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Henry, Amelia Vey; Johansson, Anton Tetov; Andréen, David

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PO Box 117
221 00 Lund
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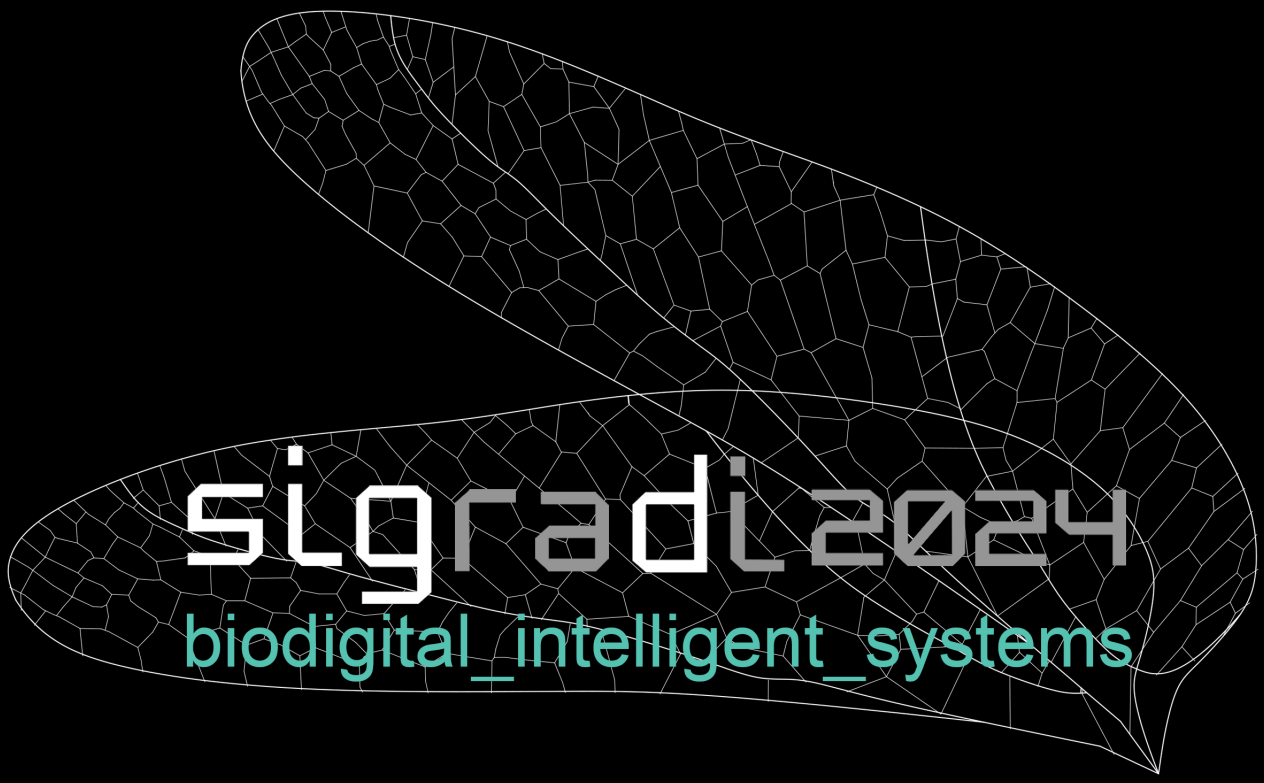

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Universitat Internacional de Catalunya (UIC)
Immaculada, 22, 08017-Barcelona, Spain
Tel. +34-932 541 800
www.geneticarchitectures.weebly.com / www.uic.es

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Bob Martens, CumInCAD, TU Wien, Austria
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Programmable Self-supporting Structures through 4D Printing on Tensioned Textiles

Amelia Vey Henry[1], Anton Tetov Johansson[1], David Andréen[1]

[1]Lund University, Lund, Sweden

ameliaveyhenry@gmail.com; tetov@abm.lth.se; david.andreen@abm.lth.se

Abstract. 4D printing is a development in additive manufacturing that enables 3D printed objects to transform over time in response to environmental stimuli. This research investigates the architectural viability of large-scale fused deposition modeling (FDM) 3D printing of thermoplastics onto stretched textiles, which retract and warp into 3D structures upon release. Employing an iterative research-by-design approach, the study explores the fabrication of self-supporting, dynamic architectural textiles. The methodology involved small-scale experiments to test material interactions, followed by larger-scale prototypes to refine and demonstrate structural integrity. Results reveal insights into adhesion, material behavior, and scalable design systems, leading to the creation of complex, programmable textile composites. This work lays the foundation for integrating 4D-printed textiles into architectural applications, highlighting their potential for creating lightweight, deployable structures with programmable behaviors

