

Architecture and its (non)permeable boundaries

Vera Parlac¹

¹University of Calgary, Calgary, Canada

ABSTRACT: The project presented in this paper is part of a larger body of ongoing design research that investigates kinetic and responsive architectural skin systems. It explores integration of custom-made soft robotic muscles into a component-based surface. The result is a prototype of a light modular system capable of kinetic response triggered by inflation and deflation of soft robotic muscles. The project focuses on kinetics of architectural surfaces and tectonics that integrate stasis and motion. It proposes a 'programmable' architectural modular system that simultaneously addresses stability, dynamics and adaptability of a singular system. This prototype-based research demonstrates the possibility of transforming aggregated structures by inflating and deflating integrated soft components (*pneu*) within them. In particular, the project explores the capacity of *pneu* structures to produce a kinetic effect in architectural surfaces. By having an elastic membrane, a *pneu* structure responds to the change of pressure by changing its mass. The change in pressure can cause considerable physical transformation of the structure. In addition, the nature of a boundary between architecture and its larger ecology is of particular concern. The project is based on two premises. First, that architecture and the built environment in general should be more tightly bound to the dynamics of local ecologies and that strong links to the undercurrents of its surroundings (near and far) could facilitate an active response to constant changes in the environment (external and internal). Second, that responsive architectural systems could act as ecologies in themselves, allowing architecture as a discipline to recalibrate its role in a larger socio-economic context by becoming a more intelligent and operative participant – a participant imbued with foresight.

KEYWORDS: Responsiveness, active material system, architectural boundary

INTRODUCTION

A boundary is defined as a line that establishes limits of an area or a sphere of influence – a dividing line. Traditionally, we think of spatial envelope in architecture as a boundary that separates exterior and interior environments or encloses spaces, and we presume that physical and spatial boundaries are one and the same. This view of the spatial boundary is probably as old as human desire for shelter and is reflected in Frei Otto's observation that "Architecture is man's oldest skill in his struggle for survival in nature. It is therefore directed against nature." (Otto, 1995, 8) However, physical phenomena extend beyond spatial boundaries. In physics, the boundary is a place of action where different energy fields transition into one another. Boundaries, therefore, could be thought of as active regions rather than surfaces of delineation (Addington and Schodek, 2005, 6).

In the 20th century, with the advent of building mechanical systems, two distinct positions towards an architectural boundary emerged: one that facilitated impermeable envelope, as seen in Le Corbusier's *Cité de Refuge*, a building with sealed walls and controlled ventilation, (Banham, 1984), and the other that encouraged permeability as described in the writings of Rayner Banham, Yves Klein's speculative projects called air architectures with walls and roofs defined by thin sheets of rapidly moving air, or Cedric Price's, Archigram's and Coop Himmelblau's experiments with inflatable structures. Technological advances and a promise of technology to deliver radically different solutions fueled both positions.

As emphasized in Rayner Banham's article *A Home is not a House*, there are two basic ways of controlling environment: building a shelter or mediating local environment by campfire. Banham points out that "a campfire has many unique qualities which architecture cannot hope to equal, above all, its freedom and variability." (Banham, 1965, 75.) Thinking in terms of energy exchange, flow and dynamics – and consequently in terms of gradients – calls for a spatial boundary that can negotiate change and transition and not simply isolate. It was Banham's argument for the inclusion of environmental phenomena and their variability into a design process that began to orient architecture towards adaptive environments. His ideas encompass the domain of environment and not that of an inert object or surface. Boundaries that modulate flows of heat, coolness, air or noise, exert subtle influence and support organization of people and activities differently than inert physical boundaries would. They could 'contaminate' design with the notion of variability, possibly leading to a richer interaction with the built environment. When the infrastructure for space organization is not only concerned with the traditional logic of the constructed environment but is informed by the logics of thermodynamic behaviors, a new notion of order and organization of space could be achieved that would increase organizational complexity, introduce emergence, and possibly result in the design of open systems. (Pavé, 2006) Energetically or kinetically active boundary has a level of agency and can, through its variability, attract, dispel or disperse users within spaces. It might unfold additional otherwise hidden layers of usable space or attract gathering by its coolness or heat (Figure 1). By gathering information from the environment, responsive boundary can serve as an effective interface between the users and their surroundings.

