ADAPTIVE PNEUMATIC FRAMEWORKS

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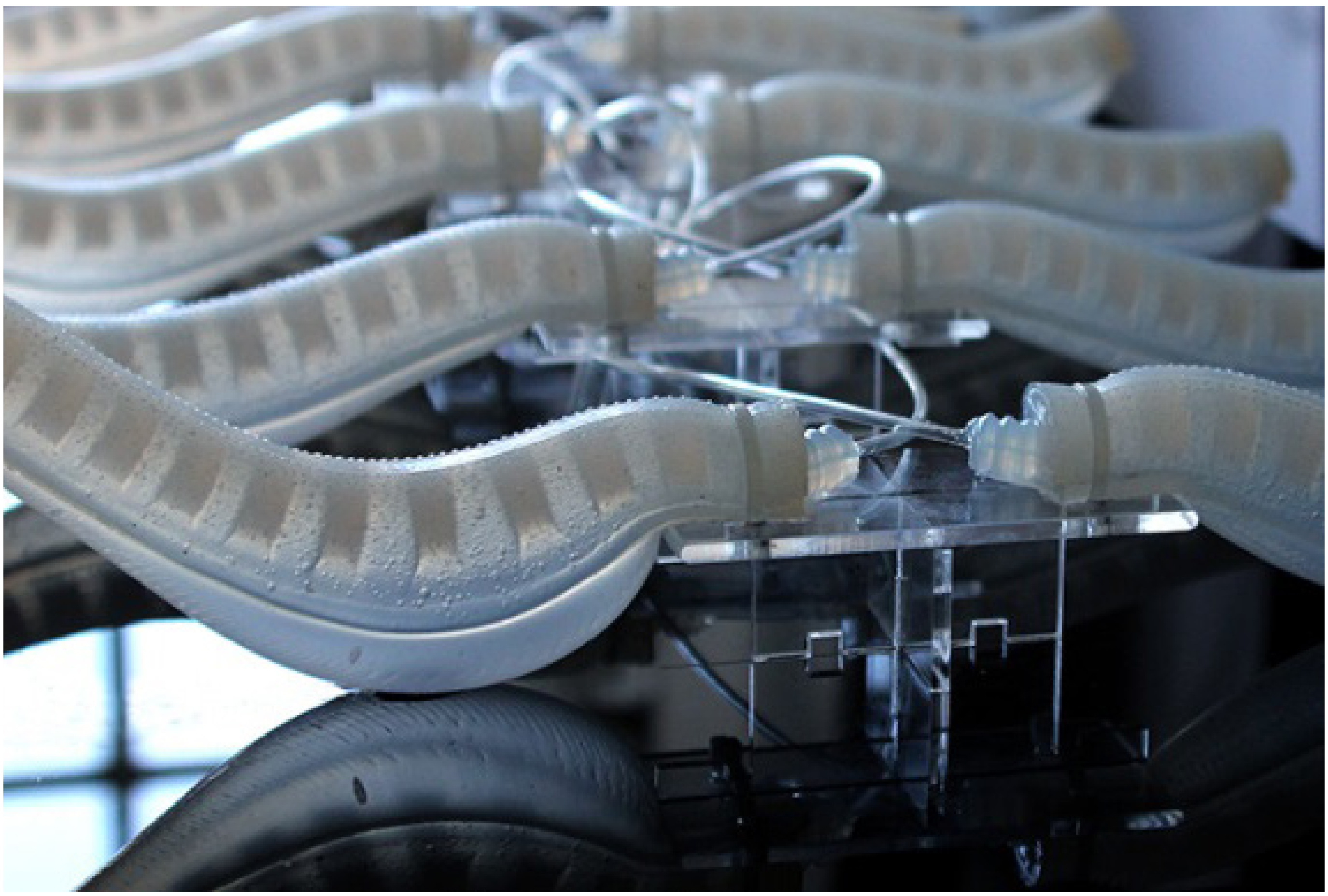


Prototype–Silicone component geometry detail

ABSTRACT

Responsive technologies play a pivotal role in the evolving relationships among humans, machines, and environments. Advances in physical computing and synthetic materials promote the agency of adaptive architectural systems that propagate nuanced responses to environment, context, and human behavior. This paper describes a work-in-progress research project entitled *Adaptive Pneumatic Frameworks*, which attempts to merge computation, fluidic actuation, and synthetic materials to explore and speculate on the potential roles of adaptive and responsive pneumatic behaviors in architectural design.

DESIGN METHODOLOGY

The Adaptive Pneumatic Frameworks research project currently serves as a preliminary prototype that demonstrates a workflow and process for digitally controlling kinetic, pneumatically-driven motions of elastomer components that fluctuate between a range of parameters and constraints. It adapts current research in soft robotics to explore possibilities for muscle-like motions and motor reflexes that drive pneumatic architectures.[1, 2] The main topics of the research involve: Pneumatics in architectural design, cast elastomer components, computation, physical computing and fluidic actuation.

