing each part in spatial relation to another to create specific and intentional behavioral interactions between shapes. Once the design system has been completed through scaling up, it allows for new forms to be imagined and broken down into their material behaviors for fabrication.

Later stage small-scale: informed by design system

The culmination of the research project focused on creating large-scale self-supporting prototypes, making use of and building upon all of the knowledge gained from the previous testing, both in terms of the fabrication process and the design system. The final prototypes were all first tested and iterated on the small-scale, in order to limit material waste of the large-scale prints. This process resulted in a series of working prototypes on the small-scale, that can be matched to each successful large-scale print. It is important to note that there was not a concrete separation of working in the small-scale versus the large, rather scale was viewed as the final iteration in a design- the geometry must first work beyond doubt on the small-scale before it can be transferred to the larger scale. Of course, with each print tested on the large-scale, more large-scale behavior was observed and documented which created an ongoing feedback loop: the large-scale results informed the next design already in its early small-scale iteration phase.

Fig. 8.6.1 Assorted tests

GEOMETRY DESIGN ITERATIONS

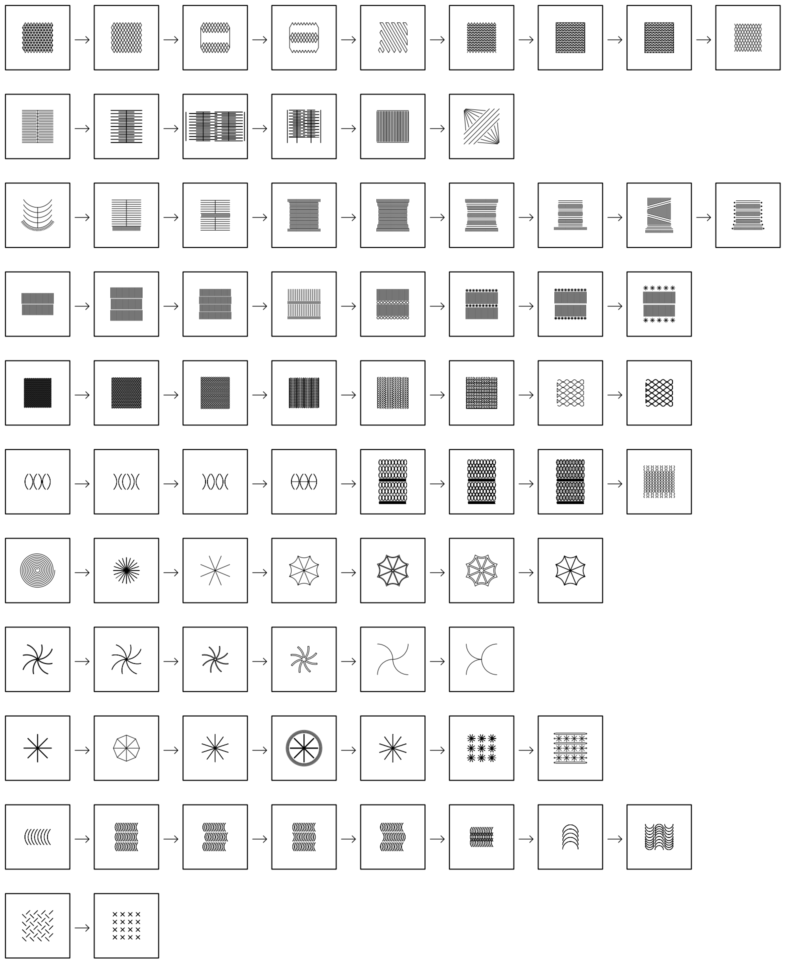


Fig. 8.6.2 Geometry iterations contributing to the overall design system

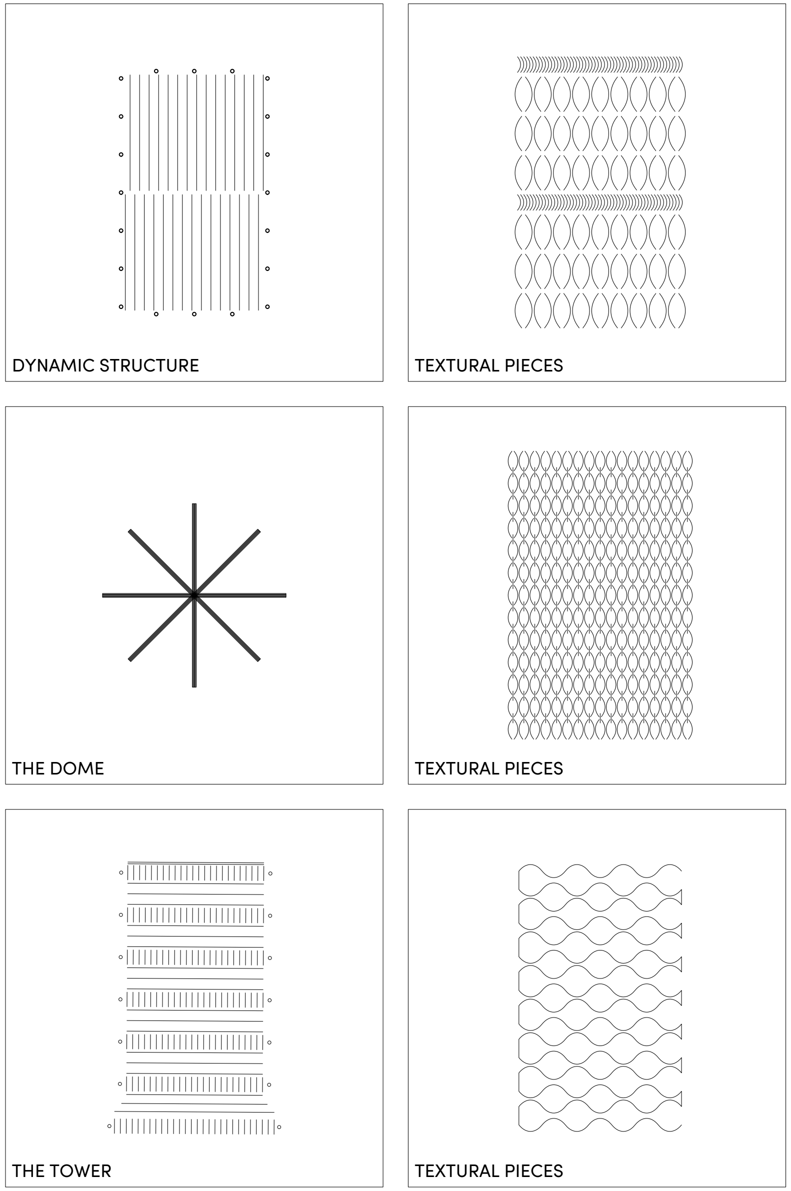
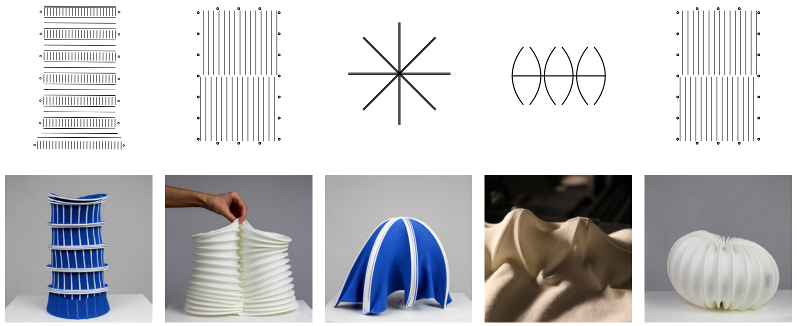


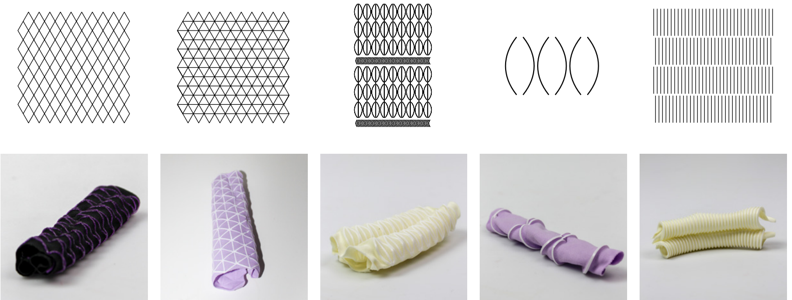
Fig. 8.6.3 Large-scale design iterations

Material Composite Behaviors

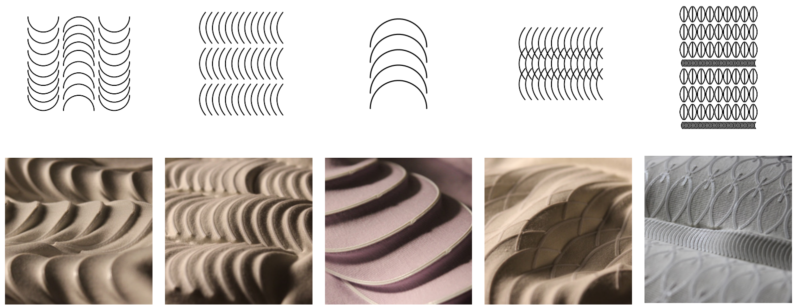
Bending: The composite bends into circular, structural shapes



Rolling: The composite rolls as a uniform shape

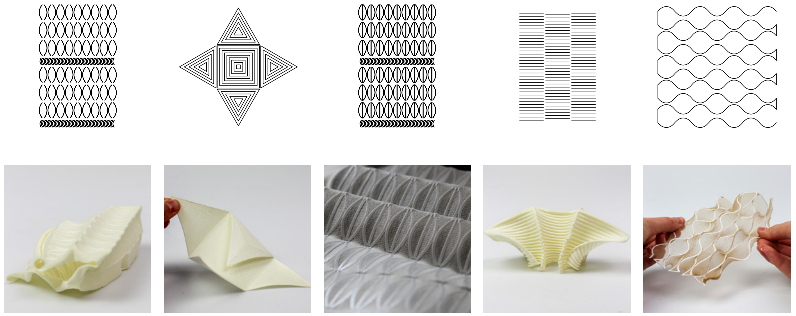


Arching: The composite arches in parts of the textile, but does not bend as a whole

