Self-Shaping Mechanisms
Prototyping of PneuKnit Systems

by

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Bachelors of Architecture
American University of Sharjah, 2017

Submitted to the
Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Architecture Studies

at the
Massachusetts Institute of Technology

May 2022

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ABSTRACT

Our surroundings are constantly in flux, whether it is changes in the environment or changes in those who inhabit it. However, most of our spaces and building components are designed for permanence and durability without acknowledging the nuanced fluctuations of the user's behavior, lifestyle, or changes in the natural environment. The strive for building permanence, designed to resist change, contributes to the 100 million tons of wasted materials annually due to recurring renovations and remodeling that inevitably addresses these fluctuations. What if our parts were active and could sense, react, respond, adapt, and co-evolve with their inhabitants and surrounding context? Rather than building with static dormant components, this alternative presents us with opportunities to advance the built environment and rethink its interrelations with its users and its context, resulting in spaces that are performative and attuned to user needs.

This thesis seeks to develop a typology of lightweight adaptable systems that are rapid and affordable to manufacture. It investigates the fabrication of responsive self-actuating mechanisms; specifically, hybrid pneumatic-knitted (pneu-knit) systems that are autonomous and adaptable to changes within the environment through embedded sensors. The integrated sensors detect the input stimuli–in this particular case study user proximity–transmitting the data to a signal processor and interpreter, which then generates output values for the air pressure settings. This acts as a direct informer and physical shaper of the pneu-knit system, whereby the differentiated shaping generates through the structure and the design of the pneumatic component. The contributions of this work include developing a fabrication framework and method to integrate the knitted, pneumatic, and sensing components for the assembly of affordable, adaptable, lightweight material systems that are attuned to their surroundings.

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ACKNOWLEDGEMENTS

I would like to acknowledge and extend my deepest gratitude to my advisors, mentors, peers, friends, and family who've helped shape my thesis and my MIT experience.

Thank you, Caitlin Mueller, for being a thoughtful mentor, educator, and advisor – you've provided invaluable guidance for this thesis, my time at MIT, and beyond. I'm sincerely grateful to have had a wonderful mentor to look up to and to learn from. You have played a significant part in my MIT experience and in shaping the way I think today, and for that I am grateful.

Thank you, Skylar Tibbits, for your insightful guidance, honesty, feedback and for inspiring many aspects of this research.

Thank you, Ozgun Kilic Afsar, for your time and invaluable discussions that helped shape this research.

Thank you, Svetlana Boriskina, for your time and enthusiasm on the research.

Thank you, Joann Lee, for your incredible insights into the world of knitting, you have been an amazing resource and I'm sincerely grateful to have learned from you.

Thank you, Ali Shtarbanov, you've been an incredible resource and I've learned a lot from you.

Thank you, Terry Knight, Brandon Clifford, Yoel Fink, Larry Sass, and Elizabeth Meiklejohn, for being sources of inspiration at MIT. I'm grateful to have learned from you.

Thank you, to my wonderful friends, for your support, energy, and enthusiasm throughout my thesis and my MIT experience. You've been a source of light on the dimmest days. Thank you, Khushi Nansi, Latifa Alkhayat, Kimball Kaiser, Meriam Soltan, ShanChun Wen, Ibrahim Ibrahim, Saad Boujane, Salwa Alkhudairi, Rania Kaadan, Nada Almulla, Rui Wang, Deborah Tsogbe, Sarah Mokhtar, Nada Tarkhan, Amira Abdelrahman, Demircan Tas, Rohit Sanatani, Myles Sampson, Lavender Tessmer and the rest of the SMArchS family.

Thank you, to my family for their constant support over the years – Mom, Dad, Fajer, Falah, Fatima, Abdulla, and Noora.

Contents

1 INTRODUCTION

1.1 Permanent Temporality & Temporal Permanence

Our surroundings are constantly in flux, whether it is changes in the environment or changes in the species that reside within it. Living organisms across scales, ranging from cells, insects, plants, animals, and ourselves, are provided with a set of sensorial tools to achieve adaptation in response to their environment and as a means for auto-preservation. (Zulas, 2004)

With change being a constant since the beginning of time and permanence being temporary, our buildings still fail to address the nuanced daily, seasonal, or yearly variabilities in user lifestyle, user behavior, or context. Buildings that are designed for permanence are inherently designed to resist change; however, due to that very reason buildings undergo invasive methods to introduce the inevitable adaptation, which consists of demolition, expansion, renovation, and re-construction. This contributes to the 100 million tons of waste materials generated annually, disrupts the daily activities of the building residents, is time-consuming, and costly. (US EPA, 2016)

Therefore, our building materials must be rethought as adaptable responsive organisms. Rather than building with static dormant components, what if our parts were active and could sense, react, respond, adapt, and co-evolve with its inhabitants and surrounding context? This presents us with opportunities to build with systems that exhibit unique states as opposed to building with unique one-off parts. This allows us to advance the built environment and rethink its interrelations with its users and its context, resulting in spaces that are performative and attuned to user needs. In that sense, the built environment can be perceived as a continuously evolving space, co-created by its occupants and context.

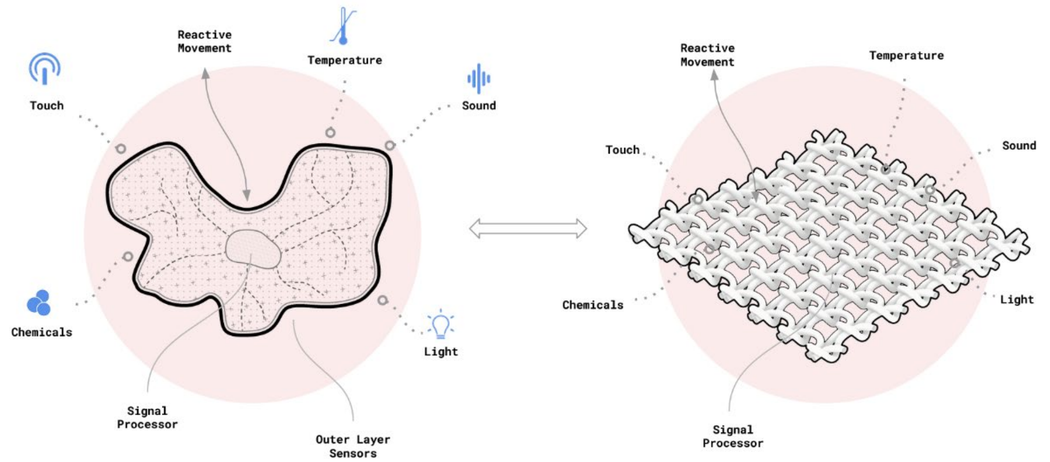


Figure 1. left: single cell, example of responsive organism, right: smart responsive knitted structure.

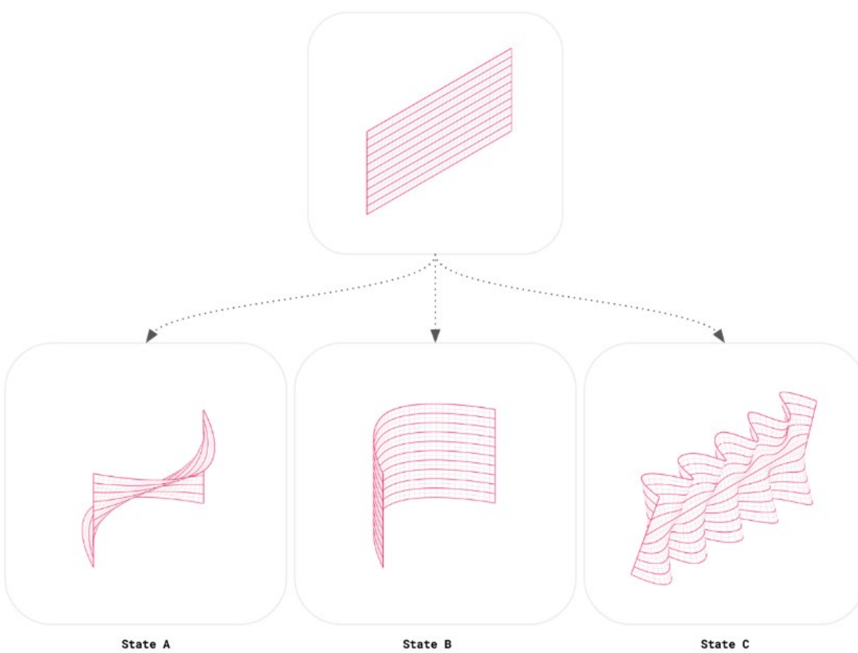


Figure 2. diagram illustrates varied configurations and states within one unique artifact.

1.2 Research Vision and Scope

Adaptation has been a topic of interest in the field of architecture and investigated under many different lenses, whether engineering highly specific materials that are responsive to a single stimulus, designing reconfigurable spaces that are dependent on humans to reconfigure them, or designing mechanically driven systems that are complex and require various discrete parts and connections.

This thesis seeks to formulate a generalized adaptable system that can be implemented for on-demand response to various stimulus, can be self-reconfigured (eliminating the need for manual labor or configuration), and requires minimal discrete parts for adaptability. The research outlines a framework for the development of lightweight adaptable systems that are rapid and affordable to manufacture. It investigates the fabrication of responsive **self-actuating mechanisms**; specifically, **hybrid pneumatic-knitted systems** that are adaptable to changes within the environment through embedded sensors.

A set of constraints is imposed on the research framework as follows:

- For the actuation system to utilize off-the-shelf materials, open-source libraries, and software. Thus, allowing for reproducibility of the system in different contexts beyond a specific institute or lab.
- For the shaping mechanism to be reversible, allowing for multiple states or configurations to exist within a single entity.
- For the fabrication and material system to be scalable and exhibit structural qualities to be implemented in architectural applications.

In regards to the adaptation timeline, this thesis follows Frank Duffy's concept of "Shearing Layers", whereby the focus is on a daily/monthly adaptive framework. This translates to building components that require regular adaptations, such as outdoor roof deployments or adjustable façade skins to be discussed in a later section. (Milwicz & Pasławski, 2018)

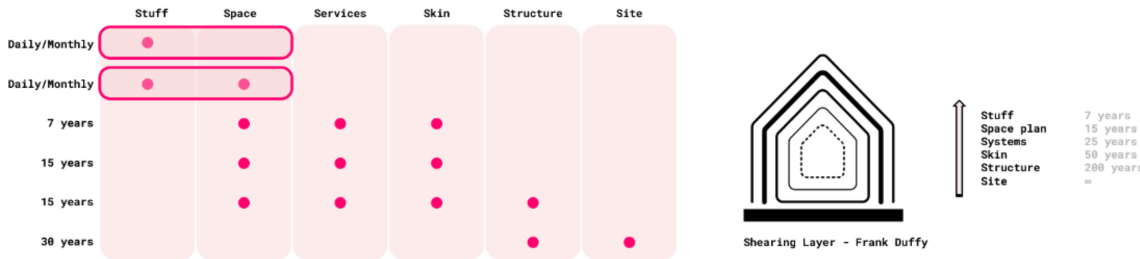


Figure 3. *frank duffy's shearing layers of change.*

The research is broken down into three categories:

1. Self-Shaping Actuation Mechanism
2. Integration of Actuator
3. Sensing and Information Exchange

The first section introduces the actuation mechanism used, providing a historical and application overview, as well as design opportunities that are possible with the developed material system. The second section tests, evaluates, and identifies the most feasible method of integrating the actuator into a flexible material system. Lastly, the third section highlights strategies for embedding responsiveness to the material system which would allow for it to self-actuate through the integration of sensing fibers and the utilization of an air control unit.

2 ACTUATION MECHANISMS

2.1 An Intro to Self-Shaping Systems

Self-shaping or shape-changing materials are autonomous material systems that can operate with minimal human or machine intervention. The system moves from one geometric state to the other once triggered by an external stimulus (change in temperature, humidity, etc..). This transformation is a result of encoding digital information into the material, translating logic of formation into the physical environment.

Research on adaptable self-shaping systems explores a multitude of materials ranging from hydrogels, composites, photopolymers, shape memory alloys (SMA), and shape memory polymers (SMP). The most prominent research has been done at the Self-Assembly Lab and the Tangible Media Group at MIT, Morphing Matter Lab at Carnegie Mellon, the Wyss Institute at Harvard University, and by Achim Menges from the Institute of Computational Design (ICD) at Stuttgart.