PNEUMATICS IN ARCHITECTURAL DESIGN

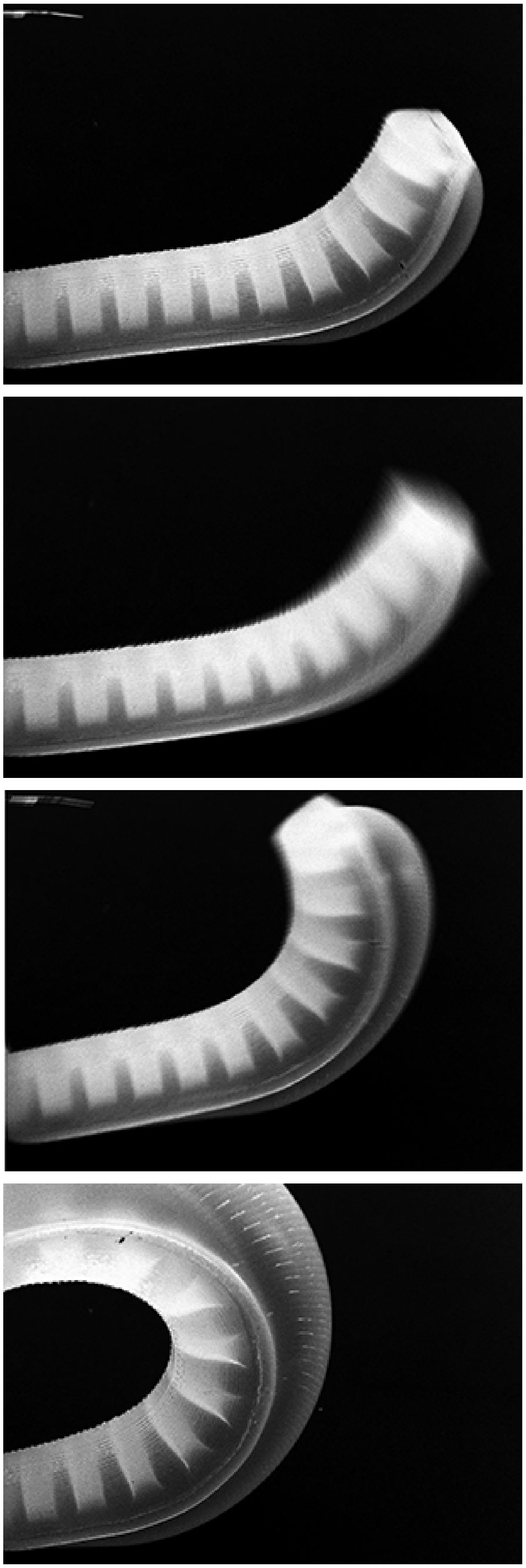
Pneumatic structures in architectural design have evolved through advances in technologies and materials, beginning with early experiments in the development of hot air balloons, and proliferating in architectural design processes, utopian ideas and exhibition structures during the 1960s and 1970s.[3] Historical and contemporary applications of Pneumatics in architectural design typically operate by inflating air into plastic membranes that expand to create pockets of space or structures which can be inhabited by users. The plastic membranes are inflated until their maximum surface areas are constrained and a maximum volume is obtained to form environments. This can be seen in early pneumatic architecture projects such as Oase No.7 (1972) by Haus-Rucker-Co in which "an inflatable structure emerged from the façade of an existing building creating a space for relaxation and play"[4] (Figure 1). Other examples include the Fuji Group Pavilion (1970) designed by the architect Yutaka Murata, which consists of a series of air inflated vinyl tubes attached together to form a larger structure. The inflation of the membranes was achieved through a solution that "allowed a limited air exhaustion and kept a continual flow of air blown into the tubes at all times. This method maintained the air pressure at a constant level" [5] (Figure 2).

In both examples, plastic and vinyl membranes are inflated to their maximum volume. The material was dependent upon a constant supply of air pressure in order to maintain its form and shape without collapsing. These projects demonstrate architectural solutions that are flexible and undergo transformations, but are not reactive or adaptive.[6]

