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Collapsible Scissor Structures with Knit Membranes

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Abstract

Transformable structures have emerged as a prominent area of research in respect to environmental adaptive architecture, recognized for their dynamic adaptability to environmental changes. This project-based research explores the integration of knitted membranes with scissor structures, resulting in unique collapsible panels that utilize the elastic material properties of knit to facilitate expansion and contraction. This method introduces a novel aspect to architectural design employing a soft tensegrity system for achieving a relaxed, open state, thereby broadening the spectrum of architectural and design possibilities.

The study evaluates various knit material patterns and orientations to determine their behaviors in different configurations. Central to this research is exploring the elasticity of the knitted membranes, focusing on understanding the material's deformation when collapsed and expanded, thus offering insights into these dynamic behaviors.

Additionally, this research assesses the impact of different scissor-shaped configurations, allowing for the customization of designs to meet possible architectural requirements. This exploration of materials is augmented by using digital tools, Rhino and Grasshopper, to aid in creating knit patterns and analyzing different design configurations through physics simulation, enhancing the design process.

Progressing further, the project incorporates mechanical enhancements using Arduino and servo controllers to automate the designs' opening and closing mechanisms. This layer of automation increases adaptability, providing responsive and interactive architectural solutions capable of adjusting to diverse environmental conditions and user preferences.

This exploratory research project advances the field of environmental adaptive architecture by fostering the integration of elastic knitted membranes with scissor structures. This is a significant evolution in developing responsive, adaptable, and intelligent architectural components. The combination of material elasticity, tensegrity principles, and automation points toward new directions for future architecture, engineering, and design advancements.

Keywords: conceptual design, transformable structures, knitting, membrane structures, tensegrity.

1. Introduction

In engineering and architecture, scissor structures have long been appreciated for their mechanical efficiency and structural adaptability, which are fundamental in creating transformable and retractable designs. These structures are usually constructed from rigid materials offering stability but often at the expense of the softness, flexibility, and aesthetic versatility that fabrics and other more pliable materials can provide. While effective for specific engineering applications, traditional approaches to scissor structures may overlook the potential for incorporating elements that add a layer of softness, playfulness, and interactive design into architectural solutions.

This research project investigates the integration of knitted elastic textiles with scissor structures. It explores how knit fabric's inherent flexibility and tactile qualities can enhance the functional and aesthetic aspects of scissor-based transformative designs, proposing new potentials for scissor structures to go beyond their conventional applications. This project develops six distinct configurations of scissor structures, focusing on the methodologies and challenges associated with each framework's fabric movement. This exploration is not only concerned with the attachment of the fabric to the scissor structures but also with how the unique properties of fabric materials, such as their elasticity, drape, and the process of developing the measured made-to-fit piece of fabric that holds the scissor at a stable state. The knit material can contribute to dynamic, adaptable, and visually engaging architectural elements.

Moreover, the final exploration of the project explores the possibility of automation, seeking to add Arduino and servo motors, allowing for programmable configurations that can respond to environmental stimuli or user interaction. This exploration of automated movements and materials is motivated by the desire to create architectural elements that are structurally sound, versatile, and capable of providing sensory experiences and playful interactions.

This study hopes to combine the traditional scissor structures with the softness and adaptability of fabric materials, utilizing elasticity and integrating automation techniques. By challenging the conventional applications of scissor structures and exploring their potential for greater design flexibility and interactivity, this research contributes to the evolving discourse on adaptive and responsive architectural designs, paving the way for future innovations in engineering, architecture, and design.

2. Context

The exploration of textiles within performative architecture using scissor structures occupies a significant niche in the broader context of adaptive and responsive architectural designs. It combines these two research fields in a new way, looking at material specification and structural design. The relationship between textiles and architectural structures has been pivotal in advancing the discourse on materiality and movement in architecture. Pioneers such as Frei Otto have extensively explored the potential of textiles in creating lightweight, efficient structures that are functional and aesthetically profound, as seen in his work on tensile and membrane structures (Otto [1]). Alternatively, Chuck Hoberman has made substantial contributions to the field of transformative structures through his invention of the Hoberman sphere and other structures, highlighting the potential for scissor mechanisms to enable architectural designs capable of transformation, change, and adaptation (Hoberman [2]). These foundational works underscore the importance of integrating flexible materials and kinetic mechanisms within architectural design, paving the way for the current research project's exploration of fabric-integrated scissor structures. By building upon the basis of these innovators, this project seeks to understand further how textiles and scissor structures can be combined to create performative architecture that is responsive and invites engagement and exploration.