One of the biggest challenges in self-shaping materials is scale, structure, cost, and speed of actuation or shaping. For instance, the self-shaping of Hygroshape and similar multi-material printed research at ICD requires a few hours for the shaping to be realized and in that case, is able to respond to one specific stimulus which is humidity. As such, the developed system cannot be customized to respond to different stimuli to trigger the self-shaping and is limited to a small number of pre-determined and engineered forms. (*HygroShape*, n.d.)

On the other hand, projects like uniMorph from the Tangible Media Group (Heibeck et al., 2015) or 4D printed shape-shifting hydrogel from the Wyss Institute (Sydney Gladman et al., 2016) exhibit a much faster response rate; however, in both cases, the materials used lack the structural capabilities to be implemented architecturally and is therefore difficult to scale up.

Consequently, this thesis aims to develop a generalized rapidly adaptable framework that does not rely on the engineering of the material for responsiveness, in that sense, it is not limited to a definite trigger but in fact can be in dialogue with multiple stimuli in accordance with the integrated sensors and can demonstrate various states and configurations. In addition, it is imperative for the developed system to implement off-the-shelf commercially available materials that are affordable, easily manufactured, rapidly deployed, and scalable. In consideration of the aforementioned criteria, pneumatic composites have been selected as a feasible material system that addresses the considerations and goals of this research. So how did these pneumatic composites come about, how have they been applied, and what can we do differently?

2.2 Overview of Pneumatic Composites (Mckibben Muscle)

2.2.1 Pneumatic Composites Across Scales

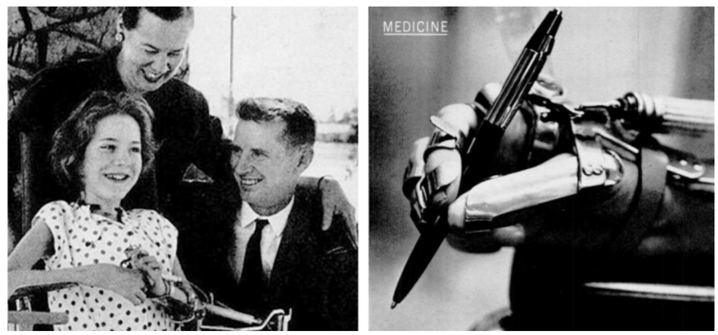


Figure 4. *left: Joseph L. McKibben with his daughter, right: close-up of assistive device.*

These particular pneumatic composites have been coined as pneumatic artificial muscles (PAM) or Mckibben muscles. They are lightweight axial actuators that were first invented in the 1950s by physician Joseph L. McKibben as an orthotic appliance for polio patients. PAM is typically composed of two layers: a synthetic rubber tube and an envelope of braided fibers; where the two layers are fitted with metal caps at each end. One of the main features of PAM is converting pneumatic power to a pulling force, high force to weight ratio, low pressurized air consumption, and variable installation possibilities. PAMs have a wide range of applications most prominently in soft robotics as they emulate the physiology of the compliant muscles and tendons, with additional applications in the fields of medicine and aerospace. (Andrikopoulos et al., 2011)

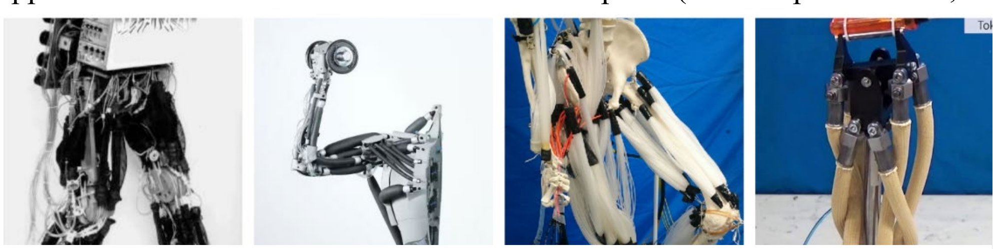


Figure 5. *Biorobotic applications of PAM. From left to right: Shadow Biped Walker by David Buckley, Airic's Arm by Festo USA, Multifilament Muscles by Suzomori Endo Lab, and Hydraulic AM for Tough Robots, Suzumori Endo Lab.*

Recent advancements include the development of very thin pneumatic composites. This is apparent in OmniFiber from the Media Lab at MIT and Active Textile from the Tokyo Institute of Technology.

OmniFiber is a reconfigurable fiber actuator based on fluidic artificial muscles, it exhibits a range of morphing states such as coiling, extension, contraction, and bending. The thin fluidic artificial muscles (ø *outer* < 1.8 mm) can be integrated into haptic devices, remote communication through tangible interface, and robotic expressivity. The fluidic artificial muscle is thin enough to act as an actuated fiber that is weaved and knitted into a fabric structure. (Kilic Afsar et al., 2021)

Figure 6. *left: Active Textile, Tokyo Institute of Technology. right: OmniFiber, Tangible Media.*

Similarly, **Active Textile** utilizes thin Mckibben muscles that are weaved through a textile, acting as an actuation mechanism. The actuated textile is implemented within the domain of wearable robots, musculoskeletal robotics, and robotic structures. (Wang, 2016)

Figure 7. *Work by the* ***HyperBody Research Group*** *- left to right: Muscle Tower 1 + 2, NSA Muscle, The Muscle Body.*

Spatial implementation of these pneumatic composites can be seen in projects developed by the Hyperbody Research Group at TU Delft. Over the years they've produced a series of interactive spatial and sculptural prototypes which integrate the air pressurized actuators into tensile surfaces such as the NSA Muscle, the Muscle Body, the Muscle Space, and the Muscle Facade. These spatial installations have a pre-determined fixed shape in which subtle deformations are introduced through the actuators such as actions of hopping, contraction, and twisting that would respond to sensor inputs. (Oosterhuis & Biloria, 2008)

Muscle Tower 1 + 2

The muscle tower is approximately 6 meters high, consistent of thin aluminum rods, galvanized steel spheres, and Festo muscles (actuators). The starting position of the tower is upright and makes use of a half-inflated muscle and can twist and deform up to 1.2 meters outside of its center. The tower provides an insight into how built structures can be e-motive and responsive to real-time. (Oosterhuis, 2012)

NSA Muscle:

The NSA muscle is a responsive inflated space, consistent of 72 pneumatic actuators controlled independently, and 24 sensors placed at reference points on the tensile surface. The data collected through the input devices converts human behavior into parameters for change in the audio and the form of the space by varying the length of the air muscle. (Oosterhuis, 2012)

Muscle Body

The Muscle Body is an interactive installation of an interior space. The space is based on a single 80m spiraling tubular element. The installation is a soft volume composed of stretchable lycra fabric and 26 Festo muscles that contract and relax. Each actuator is individually controlled, and thus the varying pressure allows for a change in the height, width, and overall form of the installation. The behavior and movement of the users serve as the input to which the actuators would relax and contract affecting the overall form. (Oosterhuis, 2012)

On an industrial level, A&P Braiding technology has utilized this pneumatic composite at a larger scale with structural capabilities such as the AirBeam and Composite Bridge Arch. The AirBeam structure developed at Solon, OH is used for framing aircraft maintenance hangers and is strong enough to lift a suspended car. This system utilizes highly oriented fiber reinforcement to create a high bending stiffness and high inflation pressure air beam. (*HDT Vertigo*

Figure 8. *left: composite bridge arch right: airbeam.*

Inc. | A&P Technology, n.d.) Another development of A&P braiding technology is the Composite Bridge Arches with the goal to reduce the cost of steel-reinforced concrete in bridge structures, more specifically the cost and time of bridge assembly. The braided structure is inflated and then infused with resin to create a composite onto which concrete is cast. (*Composite Bridge Arches | A&P Technology*, n.d.)

This overview demonstrates the wide range of applications possible by using simple, affordable, readily available materials. This material assembly exemplifies promising implementations across scales, from soft-wearables to air beams that are strong enough to replace steel-reinforced concrete. So, what can be done to further advance this material assembly and how can we contribute to this domain?

2.2.2 Further Developments

The previous section illustrates a wide range of applications of the pneumatic composites. In most spatial precedents shown, the pneumatic composites only utilize linear contraction for subtle movements on a fixed predetermined shape, or the material transforms to a fixed state. This thesis aims to utilize the pneumatics in a manner to allow for reversible shape-shifting to occur, whereby the system has the ability to transform from a flat sheet to a 3D artifact and vice versa. In addition, the research seeks to develop a material framework that allows for multiple configurations/states to exist within one entity, meaning a single entity has the ability to transform into multiple different shapes, therefore making the system truly reconfigurable and adaptive. This thesis exemplifies a step-by-step construction of the developed system, the utilization of contracting, bending, and extending versions of the pneumatic composites, and various means of integration into a flexible system to allow for self-actuation.

2.2.3 How It Works

Figure 9. *pneumatic component: silicone tube deflated and inflated state.*

The pneumatic composite is an assembly of various components, at its most basic level, it is consistent of a rubber or silicone tube encased in a sleeve. Once inflated with pressurized air or liquids, the tube expands radially. Without the addition of the sleeve, the tube will continue to expand behaving like a balloon as shown in the figure above. The sleeve aids in restricting the radial expansion and thus causes the composite to shrink linearly. Once deflated the outer mesh behaves as a spring restoring the deformed tube to its original form. (Andrikopoulos et al., 2011)

The aforementioned sleeve is composed of continuously interlocked fibers usually of two or three orientations. For the precedents shown above and the scope of this research, biaxial braided tubes are implemented. They are composed of two fiber orientations and are comparable to the Chinese finger trap, whereby the diameter reduces as the structure is pulled along its length.

Since the fibers are continuous, this allows for the even distribution of loads throughout, as a result, the structure is impact resistant and can use large amounts of energy in the instance of failure. These structures are found in fan blades within commercial aircrafts and in formula one racing cars for crash absorption. Additionally, since the fibers are weaved on bias, they are able to reinforce areas that are subjected to torsional loads. (Braid Basics | A&P Technology, n.d.)

The actuation behavior is highly dependent on two factors: the durometer of the rubber tube and the structure of the braided sleeve. For example, the lower the durometer the higher the actuation whether it's contracting, extending, or bending, and vice versa. This particular research utilizes 40A durometer tubes. Meanwhile, the braided sleeve structure is impacted by the braid length, angle, diameter, and expansion ratio. Since the braided sleeves are commercially sourced, fiber customization is not possible and is beyond the scope of this research. (Andrikopoulos et al., 2011)

3 PROCESS

3.1 Pneumatic Composite Types and Assembly

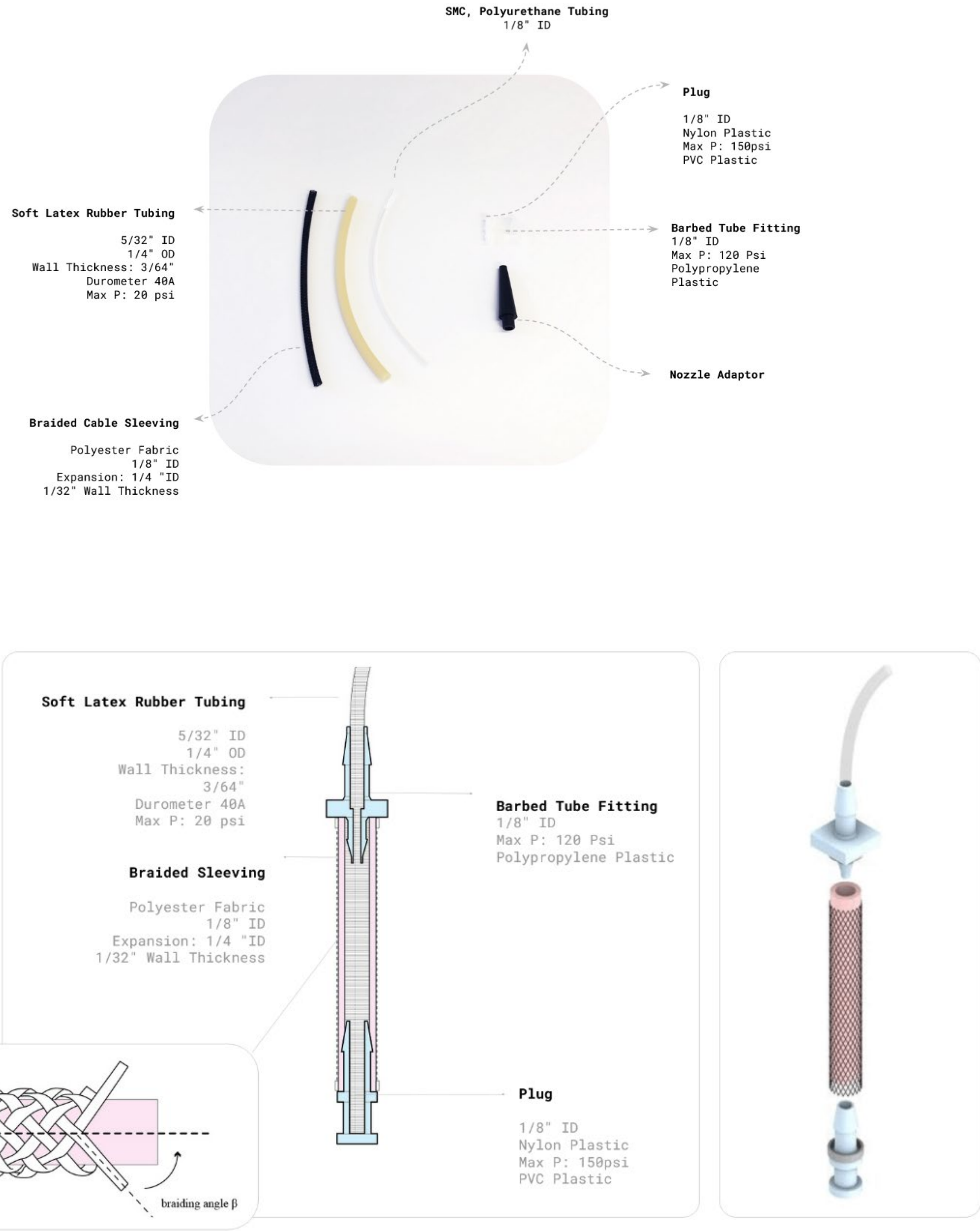


Figure 10. pneumatic composite kit of parts.

