Pneumatic Textile System

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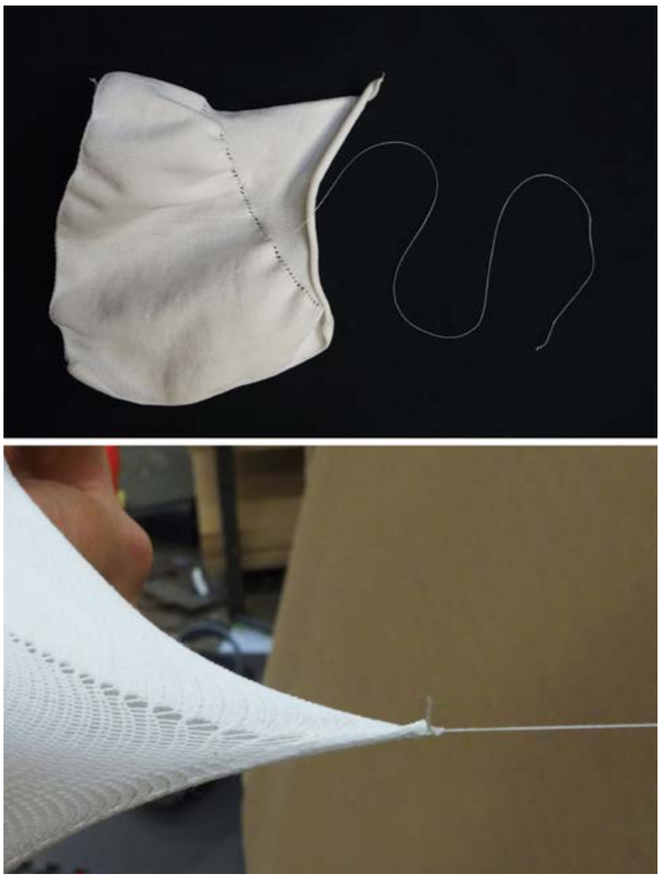
ABSTRACT

This paper attempts to demonstrate a seamless transformable material system through an interdependent designed assembly of two materials with different material properties (anisotropic knit textile and isotropic silicone) but similar behaviors (stretch). The transformable system is achieved by balancing the volumetric expansion through a silicone tube, under inflation, with the controlled resistance to stretch by a custom knit fabric. The use of a CNC knitting machine allows not only an opportunity to program the stretch behavior of a knit fabric, by controlling the amount of yarn material to be deposited, but also an ability to knit multiple layers of fabric simultaneously, in order to create a space capable of accommodating an external element seamlessly.

The paper will showcase a series of experiments ranging from the initial search for compatible material combinations to the varied structures of the tube sleeve and its relationship with surrounding region. The final prototype attempts to utilize the various behavioral properties of the material system learned from the experiments to create a transformable three-dimensional structure.

INTRODUCTION

"Material System" in the context of this paper is described as an interdependent assembly of materials based on their innate properties with an intention to create a desired material behavior instead of a preconceived geometric form. A basic material system example would be a knit fabric where the process of interlock-looping of a yarn transforms the yarn's initial linear tensile nature to an expanded field condition (Fig 1).



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This paper focuses on the assembly of a programmable anisotropic knit fabric material with an isotropic silicone tube to create a deployable and 3D transformable structure. When inflated, the expansion of the silicone tube will stretch the knit textile. When taut, the knit textile will limit the degree of expansion by the silicone tube. Together, the two form an interdependent material system.

The paper hopes to contribute to the future development of textile-related design in the field of architecture by successfully demonstrating the ability of custom-knit fabric to seamlessly accommodate an external element without a secondary aggregation process, such as sewing, and the ability to program a desired behavior into the textile to create a true three-dimensional structure.

Background

Similar to traditional knitting, CNC weft knitting is the process of laying a continuous piece of yarn onto a bed of crochet needles in interlocking loops. In the case of the STOLL knitting machine, there are two flat beds of needles arranged in an inversed V shape with yarn feeders running on top (Figure 2). The needles are raised to catch the yarns as the feeders move past them. The gauge of a knit refers to the number of needles required to make one inch of fabric. For example, if it takes 14 needles to knit one inch of the fabric, the full gauge of the knit is 14. However, in advanced knitting, it may sometimes be required to knit on every other needle, leaving an empty needle in between; this is called half gauging. The empty needle provides the additional space needed for transferring of needles to create a complex knit pattern. The needle activation is controlled numerically by codes generated from the graphic interface M1 Plus, where the designer can assign the exact location of needles to catch the passing yarn feeders.