2.1. Transformable Designs

Scissor structures are known for their unique ability to expand and contract through a simple, lightweight mechanism. The basic concept of the scissor mechanism involves two intersecting members, which are connected in a way that allows them to pivot around their intersection point, similar to the action of a pair of scissors. This design principle enables the structure to fold or expand while maintaining its integrity and strength.

Scissor mechanisms can be traced back to examples found in collapsible structures and tools across various cultures. Vitruvius hinted in his writing at mechanisms and apparatus for folding and collapsing in his descriptions, that are not necessarily precisely scissor structures, which could be considered a precursor to the concepts (White [3]).

Modern engineering and architecture in the 20th century found new uses and innovations of scissor structures that are not attributed to a single individual but rather a series of developments and refinements by engineers and architects who recognized their potential for creating dynamic and adaptable spaces.

Scissor structures are valued for their ability to create large, open spaces that can be easily modified or retracted. This makes them ideal for retractable roofs, temporary shelters, and exhibition pavilions.

A contemporary example in architectural applications is the convertible roofs used in modern sports stadiums, such as a retractable roof system based on scissor mechanisms. This innovation allows for the transformation of large sports venues in response to weather conditions, enhancing the comfort and experience of spectators.

The fundamental principle behind scissor structures is based on geometry and kinematics. The angle between the intersecting members governs the structure's expansion and contraction, which can be described mathematically by trigonometric relationships. The scissor structure design calculates the members' optimal angles and lengths to achieve the desired range of motion, stability, and load-bearing capacity.

2.1.1. Scissor Structure Mathematics to calculate overall dimensions

The mathematical analysis of scissor structures often involves the study of their kinematic behavior, that can be represented through equations that describe the relationship between the angle of the scissor members and the overall dimensions of the structure. This analysis is crucial for ensuring the structure can withstand the forces it encounters when deployed and operates smoothly and efficiently. In their simplest form, they can be analyzed using primary geometric and trigonometric relationships to understand their expansion, contraction, and overall behavior. The length and height of the overall structure change in relation to the angle between the members at the pivot point. See Figure 1.

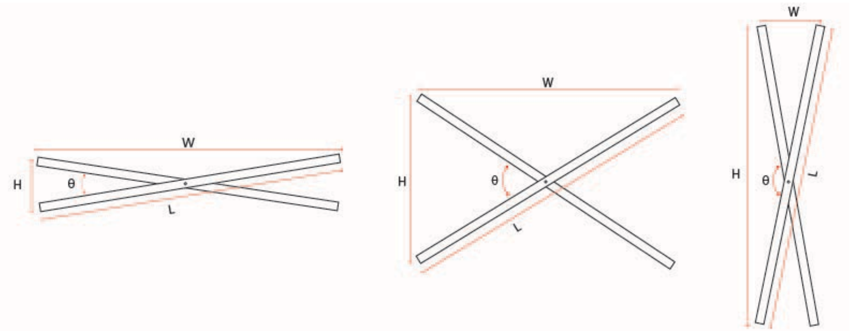

Figure 1: Typical positions for measurements of Standard Scissor Structures [Image source from author]

For example, to solve for the different overall resulting widths of the scissor structure at a specific position, it can be determined by the formula where W is defined as the overall width, and L equals the length of the members. Shown in equation 1.

$$W = L\ \cos\left(\frac{\theta}{2}\right) \tag{1}$$

To solve the resulting height at a specific scissor position, can be calculated where H equals the resulting height. Shown in equation 2.

$$H = L\ \sin\left(\frac{\theta}{2}\right) \tag{2}$$

The height and width of the design continually change based on the angle between the two members. This can change continually as the scissors open and close. If more than one scissor structure is arranged in a row, the calculation for the overall dimension must multiply the number of scissor modules.