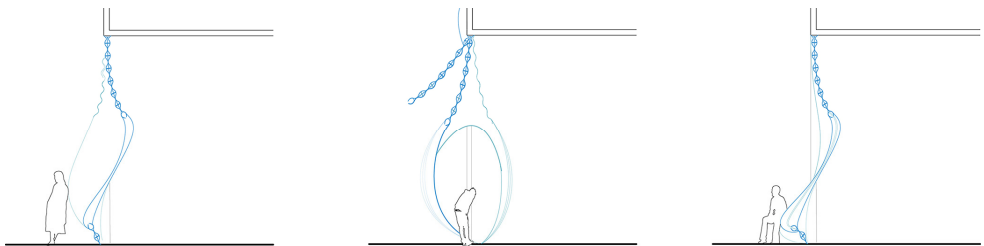


Figure 1: Kinetically active responsive building skin Source: (Author 2005)

In the introductory chapter of his 1970's book *Kinetic Architecture*, William Zuk, an engineer, architect and educator at the University of Virginia, speculates about changes in design approach that are necessary to envision architecture capable of kinematic movement (Zuk and Clark, 1970, 11). He suggests that new construction techniques, materials, and technologies would have to be established. But at the same time, Zuk predicts that even though kinetic architecture will require more mechanistic and technological approach through the use of sensing technologies, new materials, and embedded computation, it may also usher a new kind of relationships between a human body and space. According to him, social relationships, as well as personal sense of space and enclosure, would be challenged. Associations between a dynamic body and dynamic space could provide a context where organization of human activities and experiences becomes more sensitive and responsive to changing needs, changing form, and phenomena.

1.0 BACKGROUND

The project described in this paper proposes a structure for an *active* boundary. This modular structure is built from self-similar elements and is activated by pneumatic "muscles" that can react to variety of environmental stimuli, including presence or movement of people.

Dynamic behavior of the structure is introduced by integrating active pneumatic "muscles" directly into the structure. *Pneu* is a primary form of living nature, an effective structural system, as well as instrument of form giving (Otto, 1995). Every cell is a pneu structure (Helmecke, 1977). An elastic membrane that bounds pneu structures responds dynamically to the change in pressure by changing its volume. The change in pressure and consequently volume can

cause considerable physical transformation of the structure. This transformation enables a pneu structure to produce a kinetic effect in its own structure and also in structures that are attached to it. In engineering, rigid materials are employed to fabricate precise and predictable dynamic systems, but natural systems often exceed this performance with soft and flexible bodies (Rus and Tolley, 2015).

In soft robotics, the pneu-like capacity is used to design robots that move or handle fragile objects by manipulating the inflation and deflation patterns. Their bodies are capable of large-scale deformation and high level of compliance (Marchese, Katzschmann and Rus, 2015). Some of these robots can move around obstacles or squeeze under them. The research by Harvard's Biodesign Lab using soft robot fabrication techniques, described by Andrew D. Marchese et al. (2015), provided a starting point for the initial studies of pneu elements in this project. Other relevant studies that informed the project were related to the movement of soft actuators and their motion patterns (Bishop-Moser et al. 2012), and the complexity of this movement (Connolly, Walsh and Bertoldi, 2016). The capacity of soft robotic components to affect larger structures in which they are incorporated is of key importance for this project.

The project attempts to address two challenges present in designing dynamic and adaptive surfaces: the selection and design of an actuation system and its incorporation in surface tectonics. Therefore, on one hand, it explores a capacity of *pneu* structures to induce kinetic movement, and on the other, it articulates a component-based tectonic assembly that can integrate such movement. This project is informed by a history of pneumatic structures, the technology of soft robotics, and a modular design strategy (Figure 2).