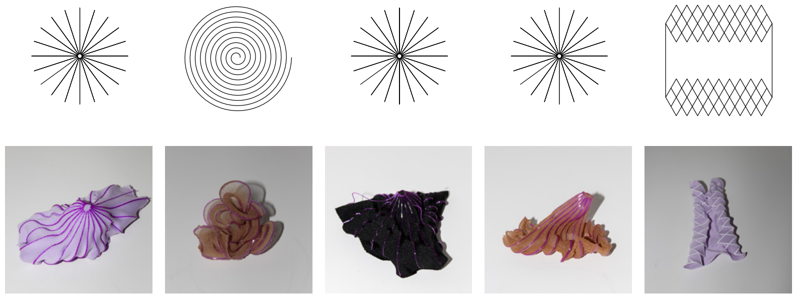


Material Composite Behaviors

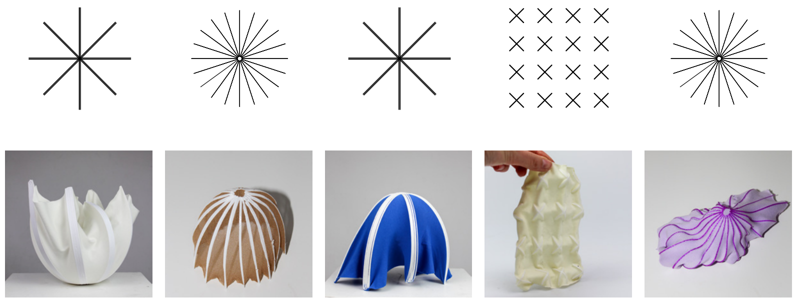
Folding: The composite folds in on itself, doesn't rely solely on bending



Curling: Parts of the composite curl in on itself



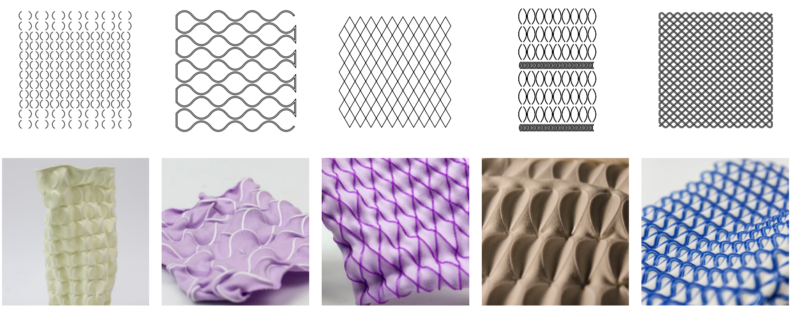
Dome: The composite creates smooth domes, lines bend



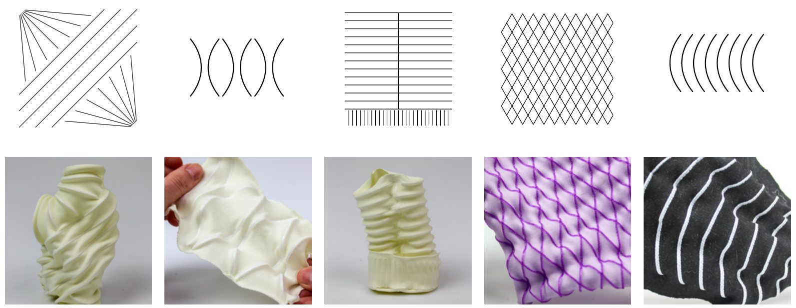
Material Composite Behaviors

Peaking: The composite creates sharp peaks, lines do not bend

Puckering: The composite puckers and scrunches up

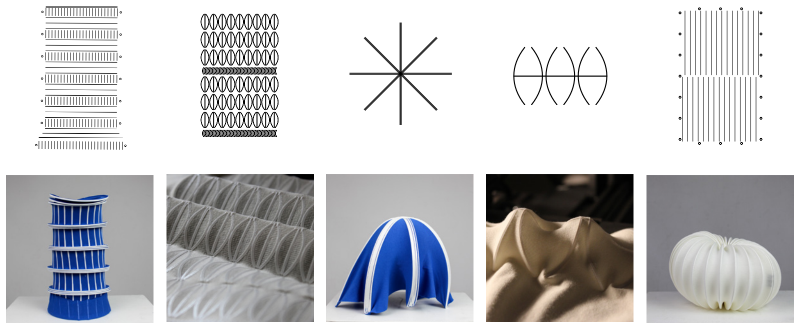


Wrinkling: The print lines are not smooth



Structural Behavior

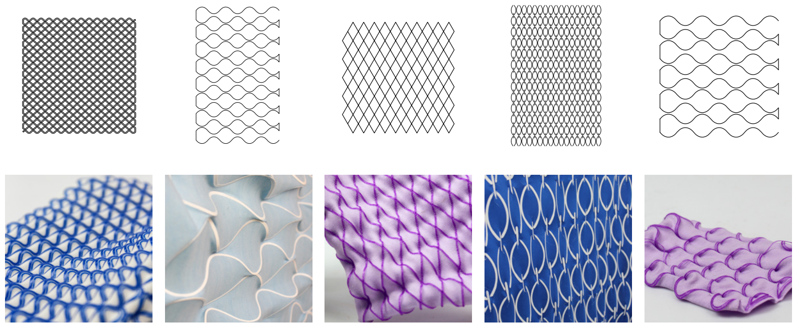
Warping on a structural level, deforms to a point it is a form rather than a textile



	1	2	3	4	5
Curling					
Doming			●		
Rolling	●				
Folding		●			
Arching	●	●	●	●	●
Peaking					
Wrinkling					
Bending	●		●	●	●
Puckering					