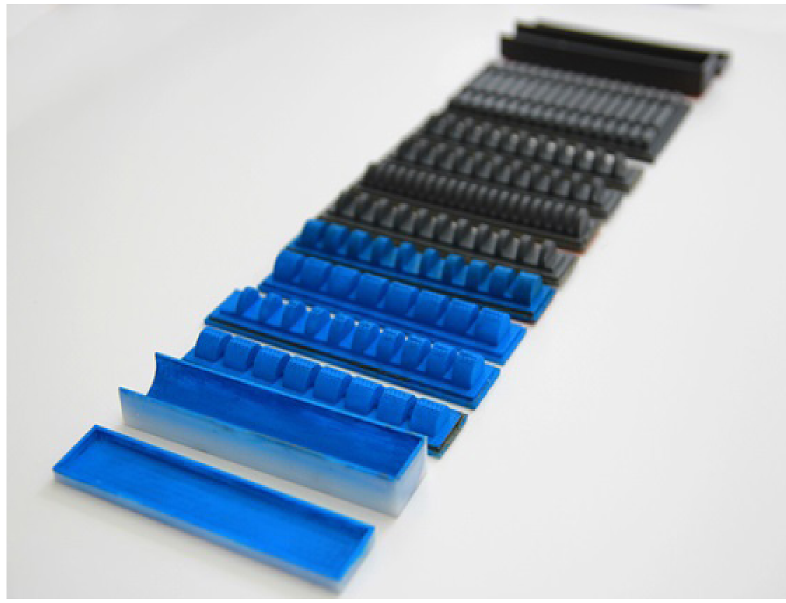
The Adaptive Pneumatic Frameworks project utilizes physical computing techniques and synthetic elastomer materials that are flexible, lend themselves to various stages of transformation, and that demonstrate reactive and adaptive mechanical behaviors. As Nicholas Negroponte wrote in *Soft Architecture Machines*, "soft materials, like inflatable plastics, are presently the most natural material for responsive architecture, because they exhibit motor reflexes through simple controls."[7] However, unlike plastic materials, elastomers demonstrate resilient behavior, maintain shape and spring back and forth between their deflated form and their inflated form. The difference being, inflatable plastics typically produce singular forms that are fully inflated to a maximum condition, while inflatable elastomers produce variations of forms based on continuous deformation and various stages of morphology. Additionally, through the expansion of internal fluidic channels and asymmetrical distributions of material mass, mechanical behaviors such as contraction and bending can be obtained (Figure 3). This enables soft actuations that are more in line with Negroponte's description of motor reflexes, producing animate qualities that resemble biomorphic movements, similar to the movement of a muscle. Through the actuation of fluid channels that are controlled through

1 Oase No.7, Hause-Rucker-Co, (Engelskirchen 1972)

2 Fuji Group Pavilion, Yutaka Murata



3 Silicone Component Study of Bending Motion and Material Behavior (film stills)



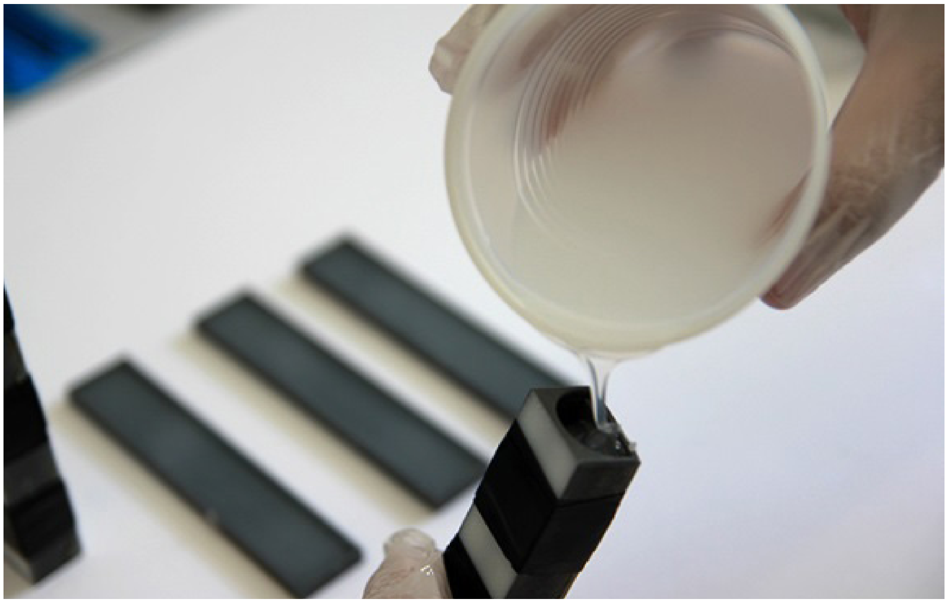
4 ABS plastic 3D printed mold variations

sensing devices, these movements can begin to adapt to particular environmental conditions or human interaction. This creates a framework for pneumatic structures that are interactive and adaptive.