Figure 2: Active pneumatic muscles move part of the structure Source: (Author 2005)

Inflatable or pneumatic structures have been used in architecture primarily for their lightness relative to the structural span. Between 1940s and 1970s these structures underwent a significant evolution. One of the first fully inflatable structures was a radome developed by Walter Bird in late 1940s. The exploration of air-supported structures quickly grew beyond their use as shelters for equipment or supplies. In 1960s and 1970s they were used in a variety of experimental projects in architecture, from the Fuji Group Pavilion, designed by Yutaka Murata for the 1970 World Expo in Osaka, to experiments by Coop Himmelb(l)au, Archigram, and Haus-Rucker-Co created at the scale of a human body. Inflatable structures offered a potential to design soft, transformable spaces with new formal (and dynamic) qualities. These mobile and mostly temporary structures were acknowledging the transformational potential of inflatable forms. They brought into architecture the notions of a dynamic, changeable and soft space, with boundaries no longer defined exclusively by rigid material enclosures.

Today researchers are experimenting with even smaller scale inflatables that could be integrated into architectural surfaces and components i.e. into tectonics of a material system itself. Current experiments with elastic inflatable elements influenced by soft robotics are suggesting new trajectories in exploring dynamic spatial boundaries. The projects such as *The PneumaKnit* by Sean Ahlquist, McGee and Sharmin and *Modular Pneu-Façade System* by Daekwon Park and Martin Bechthold are integrating inflatable elements to add new functionalities of dynamics or sensing to the architectural surface. *The PneumaKnit* is concerned with motion and dynamic articulation of inflatable components. This is achieved by using knitted constraints that regulate expansion of the actuator and direction of its motion. The emphasis is on the material structure of the knitted constraint, which, through a variable density of its weaves, produces the surface transformation when actuators are inflated. This

work is concerned not only with the actuator itself; equally important is its constricting surface. The material integration between the inflatable and knitted elements is a step forward in rethinking the material assembly in which constituent parts are dynamic, and perform synergistically as one material system. The *Modular Pneu-Façade System* is imagined as “a dynamic pneumatic interface, which can be used in building applications including responsive façade, ceiling, floor and interior screen, etc.” (Park and Bechthold, 2013). This layer of soft inflatable elements that can be integrated into a building’s skin to make them transformable and active is sensitive to human touch. Its surface utilizes capacitive sensors and conductive gel, which make it conductive to touch. Both of these experimental projects deal with a challenging question of how to integrate an active layer into an architectural assembly and speculate about architectural surface capable of interfacing information, dynamics and a user.

2.0 METHODS

The *Soft Kinetics* project brings together two strategies for designing adaptive architectural skins. One is concerned with the combinatorial variability of a light structure built by aggregating small self-similar components. The other one focuses on the integration and distribution of pneumatic muscles within an aggregated structure. The proposed system is a component-based material system whose properties range from rigid/stable (self-supporting) to pliable/active (dynamic). To achieve these variable properties particular emphasis was placed on the system’s morphology that arose from integrating self-similar rigid and pliable components with pneumatic muscles. This process produced a ‘programmable’ surface that can open, close or alter its basic form.

2.1. Light modular structure

The light modular structure is built using self-similar elements with a non-orthogonal alignment. It is aggregated through slot-friction connections and can be organized in a number of different configurations. The configuration of the construct is governed by the requirements for stability (self-support) and kinetics; both of these criteria are equally important to support dynamic transformations. Stability is achieved in two ways: by interlocking the components through simple slot-friction connections, and by the patterns of aggregation. The kinetic behavior is enabled by a system of pneumatic muscles, their full integration with the patterns of aggregation, and the capacity of the modular structure to allow for disruptions in pattern continuity without compromising the construct’s stability. The redundancy of connections and elements provides a structural resiliency.