Keywords: Digital fabrication, 4D printing, Additive manufacturing, Smart materials, Self-assembly

1 Introduction

4D printing is an emerging development in additive manufacturing (AM) 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. The concept of 4D printing is relatively new and research in the field is primarily found within an academic context; the technology has not yet been widely implemented on the commercial scale. This paper is the result of an investigation into the architectural viability of large-scale fused deposition modeling (FDM) 3D printing of thermoplastics directly

onto stretched textiles, which retract and warp into 3D structures upon release. The research is an experimental development of a fabrication process and takes the form of an iterative workflow of research-by-design to create a design system of structural-based material behaviors that can be used to create complex and dynamic self-supporting architectural textile composites.

1.1 State of the art

In the current sphere of direct-to-textile 4D printing (Koch et al., 2021; Kycia & Guiducci, 2020), the number of projects is limited at the architectural scale, as both scalability and structural integrity become significant issues when working with delicate and interdependent material relationships. Existing projects and research such as the *Active Shoe* (Guberan & Clopath., n.d.) and *Technē* (Teghini, 2021) have experimented with 4D printing textiles on the small scale, while the *Sikka Project* (Teghini, 2019) addresses the issue of architectural scalability with a large textile cladding, but there have not yet been projects addressing the issue of structural integrity by creating a self-standing textile structure via 4D printing.

1.2 Research Questions

The primary goal of this project was to explore the potential and application of this fabrication method and resulting performative textile composites in architectural contexts across multiple scales. Early experiments aimed to demonstrate the feasibility of fabricating self-supporting and self-forming 4D printed textiles on a small scale. Subsequent investigations focused on the challenges of scaling up the process, aiming to understand the relationship between small and large-scale implementations and test the feasibility of large-scale production. The second area of research focused on the structural and kinetic behaviors of the filament-textile composite, which inherently is lightweight, flat-packable, self-forming, self-supporting, and offers multiple stable states. Notably, the self-forming and self-supporting properties distinguish this material and fabrication method from other smart materials. The primary question was whether it is possible to create a scaled-up 4D printed textile structure that is both self-supporting and self-forming. Furthermore, we aimed to find out how material properties differ at different scales. As the project combines two materials into a textile composite, their interaction is as significant as the individual materials. How do they adhere, and how does the balance of textile retraction and filament resistance (where the force of the textile retracting to its pre-stretched state meets the resistance of the rigid filament) withstand scaling in some aspects (design, line thickness) but not others (weave size, stretch distance, surface fibers)? Lastly, we aimed to develop a design system that tracks repeatable material behaviors and determines how parts can be combined to create specific programmable behaviors. Can we create a set of design instructions that serve as a language with which to create desired

material behaviors? What framework can be used to evaluate and select the most effective behaviors for the research?

2 Methodology

This research is grounded in the framework put forth in Narratives of Making (Ramsgaard Thomsen & Tamke, 2009), which posits that digital architectural tools have transformed making into a material-led process. This way of understanding architectural fabrication is the basis for a framework of modes of material evidence: the probe, prototype, and demonstrator. The investigation followed a two-stage approach: an initial set of probes that evaluated and tested the behavior at smaller scales, covering a broad range of methods and materials such as jersey knit cotton, circular knit nylon, and spandex knit Lycra, and thermoplastics (PLA, TPU, and PETG), and a second stage where the outcomes of the probes guided the fabrication of larger scale prototypes. Central to the research was the development of an experimental fabrication process specifically for architectural-scale programmable structural textiles, consisting of comprehensive exploration and documentation of material behaviors, testing interdependencies in material, fabrication parameters, and printed design geometry. Apart from the design development and print variables, this research required the creation of a stable fabrication workflow: adapting to different types of 3D printers and the construction and programming of the hardware and software of a 3D printing tool for an industrial robot arm (Figure 1).