Textural Behavior

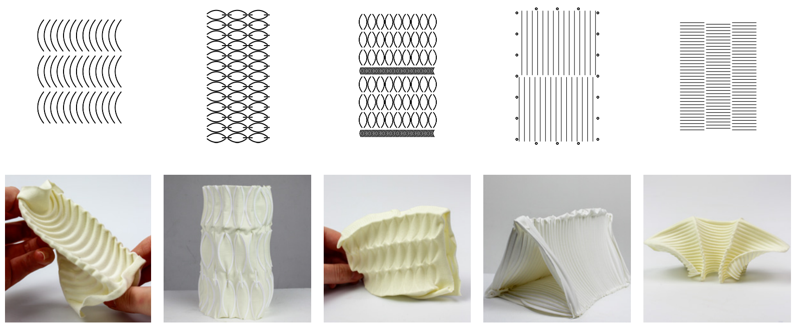
Fabric manipulation, deforms the surface of a textile



	1	2	3	4	5
Curling					●
Doming					
Rolling					●
Folding	●	●			
Arching	●	●		●	
Peaking					
Wrinkling			●		
Bending	●				
Puckering	●		●	●	●

Structural Behavior through Folding

Composites can exhibit structural warping through folding and connections



	1	2	3	4	5
Curling					●
Doming					
Rolling					●
Folding	●		●		●
Arching	●	●	●	●	●
Peaking					
Wrinkling					
Bending					●
Puckering		●	●		

9. Application Proposal

Probes and Prototypes

This research is grounded by the contextual framework put forth in "Narratives of Making", in which the authors postulate that the transition of architectural tools and practice into the digital realm has transformed the process of making into one led by material research. As with the introduction of digital fabrication, methods such as 3D printing combined with parametric interfaces allow that the "drawing, or the 3D model, becomes the direct handling of the tool, the pressing of the drill or the pointing of the saw" (Ramsgaard Thomsen, M., & Tamke, M. 2009). This new way of understanding architectural fabrication is the basis for a framework of modes of material evidence, presented as the probe, the prototype, and the demonstrator. They are defined as follows:

- "The design probe: a design-led investigation allowing speculative inquiry, theorisation and the setting out of design criteria
- The material prototype: a materially-led investigation allowing exploratory testing of craft and material behavior. The prototype answers and develops the design criteria of the design probe
- The demonstrator: an application-led investigation allowing interfacing with real world problems and constraints" (Ramsgaard Thomsen, M., & Tamke, M. 2009)

Within the context of this framework, the textile composites can be categorized into different modes of material evidence, where the early small-scale investigations are classified as probes, helping to build the design system upon which the later prototypes (at both the large and small-scales) were developed. A demonstrator was not developed as part of this research, but would look something like scaling up the fabrication process further to work with the architectural scale.

Smart materials and extreme environments

Architectural digital fabrication methods come with trade-offs, allowing architects to produce forms and structures that would otherwise be impossible, but also resulting in research and cost-heavy processes. In the context of this research, the result of the highly specific fabrication process is a series of highly specific material behaviors and characteristics that can be programmed to align with the niche material requirements of extreme architectural environments, where it becomes necessary to use smart materials that can adapt in response to ever changing environmental conditions. The proposed architectural application of this research finds a common ground between the requirements of extreme environments and the unique combination of material behaviors of the textile composites.

Architecture for space

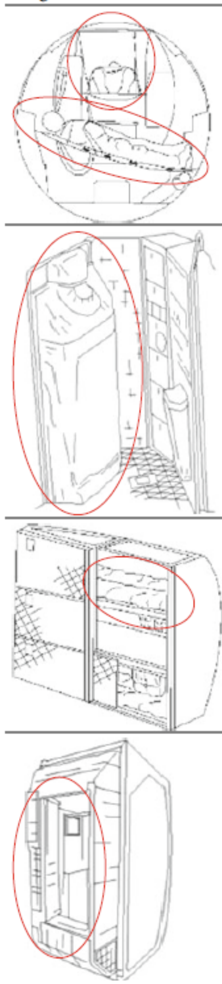
Architecture for space habitation requires extensive material research and development. Not only is the material subject to an extreme environment where its performance will be stress-tested, but it is also extremely expensive in regards to transporting cost. Everything that is transported outside of the atmosphere must be as lightweight and take up as little space as possible, but also be durable, dynamic, and pass a series of material standards.

Proposal: Dynamic Crew Quarters

This proposal suggests the use of the three prototypes, The Dome, The Tower, and The Dynamic Structure as structures to make up private quarters for the crew of an inflatable lower earth orbit habitat. Inflatable modules are a common typology for Lower Earth Habitat design, where space is extremely limited due to weight restrictions (Häuplik-Meusburger & Bannova, 2018). Because of this requirement, these forms could find a production justification in this environment, where the inherent material behaviors are extremely valuable.

Fig. 9.1 A model of the Bigelow inflatable habitat pod (Chang, 2013)

It is crucial to implement a dynamic solution that allows the users to adapt their physical environment to their needs at a given moment. All three of the prototypes can change shape and orientation, inspiring the application of these prototypes as private quarters for the crew members, that can be expanded in size while occupied and reduced when not in use. In an architectural environment where space is an extremely limited resource, the ability to combine and introduce dynamic architectural programs into a single space is imperative. When combining the function of sleeping with the function of research or work, a dynamic spatial configuration can be created, in which users have increased area to work during the day and sleep in the evening. The current solution for sleeping stations aboard the ISS takes up a significant amount of area yet is not particularly spacious for the occupants. As the quarters are also stationary, they take up the same amount of area regardless of occupation status.



