4D Printing onto Textile: Fabrication and Design Process of Bistable 4D Textiles

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Abstract. 4D printing allows the material to transform from one shape to another over time. 4D printing onto textiles results in deformation leading to self-formation and responsivity that informs potential architectural cladding applications. Due to the self-forming properties of textiles after 4D printing, 3D printing patterns can produce bistable structures. Bistable materials composed of 4D textiles shift their current shape from one state to another. The combination of knitted textiles and 4D printing enhances material properties to satisfy performative criteria of potential building skins and enclosures. This study demonstrates a novel approach to fabricate bistable materials by 3D printing onto textiles and controlling the material behavior with an actuation system. The contributions of this study include 3D printing pattern generation to achieve bistable behavior, integration of digital and traditional fabrication techniques, and the addition of a new layer of functionality and responsivity to the textile material.

Keywords: 4D printing, Knitted Textiles, Bistable Material, Pattern Generation

1 Introduction

The building construction industry causes 38 percent of total global carbon dioxide emissions according to Global Status Report for Buildings and Construction (UN Environment Programme, 2020). Building skins are one of the significant architectural elements that can enhance environmental performance by adapting to environmental conditions and altering shape configuration to optimize performance and functionality. As a potential cladding material, textiles present a great opportunity to design shape-morphing lightweight forms constructed with traditional and digital fabrication

4D printing onto textiles introduces a time-varying material system that can be described as 4D textiles, with inherent smart material properties. 4D textile is a hybrid material system that contains two or more materials combined by additive manufacturing. The four-dimensional aspect is the built-in capacity of 3D-printed items to change shape over time. The manufacturing process follows pre-stretching fabric on the build plate, extruding plastic on top of the fabric, and then releasing the tension from the fabric structure. When the tension is released from the fabric, the areas that are covered with 3D printing material resist contracting and pop out while other areas contract, which transforms the two-dimensional surface into a three-dimensional volume.

Specific printing patterns generate bistable structures because of the self-forming characteristics of textiles after 4D printing. Bistable materials perform in open and closed states and can allow architects and designers to substitute any static building envelope system with a smart kinetic material system. Bistable materials made of 4D textiles have the potential to change their shape from one state to another triggered by their response to environmental stimuli such as daylight.

This integrative fabrication method can result in a shift from using knitted fabrics as an interior material to responsive and adaptive exterior material systems. The combination of hierarchical manipulation techniques of textiles with 4D printing can increase possible architectural applications by enabling programming capabilities. This integrative fabrication method enhances material properties to satisfy performative criteria of potential building skins. This study demonstrates a novel approach to fabricating bistable materials by 3D printing onto textiles. Contributions include the generation of 3D printing patterns to achieve bistable behavior, the integration of digital and traditional fabrication techniques, and the addition of a new layer of functionality and responsivity to the textile material.

1.1 Background Information

4D textile is a hybrid material system that can be achieved by 3D printing onto pre-stretched textiles. The textile stores energy in a pre-stressed state because of its elastic memory (Koch et al., 2021, p.6). Prestressing on the textile occurs in three directions, biaxially, uniaxially, and radially (Koch et al., 2021). The prestress direction will define the self-forming properties of the textile after releasing tension from the fabric. Kycia et al. (2020) suggested that a 3D printing pattern orientation on 4-way stretched fabric does not alter any shape-morphing characteristics when the tension is released.

However, the structure of the 3D printing pattern has a profound impact on the self-forming and adaptability of the 4D textile structure. Therefore, researchers experimented with different pattern generation methods to understand the relationship between the pattern and the textile's form when the tension is released. The 3D-printed material distribution could follow uniform, gradual and customized patterns. To comprehend the impact of the thickness and spacing between 3D printed materials, Kycia et al. (2020) presented 3D printed prototypes with uniform material distribution.

Further, they printed parallel lines with various spacing distances to understand the shape-morphing behavior of the textile, learning that when the spacing increases the material starts rolling rather than bending. Notably areas that are covered with rigid 3D printed materials do not contract while free textile areas shrink. Fields (2018) utilized computational methods to generate 3D patterns onto fabric to form complex three-dimensional geometries. Material was distributed gradually on a hexagonal tessellation layout. Areas that are covered with more 3D printed material resist contracting and pop out while other areas shrink. Distributing material gradually allows designers to achieve the form designed as an initial 3D model.