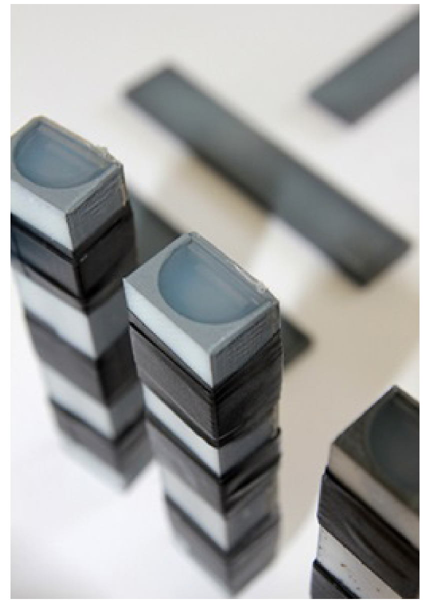
Therefore, the design objectives of the Adaptive Pneumatic Frameworks project are different from the design objectives of historical pneumatic architecture of the 1960s and 1970s. In terms of context, historical pneumatic architecture sought to create membrane barriers that separated surrounding environments from fully enclosed, well-defined, utopian spaces. To achieve this, the scale of inflatable pockets were very large, producing inhabitable spaces that operated at the building or urban scale. Conversely, the Adaptive Pneumatic Frameworks project seeks ways to merge current technologies and Pneumatics as a means of blending the surrounding environment with architecture. This allows for an architectural space that adapts to nuances within the environment, expanding on notions of ecologically-driven models for architectural design. The project leads to the speculation of a field of small-scale soft robots that expand and contract to create larger, fluctuating and adaptive architectural surfaces. These small-scale pneumatically-driven pockets can then be programmed to fluctuate in response to environmental factors such as light, wind, and temperature. Additionally, they can be programmed to detect human interaction, such as movement to produce localized responses, such as the opening and closing of apertures, within a larger surface area.

CAST ELASTOMER COMPONENTS

This research explores digital and analogue fabrication techniques of customization and mass production to create elastic components that contain fluidic channels. The form of the components was designed in 3D modeling



5 Silicone component casting process



6 Silicone component curing

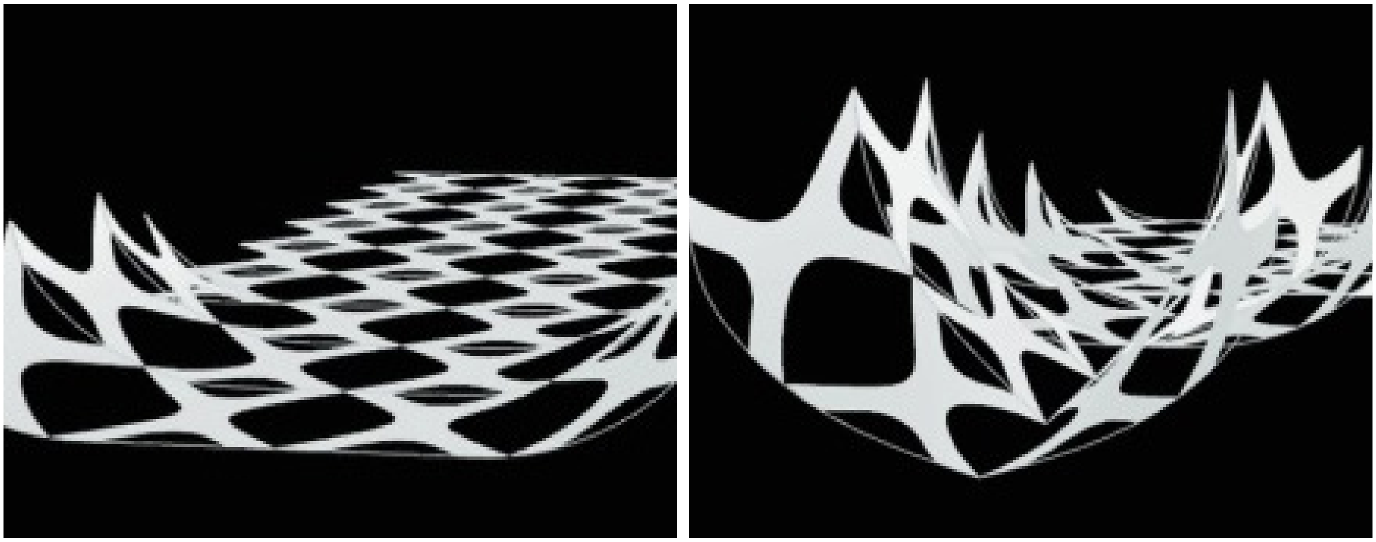
software, as a half circle shape extruded linearly along an axis to form a half cylindrical volume. The geometry was designed to distribute the massing of the cast components in such a way that produces bending motions. Digital models were used to 3D print ABS plastic parts which were coated with a release agent and used as molds to cast silicone rubber (Figure 4), (Figure 5), and (Figure 6). Versions of 3D printed parts, each designed with a unique geometrical configuration, were used to produce a series of cast elastomer components, that, when actuated, produced unique bending motions. The silicone pieces were adhered to form components that contained hermetically sealed channels. The silicone rubber that was used was selected based on its shore hardness, which rates the amount of flexibility and its stretchy behavior. The silicone is able to stretch, deform, and return to its original shape without permanent deformation. Additional selection criteria included the translucent qualities of the silicone, which allowed us to observe geometrical deformations of the material under pressure, and which captured the light to produce an atmospheric effect.