Under stress, a knit fabric typically redistributes the load along one axis more than the other due to the composition of yarns and fibers. The process of CNC knitting allows an opportunity to either exaggerate or diminish the difference in force distribution through custom-knit stitch structures that either increase the stretch of fabric by more loosely arranging the yarn or increase the stretch resistance by more densely compacting the yarn. The result of localized differentiated properties within the prototype knit textile becomes more evident when activated by a uniformly expanding silicone tube, as the volume of inflation is directly affected by the willingness or resistance of the surrounding fabric to stretch.

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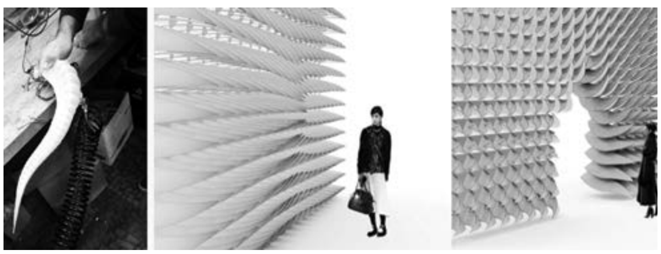
1 Upper: Unstretched knit textile
Lower: Stretched knit textile.

2 Inversed V beds of needles of STOLL knitting machine.

Precedents

In “Soft Robotics Applied to Architecture,” Kim et al. attempt to add a layer of intelligence to inflatable architecture by integrating soft actuated surfaces such as walls, ceilings, or floors (2015). Motion sensors are planted to detect the presence of occupants and trigger actuation of the pneumatic fixtures that, in return, create an opening in the wall. The soft surfaces are actuated through pneumatic inflation. The differentiated movement under inflation is achieved through custom ribs in the inflated bladder or varied thickness in the silicone membrane. In this context, pneumatics are an efficient means of generating movement in the silicone cell. My research prototype also hopes to demonstrate the potential for dynamic movements in an architectural surface through differentiated inflation by the custom-knit structures.



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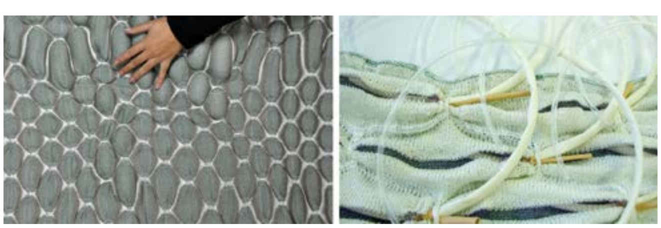
“Listener,” by Thomsen et al., “examines the integration of conductive fibers within the textile matrix to enable sensing. Using capacitive sensing, the textile membrane becomes an interface for interaction (Fig 4). This is then combined with an actuation system of integrated high-pressure bladders that allow the material to inflate” (Thomsen et al. 2015). The “Listener” takes advantage of the CNC knitting process to integrate three types of yarn (polyethylene for over structure, elastomer for stretch, and silver-coated for conduction) to create a custom textile that, when paired with microprocessor, becomes a self-sensing interactive material system. Sensors were planted and inflatable bladders were inserted into individual cells to create an interface that allowed the system to respond to its environment. In this context, the fabric serves as both the interactive interface and host to the sensory system.



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METHOD

The approach to develop a single seamless inflatable 3D structure can be divided into four categories. The first step is the selection of compatible materials for the pneumatic textile system. The second is to investigate the relationship between the knit sleeve and the enclosed silicone tube. The knit sleeve needs to accommodate the size increase of the inflated tube while maintaining enough density variation to create the desired direction of bending without overstressing the silicone material. The third aspect of the research focuses on the surface regions surrounding the planted tube. As the tube expands, it will stretch the fabric around it. Differentiated density of yarn distribution is tested to find the appropriate tensile strength to accommodate the expansion of the tube. Finally, a means of knitting multiple layers of fabric at the same time is developed to break away from the typical 2D nature of a textile.