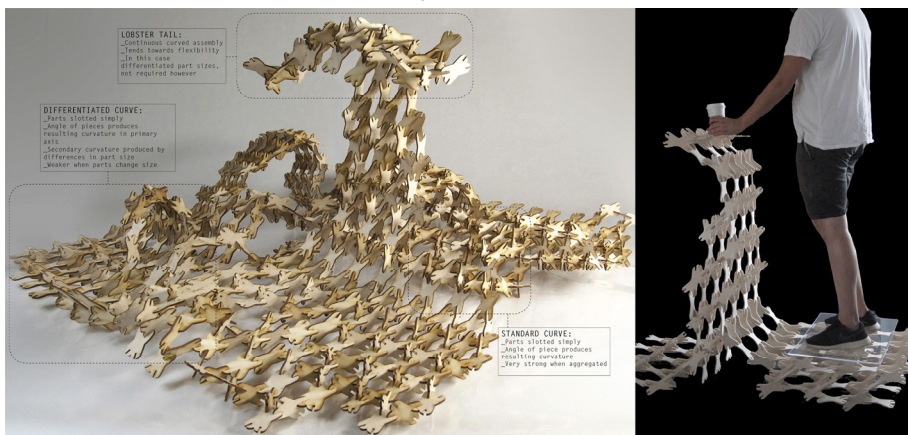


Figure 3. Rigid and pliant configuration; Integration of bendable component Source: (Author 2005)

Due to the self-similar unit shape and the standardized connection between the units the structure can be built in a variety of configurations and adapted to a variety of spaces. Following the assembly pattern, two main configuration trajectories emerged: rigid (self-supporting) and pliant (flexible) (Figure 3).

Individual components can form any number of permutations, but discrete assemblies, used to govern the form of a larger construct, were generated to support change in functionality, directionality and form. These discrete assemblies were then combined into larger formations and their tectonic and spatial capacities examined. However, the system itself remains open and able to adjust to a variety of spatial/contextual conditions as well as to support part replacement. In this way, recalibration of the construct can be maintained since its parts could be reconfigured in a variety of ways (Figure 4).

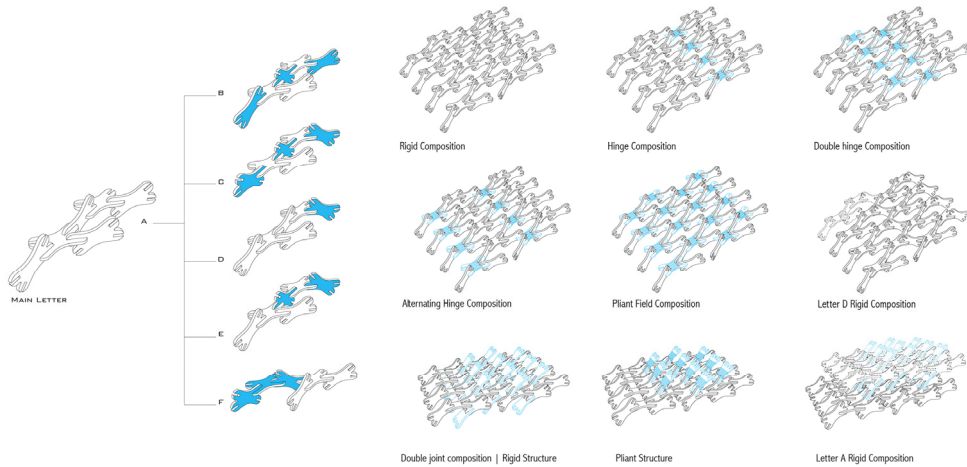


Figure 4. Combinatorial Potential Source: (Author 2005)

The component shape was chosen for its capacity to produce a significant number of different combinations while maintaining the pattern that generates rigid and pliant versions. These configurations were then modeled digitally and tested physically for their behaviour. The tests resulted in a design of a new bendable component that was positioned adjacent to pneumatic muscles to facilitate bending of the regions surrounding the muscles. Ultimately, the modular structure can negotiate a change in direction (straight, angled, curved), change in thickness by smoothly transitioning from single to multiple layers (from a surface to a three-dimensional construct) and change in structural capacity (from self-supporting to bendable).