2.2. Textiles

Textiles have been part of architectural design for centuries, offering practical solutions for enclosure and division of space, as well as aesthetically appealing and culturally significant designs. The use of textiles in architecture has changed through the centuries as modern technologies and advancements have changed the possibilities and uses for these materials.

2.2.1. Textiles in Historical Architecture

Textiles were integral to nomadic architecture for their lightweight and collapsible properties, found in structures such as the Yurt in Central Asia and the Bedouin tents across the Arabian deserts (Faegre [4]). In these applications of textiles, they were often draped or pulled in tension over a structural frame to create a stable structure once fully deployed.

In more recent history, in the 20th century, the work of architect Frei Otto marked significant developments in the use of textiles in permanent architectural structures. Otto's extensive research into lightweight, minimal surfaces and tensile structures led to groundbreaking designs such as the Munich Olympic Stadium's roof (1972), which demonstrated the potential of membranes to create expansive spans (Otto [1]). Otto's work laid the foundation for the modern field of tensile architecture, emphasizing the importance of materials, form, and environment in architectural design.

2.2.2. Contemporary Textiles

Several designers are currently conducting research into knitted materials and architecture. Some designers, like Jenny Sabin, have been integrating textiles into contemporary architectural practice, exploring how these materials can create interactive, adaptive, and sustainable designs (Sabin [5]). The work of Sean Ahlquist pushes the ideas of tactility and sensory experience in his designs (Ahlquist [6]). Meanwhile, CITA (Center for Information Technology and Architecture) and Mette Ramsgaard Thomsen have been exploring textiles and knit materials for a variety of purposes and sometimes focusing on efficiency and simulation of the designs (Ramsgaard Thomsen, et al [7]).

However, much of the innovative textile work in architecture tends to focus on stationary applications of textiles, where the fabric is usually fully tensioned to create forms that, while dynamic in appearance, do not move or change configuration.

This focus on stationary textile structures is now being challenged in this research and design experiment, which seeks to integrate movement into textile-based architectures. Incorporating kinetic elements into textile structures opens new possibilities for interactive and adaptive environments that respond to their occupants or environmental conditions in real time. These developments represent an exciting frontier in architectural design, blurring the lines between static and dynamic, building and inhabitant, and architecture and technology.

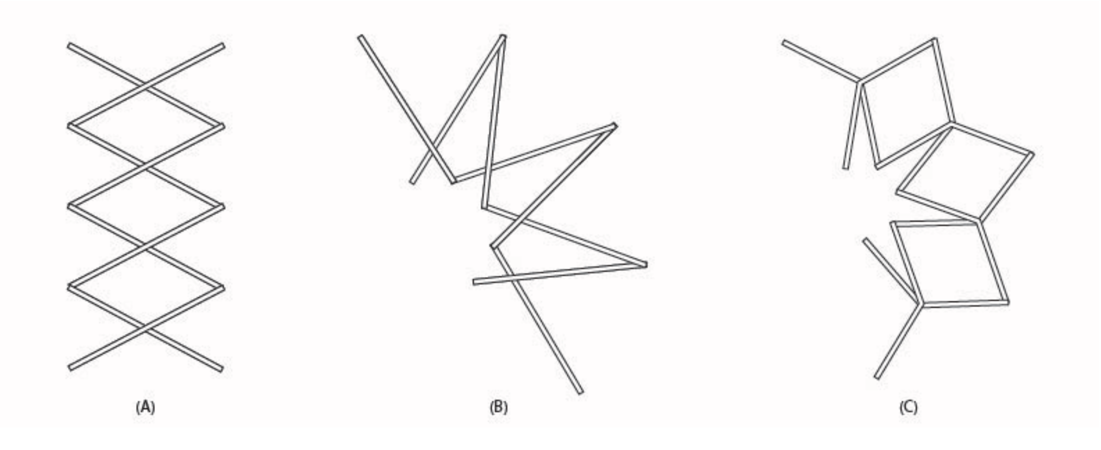

Figure 2: A few of the base scissor designs (A) Regular center pivot point scissor mechanism, (B) Off-centered pivot point scissor mechanism, (C) Angled member scissor mechanism [Image sources form author]

3. Design Process

This research project explores some diverse shapes and configurations achievable with scissor structures, integrating tensioned knit materials onto the scissor frames. A few adjustments to the scissor mechanisms' design, such as the location of the pivot point and whether the scissor member is straight or angled, can create different expanding shapes, such as arcs and circles. See Figure 2.

