Exploring Controlled Curvature: Biological Paradigms for Embedded Interaction and Responsive Forms

By

Margaret Jean Williams George

Bachelor of Arts in Integrative Biology, UC Berkeley, 2016

Submitted in partial fulfillment of the requirements for the degree of

Master in Design Studies
Technology

At the Harvard University Graduate School of Design

May, 2019

Signature of the Author ____________________
Margaret Jean Williams George
Harvard University Graduate School of Design

Certified by ____________________
Martin Bechthold
Director of the Doctor of Design Studies Program and the Master in Design Engineering Program
Kumagai Professor of Architectural Technology
Harvard University Graduate School of Design

Dedicated to

Leona Viola "Levi" Prisock

1995-2016

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Author . . . .

Margaret Jean Williams George

Advisor. . . . .

Dr. Martin Bechthold

Readers . . . .

Dr. Douglas Kirkland

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Helpful Definitions

Material/Physical Computation
The processing of information based on the properties of the material, simple, local material interactions, which allow for a "higher integration on a multitude of levels" (Menges, Achim 2012).

Form
The visible shape or configuration of something; the opposite of space (Ndjet, 2016).

Responsive Material
Materials which respond to environmental stimuli either through intrinsic material composition and properties or by means of automated systems and the integration of electrical components to provide responsiveness and movement; sensor-integrated designs.

Programmable Material
Programmable Materials consist of material compositions that are designed to become highly dynamic in form and function, yet they are as cost-effective as traditional materials, easily fabricated and capable of flat-pack shipping and self-assembly ("Self-Assembly Lab" n.d.).

Tangible Interface
A tangible user interface (TUI) is a user interface in which a person interacts with digital information through the physical environment (Ishii et al. 2012).

Information
A difference which makes a difference is an idea. It is a "bit," a unit of information. Derivations in a signal from which meaning can be derived (Gleick 2011).

Embedded
To fix an object or a property deep within a mass, to be intertwined in a irremovable manner.

Desiccation
Process of extreme drying.

Digital
Signals or data expressed as series of the digits 0 and 1 or some other binary quantification, typically represented by values of a physical quantity such as voltage or magnetic polarization.

Matter
Physical substance in general, as distinct from mind and spirit; That which occupies space and possesses mass; formless, but space occupying.

Material
"The substantial, and the tactile" (Oxman, 2010)

Morphology
In design, the geometric and organizational structure of matter. In biology, the form of living organisms, and relationships between their structures. It describes the form of substance.

Morphospace
Space and range of possible forms, structures, and shapes. Commonly used in biology.

Intelligible Matter
Incorporated into matter, a permanent and continually reactivated "memory" afforded by the refinement of an object. Matter is a substance, intelligence is order and shape. Intelligible Matter is substance with ordered shape (Kwinter 2003).

Soft Robotics
The subfield of robotics dealing with constructing robots from highly compliant materials, similar to those found in living organisms (Trivedi et al. 2008).

Turgor Pressure
Pressure exerted by the osmotic flow of water, which pushes and pulls plant cell walls and is a primary mode of plant locomotion.

Figure 1: Morphing airfoil prototype

CHAPTER 1: *Introduction*

This thesis will broadly explore the use, current role, and future of biological inspiration in design practice. In what way is bio-inspired design practice utilized as a design methodology, and how might it inform our pairing of digital and physical modes of being? This larger context provides the foundation grounding a targeted bio-inspired design study, aimed at developing plant-inspired modifications to existing soft robotics paradigms for the production of a semi-rigid, actuating surface. This new addition to the morphospace of soft robotics expands the possible applications of responsive materials. A selection of possible design outcomes is explored in this work. This thesis concludes with a proof-of-concept prototype and robust testing of a responsive, semi-rigid actuating airfoil, to demonstrate the strength, viability, and rigidity offered by the actuating surfaces produced in this work.

1.1 The Relationship of Form, Matter, and Information

In our modern vernacular, “information” is divorced of matter. “Information” is something ethereal, formless, identified solely by its ability to be conveyed. In his work *The Information*, James Gleick hypothesizes that this modern understanding of information as being formless likely began with the first spark of electricity jumping through a telegraph wire. Before the advent of the telegraph, “a message had seemed to be a physical object.” Sending messages by nothing more than electricity challenged this old notion of the property of information as being tied to the physical. As Gleick writes, this required individuals to “consciously divorce their conception of the message from the paper on which it was written” (Gleick 2011). Subsequent advancements in electrical engineering, computing, and physics continued to strengthen this concept of information as separate from matter.

However, the nature of information in relation to form has once again been called into question by designers striving for a framework in which to unite objects with the digital world. In his essay *“The Computational Fallacy,”* noted design scholar Sanford Kwinter asserts that what are commonly considered separate technological domains, the “mechanical” and the “electronic” are, instead, both part of a continuum of “interdependent historical-ontological modalities: those of matter (substance) and intelligence (order, shape)” (Kwinter 2003). Kwinter goes on to assess natural objects by these aforementioned modalities, proposing that the refinement of both natural and man-made forms is what gives matter an “embedded intelligence.” Kwinter’s meditations on the relationship of intelligence and form, afforded to us by new technological developments in computing and material sciences, are similarly echoed across the writings of a number of other design scholars. Oxman evokes “new materiality” as a challenge to previous modes of arriving at form, and Menges proposes “material computation” as a material-based design approach which relies on material properties to compute environmental agents and allows for higher integration at all levels of design (Oxman 2010; Menges, Achim 2012).