Summary sleep restraints in previous space stations	
Diagrams	Key features
	Early sleep restraint during the Apollo missions Sleeping bags and hammocks were used and proved efficient for short-term missions
	Sleep restraint during the Skylab missions Every crewmember had his own private area. Crew quarters were permanent and included sleeping bags in vertical position, private storage, and communication facilities.
	Sleep restraint for the Space Shuttle Orbiter. On-board the shuttle, different sleeping configurations were used, depending upon the schedule. On selected mission so-called sleeping boxes were used (usually when crews were meant to work shifts)
	Current sleep station onboard the ISS Currently private crew quarters are provided for the crew of 6. They have integrated storage, communication, and also radiation protection

Fig. 9.2 An overview of sleeping pods throughout different space stations (Häuplik-Meusburger & Bannova, 2018)

STRUCTURAL
TEXTILES
STOWED

ADAPTIVE ENVIRONMENTS

The ability to compress the tower structures allows for multiple functions of a space depending on the time of day and needs, crucial for allocating limited area.

MODULAR STRUCTURES

The dynamic structure is printed modularly, creating multiple sections that can be wrapped around each other when not in use.

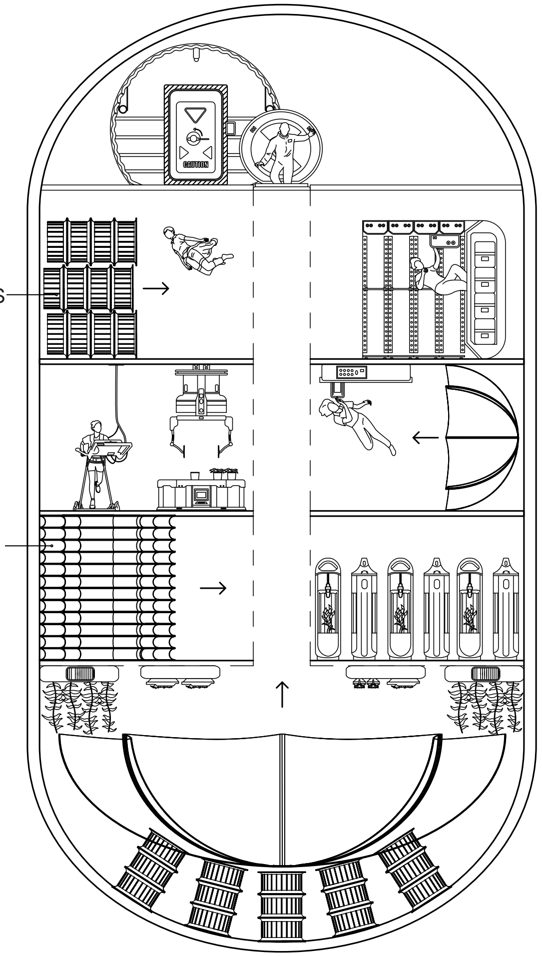
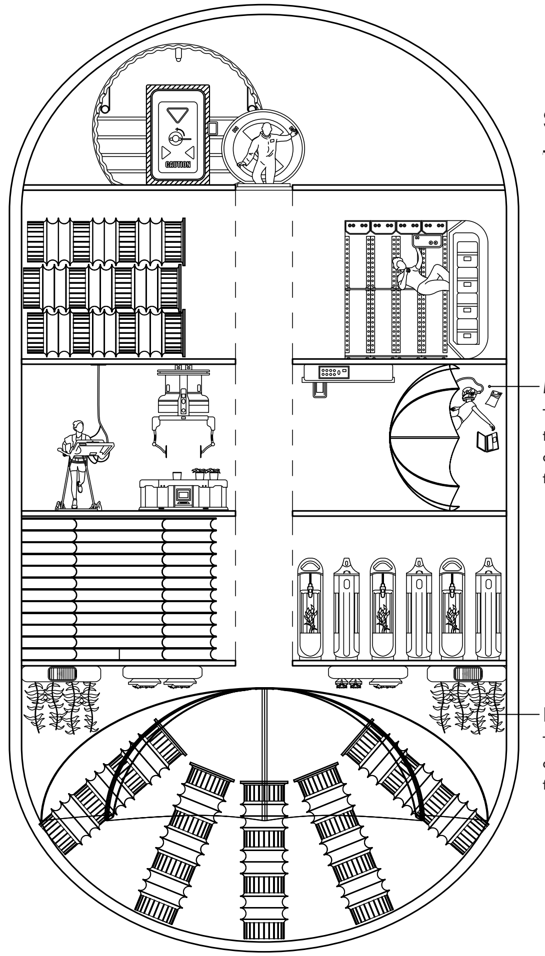


Fig. 9.3 Section views of the application proposal, with the prototypes installed