The design process began with developing simulations of these basic scissor forms using Grasshopper and Rhino, facilitating a deeper understanding of the potential shape transformations and dimensions suitable for fabrication. See Figure 3. This established a dynamic relationship between the textile material and the structure, allowing the knit to stretch and morph in response to the scissor forms' movements.

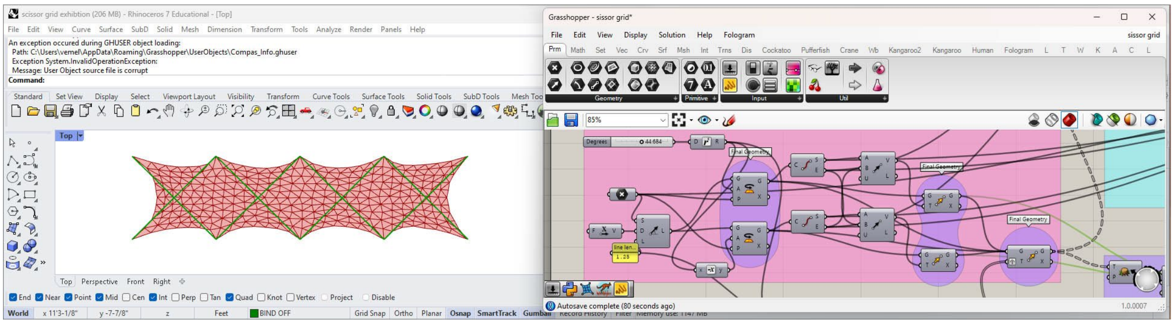

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Figure 3: Grasshopper simulation of scissor mechanism and mesh [Image source from author]

Furthermore, a significant portion of the effort was dedicated to developing methods for understanding the elasticity of the knit material and the scissor structures' movement so that they could expand and contract in harmony. Adjustments to the knit properties through stitch density create varied elasticity across the material, an essential part of the design process.

For each of the sample designs that follow, a nylon-covered elastic yarn was used to provide extra elastic capabilities within the yarn material and the knit structure. All designs were knit on a domestic Passap Doumatic 80 Knitting machine. The size and material estimates were developed digitally in Rhino and Grasshopper and then tested on the full-scale mock-ups. The textile dimensions were estimated by measuring a swatch sample of knitted material at 50 stitches by 50 rows. This is a common technique among knitters to estimate material usage, although it is not an exact measurement, as knit materials perform very differently when scaled. This allowed for an estimate of how many stitches and rows would be needed to knit the full-sized panels. See figure 4.