Figure 11. type of braided sleeves used - from left to right: regular braid, post-processed braid for extensible pneumatic, braid with rigid material insert for bending pneumatic.

Three types of pneumatic composites have been explored: contraction, extension, and bending. The following section describes the assembly process and components required to achieve each behavior. All components and materials have been sourced from Amazon and McMaster.

Contraction:

Contraction is the simplest behavior of the three, requiring the least number of components and no post-processing of any of the materials. At its most basic level, it requires a silicone tube which is encased in a biaxial polyester braided sleeve and capped with barbed tube fittings.

Extending:

To achieve the extensible pneumatic, the braided sleeve must be post-processed by pushing the sleeve downwards along a metal rod and securing it to create crimps. While it is at that state, it must be baked for about 20 minutes at 250 degrees Celsius. This process bakes in the memory of the crimped geometry into the fiber. As the silicone tube expands radially, it adds pressure on the crimped fibers pushing on the sleeve in all directions. This pressure flattens the crimps hence extending the overall tube linearly when actuated.

Figure 12. left: contracting composite, right: extending composite.

Bending:

The bending pneumatic follows the assembly of the contraction pneumatic but with an additional component. A simple inelastic yet flexible stiffener is added in-between the sleeve and the tube. This restricts the expansion in a radial axis and allows for bending to occur. According to where the stiffener is added, a wide range of 2D and 3D bending motions can be achieved as illustrated in the diagram below.

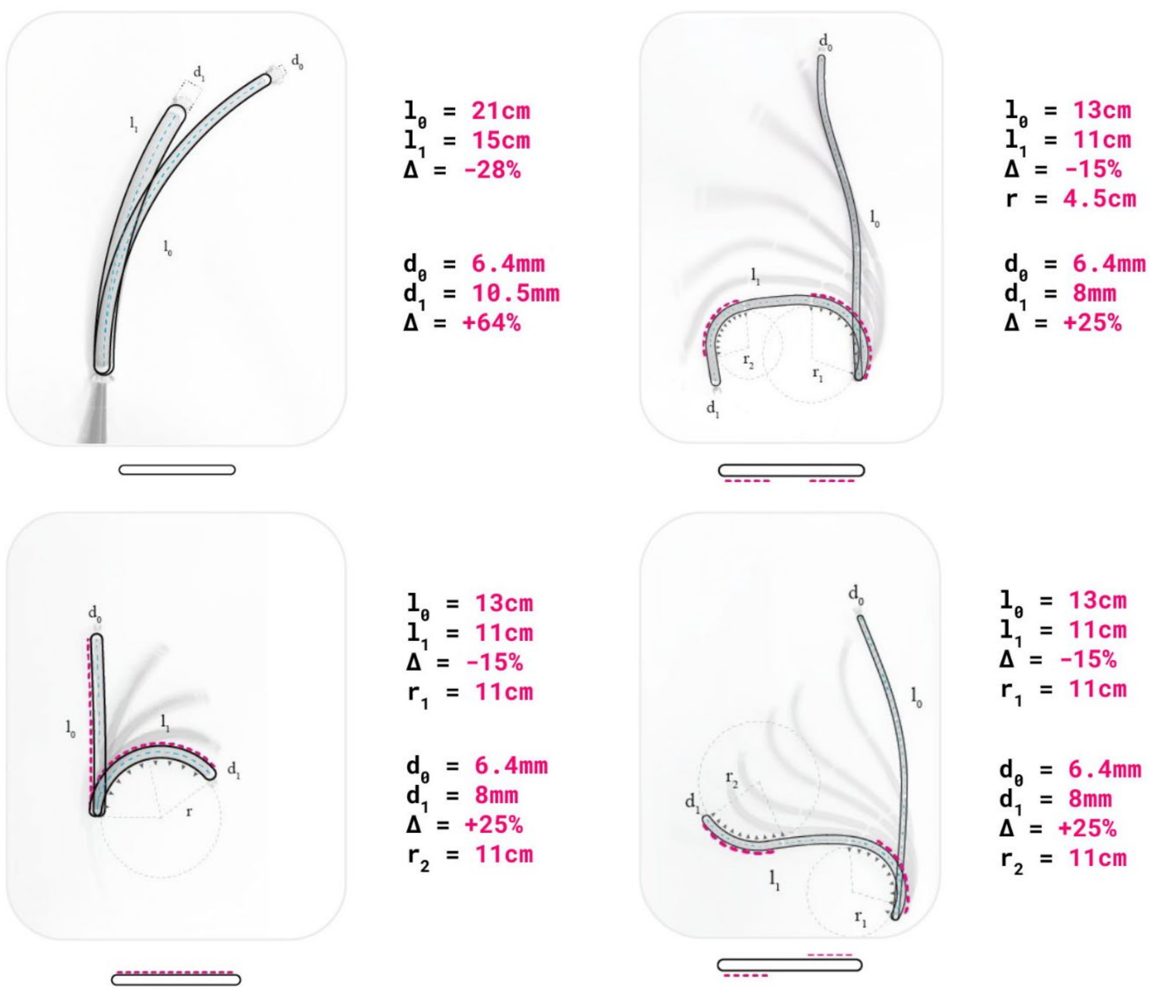
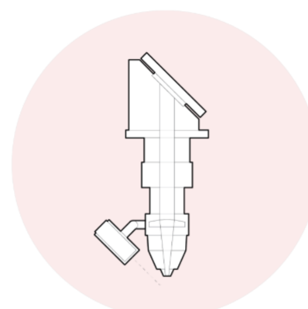


Figure 13. bending pneumatics directory.

3.2 Embedding Pneumatic in Tensile Surfaces

Three strategies were explored in integrating the pneumatic into the tensile surface: cutting + adding, weaving, and knitting. The criteria for evaluation included the speed of the fabrication process, ease of customization, and ease of integration of the pneumatic and sensing component. After testing and evaluating each of the mentioned methods, it was concluded that knitting, specifically using a double-bed machine would be the most efficient in accordance with the outlined criteria. The sections below highlight the fabrication process, the opportunities, and limitations of each method.

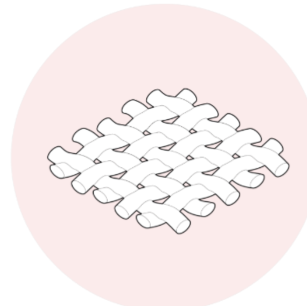
3.2.1 Subtract and Add



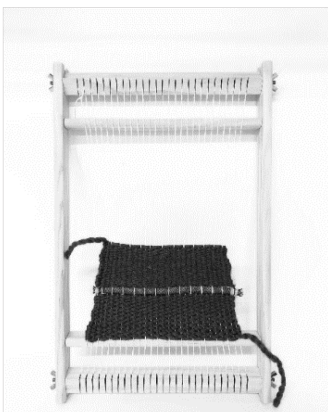
Instead of constructing the fabric from scratch, this exploration uses commercially available textiles. A series of slits are cut through the fabric either by hand, using the laser cutter, or the zund machine. To integrate the pneumatic, it is manually weaved through the slits. One of the limitations encountered with this strategy is that this system only works with thick, rigid fabrics such as felt, as the thinner more elastic fabrics such as lycra are too feeble and delicate for the actuation to have any kind of defined shaping. The drawback of using thicker textiles with the pneumatics is motion resistance, in particular to bending. As such, the globalized geometry of the fabric is misshapen with many undesired lumps forming in between the pneumatics. In addition, the integration of the pneumatic component is laboriously intensive, as it requires manual weaving, in and out of every distinct slit. Therefore, this fabrication method is regarded impractical and does not satisfy the criteria outlined in the earlier section.

Figure 14. *actuated prototype.*

3.2.2 Weave



The second strategy explores weaving. Weaving is the production of fabric by intertwining two sets of yarns so that they cross each other perpendicularly using a hand or power-operated loom. There are three basic weaves: satin, twill, and plain. In this particular exploration, a small hand-operated wooden loom (9.85" x 15.75" x 1.3") is used to create a plain weave. Plain weaves are produced by passing each row of weft yarn over and under each column of warp yarn in an alternating fashion. (*Textile - Basic Weaves | Britannica*, n.d.)



The pneumatic component is weaved through in the weft direction, passing it over and under each warp yarn. This results in a very well secured binding; however, some of the limitations encountered included lack of customization of the overall weaved fabric, inability to remove or exchange the pneumatic component once integrated, and finally lack of concealment of the pneumatic which causes exposure to damage. Therefore, this fabrication method is regarded impractical and does not satisfy the criteria outlined in the earlier section.

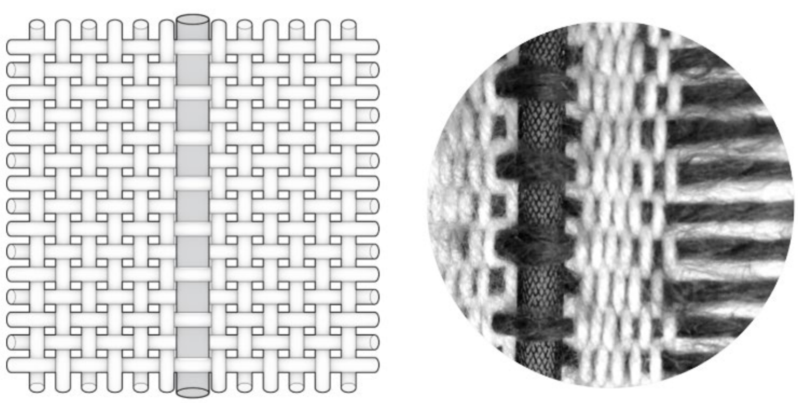


Figure 15. *left: pneumatic integration diagram, right: close-up of pneumatic integration.*

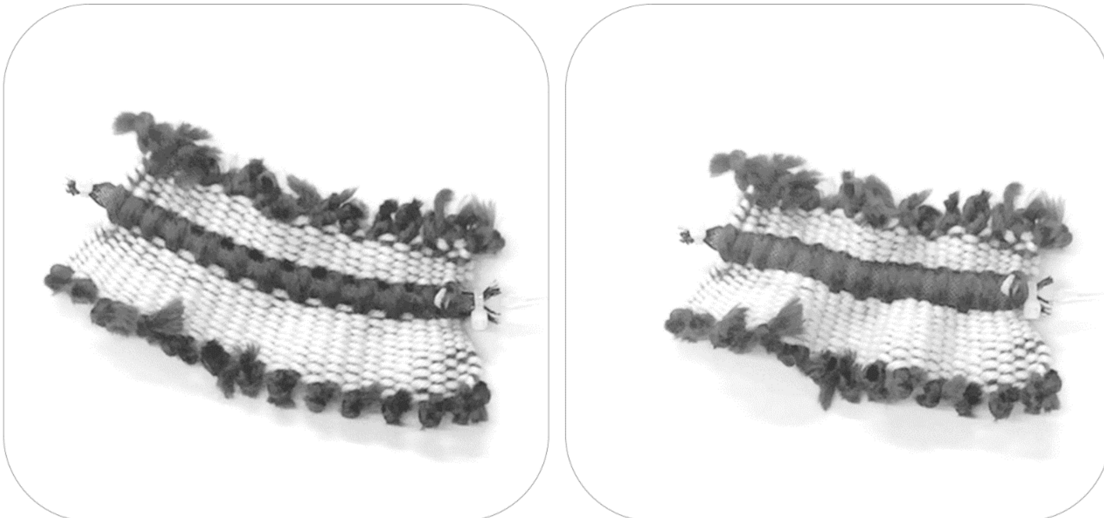
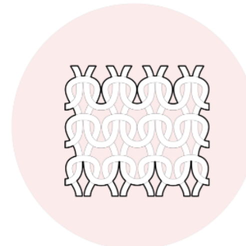


Figure 16. *actuated weaved prototype using contracting pneumatic.*

Figure 17. *actuated weaved prototype using bending pneumatic.*

3.2.3 Knit



The third exploration implements knitting, where both a single and double bed knitting machine were tested. Knitting is an additive fabrication process that utilizes needles to form a series of interlocking loops of one or more continuous yarn. (*Knitting* | *Textile* | *Britannica*, n.d.). This process allows for customization on the micro and macro scale, ranging from the local stitch length and type to the global fabric form.