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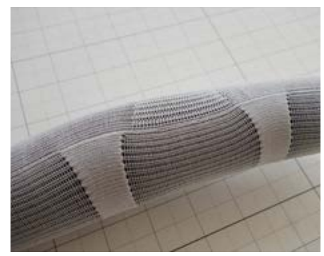

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The first stage of the research focused on the search for compatible textile sleeve and inflation bladder material. The first attempt used latex balloon and nylastic sleeve. Despite the light weight and relative thin gauge of the nylastic yarn, it produced too much friction for successful inflation of the latex balloon inside. The membrane of the latex balloon was very thin, and the weight of the fabric blocked air flow within it. Even with water-based

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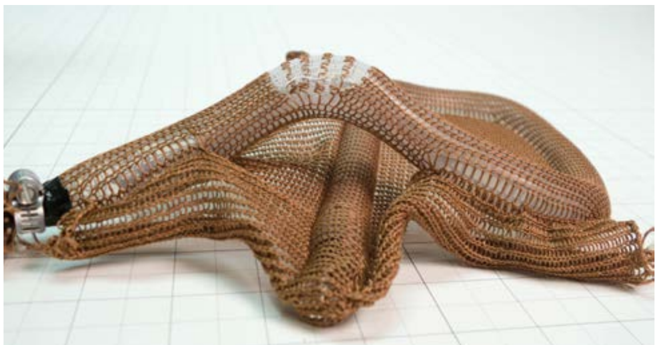

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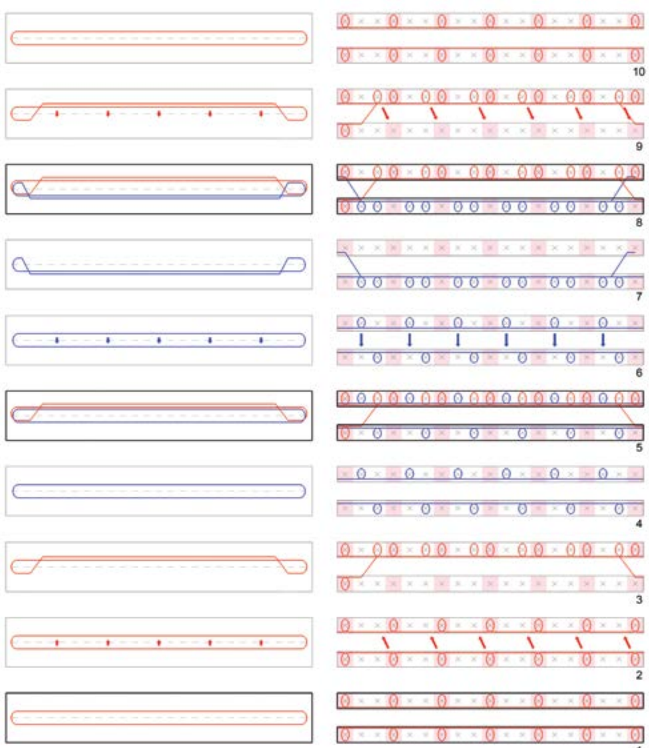

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3 "Soft Robotics Applied to Architecture," (Kim et al. 2015).

4 "Listener," (Thomsen et al. 2009.)

5 Latex balloon and nylastic sleeve.

6 Rubber tube and nylastic sleeve.

7 Bending tests.

8 Regional tests.

8 3D bridge.

10 Needle assignment diagram.

lubricants or soap, smooth continuous inflation was not possible. The sausage effect still persists, as shown in Figure 5. The second half of the first stage substituted the latex balloon with segmented bicycle inner tube. Continuous inflation was achieved, but the nylastic sleeve failed to provide consistent direction of planned bending due to lack of resistance to overall tube (Fig 6).

The second stage used polyester yarn as main material for the inflatable housing. It proved to be consistent in initiating the desired direction of bending. If the knit structure was loose on the top half of the sleeve and tight on the bottom half, the inflated tube would bend downward as the top half would be stretched more. The degree of bending could even be exaggerated with the introduction of nylastic yarn at selected locations. This is shown in Figure 7.

The third stage of the experiment focused on the interaction of the surrounding surface area by the inflated tube. Figure 8 shows that without a custom-knit structure, the inflated tube boundary would expand evenly in a circular manner. With the introduction of alternate miss stitches, every missed stitch reduced the loop length of the fabric to stretch and therefore limited the expansion of the tube boundary to a rectangular manner.

The fourth stage of the experiment focused on ways of ensuring the 3D quality of the future prototype. Figure 9 shows the transformative quality of the layered textile with a bridge-like tube breaking away from the 2D plane. Multiple layer knitting is done by providing additional empty needles for transferring. Figure 10 diagrams the sequencing of needle assignments to achieve multiple layers of free fabric that can share the same area on the knitting machine. Step 1 shows a loop of red yarn occupying every third needle (marked in red) on both beds. Steps 2 and 3 show how the red yarn is transferred from front to back to be deactivated. Step 4 shows the introduction a new independent blue yarn and step 5 shows the location of blue relative to the red. Steps 6 and 7 show the deactivation of the blue by transferring from back to front, while step 8 shows that the machine is now housing both red and blue yarn in four layers of fabric. Step 9 shows the transferring of red yarn from back to front again to be reactivated, and step 10 shows the start of cycle.