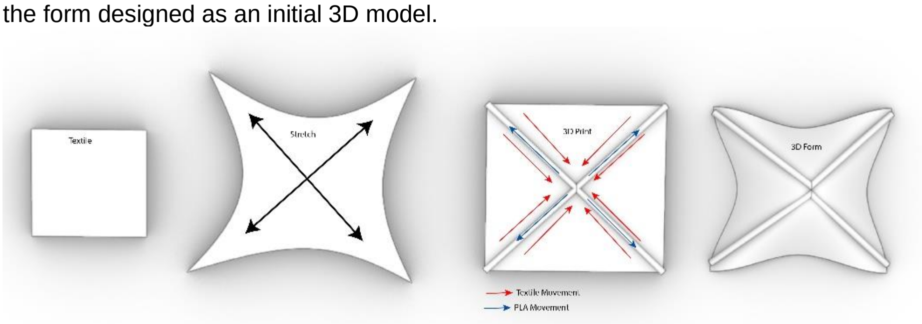

Figure 1. 3D Printing as a textile manipulation technique

Configurations can be based on Voronoi, auxetics, and geometrical tessellations. Voronoi tessellations were explored by Agkathidis et al. (2019) due to their multi-directional structure. Researchers experimented with adding irregularities within the Voronoi pattern. As a result, the regular Voronoi structure rolled up, and the Voronoi configuration with the most irregularities performed like a vaulted structure. Alternatively, auxetics configurations have a negative Poisson ratio which causes the material to expand laterally while being stretched longitudinally (Grimmelsmann et al.,2016).

The most common tessellation strategy uses geometrical structures based on triangles, rectangles, and hexagons. Bhagat and Gursoy (2022) studied the manipulation techniques of 3D printing parameters to optimize printed forms during garment-scale prototyping. They experimented with different parallel line spacing, line thickness, and heights complementing the study done by Agata Kycia et al. (2020). They employed triangular, square, and hexagonal tessellation as 3D printing patterns to understand the influence of various intersections on the material. Another strategy of pattern generation examines the influence of closed-shape geometry printing on textiles. Kycia et al. (2020) and Fields (2018) suggest that the printing circle allows the outer boundary to resist contracting while the inner area wants to shrink. This conflict between rigid and soft material transforms 2D textiles into saddle shapes with negative Gaussian curvature. The concentric circles can be added onto the textile surface to control bending behavior (Fields, 2018).

Besides tessellation strategies, some studies showcase unique pattern arrangements. Agkathidis et al. (2019) employ the principal stress lines that they retrieve from Karamba 3D simulation to act as a stiffening element onto textiles. They model the target 3D surface and then simulate the shape to receive stress lines. As a result of the simulation, the stress lines produce optimal material distribution to achieve the determined form. In the end, the stress lines are used as a guideline to place rectangular spiral patterns within square boundaries. They design a wearable accessory for the arm following their pattern generation strategy.

2 Methodology

Pivoting from the literature review, we propose experimental methods to pursue our research goal which is to add a fourth dimension and functionality to the textile material, which could inform eventual use as an architectural cladding system. The experiments we conducted focused on the garment scale, however, these prototypes and analyses can inform architectural scale.

2.1 Pattern Generation

This research project aims to understand the relationship between 3D printing parameters and material behavior to manipulate 2D textiles to perform as a 3D shape that can change from one state to another. These parameters include pattern width, height, density, curvature, geometry, and different pattern styles, such as tessellation, grid-based, and directional (Table 1).

Table 1. 3D Printing Parameter

Parameter	Variable
Layer Width	1mm, 2mm, 4mm
Layer Height	0.25mm, 0.50mm, 0.75mm, 1mm
Density	100% ,200%
Curvature	Slight, medium, intense
Geometry	Circle, square, hexagon
Arrangements	Tessellations, grid-based, directional, different angles

After deciding on the variables (Table 1), we started printing with various widths, heights, and densities to analyze the relationship between material behavior and parameters. Then, we generated other 3D patterns based on our analysis to understand how geometry and different arrangements affect textiles' final form after 3D printing. Our goal with testing different pattern parameters is to add bi-stability to the pre-stretched knit textile. As discussed below, geometrical tessellation structures generate bistable structures when they are created with a certain number of cells, line thickness, and stretch level. In this study, we focused on generating patterns that allow a knit textile to switch from one state to another.