The geometries of the digital models were kept simple and within tight constraints, in an attempt to obtain control and better predict the elastic behavior of the material. Elastomers tend to be unruly and undermine the design of their initial geometries when subjected to forces.[8] In spite of the simple geometric rules and constraints, the silicone components reflected complex geometries and motions when introduced to internal fluidic pressure. Through a series of tests and trial and error, the geometries of the models were modified to achieve a maximum bending movement.

COMPUTATION

Computational tools were utilized to better understand and study the behavior of Pneumatics. A series of studies were produced in which scripting and parametric modeling techniques were used to represent the components as systems of particles and springs to simulate elasticity and inflation. The objective of these techniques was to generate simulations to predict the expected behavior of a single component, of arrays, of components and of an applied surface in between components (Figure 7). The computational model allowed for the experimentation of various pressure forces with particles and various elastic behaviors with springs. It was possible to implement informative simulations for components with simple geometry and topological surfaces without thickness. However, with the introduction of complex geometry and various material thicknesses, our studies using computational means to simulate the phenomenon of inflation, elastic material properties and the behavior of the overall assembly posed a series of challenges. This is due to the complexity of the forces, flows and unruly elastic motions of the material.

Experimentation with parametric modeling was used to approximate the behaviors that were being observed; however, a parametric system that can be used as an aid to predict the pneumatic elastomer behavior needs further exploration. Part of the intention of this research is to develop a set of tools which can be utilized by architects and designers to predict, visualize and better understand the motion of elastic materials and pneumatic systems, as there currently does not seem to be a simple analytic model which allows for the simulation of such complex systems.



7 Computational Simulation of Elastic Behavior (animation stills)

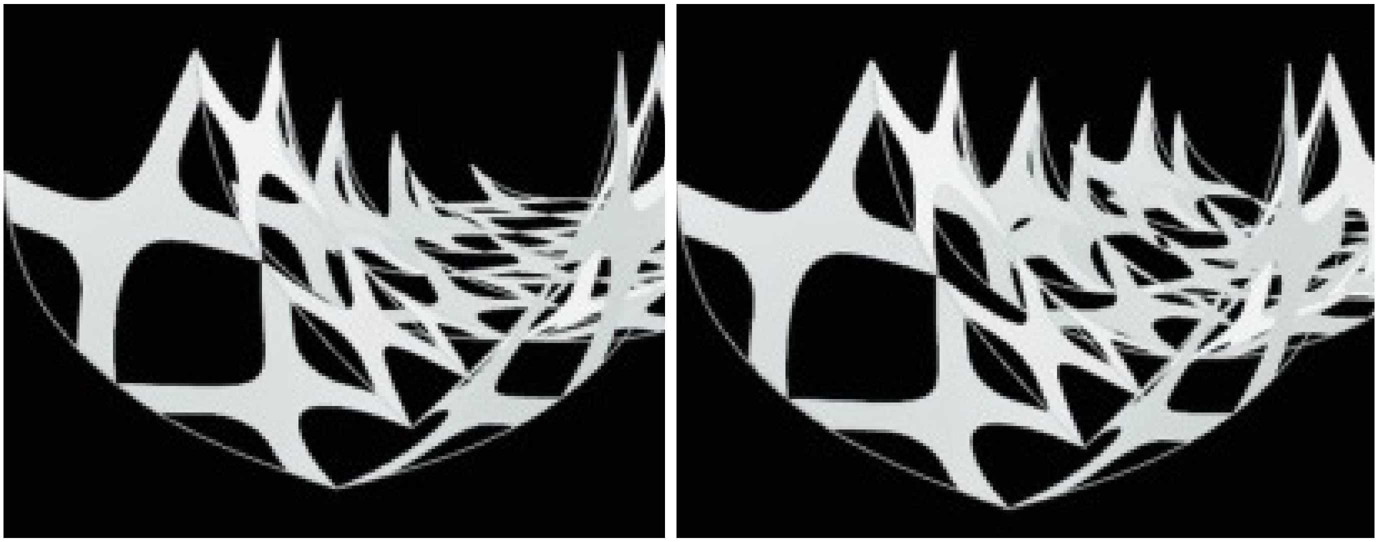
However, in the next steps of the project, additional research will be placed on *Computational Fluid Dynamic* (*CFD*) systems and the possible integration of *CFD* systems with parametric modeling systems.