A flatbed and double bed machines were tested, examining the fabrication process of the knit, the creation of channels for pneumatic integration, and sensor integration as follows:

1. **Single Flatbed** (Silver Reed SK280):
   a. **The Knitting Process**
   The first step before knitting on a flatbed is to ensure the machine is set up properly and the yarn is threaded through the Auto Tension and Tension Dial. Once that is done, the yarn must be added onto the bed through a process called an **e-wrap cast-on**; where stitches are manually wrapped around the needles counter-clockwise. This step is followed by sequentially moving the carriage back and forth across the bed until a desired row of stitches is achieved. To finish off, the final step is to **cast-off** or bind-off the knit, this is a critical step as it prevents the knit from unraveling by creating an end to the structure. This step requires the user to manually close off each stitch individually, although tedious at the start with practice it becomes a fast process.

   b. **Pneumatic Integration**
   The air tube integration into a knit requires hollow channels to be created. The process of creating channels on a flatbed machine requires the manual transfer of stitches from one needle to another in order to close the channel, this was a slow and labor-intensive process requiring meticulous handling. During the transfer, if a stitch accidentally falls off of the needle latch, the knit unravels prompting a redo of the entire cast-on knitting process.

Figure 18. top images: process of transferring each stitch to create a channel, bottom images: knit sample with channel.

c. Sensor integration

The flatbed machine only allows for the integration of conductive yarn by mixing it with an existing yarn as shown in the figure below. Some issues faced with blending the two yarns was a difficulty in knitting unless the tension dial was set on a high number which results in a very loose and stretchy knit. The looser the knit, the more difficult it is to actuate with the pneumatic composite.

Figure 19. close up of knit sample with conductive yarn.

Although the flatbed machine allows for customization on both the macro and micro scale, challenges were faced when fabricating the channels and integrating the sensing yarn. Therefore, the double-bed knitting machine was tested next.

2. **Double Bed** (Silver Reed SRP-60N Ribber):

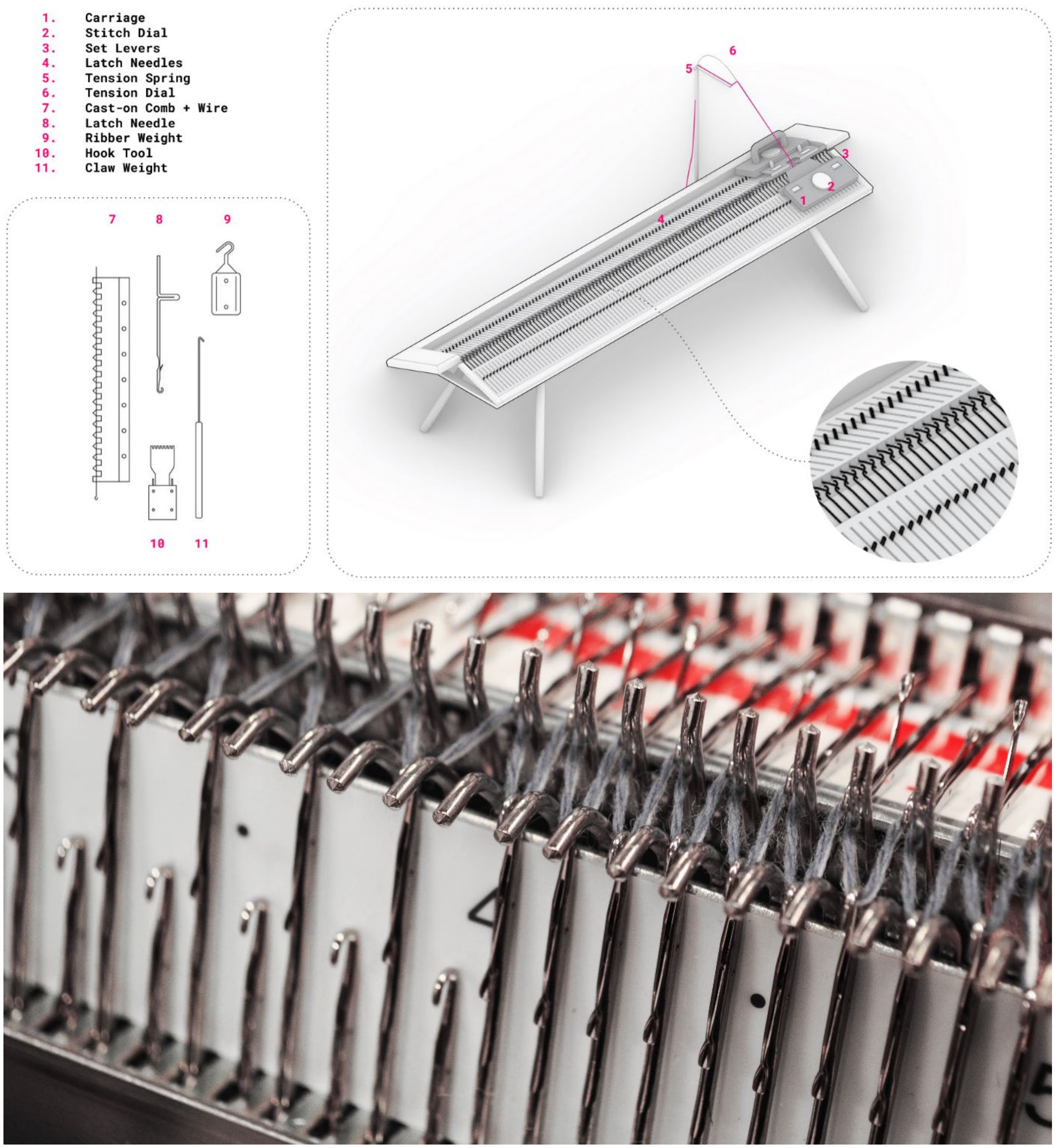


Figure 20. *top left: double bed machine knitting tools, top right: double bed machine model, bottom: close-up of the double-bed machine with both beds engaged.*

The double bed is a knitting machine with two beds of needles (front and back). The beds are in an inverted V shape so that the knitted fabric is formed with the yarn evenly tension between the beds.

a. The Knitting Process

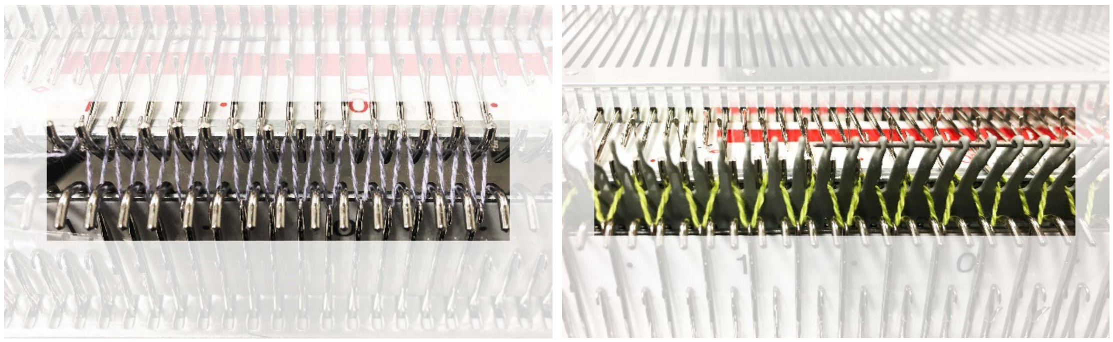


Figure 21. left: initial cast-on process, right: cast-on comb while wire is being inserted.

Similar to the single bed, the machine must be set-up and yarn threaded. The **cast-on** process on the double-bed machine is straightforward and quick. Done by simply pushing the needles on either bed forward, threading the yarn into the yarn feeder, then moving the carriage from right to left. This motion automatically hooks the yarn into the knitter and ribber needles.

The final step for the cast-on is to suspend the cast-on comb with weights from the stitches formed. That is done by inserting the comb between the knitter and ribber, then pushing it upwards until the teeth of the comb are between the stitches formed. Next, a wire is inserted through the holes of the comb to secure it in place. Once that step is done, we can start to knit regularly until a desired length/number of stitch rows is achieved.

As for the **cast-off**, it is a two-step process. First, we need to transfer every ribber stitch to the corresponding knitter needle using a double-eye transfer tool, the next step is similar to that of the single-bed.

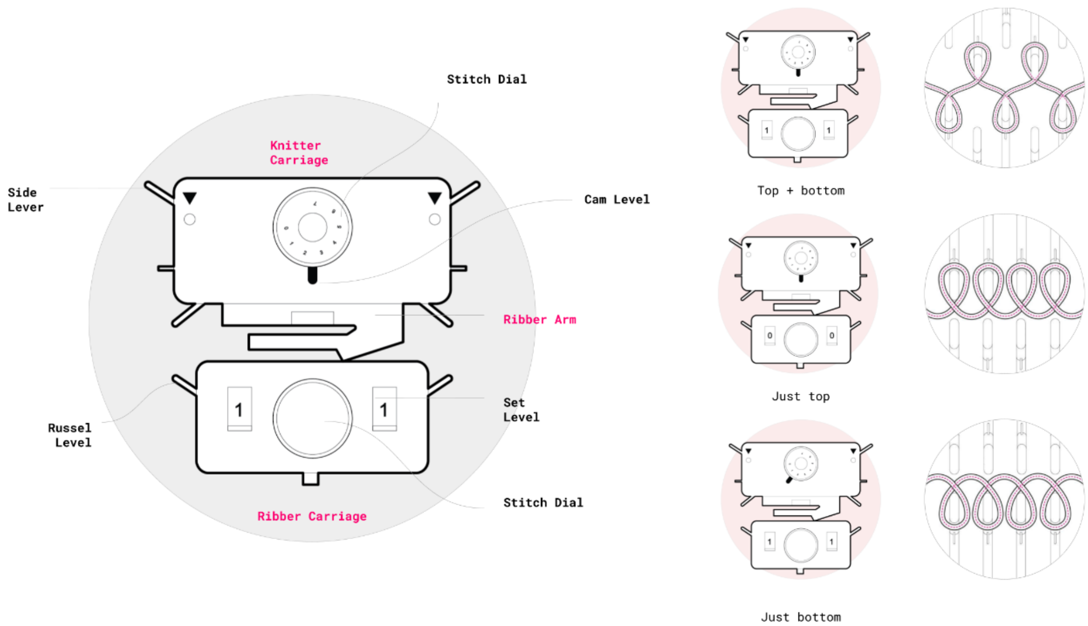


Figure 22. machine configuration for having either bed engaged(active) or both engaged.