RESULTS

The basic prototype design is an assembly of ½ inch internal diameter (5/8 external diameter) silicone tube, as the inflatable bladder (Figure 11), inserted into a seamless custom CNC knit fabric, with the tube house dividing the textile into a 3 x 3 grid configuration (Figure 12). The diagonal rectangles of the 3 x 3 grid, marked in red in Figure 13, are high tensile zones of densely knit stitches that have limited stretch in both x and y axes. The

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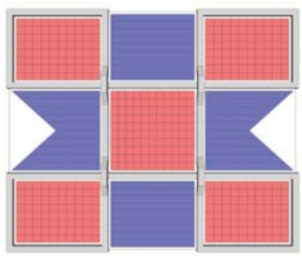

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four middle rectangles on the outer boundary mark in blue (Figure 13) are medium-tensile zones with alternate miss stitches that create limited stretch in the x axis only. When inflated, the 3 X 3 grid boundary area of the tube is allowed for maximum expansion in volume, in order to activate the stretching of the fabric in the various zones. The resistance created by the stretching of the fabric will in return trigger a three-dimensional transformation.

There are three sets of prototypes: A.1, A.2, and B.1. Prototype A.1 is the 3 X 3 grid with emphasis on the 3D arching bridges as a means of bending to actuate the 3D transformation. Prototype A.2 is a duplicate of two sets of A.1 in one seamless textile. The lengths of the 3D bridges are varied in an attempt to differentiate the degree of deformation. Prototype B.1 is similar to A.1 but has an extended layer of fabric from the edges of the 3D bridges in an attempt to generate a pocket space between layers of fabrics.

The initial results of these inflated prototypes without the implementation of custom-knit structures reveal success in hosting the inflated bladder, but a failure to create significant 3D transformation (Fig 14). After adjusting the knit structure by reducting stitches (materials) in the webbed region to increase the tightness in the fabric, all three adjusted prototypes are able to successfully transform from the original 2D set up to a

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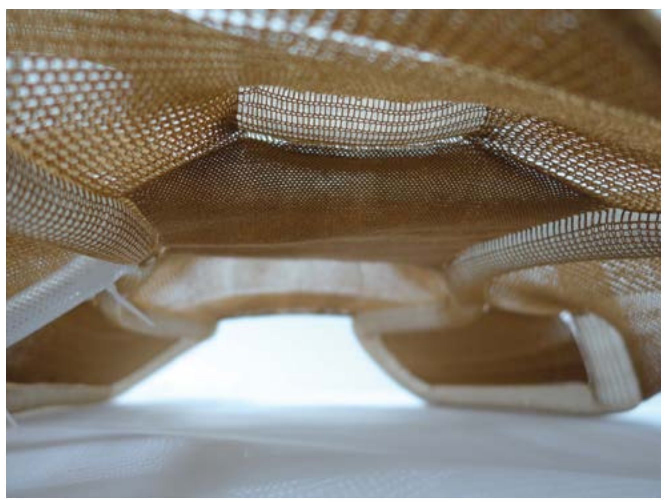

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11 Prototype materials.

12 Tube location.

13 3 X 3 grid division.

14 Inflated prototype without successful 3D transformation.

15 Prototype A.1, top view.

16 Prototype A.1, interior view.

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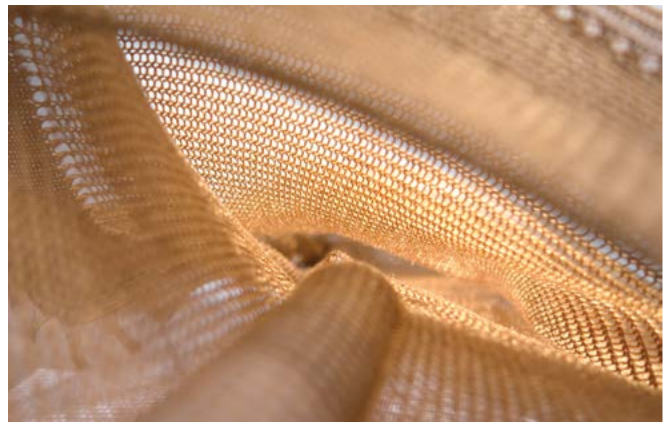

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17 Prototype A.2, interior view.