PHYSICAL COMPUTING AND FLUIDIC ACTUATION

This research focuses on controlling fluidic pressure as a means of actuating biomorphic movements and behaviors in elastic materials. As a means of controlling fluidic pressure, in this case air, the flow from the pressure source to the channels in the components must remain hermetically sealed without any leakage. The source of the air was a pressurized air tank and regulator which provided a constant supply of pressure within the hermetically sealed channels. A microcontroller was used to computationally and electronically control multiple solenoid valves, which were operated in a binary manner to control the input and output of air within each component (Figure 8) and (Figure 9). The code was used to set the duration and rate in which the valves open and close. This duration was established through producing the effect of bending without compromising the overinflation or rupturing of the component. An additional code was developed, allowing the integration of five photo sensors which could be used to control the input and output of air pressure through the actuation of the solenoid valves. This allowed users to cover or uncover the sensors as a means of actuating pneumatic responsive behaviors within the prototype and demonstrating the potential for human interaction. Although the photo sensors demonstrated one specific method for creating an adaptive and interactive prototype, this provided a means of understanding other potential applications for the integration of sensors to actuate response by users and/or environmental conditions. This introduces topics of feedback and ecological systems.

PROTOTYPE

The Adaptive Pneumatic Frameworks prototype consists of ten identical silicone components that are distributed symmetrically along an axis in a spine formation. The casting process allows for the mass-production of identical parts that perform with the same kinetic behavior. The number of components that were used provided a field condition that allowed for the speculation of the behavior of the framework across a larger surface area. Each component is secured on one end, allowing the opposite end to move freely when inflated. Vinyl tubing connects the air tank, solenoid valves and individual silicone components. This creates a hermetically sealed network of chambers in which air can flow from a single source of pressure to multiple discrete destinations. Once the amount of fluidic actuation is calibrated, the computationally regulated solenoid valves can be controlled in many different ways to create various pneumatic pulses, biomorphic movements, and patterns of behavior along the axial array of elastomer components that play in a loop (Figure 10), (Figure 11), (Figure 12) and (Figure 13). This opens up multiple methods for the algorithmic control of fluids, air or water, to be distributed to and from multiple sources, and to create nuances in behavior and effects at the component level as well as within an overall field of components. This workflow and prototype serves as a diagram, or framework, which highlights potential methods of controlling pneumatic behavior in architectural design.



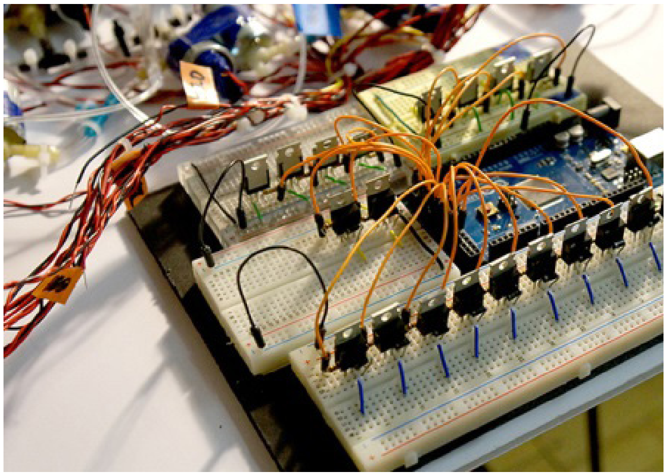
7 Computational Simulation of Elastic Behavior (animation stills)

NEXT STEPS AND FUTURE POTENTIALS

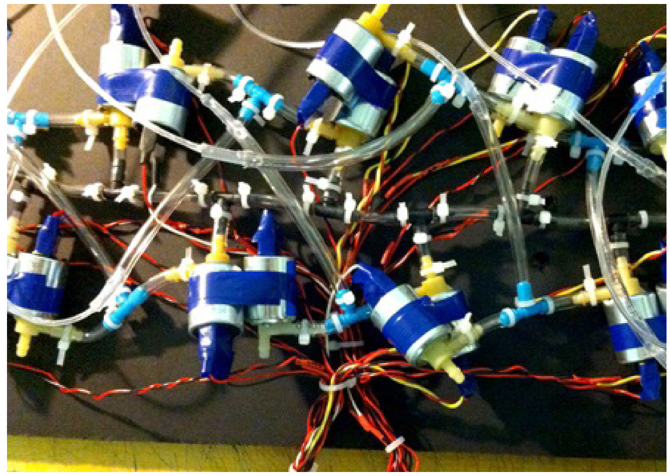
As a work in progress, the Adaptive Pneumatic Frameworks research project outlines a potential workflow for controlling and regulating Pneumatics in architectural design. The next steps in the research includes additional research into sensing devices that allow users and environmental phenomena to drive the pneumatic behaviors of the soft robots, which will be reactive and adaptive, allowing for feedback loops between the users-environment-architecture to emerge. Additionally, the prototype currently serves as a scaffold, in which an elastomer surface can span across. The introduction of a surface to the framework begins to suggest an architectural membrane that can open or close to provide various ranges of porosity. Unlike the large-scale pneumatic structures of the 1970s, the Adaptive Pneumatic Frameworks prototype suggests a small-scale array of pneumatic elastomer muscles that control the opening and closing of surface geometry within a membrane. Potential applications might include the design of adaptive pneumatic systems that expand to create thermal mass, influencing heat gain/heat loss and temperature control, or the design of adaptive pneumatic systems that actuate to open or close apertures in an architectural envelope.