2.2. Pneumatic Muscles

The soft body of the *Soft Kinetics* project is imagined as a continuous and interrelated network of pneumatic muscles integrated into an assembly pattern of the modular structure. It consists of clusters of interconnected soft inflatable pneumatic muscles. They are linked by silicone tubes that allow passage of air through a number of muscles, inflating and deflating them in a sequence. When activated these clusters move entire regions of the modular structure, producing opening and closing apertures (Figure 5).

The movement of pneumatic muscles depends on the flexibility of the elastic material, and the volume of internal chambers and their geometry (Bishop-Moser et al 2012). Andrew Marchese et al (2015) list three soft robot morphologies differentiated by their internal channel structure: ribbed, cylindrical, and pleated (Marchese, Katzschmann and Rus 2015). The soft body (actuation system) of the *Soft Kinetics* project is developed using a ribbed morphology but its internal channels are produced using two different techniques: the lost wax casting, and a combination of the lamination casting and the soft lithography fabrication method. As a result, two types of muscles are produced: the central channel muscles (S, B, and V) and the distributed channel muscle (M) (Figure 6). The fabrication technique is important in achieving consistent properties of the muscles as they get reproduced; it plays an important role in achieving consistent elasticity and inner channel geometry.

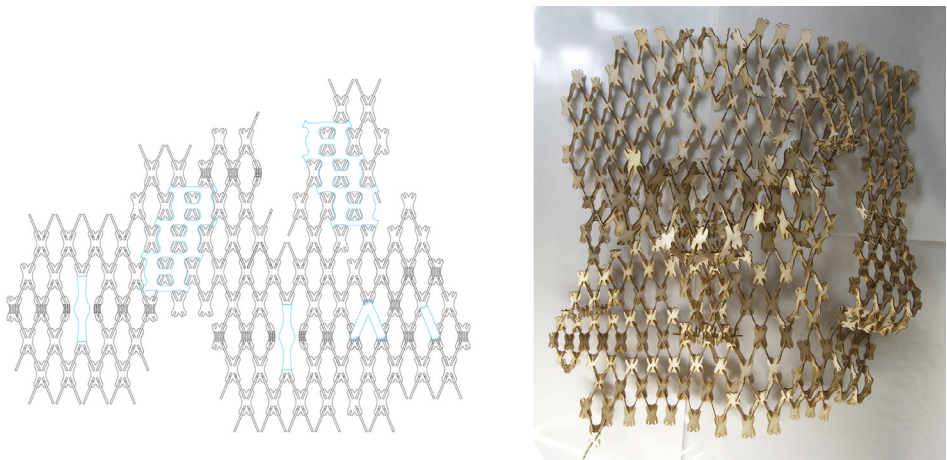


Figure 5: Assembly pattern and surface deformation Source: (Author 2005)