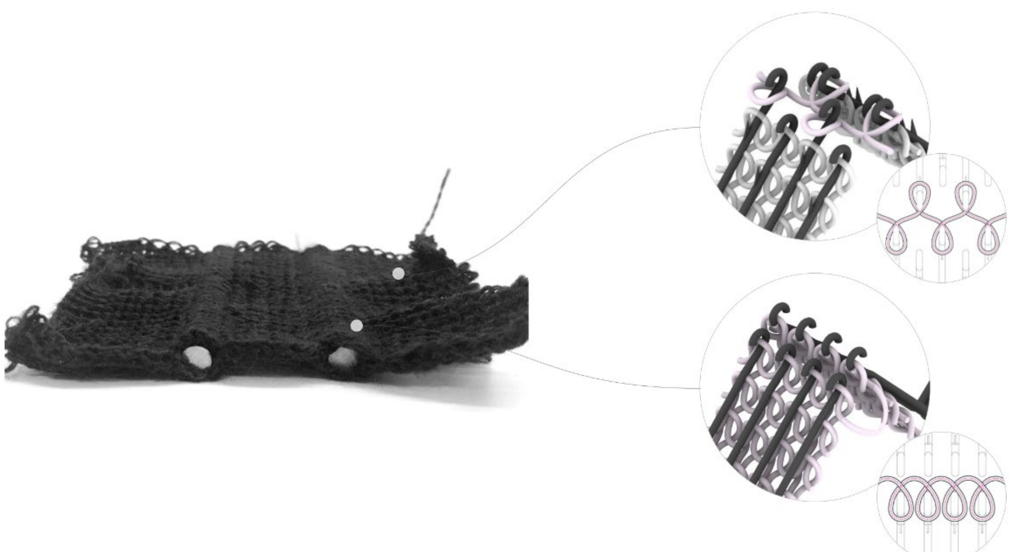


Figure 23. knitting technique for different zones of the textile.

b. Pneumatic Integration

Similarly, to integrate the pneumatic component, channels must be created. Fabrication of the channels using the double bed machine is significantly simpler than the flatbed, requiring only switching of the set levers and the pick knob. For starters, to create a regular full rib knit, both levers much be switched to 1 and the knob pointing towards the middle, in this case, both the front and back needles are in use. The yarn travels from the needle on one bed (front) to a needle on the other bed (back).

To create the channel, the front and back beds should be active and independent from one another, starting with activating the back bed and deactivating the front bed by setting both levers at 0 and rotating the knob to the (-) sign. This allows the knit to be continued on one bed (back), once the required length is achieved the back bed is deactivated with the front activated, this creates a knit on the front bed leaving us with a Y knit.

To close the loop, we switch back to having both beds activated similar to how we started, and continue moving the carriage back and forth until the desired length is achieved. To take off the knit, a simple cast-off is required.

c. Sensor Integration

The double bed machine allows for the integration of both, conductive yarn and conductive fiber (slightly thicker in diameter). For this test, a conductive fiber with controlled elasticity is used. This particular conductive fiber was produced by FIBERS@MIT. The conductive fiber is composed of a buckled 50µm copper wire in a hollow COCe (Cyclic Olefin Copolymer Elastomer) channel. The buckling of the wire creates an elastic fiber that is critical within the fabric construction process in either knitting or weaving. (Marion et al., 2022)

Figure 24. *integration of conductive fiber in knitting.*

Once a row of stitches is formed between the two beds, the conductive fiber is inlaid in between, moving the carriage once more to create a row of stitches and then again placing the fiber repetitively. The weaving of the fiber between the rows of stitches firmly secures it in place.

To conclude, the double bed knitting machine has been selected as the preferred fabrication method as it is the most efficient for the embedding of the pneumatic composites and for the integration of the sensing element.

To summarize, the double-bed knitting machine allows for the following:

- Freedom of yarn choice, as some yarns are not suitable for weaving.
- Ability to use one continuous yarn without requirement of machine set-up in contrast to a loom.
- Ability of customization on the micro and macro scale. Stitch types, length, fabric porosity, and form.
- Ease and speed in fabricating channels.
- Ease and speed of integrating sensing components.
- Ease of scaling-up, simply by switching to a fully automated version of the machine.

3.3 Embedding Responsiveness

One of the goals of this thesis is to embed responsiveness to the material system without necessarily engineering the material to respond to a specific stimulus, but rather having a material system that can accept and integrate various sensors. In this case, functional sensing fibers are integrated into the knitted textile. For this particular case study, a capacitive sensing fiber is implemented; however, the system can swap out and exchange it with other sensors. Regarding the general framework, the sensing fiber collects input data to control the opening and closure of a set of valves which either restricts or facilitates airflow for the inflation of the pneumatic component.

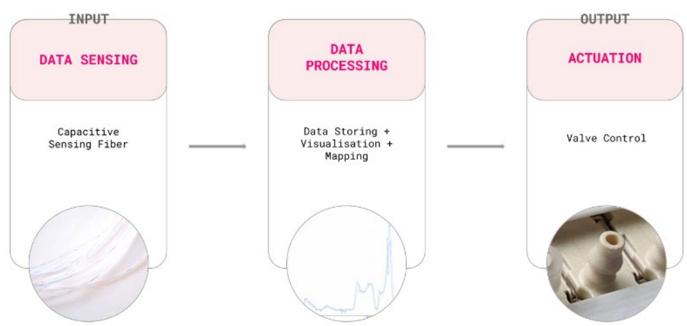


Figure 25. *system architecture.*

The capacitive sensor utilized in this study has been developed at FIBERS@MIT, research group led by Professor Yoel Fink. (Marion et al., 2022) Additionally, FlowIO is implemented, an open-source guide for the design and assembly of a set of valves and pumps for actuation control. (Shtarbanov, 2021)

3.3.1 Sensing Fibers

Yoel Fink, alongside researchers from FIBERS@MIT, have been developing a series of functional fibers, ranging from capacitive sensors to temperature sensing fibers, which follow Moore's Law; a new class of functional fibers that behave more like computer chips with the ability to sense, store, process information, analyze, and communicate. (Loke et al., 2020)

This research implements a capacitive sensing fiber into the knitted textile, whereby the fiber senses the electrical capacitance of the human body. The closer you are to the sensor the higher the values are and the further you are away the lower the values are.

The first prototype implements Arduino UNO – a microcontroller board based on the ATmega328P - to test simple ways of transmitting information from a single capacitive fiber. The circuit consists of the capacitive fiber for input, two 10ohm resistors, and an LED lightbulb for signaling. A simple code was made on Arduino utilizing the CapacitiveSensor library created by Paul Stoffregen. (*CapacitiveSensor - Arduino Reference*, n.d.) The first circuit implements a program that can detect a hand nearby and signals to the user that it has been recognized. Moving from an inactive state (light is off, hand is distant from the sensor) to an approaching state (light is blinking, hand is approaching the sensor) to an active state (light is on, hand is touching the sensor)

A flaw with circuit design and programming was the amount of noise that was detected from nearby devices, such as laptops, phones, etc. In order to minimize the noise and stabilize the sensor readings, a moving average is implemented in the programming and an additional 100pF capacitance is added to the circuit between the ground and sense pin. Although this significantly stabilized the readings produced, it still did not filter out all unwanted noise; however, it was robust enough to carry out the case-study.

Figure 26. *capacitive sensor in action. left: proximity not detected, right: proximity detected, therefore led turns on.*

With the isolated circuit operational, the next step is to map the values from the sensor to a set of valves that either restrict or facilitate airflow. Details are outlined in the next section.

3.3.2 Actuation Control

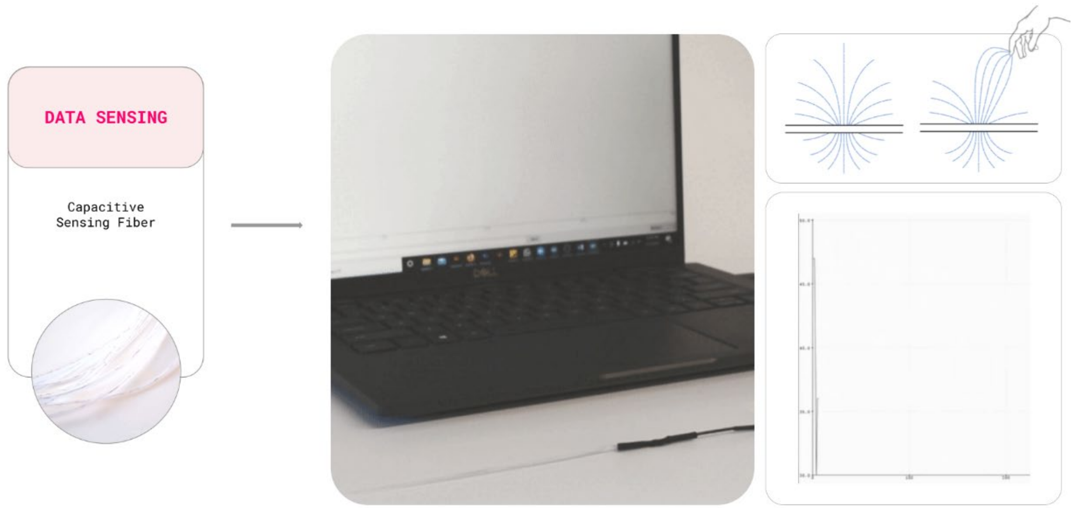


Figure 27. capacitive sensor with values being plotted on Arduino IDE.

A set of valves are used for the control of airflow into the pneumatic system. The design, fabrication, and assembly of the valves follow FlowIO which implements commercially available hardware and open-source software. It is consistent of five pneumatic ports and exchangeable modules for various pressure and flow needs. The system is fully compatible with Arduino, JavaScript, and google chrome. Therefore, it is suitable for makers from any technical background (Shtarbanov, 2021)

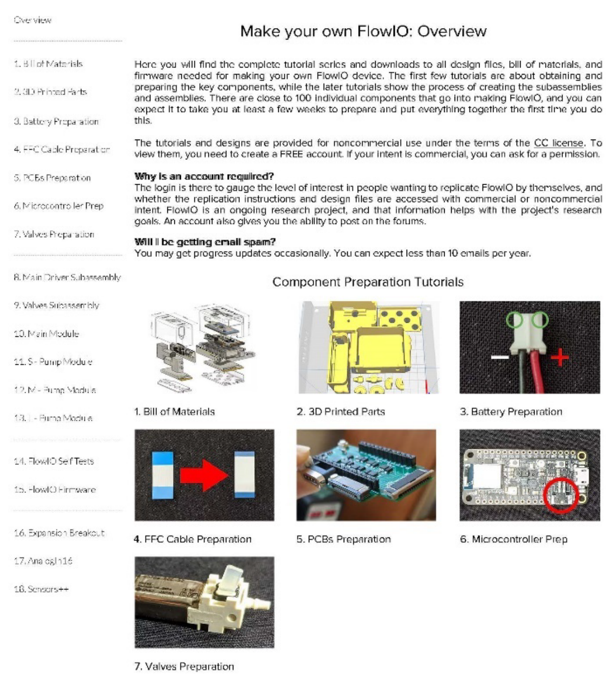


Figure 28. screenshot of guidelines to build FlowIO.

The main module consists of five operable valves, with the inlet connected to an external air source and one or many of the operable valves connected to the pneumatic components. In this particular module, C valves are implemented as they have an operating maximum pressure of 44 PSI which satisfies the 30 PSI minimum required to actuate the pneumatic composite.

In order to map the values of the capacitive sensors to the valves, an expansion board is added to the main module using a flex cable which follows a similar circuit design to the prior tests, however, in this example, it is connected to Adafruit Feather nrf52840 sense microcontroller. The sensor values are calibrated and mapped to control the opening and closure of the valves, for instance, if the sensor reading goes beyond a certain threshold, say 50, an electrical current is sent to one of the specified solenoid valves which cause the spring to contract and therefore air to flow out of the specific valve. This causes the actuation of the pneumatic component connected to that particular valve.

The configuration of the actuation control is light, compact, and allows for the portability of the entire material. Additionally, as there are 5 ports, we are able to control and actuate 5 independent channels; however, for the scope of this research only one valve is utilized in the prototypes. Future work will incorporate full utilization of the 5 ports and more.