2.2 3D Printing

After generating patterns, we tested these variables by 3D printing specific patterns on four-way stretch 90% cotton and 10% spandex jersey knit fabric. There are several ways to stretch textiles on the build plate; using nails, tape, and clamps, however each method has advantages and disadvantages. For instance, nails can damage the textile surface and clamps can cause uneven distribution of stress on the surface. For even stress distribution on textiles, we utilized embroidery hoops to stretch the fabric radially. We applied 150% stretch on the fabric for each prototype.

At the same time, we generated the G-code to print polylactic acid (PLA) with concentric 100% infill and a speed of 50 mm/s. After the textile within the hoop is placed on the build plate, the 3D printer extrudes the PLA to create multi-layer structures. The melted material gets absorbed by the textile's porous surface. After the extrusion is completed, the textile is released from the build plate illustrating its self-forming functionality. 3D-printed portions of the textile resist contraction while the remaining fabric areas shrink. The tension between rigid 3D printed material and the textile causes the fabric to transform into a three-dimensional shape (Fields, 2018).

2.3 Evaluation Process

After releasing the textile from the embroidery hoop, the textiles turned into 3D shapes with different characteristics. We categorized those behavioral characteristics as curling, bending, folding, rolling, and flattening. We documented all the prototypes by creating a parameter chart that summarizes the relationship between 3D printing parameters and material behavior (Figure 2).

Figure 2. Classification of Textile Behavior after 3D Printing

We realized that triangulated patterns within a closed geometry performed as a bistable material. Therefore, we selected prototypes that performed like a controlled bistable material, and we constructed a point cloud of these prototypes by utilizing photogrammetry via Agisoft Metashape software. These point clouds led us to evaluate the height and area ratio of each prototype in two states. Further, we classified each prototype's material behavior to achieve a snapping effect as it transitioned from one state to another. We also calculated the area of the open and closed state of the 3D-printed textile. A larger difference in area between these states potentially provides better control for any response to daylight levels.

3 Results

3.1 Material Behavior

As noted, we classified material behavior as curling, rolling, folding, bending, and flattening. We started with printing straight lines with various widths, heights, and densities. As shown in Figure 3, the printed line patterns with less thickness started curling on the surface, while increasing the thickness allowed for more bending behavior, increasing the tension between the lines. Similarly, increasing the height of lines shifted the curling behavior of printed textile prototypes to bending behavior. Alternatively, increasing the density of lines, which also means decreasing the spacing between the printed pattern, flattens the textile.

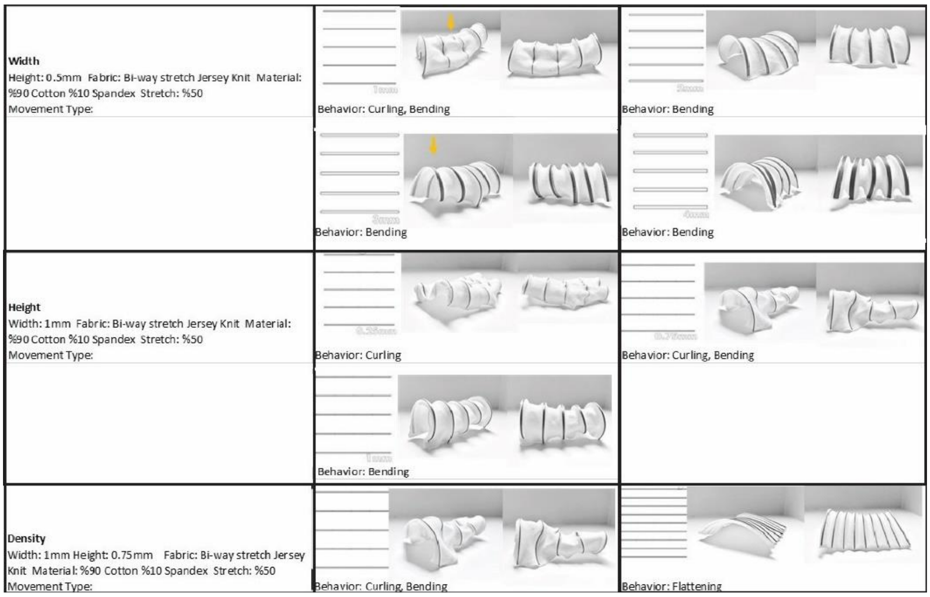

Figure 3. 3D Printed Pattern: Various width, height, and density

Further, we printed curves with different curvature levels (Figure 4). We mirrored the curves with two different curvatures. The prototype with less curvature started bending after 3D printing, and the prototype with higher curvature started folding. Additionally, we tested parallel curves with different curvatures, but both of the printed textiles were flattened after releasing the tension on them. Where we printed a closed geometry as a boundary on the textiles, prototypes assumed a saddle-shaped surface with negative Gaussian curvature. Such samples encouraged us to investigate the closed geometries further.