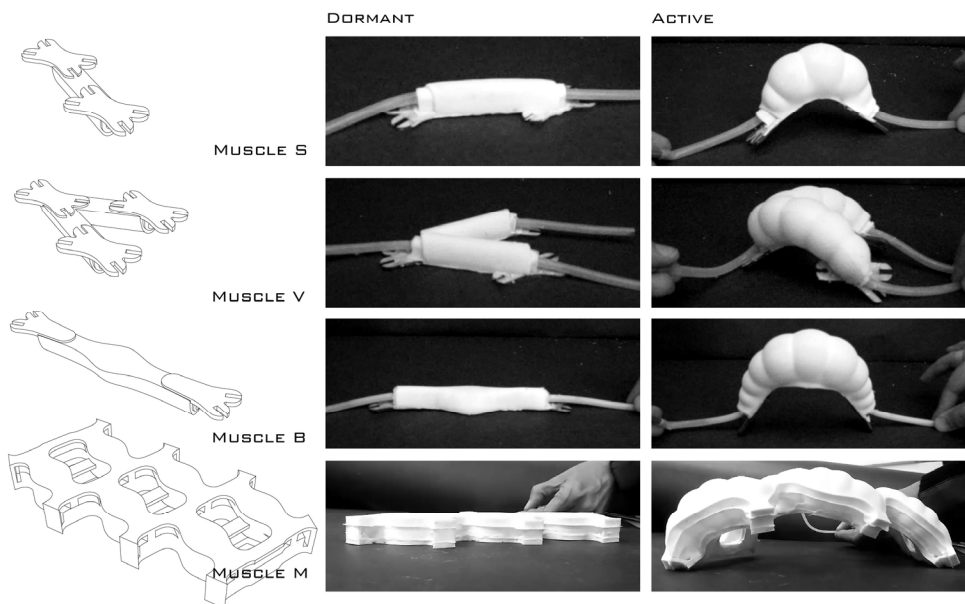


Figure 6: Muscle types and their performance Source: (Author 2005)

The behavior of designed pneumatic muscles was explored through prototyping and iterative design and their performance observed as they were activated within a modular structure. The central channel muscles produced using the lost wax technique were resilient and durable (by not being cast in laminated fashion). Compared to the distributed channel muscle it achieved significant bending. In general the lost wax technique allows for a great variety of cavity forms since the muscle was made as a solid body and was designed that way, not in layers. The proposed central channel muscles underwent several modifications to achieve maximum bending after inflation.

The muscles were conceived as modular elements of the structure and as such could be integrated into the structure interchangeably; two muscles (S and V) were designed to integrate into the assembly grid pattern while the other two (B and M) to nest within the voids of the grid. In terms of their behavior, the central channel type muscles (S, B, V) act as linear actuators while the distributed channel muscle (M) acts as a folding hinge (Figure 6).

The muscle morphology and geometry were designed to balance the wall thickness and the volume of air channels. These two different types of muscles required different approaches to mold production. The central channel muscle molds were CNC milled, while the distributed channel mold was produced by layering laser-cut acrylic material. Both muscle types were made from silicon rubber. To direct their motion, one side was fabric-reinforced. Soft elastomer pneumatic muscles are capable of continuous deformation but the challenge is to isolate a particular bending movement within its length (Ahlquist, McGee and Sharmin 2017). For that reason, the pneumatic muscles used in this project were short and compliant with the grid pattern of the modular structure (Figure 5); their length and cluster organization, however, will be further explored in the next phase of the project, to produce asymmetrical shifts within the fabric of the modular structure.

2.3. Integration and prototypes

The “soft” body of pneumatic muscles could easily be integrated with the “hard” body of the light modular structure. The connection was achieved by embedding the modular component within the central channel muscles or by weaving the components through the openings in the distributed channel muscle. (Figure 7).