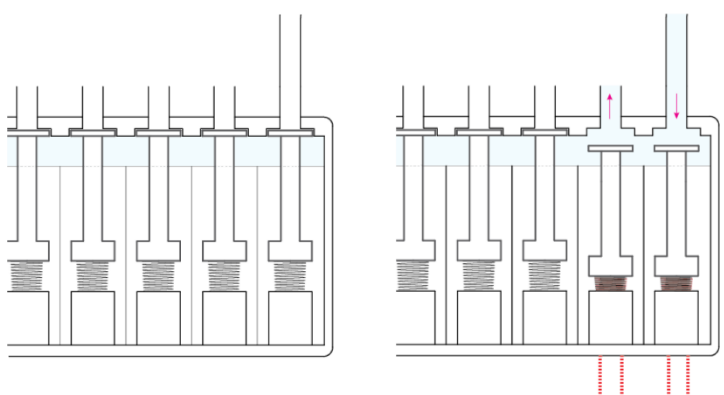


Figure 29. *left: air restricted, right: air flows through on specific valve.*

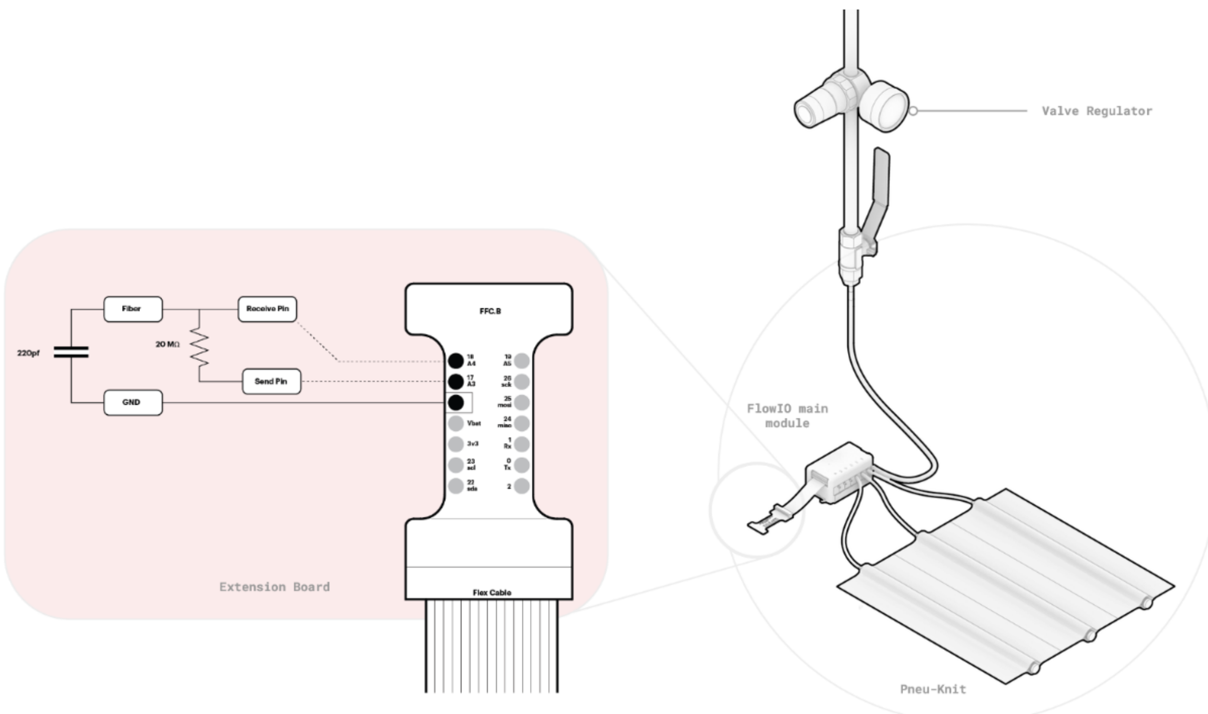


Figure 30. *left: expansion board circuit diagram, right: system architecture overview.*

4 Prototypes

4.1 Knit Prototypes

The figure below indicates the first set of prototypes developed (22cm x 8cm) which use regular cotton yarn and incorporates two channels for the pneumatics to be inserted. The tension dial was set on 6 for the upper carriage and 7 for the lower carriage which resulted in a very loose knit. A series of contracting and bending pneumatics were inserted and inflated using a regular air compressor.

Figure 31. *first prototype studies with bending and contracting pneumatics.*

In order to introduce rigidity and stability to the knit, a series of tight rib structures were tested: 1x1, 2x1, and 2x2. The stitch dial for all three was placed on 1 for the upper carriage and 0 for the lower carriage. The 1x1 test was the most rigid structure out of the three in both its activated (inflated) and deactivated (deflated) states. At its deactivated state the textile is tight and firm; however, due to the structure of the ribbed knit, once activated it allowed for seamless expansion and growth of the knit. The 1x1 ribbed structure was then utilized for a second prototype (22cm x 14cm), which incorporated three channels as shown in the figures below.

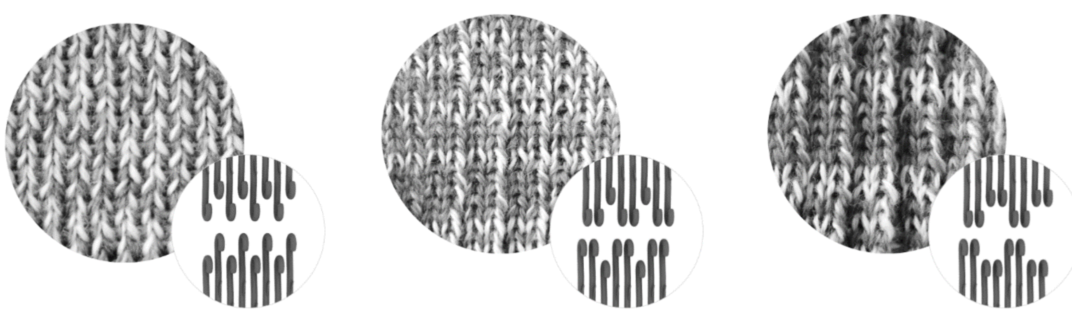


Figure 32. *left: 1x1 ribbing, center: 2x1 ribbing, right: 2x2 ribbing.*

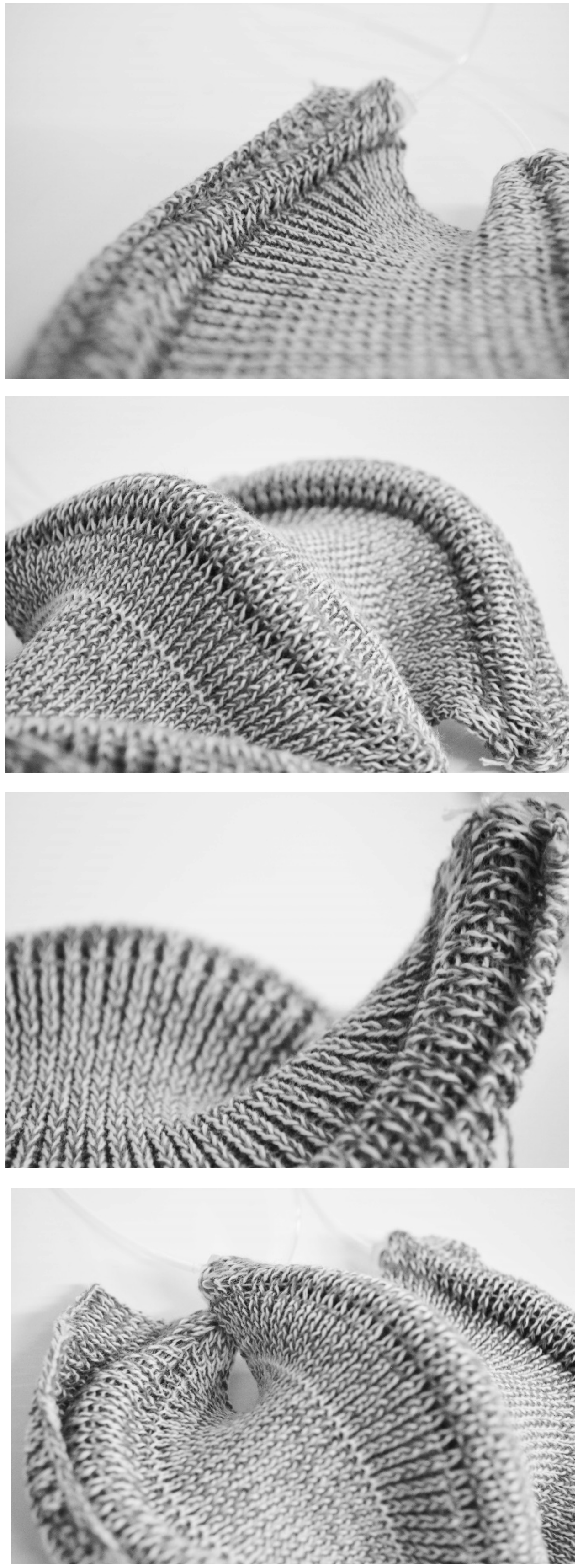


Figure 33. *close-ups of prototype 2.*

Figure 34. *top: bending pneumatic, bottom: combination of bending and extending pneumatics.*

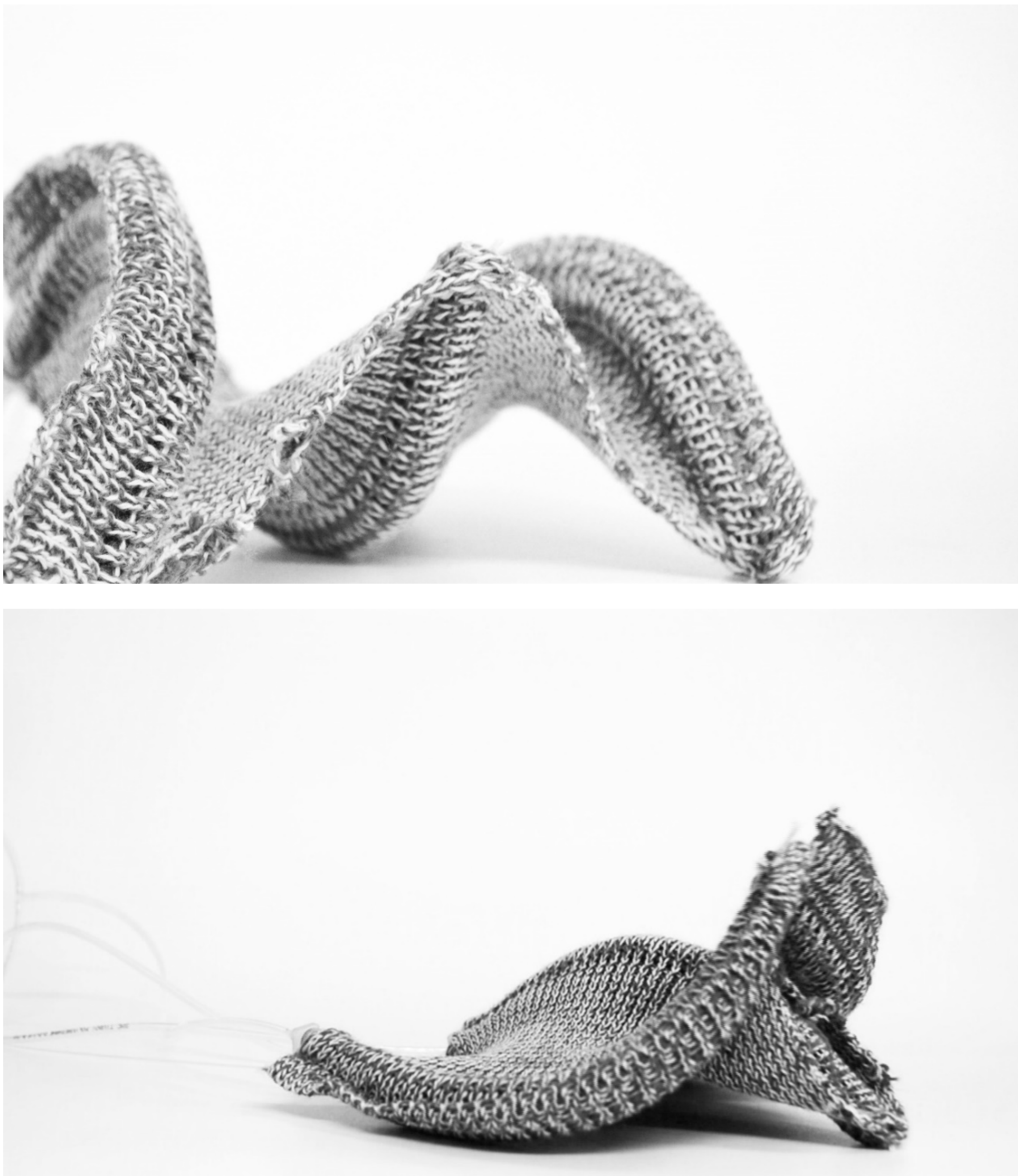


Figure 35. *combination of bending and extending pneumatics.*

An issue encountered with the second prototype was in the channels, as they were slightly loose and thus allowed the pneumatic component to twist and slip out occasionally, specifically when the extensible pneumatics were used. In order to mitigate that, a tight elastic yarn is implemented in the formation of the channel where the stitch dials on the front and back carriages were set on 1 and 2 respectively. That allowed for a tight grip on the pneumatic component which prevented it from slipping or rotating. The third prototype (25cm x 20cm) implements three elastic channels as shown in the images below, no issues were faced during the inflation process.