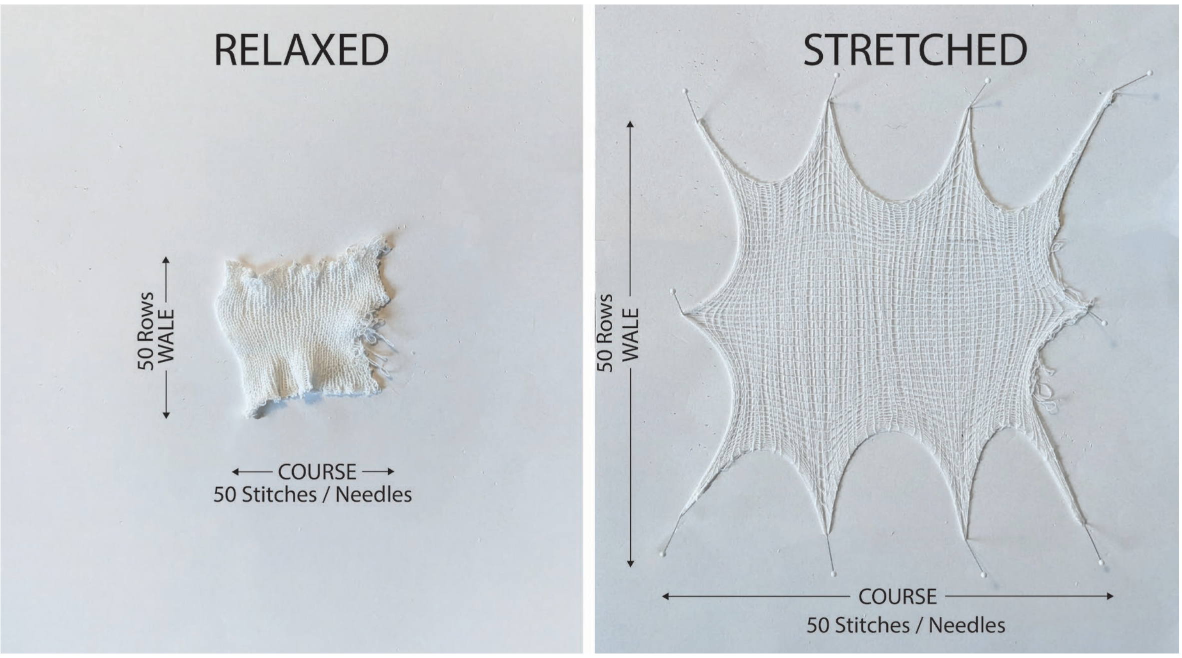


Figure 4: Swatch sample of 50 x 50 double jersey knit relaxed and stretched. [Image source from author]

3.1. Linear Scissor Structure

The first scissor structure studied was based on the simplest, starting with linear members and a centered pivot connection. The design took a base member of .42m (19in) and four modules wide. This structure uses a shifted array to stack two rows together to form a grid (see Figure 5). This created a simple open and closed position, with the most open relaxed at about 45-degree angles.

Figure 5: linear scissor structure with knit membrane [Image source from author]

For the design of the knitted textile, since the movement of the form was vertical and horizontal along the wale and courses of the knit, the pattern was kept as a simple double jersey knit. A few needles were dropped to provide porosity and density variation, but adjustments were not made to the elasticity or form of the knit. The pattern is seen in the stitch rows as the materials are stretched in a zig-zag across the structure.

3.2. X Scissor Structure

The second design took the simple linear arrangement of scissor mechanisms and arranged four scissors in the X direction and four along the Y direction. This created a scissor formation that, when expanded in one direction, the other direction collapsed. See Figure 6.

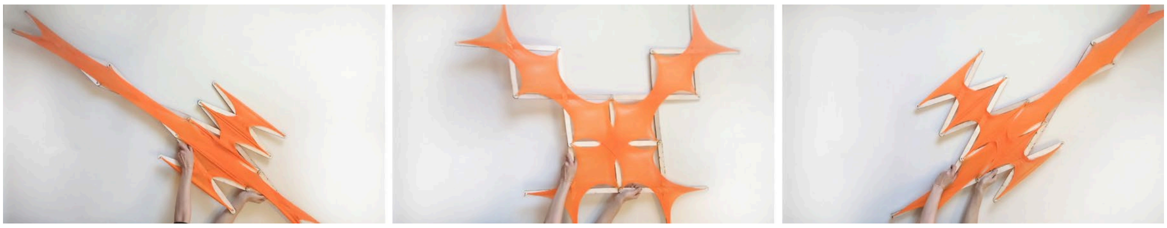


Figure 6: X scissor structure with knit membrane [Image source from author]

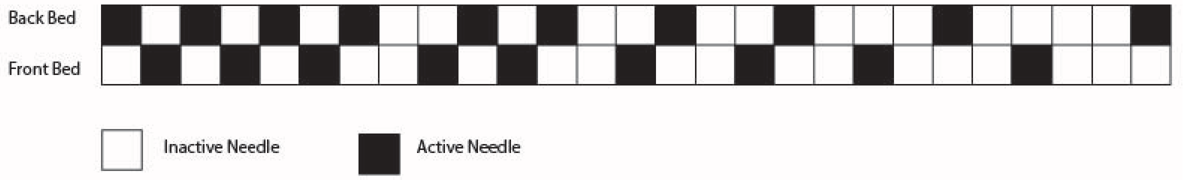
For this configuration, two panels were knit and overlapped. These were double jersey knit with a few variations in skipping needles for aesthetic texture and porosity. The variation in the knit is less noticeable than the curved shape, which comes from how the fabric expands and contracts and how it wrinkles when compressed.