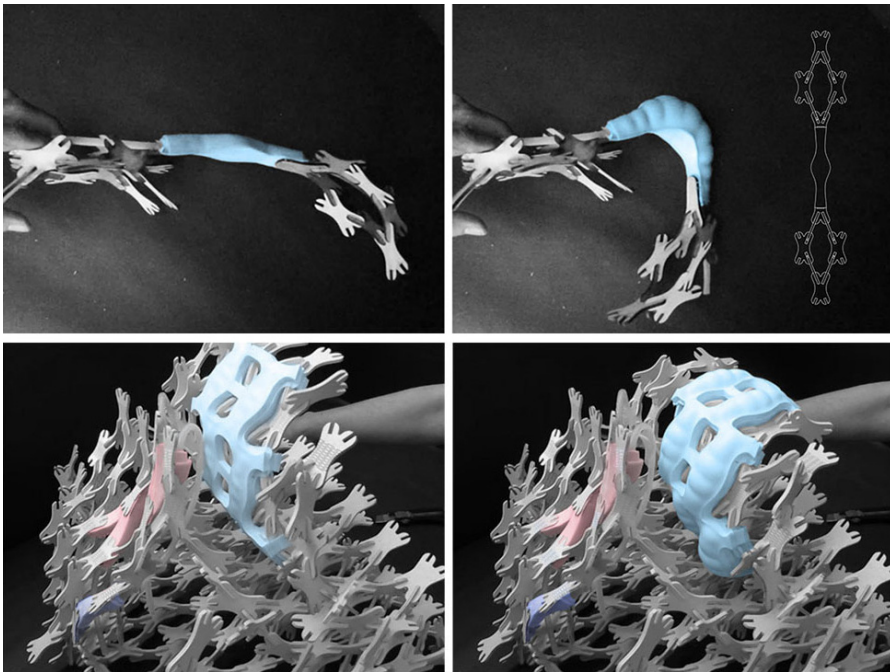


Figure 7: Testing the connection and movement of the muscle; dormant and active muscles Source: (Author 2005)

The central channel muscles integrate into the hard body of the structure by a slip joint, just like any other modular component of the system. Therefore, the soft pneumatic muscles could be positioned to displace the “hard” parts of the modular structure, working as an active connective tissue, while the overall assembly pattern was maintained. This strategy allows muscles to be asymmetrically distributed throughout the structure, concentrated in some areas, or placed sporadically in others. This is seen as a very promising direction that will be further explored in the next phase of the project. For example, larger segments of the modular structure could be dynamically altered to open and close apertures of varying sizes and shapes (Figure 8).

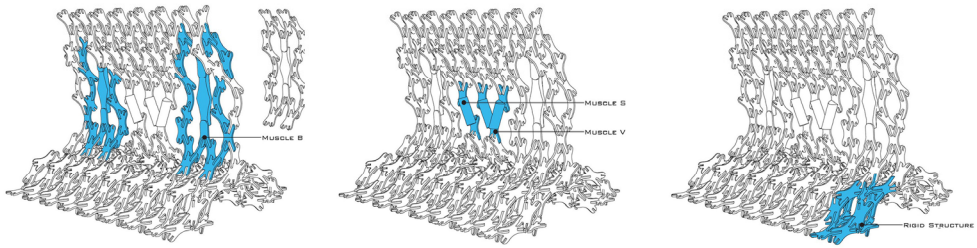


Figure 8: Illustration of muscle integration Source: (Author 2005)

Several small prototypes were constructed to test various ways and combinations of muscle integration. It is in the prototypes that the clustering of muscles was explored. The clusters, consisting of three to five pneumatic muscles, were inflated in sequence. Solenoid valves controlled the inflation and deflation pattern (supply and exhaust) and their work was regulated through an Arduino microcontroller. The rate and duration of valve opening and closing was set to allow all linked muscles to inflate in a sequence; the pressure was controlled through a pressure sensor to prevent over-inflation and damage to the muscles. Muscles linked in a cluster worked as a group, affecting dynamically a designated region of the structure. The work of the “soft” body could be controlled through proximity sensors to reveal a clear view out or in, or could be regulated by light sensors to serve as a functioning shading device.

CONCLUSION

The research shows a promising way of integrating an active pneumatic layer within a light modular structure. An important aspect of this project is the smooth transitioning between stable and dynamic regions of an aggregated structure. Additional components that would facilitate that transition or compensate for motion were not necessary. Other essential features are the slot-friction connections, consistent aggregation patterns, and modular pneumatic components that integrate seamlessly into the designed patterns. The transitions between dynamic and static regions are achieved through carefully designed (and tested) component distribution pattern and varying densities of pneumatic muscle components within the aggregated construct. Some parts of the resulting structure are self-supporting, providing structural stability, while other parts permit different levels of movement without compromising the structural integrity.

The design of pneumatic muscles strives to seamlessly integrate soft and hard layers into a composite system using the same aggregation patterns. The key feature of *Soft Kinetics* is an actuating system that is embedded, through the geometry of its components, into the overall structural pattern of the construct, while simultaneously making the regions of that construct dynamic. This project attempts to produce additional functionality of an architectural assembly by integrating functionality and materiality of soft/dynamic and hard/structural layers to produce a dynamic architectural assembly.