Figure 36. *integration of elastic channel studies.*

Figure 37. *prototype with elastic channels.*

Figure 38. *prototype with elastic channels.*

Figure 39. *activated knit to proximity.*

Other Explorations:

The next two prototypes highlight a work-in-progress textile collaboration done with RISD student JoAnne Lee, this collaboration was made possible through the Computing Fabrics class taught by Yoel Fink in the spring 2022 semester. Both textiles were made using the STOLL machine at the Rhode Island School of Design.

Prototype 4 investigates a change of cross-section in a knitted textile, moving from a deep cross-section at its deactivated state to a thin cross-section at its activated state. The interest in this particular prototype is to investigate textiles with potentials in thermal regulations and integrating temperature sensing fibers.

Prototype 5 investigates volumetric shape-shifting of the system, it integrates six bending pneumatic components placed radially in a tubular knit. In its deactivated state, the knit is suspended from its top-end using elastic fishing wires and anchored at the bottom end. Once activated, the upper half of the pneumatic components bend outwards in a radial manner, creating a canopy formation.

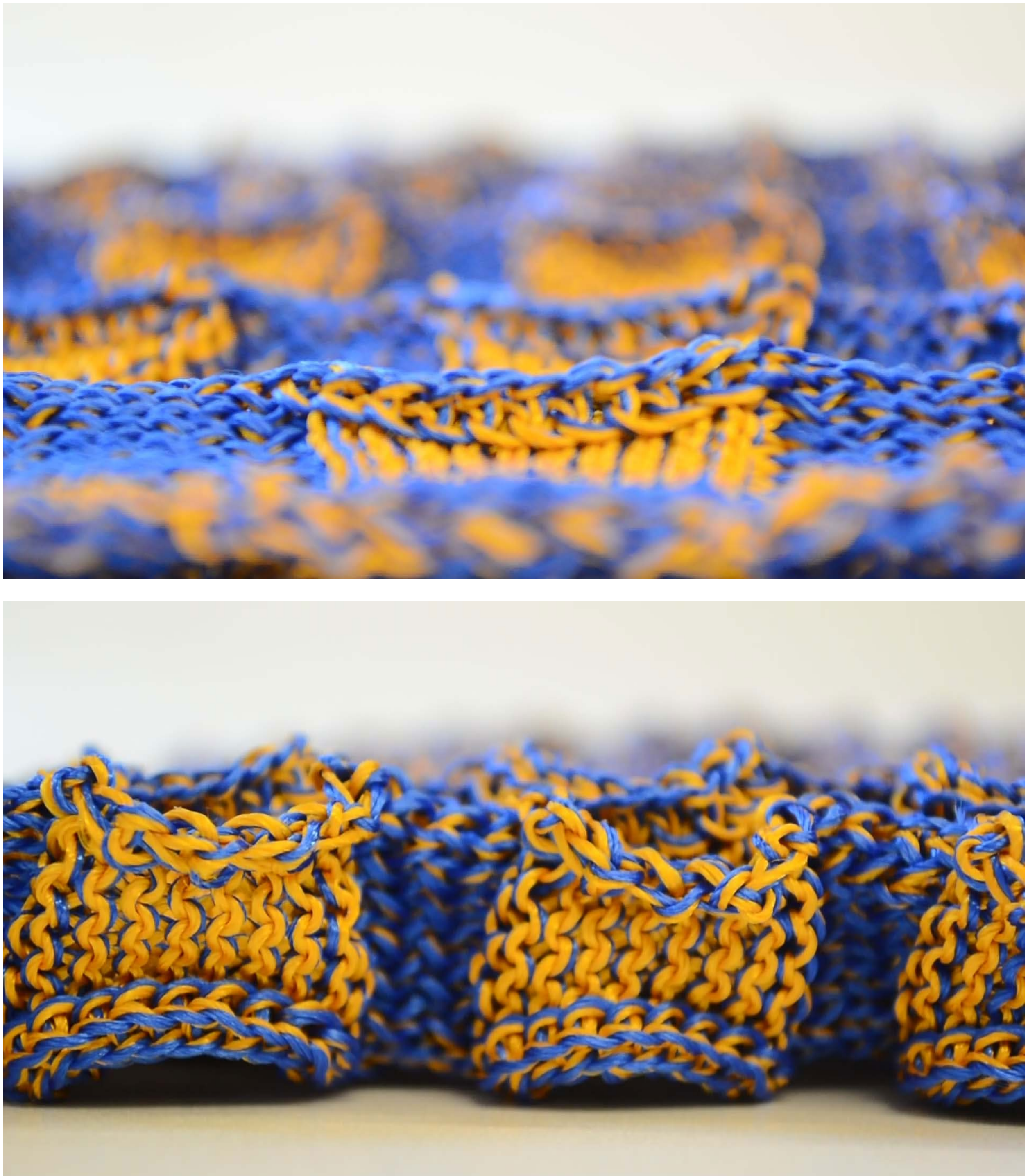


Figure 40. *varying cross section of knit, deep cross section when inactive, shallow cross section when active.*