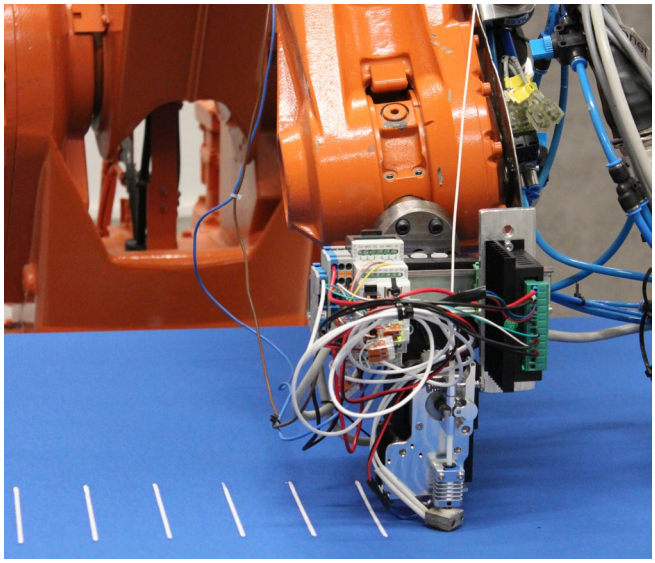

Figure 1. Custom-made 3D printing attachment, mid-print.

2.1 Fabrication Set-up

Two types of printers were used in the research, a Creality Ender-3 V2 desktop FDM printer with a 250 x 250 mm printing bed, and an ABB IRB 2400 industrial robot arm with a 1000 x 800 mm printing bed (Figure 2). To print at a larger scale, a tool for FDM 3D printing was developed for the robot arm. This involved designing and printing a tool attachment for the robot and programming a Controllino Mini (an Arduino based microcontroller) to control the temperature, flow, extrusion, and retraction of the filament extruder in sync with the robot's movements (print paths). This information was sent to the robot controller via Rhino 3D and Grasshopper and COMPAS RRC (Fleischmann, Casas, & Lyrenmann, 2020).

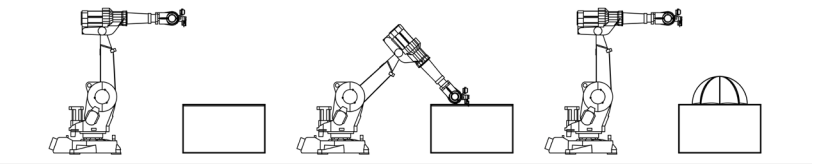

Figure 2. Diagram showing the process of 4D printing on tensioned textiles.

2.2 Initial Experiments - Probes

In the project's initial phase, 4D printing behaviors were tested on a small scale using various materials and geometries on a desktop printer. The aim was to get a broad understanding of how the filaments and textiles interact; identical geometries were printed using a combination of different fabric and filament pairings (Figure 3).

Figure 3. Matrix of initial experiments testing warping behavior across variables of filament, textile and geometry type.

External factors, such as textile stretching, nozzle height, and flow were controlled. As research shifted to creating a self-supporting structure, simplifying variables became imperative. Focus narrowed to a single material for filament and textile, and printed design geometries were simplified (Figure 4). This required a shift from evaluating geometries as repeating patterns to analyzing individual geometrical parts as building blocks. These isolated parts could then be combined to form a larger textile with multiple programmed behaviors.

Figure 4. Small-scale probes designed to test geometries for structural behavior across controlled textile and filament variables.

2.3 Large-scale Experiments - Prototypes

Once printed textile composites were performing in a structural way on the desktop printer scale, they were brought to the larger robotic scale (Figure 5). Interdependent material and fabrication parameters, such as adhesion, stretch, geometry and material all had to be adjusted and iterated on to account for the change in scale, particularly regarding the lack of scale increase in the thickness of the textile.

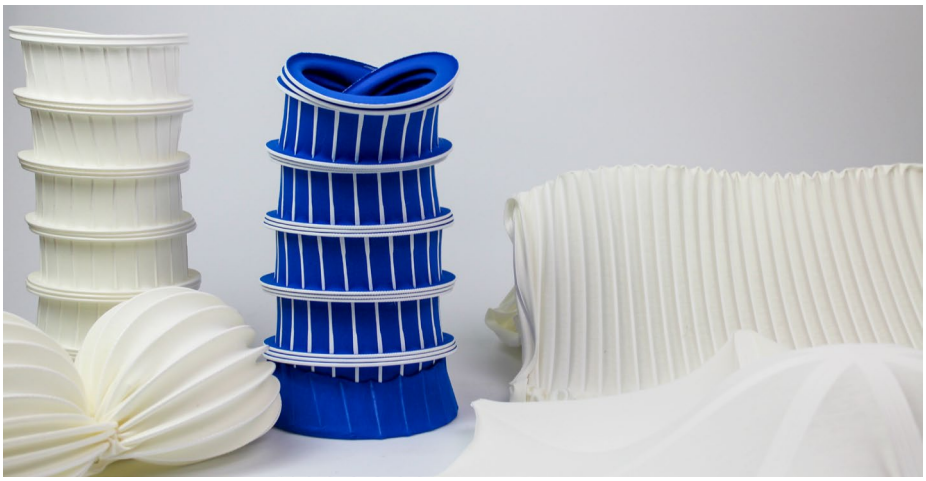

Figure 5. Large-scale prototypes, including the self-supporting tower, the dome with multiple stable states, and the dynamic structure with various foldable forms.