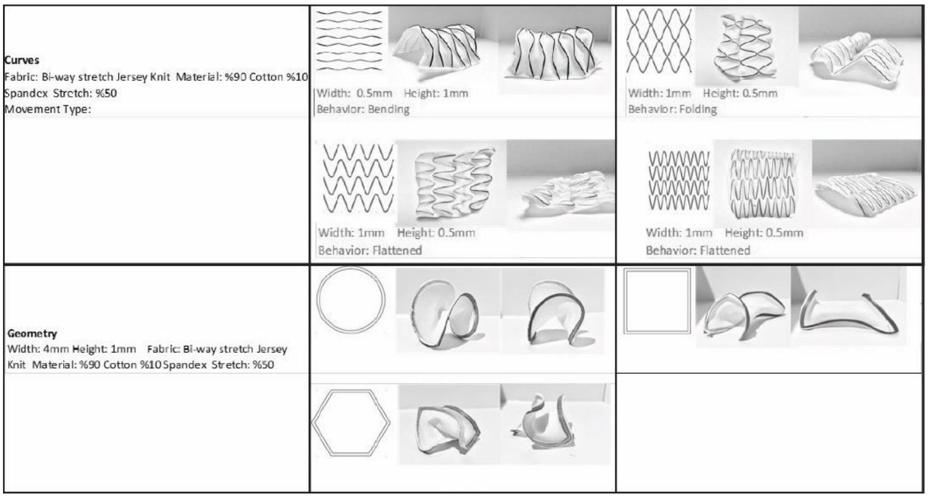

Figure 4. 3D printed patterns: Curves and Closed geometries.

Understanding the effects of width, height, and density is significant to develop any kind of 3D printing pattern. Based on our findings, we explored various pattern arrangement strategies such as tessellation, grid-based and directional patterns. As seen in Figure 5, tessellation with triangles performs as a bistable material, and grid-based pattern arrangements showcase only folding, bending, and rolling behavior depending on the geometry of the pattern. Later, we tested directional patterns and when lines intersected in two different directions, the prototype changed from one state to another while the textile was folding.

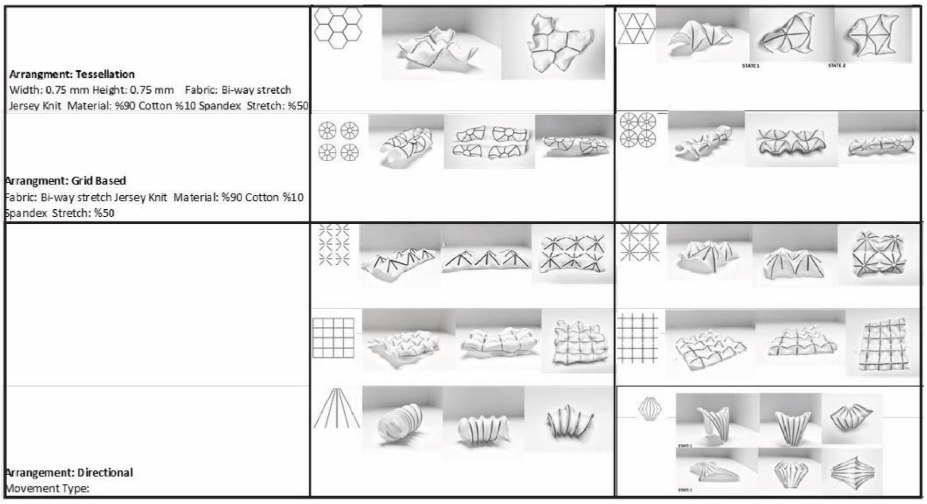

Figure 5. 3D Printed Pattern: Different Arrangement Strategies

The studies of pattern arrangements show that the triangulated patterns on textiles have a great potential for bistability after 3D printing. This allows the material to change shape over time responding to external stimuli and adding a fourth dimension to the textile. We combined triangulated patterns with closed geometries to further develop the idea of creating bistable material by combining knitted textiles with 3D printing patterns (Figure 6). We tested different geometries to create various boundary conditions and noticed that when the number of edges increases, the textile is more bent and performs a quick snap from one state to another, which leads to bistability. Further, we examined the impact to snapping behavior with changes in the angles between lines. Notably, the smaller angle between the lines allowed for a larger difference and a more uniform shape in the textile while transitioning between states.