18 Prototype A.2, top view.

19 Prototype B.1, top view.

20 Prototype B.1, external layering.

21 Prototype B.1, internal layering.

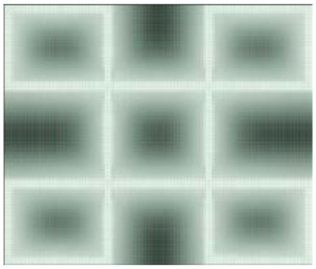
3D structure. Without the knit sleeve, the silicone tube usually shows signs of overstress at approximately 16 psi of pressure by becoming more opaque, but it maintains its integrity inside the knit sleeve to pressures of up to 40 psi without any color change. At approximately 30 psi, the inflated tube shows significant stiffness to support the knit textile lifting parts of the assembly off the ground. It is clear that the original straight orthogonal 3 X 3 grid design transforms under inflation to curvilinear forms.

Prototype A.1 and A.2 demonstrate the effect of the bridging arches in the bending of the overall structure. The longer the bridge, the more bending forces are exerted at the anchoring points.

Prototype B.1 shows how the varied knit structures not only have effects on the tensile behavior of the fabric, but also the transparency of the overall structure (Figure 20).

Computation

The study initially used Kangaroo and Maya Cloth to simulate the pneumatic textile system, but both packages focused on simulation of fabric behavior as a uniform soft body without addressing the possibility of a differentiated structural behavior within the



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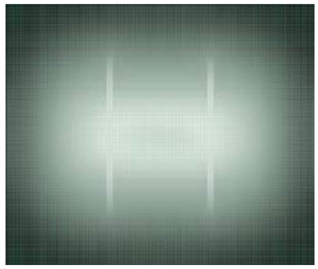

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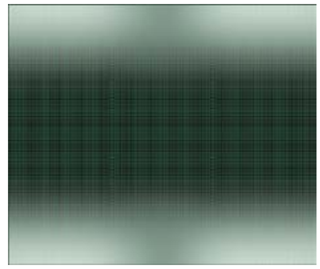

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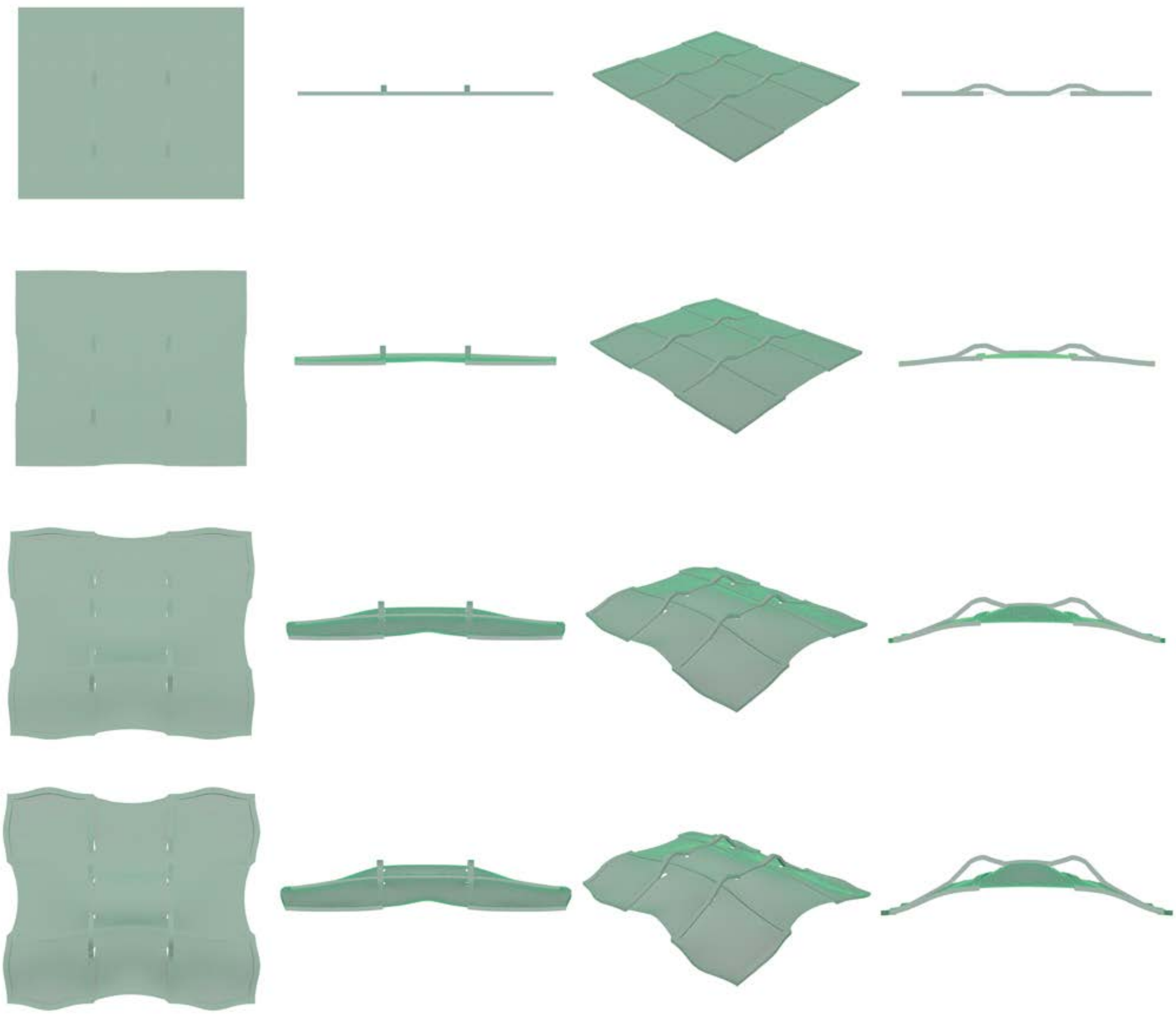
22 Uniform scaling (inflation) map.