This project and research currently leads to the speculation of adaptive pneumatic systems as they relate to the design of architectural surfaces. In terms of thermal massing possibilities, a potential next step includes measuring the amount of heat transfer from inflated and deflated pneumatic pockets that can be filled with air or water. Through the integration of temperature sensors, this type of pneumatic system could potentially allow for the design of building skins that regulate air temperature, heat gain, and heat loss within a building, based on the sensed environmental conditions that are constantly fluctuating based on the time of day, year and geographic location. Additionally, a network of hermetically sealed fluidic channels would allow for air and/or water to be distributed to various regions within a surface, to produce thermally driven concentrations within local regions of the surface. Regarding the opening or closing of apertures, a potential next step includes generating an adaptive surface that integrates photo sensors as a means of regulating light levels or visibility within an architectural space. This type of pneumatic system would allow for the design of building skins to respond to day lighting conditions that are consistently changing during the course of the day. Through the integration of photo sensors, fluidic actuation can be utilized to control pneumatic pockets that close or open apertures to block or bring light into a space. Additionally, motion sensors can be used to detect human occupancy to open or close apertures as a means of producing transparency or opacity.

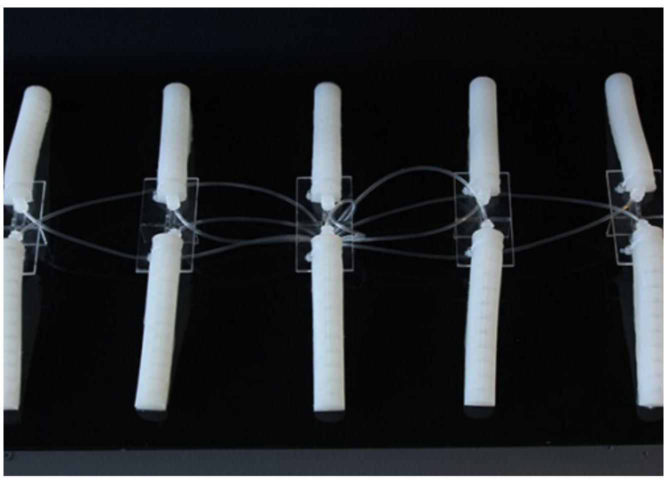
This allows occupants to interact with a surface that produces or hides views into or out of an interior space. Through further exploration of the speculative examples described, this research will continue to focus on computation, fluidic actuation and synthetic materials to posit a framework for rethinking pneumatic systems as adaptive, soft robotic architecture that incorporate volumetric expansions, geometric deformations and muscular motions to define and control spaces and environments.



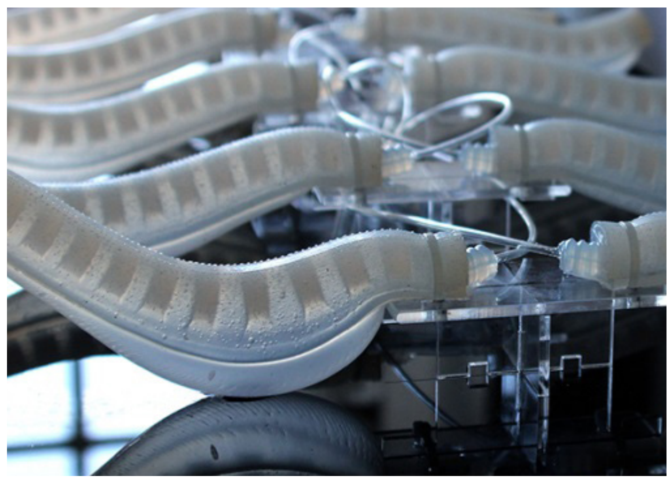
8 Microcontroller and Electronic Circuitry



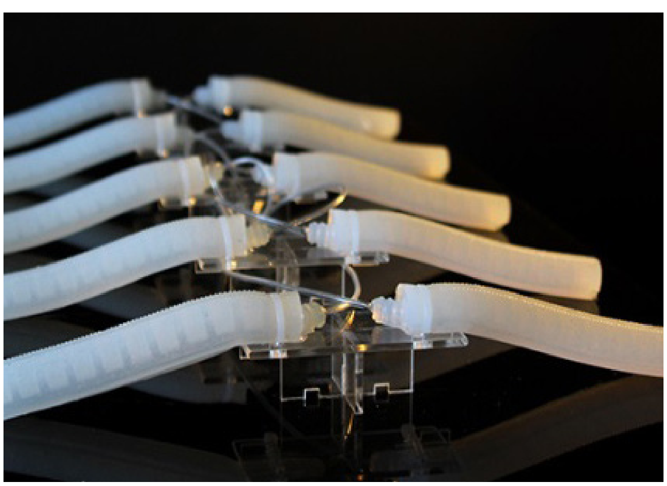
9 Solenoid Valves and Air Pressure Control