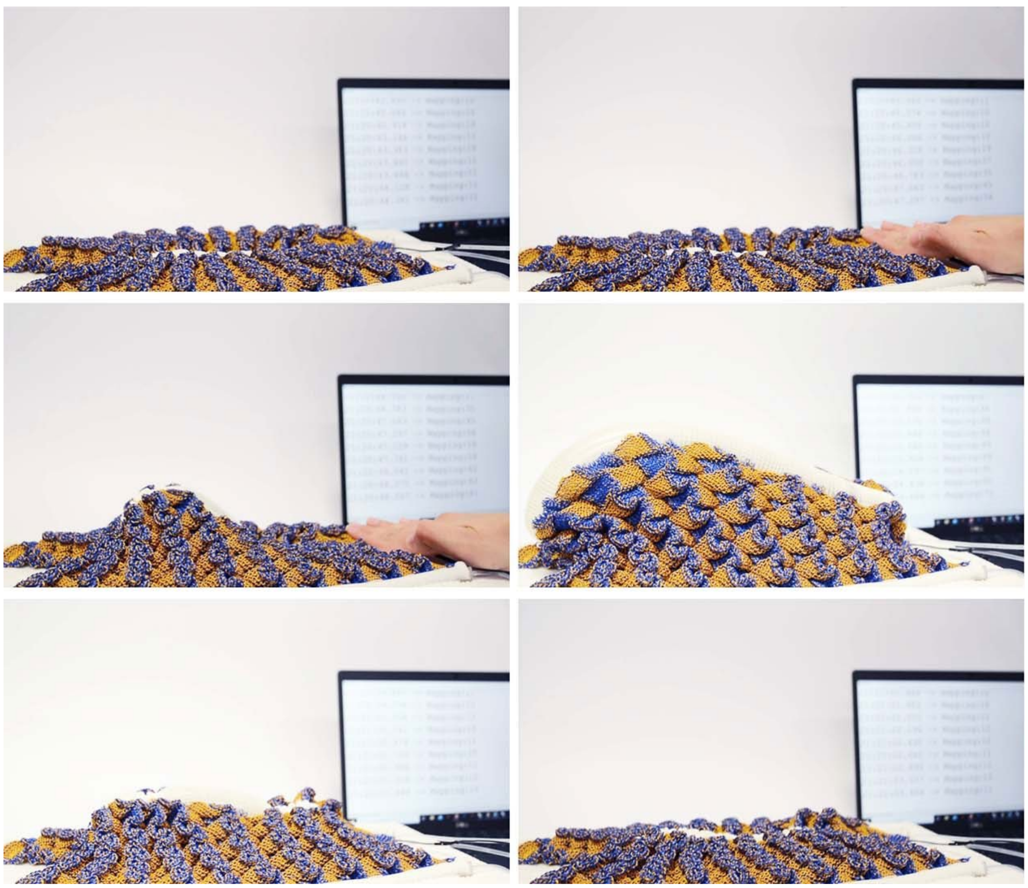


***Figure 41.** prototype test with sensing fiber.*

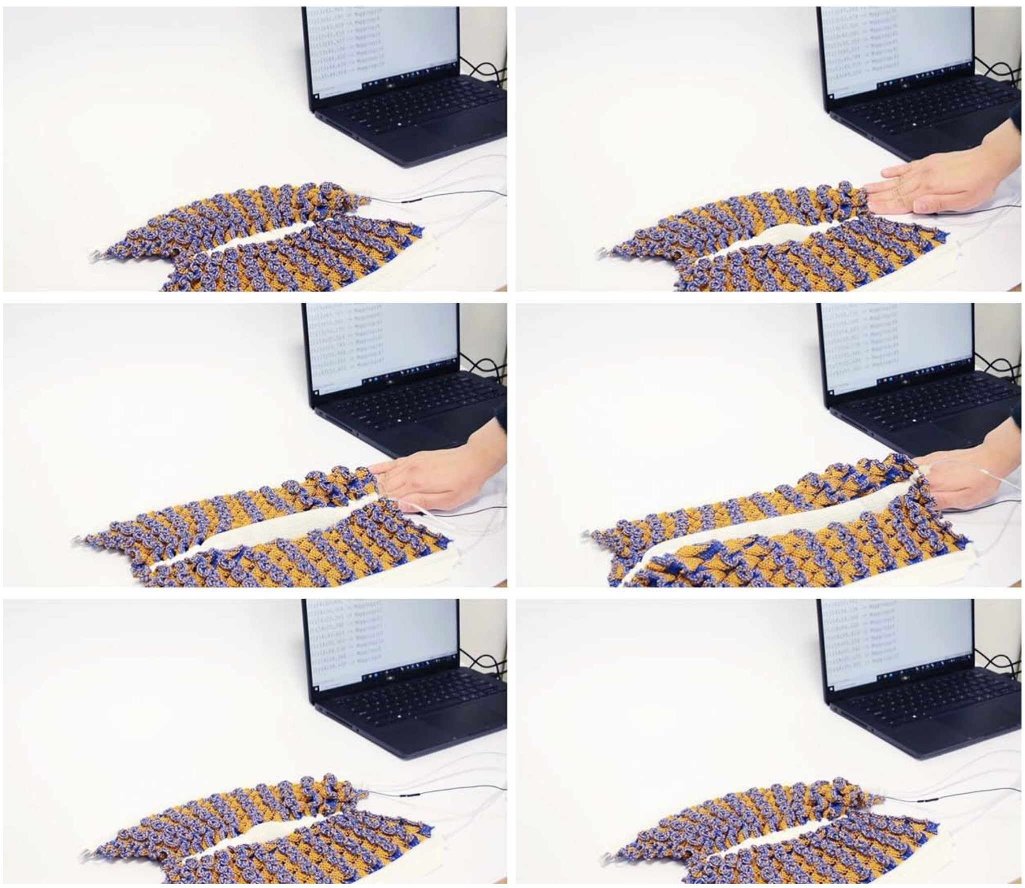


Figure 42. *prototype test with sensing fiber.*

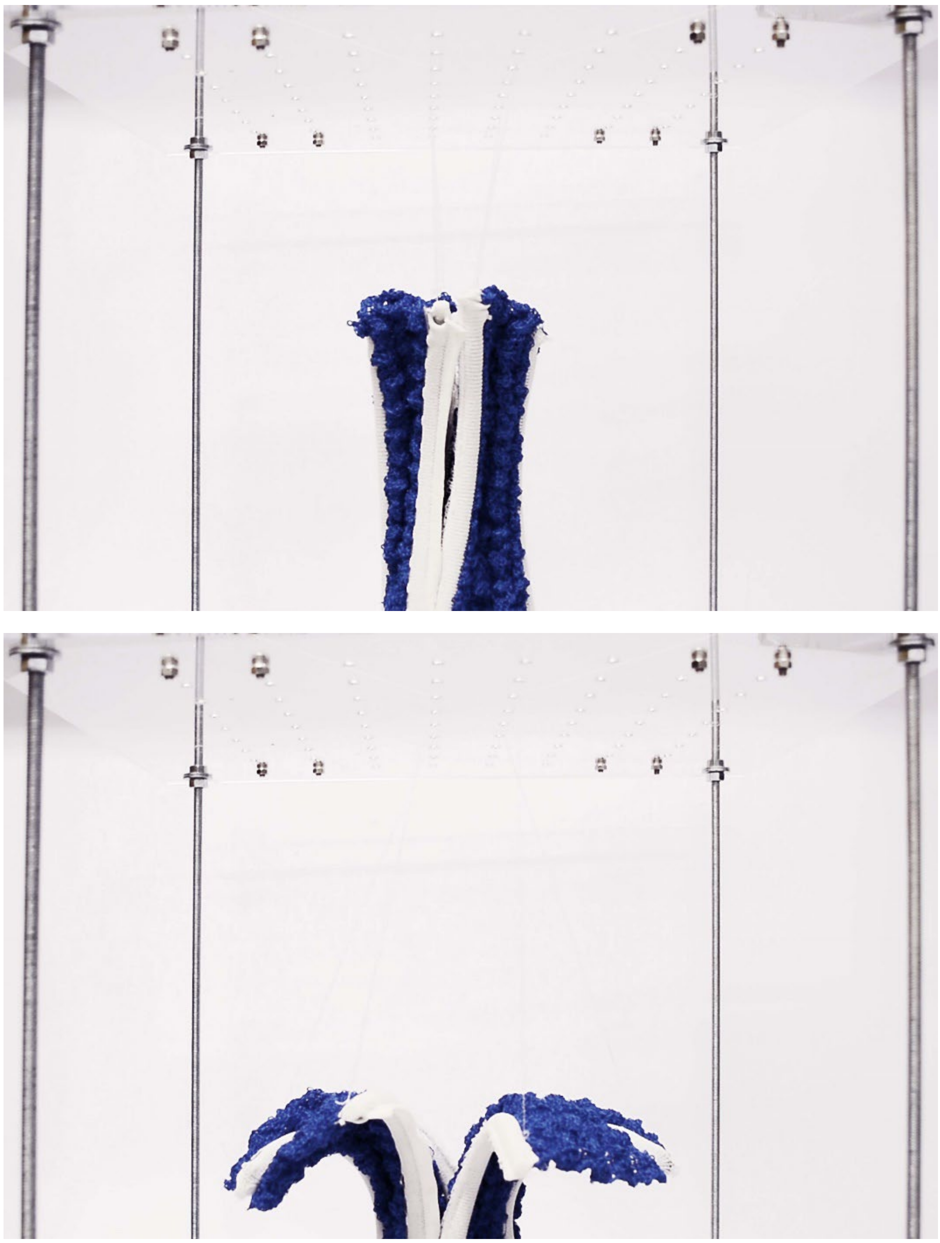


Figure 43. *volumetric knit with 6 activated pneumatic components.*

4.2 Vision and Opportunities

The goal of this research is to embed soft responsive systems in the domain of architecture. The images below illustrate potential applications that integrate motion detection and temperature sensors in the system. This embedding of responsiveness into the built environment challenges the notion of authorship going beyond the architect or designer, but rather can be thought of as a collective authorship between the designer, the material system, the context, and the users. As opposed to designing fixed inert spaces, this material system leverages opportunities in an architecture that co-evolves, learns, and anticipates from its surrounding context and users.

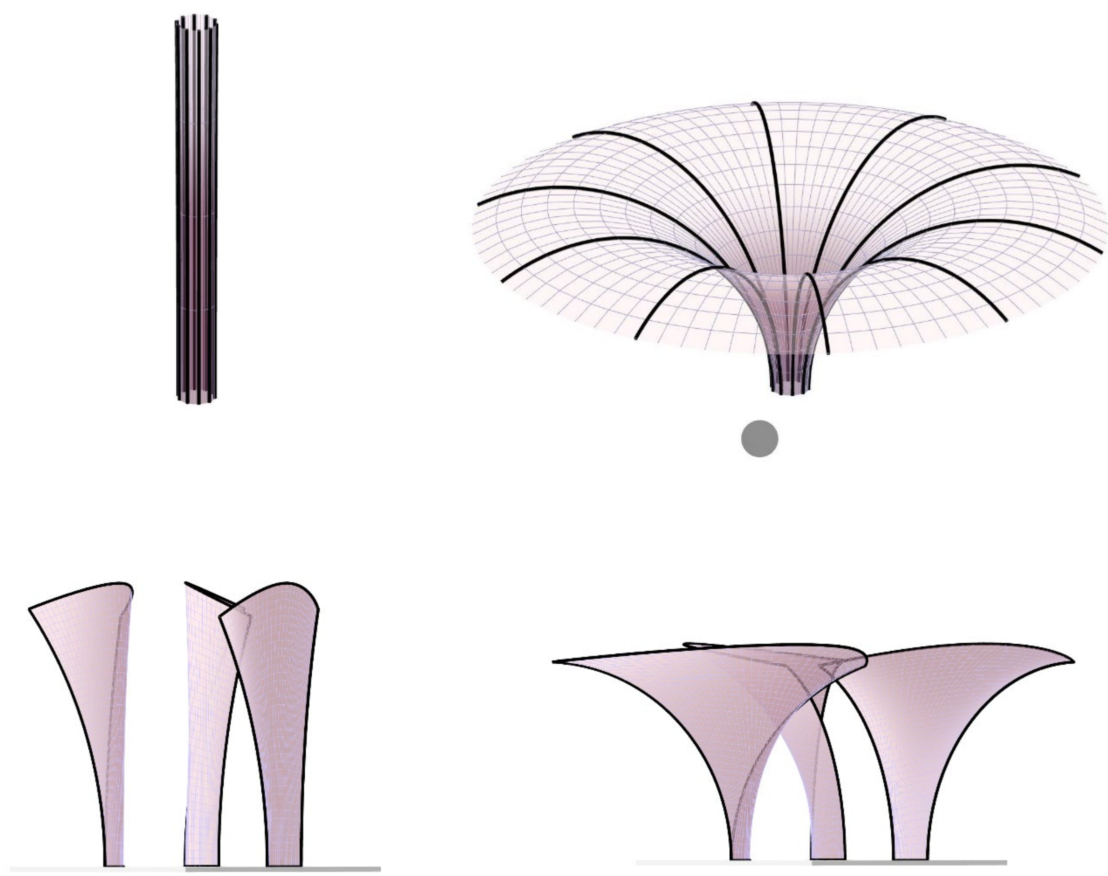


Figure 44. *active knit simulation proposal.*

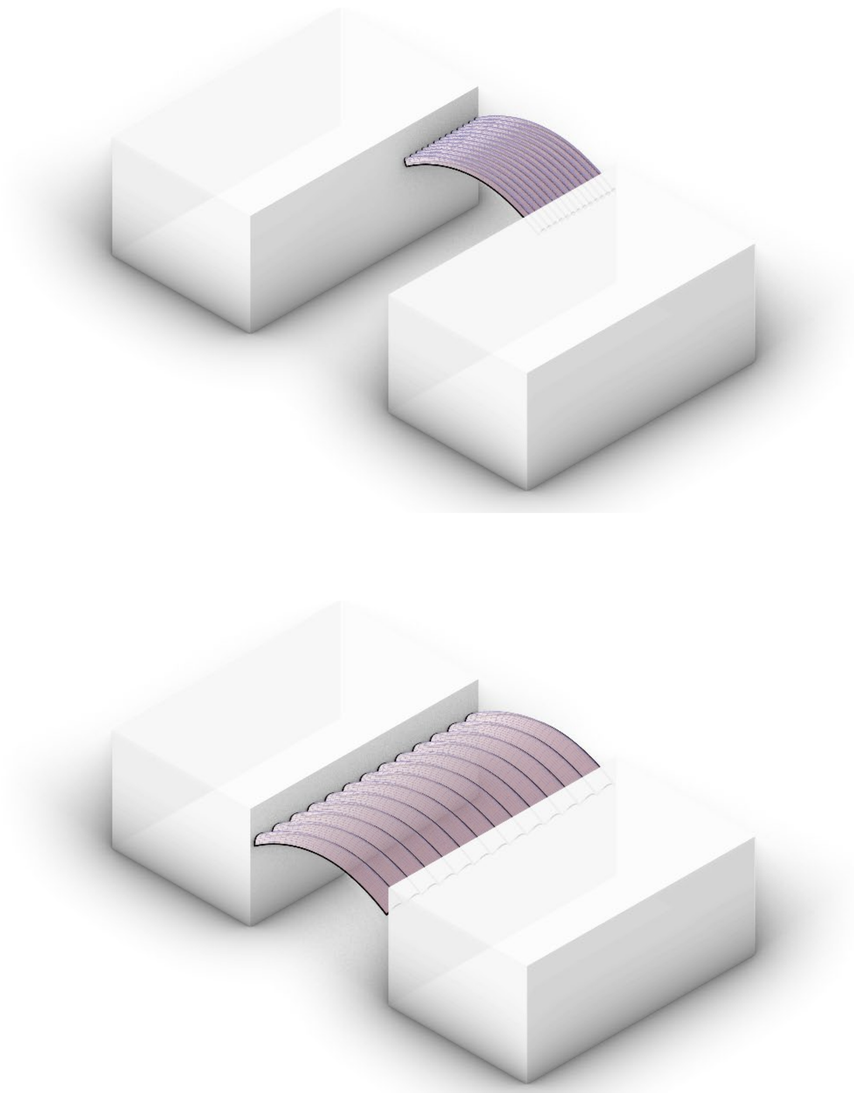


Figure 45. *active knit proposal simulation.*

5 CONCLUSIONS

5.1 Challenges and Next Steps

Certain challenges were faced in each phase of the research. Below is an outline of the issues encountered and the next steps.

Pneumatic Composite:

Issues

- The current pneumatic composites require a high PSI of 45 to be activated and as such the prototyping process is noisy. This issue can be mitigated as we scale up, since the larger the diameter of the pneumatic composite the lower the required PSI.

Next Steps

- Test and evaluate the structural capabilities and limitations of the pneumatic composites across different scales.
- Scale up for larger architectural applications

Knitting Process:

Issues

- Intricate details and various configurations of the channels that are not linear are difficult to achieve with the current semi-automated double-bed, as such we are limited to linear channels only.
- Although we can technically knit infinitely on a certain axis using the knitting machine, the width is always limited to the number of needles available. So, scaling and assembly of textile sheets remain a challenge yet to be explored.

Next Steps

- Incorporate large-scale channels for architectural applications.
- Utilize a fully-automated machine for the fabrication process.
- Test out different patterning possibilities for non-linear channel arrangements.
- Test out structural capabilities of the overall system once activated with the pneumatic component.

Sensors:

Issues

- The biggest challenge faced with the sensors is the noise. Sensor noise is the random variations of the sensor output unrelated to the input. Although most of the noise has been filtered out as mentioned in the earlier section, it is still not fully eliminated.

Next Steps

- Create a robust system to discard unwanted noise.
- Integrate different types of sensors into the knit.
- Create a system that is able to record and collect data over time so that the material system can anticipate and learn from its surrounding.
- Control channels independently using the ports available in the main module.

5.2 Recap and Contributions

Building with easily deployed active and adaptive materials is one of the key principles to further advance our built environment on an individual, social, economic, and sustainable level. On an individual level, responsiveness and adaptation promote safety, comfort, improve the user's well-being and living quality. (Nakib, 2010) On a social level, adaptation facilitates an exchange between user and space and user and user, resulting in a co-authored space of shared identities. On an economic and sustainable level, adaptability reduces material waste and the need for constant remodeling/refurbishment of the space as building components are able to co-evolve with the building/user needs over time and therefore can last longer.

Subsequently, this thesis investigates adaptable soft systems. It demonstrates a feasible continuous fabrication system of the integration of knits, actuators, and sensors that is low-cost, easily reproducible, and utilizes open source software and technologies. The proposed material system is a generalized adaptable system that can be implemented for on-demand responses to various stimuli, can be self-actuated, and requires minimal discrete parts for adaptability. The research outlines a framework for the development of lightweight adaptable systems that are rapid and affordable to manufacture. It investigates the fabrication of responsive **self-actuating**

mechanisms; specifically, **hybrid pneumatic-knitted systems** that are adaptable to changes within the environment through embedded sensors. The research promotes notions of building with active responsive systems that behave similarly to living organisms that can adapt and evolve with their surroundings.

Figure 46. *QR code for video.*

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6 IMAGE CREDITS

All non-captioned and non-credited images are project photos and drawings provided by the author.

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Figure 6a
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