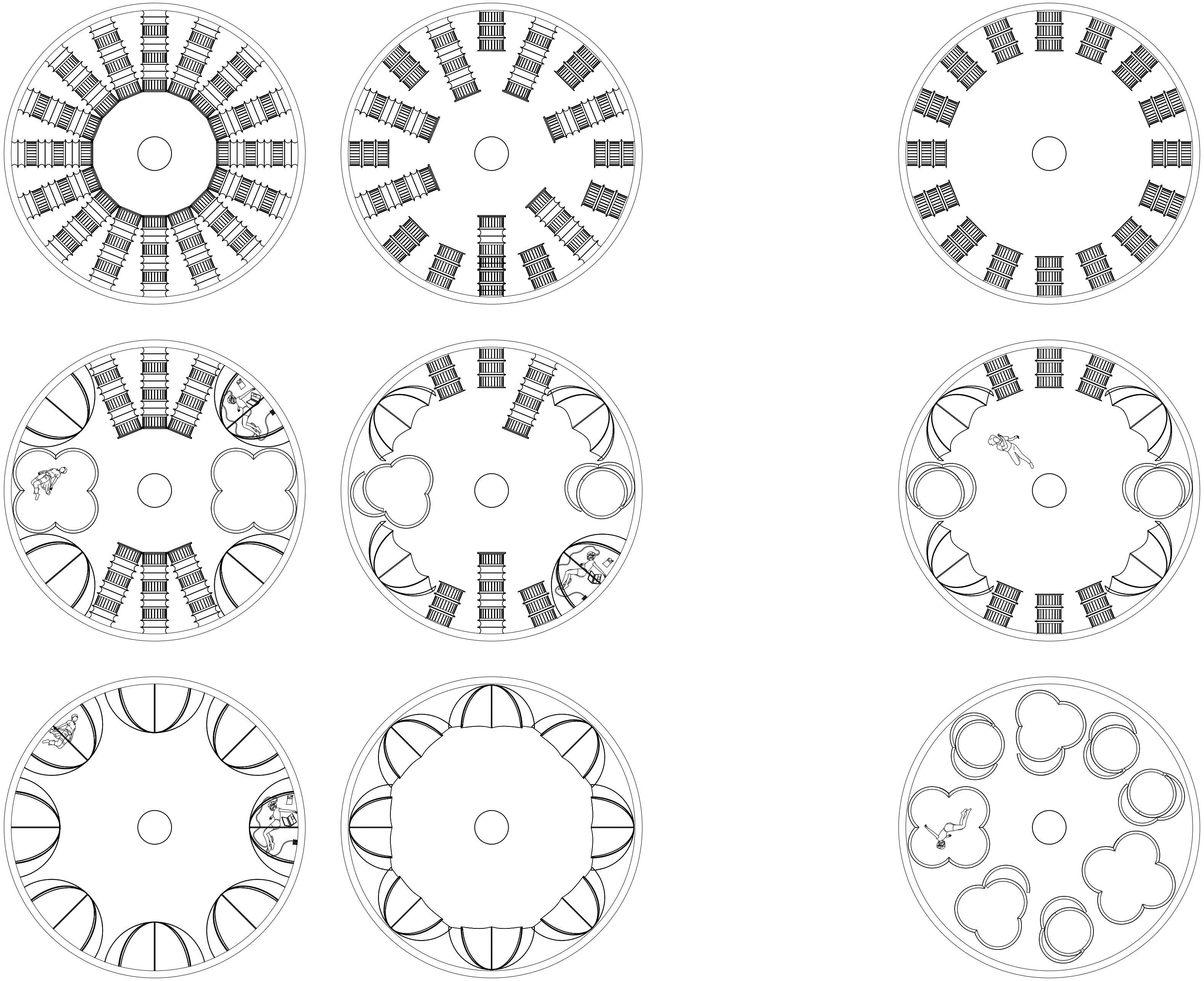
STRUCTURAL
TEXTILES
DEPLOYED

MULTIPLE STABLE STATES

The multi-purpose dome can transition between convex or concave states by applying light force to the center.

DYNAMIC SPACES

The deployable textile composites can be combined in one space for increased dynamic functions.



TOWER HABITAT MODULE
VARYING STATES OF DEPLOYMENT

MIXED STRUCTURES MODULE
VARYING STATES OF DEPLOYMENT

DOME & TOWER MODULES
VARYING STATES OF DEPLOYMENT

Fig. 9.4 Plan views of the application proposal, with the prototypes installed

The prototypes themselves have multiple intrinsic benefits to be used in an off-earth environment, particularly in regard to transport. Regardless of specific site location, the most significant factor determining off-world material and fabrication processes is the initial transportation. The characteristics of these composites of being lightweight, flat-packed (before release from the print bed) and self-deployable are all inherent benefits of this material system that can be applied to the unique requirements of architecture for space. The textile structures also have the potential to be fabricated on site, allowing for even simpler transportation methods and function-specific fabrication as needed.

Of course, more research and development in this area is required to consider the use of the textiles in an extreme environment such as space. Examples of sleeping modules can be viewed in Figure 9.2, where they take up the same amount of space regardless of the occupancy. With further material and design development, it can be hypothesized that the next iteration of a sleeping module could be one made of 4D printed textiles with dynamic behaviors, assuming developments in material can also be made to provide the same benefits as the current modules both in terms of radiation protection and privacy.

The material itself is perhaps the most significant research area to develop, as materials must meet rigorous standards in terms of off-gassing, durability, and radiation protection. As part of this process, Drew Hoyle, an Aerospace Textiles and Softgoods Engineer at NASA was contacted about potential space-grade materials that could be tested in this research. He stated that their process was to develop space-grade materials in-house after the successful demonstration of a given technology created with non-space-grade materials. In this line of thinking, the development of a stretchable textile material that could withstand a harsh external environment would open up the possibility of using self-assembling programmable 4D printed textile structures as the exterior shell of immediate and temporary deployable lunar or martian habitats in the future.