23 Upward push (lift) map.

24 Downward sag (gravity) map.

25 Pneumatic simulation with cluster deformer.



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fabric and the continuity of the original linear yarn. Therefore, the project decided to mimic the behavior of the design structure in Maya through the systematic use of cluster deformers.

A geometric model is created in Maya and a cluster deformer is later applied. The cluster deformers generate uniform scaling similar to inflation and effect vertical movement similar to gravitational force. Assigning varied weights to the individual vertices in the geometric model, differentiated mesh movements are generated in response to the same uniform scaling or vertical movements by the cluster deformer. The weight of the deformer is scaled 0.000 to 1.000 and is applied to an individual vertex through a graphic interface of "painting" that has 255 levels of grey (white to black) to mimic the dissipation of the tensile forces. Three clusters are used to simulate inflation (uniform scaling), upward movement by expanding tube (+ Z axis translation), and gravitational pull (- Z axis translation). Figure 22 shows the inflation map were areas of the tube location are at the 100% effective range (white color) of the cluster. The tube area then gradually dissipates toward the center of each rectangle into shades of grey. Figure 23 shows areas of the prototype that will be propped upward during the expansion of the inflating tube. Figure 24 shows the downward drag around the outer edges due to weight of the prototype.

CONCLUSION

The prototypes demonstrate the ability of custom knitting to integrate external elements to form a transformative material system. However, the process of textile design requires many rounds of trial and error until the desired behavior is achieved. The knit textile design process is actually suited for computational design because either the "knit" or "miss" conditions of knitting are similar to the binary conditions of 1 or 0. Computing will resolve the different shades of grey between black and white similar to the way that knit fabric redistributes its applied forces. Figure 22 attempts to show how areas of different fabric density respond differently to the stretch caused by the same inflated tube. The tedious task of measuring the individual stitch spacing will eventually lead to the rendering of mathematical equations that describe the force dissipation by the linear yarn of the fabric. Data gathered from the analogue model can feed into the design of a more accurate computational model.

Immediate advancements in the pneumatic textile system can be obtained with more experiments with different yarn materials, different geometric patterns of bladder inflation implementation, or even the use of the custom textile as soft formworks, since casting plaster or concrete can lead to stretching in a manner similar to inflation.

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Thomsen, Mette Ramsgaard, Martin Tamke, Phil Ayres, and Paul Nicholas. 2015. *CITA Works*. Toronto: Riverside Architectural Press. 178.

IMAGE CREDITS

Figure 3: Soft Robotics Applied to Architecture, Kim et al., 2015
Figure 4: Listener, Thomsen et al., 2009
All other figures: Wang and Alquist, 2016

Adam Wang graduated from the University of Michigan with an MS in Architecture, with a Material Systems concentration, in 2016. Prior to Michigan, Adam received a B.Arch from the University of Kentucky and has worked in the field of architecture both in the United States and Asia for the past 10 years.

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