3 Results

Through the experiments and prototypes performed, we accumulated knowledge about the fabrication workflow needed to create performative textile structures, addressing issues such as adhesion, materiality and consistency in textile stretching. This includes three large-scale prototypes and a design system of components that can interact to create specific behaviors.

3.1 Adhesion

It was observed that proper adhesion is integral to the fabrication process. If the filament does not properly adhere to the textile while printing, the filament will come loose upon release from the print bed or over time. Many factors were observed to affect adhesion quality, such as nozzle distance, temperature, filament resistance vs. textile retraction ratio, and surface texture of the textile. Nozzle distance to fabric significantly affects adhesion quality, as the filament needs to be pressed into the fibers and stretched weave of the textile. A shorter distance results in better adhesion, but also has adverse factors such as the lateral spread of the print line due to squeezing as well as the potential of the nozzle to clog and skid on the print bed. To counteract these issues, another framing system was developed that stretched and suspended the textile. This allowed for the nozzle distance to be shortened to press down into and stretch the fabric while printing (Figure 6), creating stable adhesion while also accommodating variations in both fabric resistance and the frame itself. This resulted in an improvement in print quality overall and time required to make a single print, reducing from an average duration of eight hours per print to one hour.

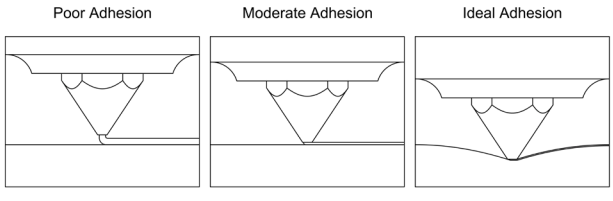

Figure 6. Adhesion quality in relationship to nozzle height.

3.2 Material Significance

This fabrication process distinguishes itself from other 3D and 4D printing techniques through the intricate interplay between textile and filament materials. Their retraction and resistance relationship causes mutual warping, compounded by interdependence on factors such as print geometry and stretching, ultimately making the behavior difficult to predict and simulate. When the fabrication scale was increased, the printing nozzle diameter was also increased to create stronger lines of filament. However, the fabric strength does

not increase proportionally as the thickness does not scale to the same degree as the area, which significantly affects the balance of the textile retraction and filament resistance that was established at the smaller scale. This must be compensated for through other parameters such as textile stretch, print geometry, and filament thickness. The research primarily utilizes two thermoplastics, PLA and TPU. PLA maintains a semi-rigid structure with varying bending capabilities, occasionally overpowering the force of fabric retraction to minimize overall warping. In contrast, TPU is highly flexible and less structural, enabling significant fabric warping. However, pairing TPU with extremely stretchy textiles like nylon can lead to excessive and uncontrolled warping. Successful desktop printer scale prints predominantly employed cotton alongside TPU or PLA. Cotton's intermediate stretch factor— between Lycra and nylon— proved optimal, balancing filament interactions across various prints. Transitioning to larger scales necessitated testing thicker fabrics, yet cotton remained the top performer, though requiring increased fabric stretching for optimal outcomes. Implementing offset print paths helped mitigate scale-induced challenges caused by changing ratios of fabric retraction and resistance. A notable difference emerged when scaling up: the fabric's wale direction had to align parallel to the long printed lines to facilitate uniform bending, due to the loss in retraction force from working with larger pieces of textiles (Figure 7). In assessing warping behavior, the relationship between material stiffness and filament rigidity was pivotal (Figure 8). High-stretch, high-retraction materials like Lycra struggled with the rigid PLA due to excessive retraction force, while achieving satisfactory results with the flexible TPU. Cotton, with moderate stretch and retraction, performed well with both TPU and PLA, making it a versatile textile option. Nylon, characterized by high stretch and low retraction, exhibited varied performance with both filament types, depending on geometric factors.