3.3. Arc Scissor Structure

The following design iteration involved adjusting the pivot pint to one-third of the linear members. This causes the scissor structure to expand in an arc formation. Six modules make an arc that opens and closes from small to complete circular forms. See Figure 7.

Figure 7: C scissor structure with knit membrane [Image source from author]

For this design, the outer edge of the membrane needs to stretch much more than the inner edge. To achieve this variation in the stretch, the needles on the knitting machine were graduated so that every needle from the front bed and back bed was activated towards the inner edge. While on the outer edge of the knit, many needles were skipped to provide larger gaps in the knit, providing more elasticity and stretch on that side of the material. See Figure 8.



Back Bed	■	□	■	□	■	□	■	□	□	■	□	■	□	□	■	□	□	■	□	□	□	■	□	□	□	□	■
Front Bed	□	■	□	■	□	■	□	□	■	□	■	□	□	■	□	□	■	□	□	■	□	□	□	■	□	□	□

□ Inactive Needle ■ Active Needle

Figure 8: C scissor structure with knit membrane [Image source from author]

This skipping of needles also creates more transparency, which can be seen in the outer edge. See Figure 9.

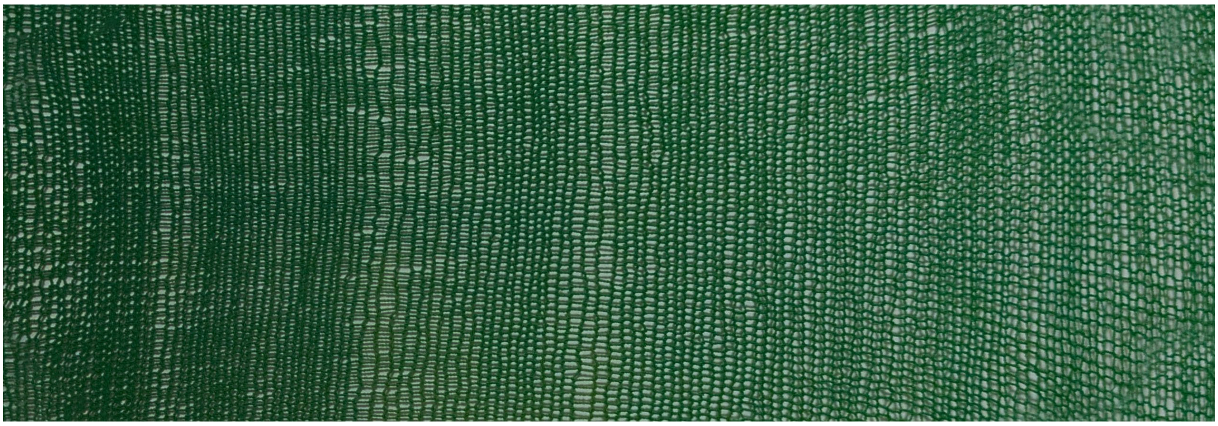


Figure 9: Squiggle Scissor structure with knit membrane [Image source from author]

3.4. Squiggle Scissor Structure

The next scissor design used the same off-centered pivot point to create two arcs and an overall squiggle shape. To do this, after the first four scissor modules, the pivot point shifted from the first 3rd of the members to the second third of the members for four more modules.

Figure 10: Squiggle Scissor structure with knit membrane [Image source from author]

The textile knit for this structure used a similar idea as the first pattern: skipping needles to provide more elasticity in portions of the knit. Rather than skipping on one side of the knit, both edges skipped needles so that the main elasticity was based around a center spline of the structure's expansion and contraction.

3.5. Circle Scissor Structure

Angled members were used to formulate a circular structure that could expand and contract. The linear member was broken at the center pivot point and rotated 40 degrees to allow for an angled member. These are arranged in a symmetrical pattern around the circle. The different angles at which the member can be bent would provide a different number of modules to create the circle. In this case, a 40-degree bend results in a circle consisting of 9 modules.