10. Future Implications

Next steps

Although a multitude of areas were explored throughout the research, there are many more topics that are yet to be investigated. Some of the following areas were investigated and abandoned due to issues with fabrication set-up, material, or time constraints, but would have considerable implications on this specific research or the field of 4D printing as a whole.

Multi-material printing

As seen in the results of this research, different filaments produce vastly different warping results. This could be applied to the printing process through the exploration of multi-material printing. As the creation of the design behavior library was primarily focused on PLA, there is a gap in the research when it comes to using TPU on the large-scale, as well as using both filaments in the same print on both scales. Multi-material printing could allow for the programming of behavioral properties at multiple scales and functions, such as as small scale TPU textures on a large scale PLA structure or dual-sided textile printing.

Off the Roll

There is certainly further research to be done in the area

Fig. 9.5 Multi-material printing on separate fabric sides

of off the roll / infinite printing, which will likely be solved with improvements to a frame system that not only moves the fabric, but also stretches it simultaneously, perhaps taking inspiration from 90 degree "infinite" conveyor belt printers. This could allow the print area to be limited in only one direction, printing pieces that are as long or wide as the textile can be made. Of course it cannot be assumed that the textile composites will scale up infinitely, so further research on scaling up would also be required.

Mobile printer and scaling

Another way to scale up could be through the development of a mobile printer that moves around a stretched textile. This would remove the requirement of a larger printing cage and robot, and could perhaps keep the fabrication cost down as it provides an alternative to using a larger robot. This also solves the width problem found in the conveyor belt frame solution, as the mobile robot printer would only be limited by the size of the textile itself. This fabrication methodology also invites the idea of locally optimized in situ fabrication, making the research even more plausible for extreme environments.

Scaling the frame, ensuring equal stretch

The stretching frame is the area that requires the most research and development to take this fabrication method to the next stage. In the current workflow, the fabric is stretched by hand, fastened to a frame at multiple points. This results in significant variations in the stretch and can result in uneven composite warping. If the composites are to be scaled further, these slight areas with uneven warping can be increased and may affect the stability of the structure as a whole. Going forward, there would need to be some sort of mechanical solution that ensures equal stretching of the fabric, fastened along entire edges rather than specific points.

Reinforcing textiles

In the early experiments printing grids onto nylon was tested, in order to understand the implications of reinforcing

Fig. 9.6 Nylon reinforced with a TPU grid and spiral

the fabric to create a composite that was stronger than both individual parts. This seems to be an area worth developing further, perhaps combining with structural warping.

Connections

The connectors are also an area that can be further iterated upon. This research came to the conclusion that the connectors themselves are not necessary, rather the assembly instructions fabricated into the composite provided the most value and flexibility for the end user. However, there could be developments in this area, whether it is with coatings, magnets, or other printed attachment methods.

Accurate simulations

Attempting to create an accurate simulation would be another valuable area of research, as the current simulations do not provide enough detail in regard to the intricacies of the technical textile properties and their behavior when stretched and resisted. Accurate simulations would be particularly valuable for the large-scale experimentation, as both the material waste and fabrication duration increase with the scale.

Non-linear print lines

Taking inspiration from the SIKKA project, the idea of looping print lines to allow for increased surface filament area without a signficant increase in mass could have significant implications on the structural integrity and the material behaviors.

Textiles

Finding or developing the proper textile for 4D printing architectural textiles may be a research project in of itself- as parameters such as durability, transparency, strength, weight, and stretch will all affect the established design system in multiple ways. The most difficult requirement of sourcing material is the stretch factor, as durable architectural fabric is often not woven. Development into this area has the potential to transform the application proposal from something of conjecture to a plausible design solution.

Printing the textile itself

Printing a textile from TPU to then print directly onto with PLA was explored as a concept, taken through to the stage of printing multiple TPU fabric swatches. However, the TPU swatches did not stretch in a way that was significant enough to create warping. This is an area that could be researched further, investigating different print geometries and weaves to promote stretching.

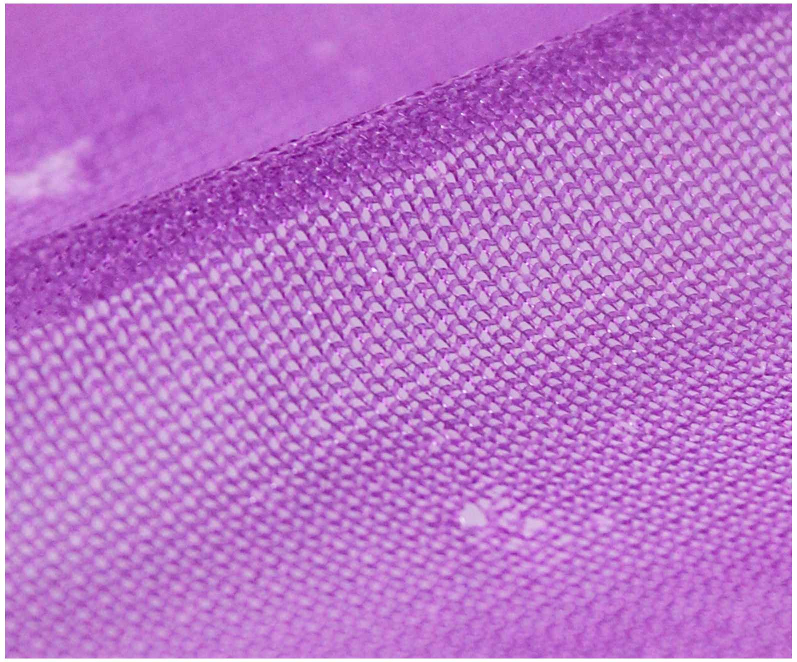


Fig. 9.7 A printed TPU textile sample

11. Reflections

This project was born from a personal interest in textiles, intricate textures and 3D printing, starting out as small one-off tests on a desktop printer, and was gradually transformed into a much larger project once the potential was understood. As 4D printing is such a new research area, there was no fabrication workflow or manual to follow, and for every experiment and test documented here, there were countless failures and readjustments.