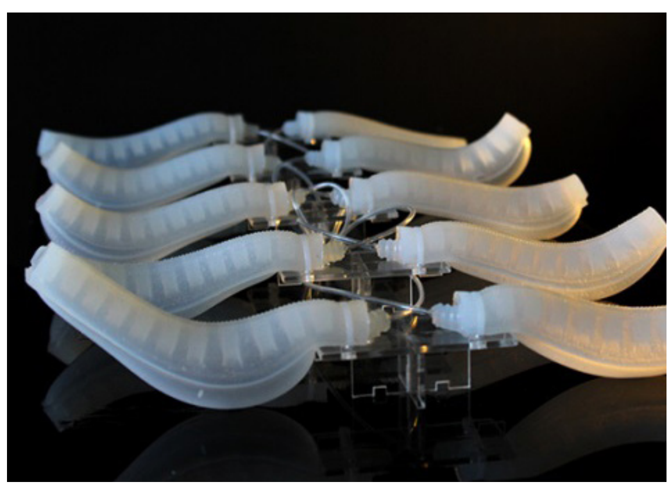
10 Prototype–Hermetically sealed fluidic channel network



11 Prototype–Silicone component geometry detail



12 Prototype–Pneumatic system deflated (film still)



13 Prototype–Pneumatic system inflated (film still)

ACKNOWLEDGEMENT

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NOTES

[1] Ilievski, Filip, Aaron D. Mazzeo, Robert F. Shepherd, Xin Chen, and George M. Whitesides. 2011. "Soft Robotics for Chemists." *Angewandte Chemie International Edition* 50(8): 1890–1895, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

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[6] Negroponte, Nicholas. 1975. *Soft Architecture Machines*. Cambridge, Massachusetts and London, England: MIT Press.

[7] Ibid.

[8] Beesley, Philip, and Omar Khan. 2008. Situated Technologies Pamphlet 4: Responsive Architecture/Performing Instruments. New York: Architecture League of New York.

IMAGE CREDITS

Figure 1. Oase No. 7, Fridericianum, documenta 5, Kassel 1972. Photo: Hein Engelskirchen

Figure 2. Mollaert, M., Expo 1970 (Osaka) Fuji Group Pavilion, http://www.tensinet.com/database/viewProject/3765.html

Figures 3-13. Frank Melendez, Madeline Gannon, Zachary Jacobson-Weaver, Varvara Toulkeridou

FRANK MELENDEZ was awarded the George N. Pauly Jr. Fellowship, joining the Carnegie Mellon University School of Architecture faculty as a Visiting Assistant Professor. His research is focused on the advancement of digital technologies in architecture and design. Melendez has taught at Louisiana State University and Arizona State University, and has participated in workshops at various architecture schools throughout the U.S. and abroad. His professional experience includes working at the office of Frank O. Gehry & Associates in Los Angeles, California, and serving as the Design Director at Urban A&O in New York. Melendez received his Bachelor of Architecture degree from the University of Arizona, followed by a Master of Architecture degree from the Yale School of Architecture.

MADELINE GANNON is a Researcher/Designer/Educator whose work merges disciplinary knowledge from architecture, robotics, computer science, human-computer interaction and design. Her research explores how the edges of digital creativity can integrate into the physical world. Gannon is currently pursuing a PhD in Computational Design from Carnegie Mellon University. She also holds a Master of Science of Computational Design from Carnegie Mellon University and Master of Architecture from Florida International University.

ZACK JACOBSON-WEAVER is currently a PhD candidate at Colorado University's ATLAS Institute, exploring open-source technology and education. In 2013-2014 he taught interaction design and digital fabrication at the School of Architecture, Carnegie Mellon University. In addition, he was a member of the Human-Machine Virtuosity and Biologic research groups, a speaker and exhibitor in computational, robotic and digital-fabrication symposia and an interdisciplinary collaborator. Jacobson-Weaver is a graduate of Carnegie Mellon's Master of Tangible Interaction Design (2012) and the University of Michigan School of Art and Design (2001).

VARVARA TOULKERIDOU is an architect, researcher and educator, currently pursuing a PhD in Computational Design at Carnegie Mellon University. She holds a Master of Science in Design and Computation from Massachusetts Institute of Technology and a Diploma in Architecture from Aristotle University of Thessaloniki. Her doctoral research investigates how end-user programming tools for design software can support parallel exploration of design alternatives. She has taught and assisted courses at CMU and MIT on parametric design, scripting, descriptive geometry and analog/digital fabrication.