Figure 11: Circle scissor structure with knit membrane [Image source from author]

Similar to the Arc scissor structure, the knit material again uses a method of skipping needles on one side of the knit panel to create a material that expands and contracts more on the outer edge of the circle than on the inner edge. The panel was knit as a linear strip and then sewn at the two ends to create a circular shape.

3.6. T Scissor Structure

The final scissor design utilized the leftover angled members and reconfigured them into a new form by arranging them linearly in a "T" shape. This provided a unique feature: when one scissor module collapsed in one direction, it was open in the other. This caused the textile membrane to always be in open and closed positions, shifting between which parts of the material were activated.

Figure 12: T scissor structure with knit membrane [Image source from author]

Similar to the earlier X-scissor design, two linear panels were knitted and attached in the corresponding directions. The results are that this knit never fully closes or opens, but each strip is open and closed at moments, depending on the configuration of the scissors.

4. Automation

The final exploration used the linear scissor configuration to add Arduino and servo motors to automate the opening and closing movement. In this scenario, the knit textile was knitted larger so that it would only be in tension along the cross direction allowing for easy expansion in the length. This aided in reducing the resistance against the motors, as the servos could only withstand so much force. The resulting hanging design transformed the knitted fabric from a ruffled state when in a collapsed scissor position to stretched state when in an open position. See Figure 12.

Figure 13: Arduino and servo motor automated scissor structure with loose knit [Image source from author]

4. Results

The resulting designs look at ways to integrate textiles into forming different configurations of scissor mechanisms. The designs for the different elastic performance by skipping some needles were developed not through Grasshopper and computation but in a later process through trial and error, the knitting machine, and testing the materials' results.

The results created a fabric in a state of balanced tension, causing the scissor forms to rest naturally in the partially open relaxed state. This means that the scalloped catenary from the material edges expresses the way the material is stretched. As in the relaxed state, it is balanced tension. When expanded or contracted, the material is stretched in different directions. Therefore, extra force was needed to squeeze the scissor to collapse the mechanism and stretch the fabric, resulting in a sort of tensegrity where the tension of the fabric held the scissor mechanism open. As before, the membrane was added to the scissor structure, and it did not need any force to open or close the mechanism.

This is why the automated version of the scissors with the servos motor struggled to open and close when the material was too tight, as it needed extra force to stretch the textile. This could have possibly been resolved with larger servo motors. However, for this experiment, the concept was clear enough to consider the textile more as an enclosing feature and not as a tensile element in the mechanics of the motorization.

5. Conclusion

This research successfully combines scissor structures with the elasticity of knitted textiles, culminating in innovative designs that play with material behavior and performance. Through simulation, fabrication, and experimentation processes, the complexities of integrating elastic knit materials with various scissor configurations represent the transformative potential of this combination for adaptive architecture.

The project's iterative design process, underpinned by digital simulation tools and hands-on material investigation, has yielded insights into the interplay between textile elasticity and structural movement. At each design phase, the specified knit membranes became more tailored to complement each scissor structure's unique geometry, introducing a novel mode of structural tensioning that forms the equilibrium states of each structure. This balance between material flexibility and structural rigidity is symbolic of the project's overarching goal: to conceive new architectural elements that are responsive and adaptable.

Moreover, the venture into automation has opened new avenues for the dynamic activation of these structures, suggesting a future where architectural forms can morph in response to environmental cues without human interaction. While challenges remain in optimizing the integration of automated systems with material constraints, this preliminary exploration serves as a stepping stone toward realizing more interactive, adaptive architectural environments.

The next steps of the research would be to continue developing processes for scaling up the designs for larger, more architectural uses and exploring more Three-dimensional structural forms. Furthermore, some designs were more successful than others, and more refinement was needed to generate the knitting patterns and skipping of stitches.

In conclusion, this research opens discussion into the possibilities that emerge at the intersection of scissor mechanisms and knitted textile innovation. Combining these different territories of research provides possible ways for buildings to adapt and engage with their environment. The next steps are to continue refining the various forms and material properties and further developing the automation of these structures. The dynamic capabilities of these textiles and transformable structures continue to advance the dialogue on sustainable, responsive, and human-centric design.

Acknowledgments

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