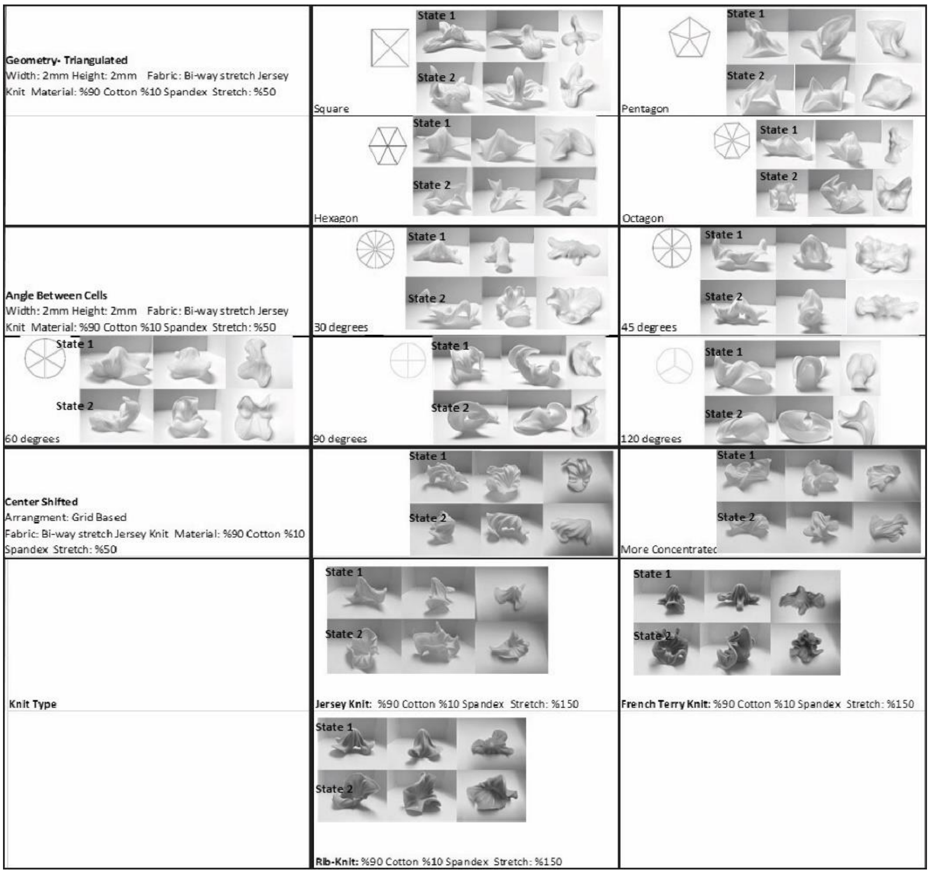

Figure 6. 3D Printed Pattern: Triangulation Strategies and Various Knit Types.

3.2 Material Performance Results

As a result of prototyping, we created performance criteria to analyze the material behavior to select prototypes that promise possible architectural applications. We aimed to create enough tension in the textile between 3D printed layers to achieve "bending" behavior while avoiding flattening of the textile. The parameters that impact the bending behavior include the density of the 3D printed pattern, the angle between cells, the distance between cells, pattern width, and height. Additionally, understanding the location of the control points is significant to transition from one state to another. The arrangement of cells, the angle, and the location of the intersection points define the control point where the textile can flip states by pulling and pushing in response to designated external stimuli.

3D printing onto textiles can result in bistability, in which the material will have two states: open and closed. Shifting from the open state to the closed state occurs through time, adding a fourth dimension to the 2D textiles. Potentially, an open state provides more opportunities for daylight access, while a closed state controls daylight. Therefore, we calculated the area of the open and closed states, and the height of the selected prototypes as seen in the results of photogrammetry (Table 2). The Octagon prototype has a higher ratio of open-state to closed-state areas, which promises efficient daylight control compared to the hexagon. Additionally, the circle with the smaller angle (15 degrees) between radial lines has the largest difference between open and closed state areas compared to the other prototypes.