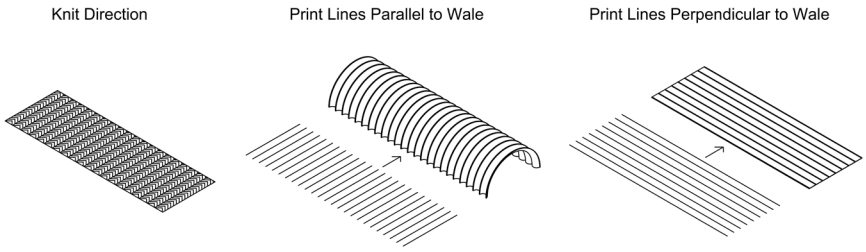

Figure 7. Parallel vs. perpendicular print lines in relation to course and wale direction influences the degree of warping behavior when scaling up, due to the inherent different degrees of stretch and retraction that are magnified when working with a larger piece of textile.

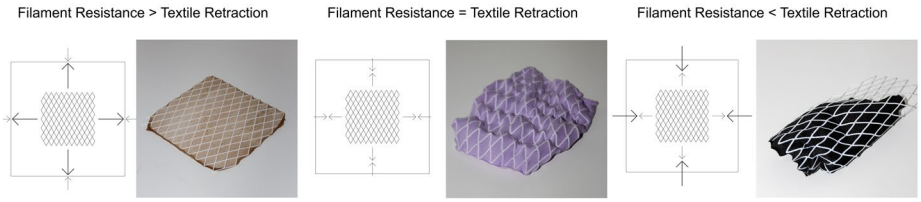

Figure 8. Effects of the balance of forces between textile retraction and filament resistance on warping behavior and adhesion, across a single geometry printed with PLA onto nylon, cotton, and Lycra.

3.3 Consistency in Textile Stretching

As there are multiple interdependent parameters and factors, 4D printing on textiles is vulnerable to significant human error. The multiple variables influencing both the plastic and fabric, as well as their adhesion, make it difficult to achieve consistent warping across duplicate prints. Maintaining consistent textile tension is crucial, as the warping behavior depends on the ratio of the fabric's tension to the plastic's rigidity. If the fabric is uniformly stretched with equal tension, the potential energy (retraction force) stored in the fabric will interact consistently with the plastic's resistance across the entire fabric (Figure 9). In the second frame iteration, a more rigorous approach to obtain equal stretching via an increased number of fastening points was tested, resulting in more dramatic and consistent warping behavior throughout the textile. The setup encountered scalability limitations due to the spatial constraints of the robot cell, which restricted the continuously tensioned surface area available for printing and limited the achievable size of prototypes.

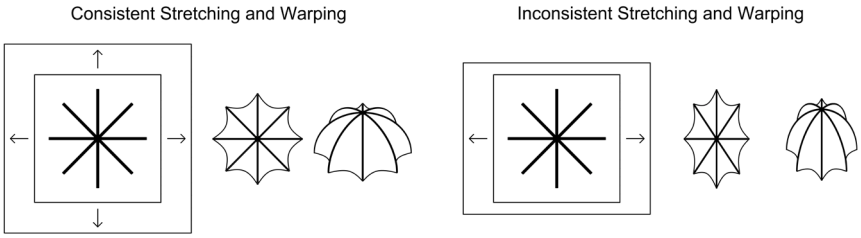

Figure 9. If the fabric is pulled tighter in one direction, causing uneven tension, it will retract more forcefully, leading to inconsistent warping.

3.4 Geometry and Design Systems

The design system of material behaviors both formed and was informed by the design iteration process. In the early experiments, the design process was extremely broad, intended to facilitate a wide understanding of the potential

types of material behavior and their associated print geometries. As behaviors were observed and documented, the focus was narrowed to refining specific behaviors and iterating upon them. This approach led to identifying specific print geometries as foundational building blocks of material behavior, essential for creating complex and repeatable structural patterns within textile composites (Figure 10). Iterations revealed that geometries with more open space experienced greater warping due to concentrated areas without filament allowing for greater textile retraction, resulting in dramatic bends reinforced by thicker lines. 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 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 geometries. Once the design system has been tested across multiple scales, it allows for new forms to be imagined and broken down into their material behaviors for fabrication.