Stage 1

The first stage of the research was a challenging yet crucial time, as it was confined to the smaller scale, yet so much of the knowledge from this stage served as the foundation for later iterations. Digital simulations proved to be only somewhat accurate, requiring hundreds of test prints. So much rests upon on the material interdependcies contained in a single textile composite before the actual printed geometry even comes into play (filament type, temperature, textile thickness, weave, surface texture, nozzle height, extrusion rate, to name a few) that it is difficult to disqualify ideas when it is nearly impossible to test all the possible combinations. Finding stable control variables in the early stage was both time consuming and produced material waste, and at times it was difficult to decide to continue deeper into one path of experimentation or branch off into new areas. However upon reflection, this time of seemingly "blind experimentation" was actually imperative into the design process later, not because of the actual physical samples produced, but rather for allowing the creation of an inherent understanding of these material interdependencies before the big issues of scale and structure were on the radar.

Stage 2

Once basic material behavior and parameters were established, the move into the informed design iterations was more focused, but not without trial and error. This stage was all about creating repeatable and stable design behaviors and puzzling them together, with the goal of creating something structural. The most promising output at this stage was the material behavior of folding and the "parentheses wall" (Fig 7.3.10), which was a combination of geometries that let the fabric both retract and remain taut.

Stage 3

The final stage focusing on scale and iteration was the most significant. A change in scale does not just mean scaling up the print geometry. Each material factor that is included in the system of interdependence required to produce the textile composites must adapt individually to the new parameters. This requires a whole new set of iterations, often returning to the small scale to test geometry tweaks. As mentioned earlier, scale is the final iteration in a long process of iterative design, and in this process, the "parentheses wall" was not able to perform on the larger scale. However, after the initial few processes of successfully scaling up designs, the scaling behaviors could also be observed and used to inform the designs already on the smaller scale.

Setup Challenges

Of course, the robot build and the attempts to increase the print area were challenging. Creating and programming a 3D printer for the robot arm was a significant task in of itself, and required a lot of learning by doing. The large-scale textiles were stretched more than their small-scale counter parts to account for an appropriate retraction force, but this also caused the final textile composites to shrink to be significantly smaller than their print area. Going forward, this means that the printing areas need to actually be much larger than the desired composite size.

Research Questions

The most signifcant adjustment throughout the process was the acceptance of creating simpler forms and geometries. Due to initial inspiration and interest in textural textiles, there was a bias towards creating geometries that were complex before warping, rather than testing extremely simple geometries. This definitely slowed down the creation of the material library, which really started to grow once the design focus shifted entirely to behavior and structure over aesthetics.

The project has left a few research questions open ended for future investigations, such as the questions of application and material, both of which have promising results but could be further expanded upon, and are perhaps the last hurdle to bring this technology out into the architectural world.

The question of a material behaviors design system was answered with the successful creation of a library of building blocks for repeatable material behaviors, but could also be further expanded with more behaviors and precision.

The question of scaling up was somewhat successfully adressed. The textile structures were able to remain functional across a significant increase in scale, but due to limitations in the fabrication setup, it was not possible to test them at a full human or architectural scale. However, it can be hypothesized that the knowledge gained from scaling up the desktop printer to the robot could also be applied to a scale jump from the robot to an even larger size.

The final question of structural and kinetic integrity is where this research saw the most success. Going into the project, it was not known if it was possible to create a self-supporting structure, and no previous examples of this could be located. After the fact, it seems obvious that it was possible, but at times throughout the project it seemed that this would not be achievable within the scope and timeframe of this research. However, this project can now serve as a starting point for future development in structural 4D printed textiles.

12. Conclusion

In conclusion, this project's output is a comprehensive material behavior design system and prototype set on 4D printing textiles across multiple scales. It provides a foundation of knowledge to be further built upon in future research and scales, providing insights into the significance of interdependent factors such as adhesion, stretching, filament rigidity, and textile properties.

This project began with two main research questions; if it was possible to create a self-supporting and forming 4D printed textile structure, and if direct-to-textile 4D printing was a viable research area within the architectural field. The short and unequivocal answer to both questions is yes- yet the research also created and answered many more questions along the way.

There is so much more research to be done in this area, both in the actual fabrication and design process, as well as the potential applications. It was not long ago that the idea of 3D printing was thought to be a fantasy, let alone the idea of 3D printing houses. While the idea and practice of 4D printing architectural textiles may still be contained in the area of experimental research, explorations into its viability and scalability are crucial.

The primary outcome of this project lies in its validation that there is a viability for this fabrication methodology within architectural discourse, and that it is indeed possible to create self-supporting 4D printed textile structures. It is my hope that the research in this thesis contributes to a foundation of knowledge for future development of structural textiles.

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