The weight of the structure is an important factor; therefore more research is required to define the “blended” materiality of the modular structure as well as the durability and weight of the embedded pneumatic components. Current composite structure is made of plywood; but the use of aluminum and plastic will be explored in future iterations.

In his seminal article on “Resilience and Stability of Ecological Systems,” C. S. Holling points out different ways in which we see the behavior of a system. Engineered systems or devices that perform specific tasks under predictable external conditions have their performance immediately adjusted if the variation in performance is observed. They are concerned with constancy of performance and lean towards stability. Natural systems that are constantly confronted with unpredictable external changes are less concerned with constancy and more with persistence of the relationships (Holling, 1973). An equilibrium-centered view of a system

is static and doesn't offer the flexibility necessary for systems with transient behavior. The project presented here is an exploration into how to incorporate variability in performance (from stable/structural to dynamic), and how those variable conditions integrate and interface with each other.

When designing active and adaptive artificial environments, whether they are intelligent facades or built environments that interface with natural ecologies, we want to establish a flow of information and energy. The adaptive built environment should behave similarly to natural systems. Therefore, we might design them by being less interested in stability as an on/off condition, and more in the zone of stability or motion, their gradient and ability to perform under constant changes.

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REFERENCES

- Addington, M., and Schodek, D. 2005. *Smart Materials and Technologies for the architecture and design professions*, Oxford: Architectural Press. 6.
- Ahlquist, S., McGee, W., and Sharmin., S. 2017. "PneumaKnit: Actuated Architectures Through Wale- and Course-Wise Tubular Knit-Constrained Pneumatic Systems" In *ACADIA 2017: Disciplines and Disruptions*, Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture, edited by T. Nagakura. Cambridge: ACADIA. 38-51.
- Banham, R. 1984. *Architecture of the Well Tempered Environment*, Chicago: The University of Chicago Press.
- Banham, R. 1965. "A Home is not a House," in *Art in America* 2, April. New York: Art Media Holdings. 75
- Bishop-Moser, J., Krishnan, G., Kim, C., and Kota, S. 2012. "Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations." In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 4264-4269.
- Connolly, Fionnuala, Conor J. Walsh and Katia Bertoldi. Oct. 2016. "Using Analytical Modeling to Design Customized Fiber-Reinforced Soft Actuators." In *Society of Engineering Science 53rd Annual Technical Meeting (SES 2016)*.
- Helmcke, Johann-Gerhard. 1977. "The Biological Pneu." in *IL9 Pneu in Nature and Engineering*, Stuttgart: Institute for Lightweight Structures (IL). 138-150.
- Holling, C S., 1973. "Resilience And Stability Of Ecological Systems." in *Annual Review of Ecology and Systematics*, Annual Reviews, Vol 4. 1-23.
- Marchese, Andrew D., Robert K. Katzschmann and Daniela Rus. 2015. "A Recipe for Soft Fluidic Elastomer Robots." *Soft Robotics* 2 (1): 7-25.
- Otto, Frei. 1995. "Pneus in Living Nature." in *IL35 Pneu and Bone*, Stuttgart: Institute for Lightweight Structures (IL). 8.
- Park, Daekwon and Martin Bechthold. 2013. "Designing Biologically-Inspired Smart Building Systems: Processes and Guidelines." *International Journal of Architectural Computing* 11 (4): 437-464.
- Pavé, A. 2006. "Biological and Ecological Systems Hierarchical Organization", in *Hierarchy in Natural and Social Sciences*, ed. Denise Pumain, New York: Springer-Verlag. 39-70.
- Rossi, Dino, Zoltán Nagy and Arno Schlueter. 2014. "Soft Robotics for Architects: Integrating Soft Robotics Education in an Architectural Context." *Soft Robotics* 1 (2): 147-153.
- Rus, Daniela, and Michael T Tolley. 2015. "Design, Fabrication and Control of Soft Robots." *Nature* 521 (7553): 467-475.
- Zuk, W., and Clark H. R. H. 1970. *Kinetic Architecture*, New York: Von Nostrand Reinhold Company. 11