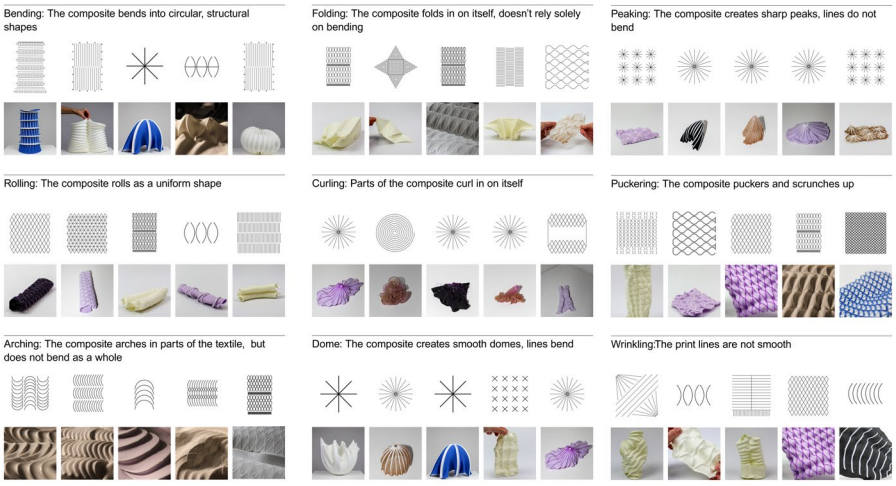

Figure 10. Behavioral building blocks and the geometry that resulted in them. Building blocks can be combined to create multiple behaviors in a single print, such as bending and rolling in the tower prototype. These blocks serve as a foundation to predict behaviors, given the intricate and interdependent nature of the materials and forces.

3.5 Self-supporting Structural Prototypes

The culmination of this research is a collection of 4D-printed programmable textile structure prototypes. These prototypes are the outcome of iterative testing across various scales and materials, affirming the hypothesis that self-supporting 4D-printed textile structures can be achieved successfully across multiple scales. The final prototypes underwent initial testing and iteration at a small scale to minimize material waste during large-scale printing. This approach yielded a series of functional prototypes at the small scale, each corresponding to successful large-scale prints (Figure 11). The process did not rigidly distinguish between small and large scales; rather, scale was considered the final stage in design iteration. Testing at the large scale provided additional observation, forming an iterative feedback loop where large-scale results informed subsequent designs at their early small-scale stages.

Figure 11. The first tower prototype, inspired by a rib cage, emerged from an iterative design process, showing behaviors of bending, arching, and rolling. This prototype stands compressed, can be stretched and elongated, and confirmed the self-supporting structure theory by maintaining its shape and position for months on display and landing upright when dropped from 1.5 meters. Dimensions: ø200 mm, height 450 mm.

4 Discussion

The presented results indicate a potential for using this technology to make free-standing architectural structures whose behaviors and forms may be predicted through a more or less generalizable design system relying on simulation or modularity, or a combination of the two (force-active systems) (Ahlquist & Menges, 2013). The produced prototypes achieved a free-standing height in the half-meter range, and exhibited enough stiffness to support themselves, but not a large external load. To achieve further scalability, one of

the main challenges to overcome is to establish a larger production arena, which is particularly difficult as the stretched nature of the fabric makes it larger in the production stage than in the use stage. Interesting avenues here may include mobile robots or even a dynamic stretching mechanism that can act like a continuous assembly line to enable off-the-roll printing. Workflow innovations, such as advancing controlled documentation and predictive models of warping behavior (Tahouni et al., 2023) will open the potential of increasingly advanced structural forms. Material innovations could allow for increased precision and programmability, such as developing custom performative textiles to print on or integrating TPU with PLA across different textural and structural scales through multi-material printing. The deployable and light-weight nature of the structures make them suitable for mobile applications such as transformable interior spatial dividers (Sparrman et al., 2017) or space architecture (Häuplik-Meusburger & Bannova, 2018). Other research that develops reactive textiles and materials such as self-shaping 3D printing (Tahouni et al., 2023) or climate-responsive materials (Krieg & Menges, 2013) hint at possibilities for not only structures that can be deployed, but which can actively respond to changing climatic factors such as temperature or humidity.

4.1 Conclusions

In this paper we have presented a methodological approach and workflow that responds to the particular challenges that come with 4D printing on tensioned textiles. Through the experiments and prototypes, we have demonstrated the feasibility of free-standing, deployable structures and begun compiling a catalog of bottom-up designs and their resulting geometric behavior. The area of 4D printing is at its very beginning, but the potential for efficient, functional, and aesthetically pleasing architecture implementations is significant, and should be further explored.

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