Table 2. Height and Area Difference of Selected Prototypes.

	Open State Area (A)	**Close State Area (B)**	**Ratio (A/B)**	**Height Difference**	**Height Difference Between Control Points**
Hexagon	6.93	6.88	1.01	0.56	2.32
Octagon	6.66	5.95	1.12	0.50	1.81
Circle- 15 degrees	8.45	3.97	2.13	0.32	1.81
Circle -30 degrees	7.24	3.78	1.91	0.32	1.75

4 Discussion

4.1 Architectural Application

3D printing onto textiles adds a layer of adaptability and responsivity to the material that enables many potential architectural applications which embrace soft, lightweight, and adaptable spaces. As Frei Otto (1995) said "Our times demand lighter, more energy-saving, more mobile and more adaptable, in short, more natural buildings, without disregarding the demand for safety and security." The studies focused on 4D printing onto textiles prove that this fabrication method offers a compelling direction for building responsive and energy-efficient building elements. Further, advancements in knitting technology can lead to a shift from using knitted fabric as an interior material to an exterior material to create adaptive material systems (Jane Scott, 2021, p.481).

Even though this study focuses on garment-scale prototyping, there are some possible architectural applications of the 4D textile prototypes. As seen in small-scale studies, 4D printed patterns on pre-stretched textiles can offer responsivity and adaptability, which may lead to innovative and smart composite solutions for architectural applications. Because of the material performance provided by 4D textiles, Agkathidis et al. (2019) note that 3D-printed composite panels could be a part of shading devices, space dividers, temporary buildings, and tents. Schmelzeisen et al. (2018) envision 4D textiles to be used as a sound-absorbing element for potential architectural applications. Grimmelsmann et al. (2016) echo the potential of 3D printing auxetic patterns to bring soundproofing properties and permeability to the 4D textiles, which could potentially be used as filter materials. Alternatively, possible reciprocal applications of 3D-printed textiles are described by Bhagat and Gursoy (2022). They envision the results as self-standing temporary structures that can be deployed on the site without storage and transportation problems.

Alternatively, we envisioned 4D-printed self-forming textiles to be utilized as a cladding system that may achieve open and closed states with an actuation or trigger system. These performative surfaces could become a passive solar design strategy to increase energy efficiency and thermal comfort. The combination of knitting and 3D printing can generate smart building envelopes that respond to external stimuli such as light and heat in changing their shape. This fabrication method can enhance material properties to satisfy the performative criteria of potential building skins and enclosures.

4.2 Next Steps

There is still a scarcity of architectural-scale applications of 4D textiles. The reason that researchers focus on garment scale prototyping is that conventional FDM 3D printers have size limitations. As Koch et al. (2021) discuss “There is no research published on concrete applications of 4D textiles. The material structure has therefore not yet been used commercially. There are various visions for the application.” However, recently an extruder end effector has been designed as a robotic arm attachment to allow larger-scale printing, and this development provides the possibility of 3D printing full-scale building elements via robotic printing. Robotic printing solves the size limitations of conventional 3D printers and can eliminate the obstacles to designers’ creativity. We will shift from garment scale to architectural scale 3D printing as the next step of our research. Our goal is to fabricate a full-scale cladding system made of bistable 3D-printed textiles that are controlled by an actuation system to respond to daylight conditions (Figure 7).

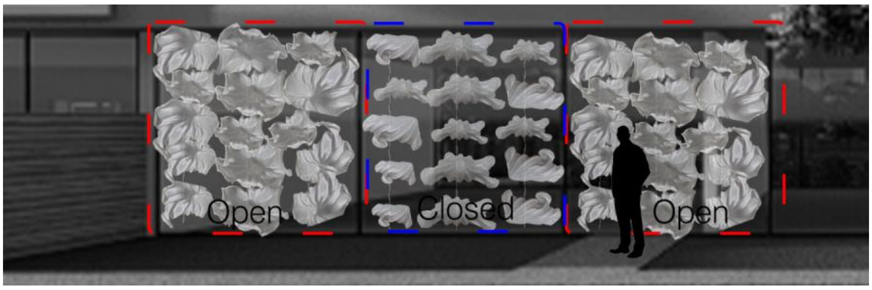

Figure 7. Architectural Application

4.3 Acknowledgments

This research is funded by Alberta Innovates Graduate Student Scholarships with the support of Alberta Innovates and Alberta Advanced Education.

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