What these proposed design frameworks have in common is the set of central questions that they seek to answer. Perhaps chief among them is the question of *“what to do with all this information?”* The laying of telegraph lines in the mid-19th century saw the beginnings of what would become a “*net-work* of nerves of iron wire.” (Gleick, 2011). A global nexus of connected nodes, emitting electrical impulses as a means of sharing information, which has only continued to grow into our now vast, connected, digitally-driven world. It is no wonder that very nearly at its inception, it was proposed that this network might work like neurons in a brain. Research into the nature of the brain in the following centuries proved that this was not just an apt metaphor, but a direct comparison. Like a brain, these networks hold an enormous amount of information. Our global networks have accelerated the pace of knowledge production, with the total sum of knowledge in the world doubling every ten years (Bornmann and Mutz 2014).

How does this incredible, man-made nervous system of information become an emergent property of our built environments, as electrical wiring and phone lines have before it? The “internet of things” promise—that every object, every piece of our lives will be connected to its digital ghost—has thus far generally resulted in the awkward marrying of static forms with digitally connected sensors and mechanics. The efforts to encode our information networks into physical form continue.

In one of the seminal works envisioning the future of our digitally connected world, *Tangible Bits and Radical Atoms*, the authors lay out a framework with the goal of connecting users to digital information through new interfaces, which seek to continually capture more of our natural human capacity to interact with and understand changes in our environment (Ishii et al. 2012). This focus on making digital information tangible is yet another strategy intent on answering the question *"what to do with all this information?"* In Ishii's work, the answer proposed is, weave it into our built environment. Responsive designs, material computation, "new materiality," and "intelligible matter" are all concepts which have a role to play in the effort to bring our wealth of information back into the physical forms that surround us, so that we might access the full environment-sculpting potential of our information networks (Kwinter 2003; oxman 2010).

1.2. Natural Systems as a Guide

Today, there is more computational capacity and information density available to designers than ever before. Digital, computational, informational modes of being are now present in almost every aspect of our lives. Expressing and enacting humanity's global network of information within our tangible, built environment continues to be the subject of much study and scholarship, especially as our visual field has become cluttered by screens and information overload has become a common exhaustion. How can we bring this wealth of information into the human interactive space of objects, to make real the visions of new materiality, of intelligent matter, and of computational material, which are so often proposed?

There is a logical precedent to turn to as a guide for how to think about building an interconnected system of systems, a precedent in which information is inexorably tied to form and geometry, in which every layer is integrated with the next to produce emergent and responsive properties—the natural world. Pulling inspiration from nature in design is nothing new, nor is comparing man-made networks to natural systems (Aziz and El sherif 2016). One might consider the bio-inspired wings of Da Vinci, the arches of Gaudi, or Frei Otto's lightweight architectural forms in the long history of biologically inspired design work (Aziz and El sherif 2016 ; Moffatt and Taglialagamba 2019). Of late, bio-inspired design work has typically taken the approach of pulling specific biomechanical properties from nature and applying them to clearly defined problems in design (Aziz and El sherif 2016). The practice could be better understood, though, as not only a way to produce singular design solutions, but as a lens through which to achieve a greater union between physical objects and computational capacity.

The implementation of bio-inspired design practice varies widely, as does the claims practitioners make about its value. Typical focuses of bio-inspired design are biomechanical; drawing on inspiration from a specific structure, mathematical; mimicking processes of evolution, or organic; engineering cells and tissues to construct new forms (Gruber and Imhof 2017). Criticism of bio-inspired design work often calls into question whether or not specific bio-inspired technologies are any better than other design and engineering solutions one might arrive at without mimicking some function of a natural feature. In this context, it is hard to see the consistent value of turning to biological systems for inspiration in design and engineering. Upon a more expansive and holistic view, the wisdom of considering natural structures and systems in design solutions might become evident.

It is the organization of biological forms that makes nature a compelling source to pull lessons from when seeking to unite “intelligence” with “matter.” Biological systems are inherently information-dense. A section of wood from a tree is not just a section of wood—encased within it are hundreds of thousands of miles of DNA and RNA. Every cell in the wood has grown in response to the forces acting upon it—the weight of the tree, the strength of the wind, and the pull of gravity. Plumbing, actuation, structure, responsiveness, electrical networks, and a myriad of other systems are integrated into the form of the tree, which is in turn connected to a network of plant life through electrical and chemical signaling pathways. A tree is not a tree, but a part of the superorganism of a forest (Christopher 2017).

The role of bio-inspired practice in the realm of design is, then, not only to produce singular geometries and forms of interest, but also to serve as a template for how we build systems that integrate intelligence with matter, to fill our built world with materials that are responsive, perform computation, deeply interconnected, and make tangible a reflection of the vast density of digital information at our disposal.

1.3 Core Focus

A small manifestation of the lofty ideal of intelligible matter in design is explored in this thesis by proposing a negative-pressure actuated, semi-rigid actuator system. This strategy for producing actuation is based on the study of plant geometries which take advantage of desiccation. The objectives of this work are to (1) investigate the performance of a number of geometries cut into a semi-rigid material and exposed to negative pressure (2) apply this technique to the production of a semi-rigid actuating surface that may then be tested against specific performance criteria, and (3) envision the possible use cases for this approach.

This negative pressure-actuated system will be applied to semi-rigid plastic, with digitally fabricated complex surface geometry inspired by desiccating structures in resurrection plants, fern sporangia, and pinecones. The system will then be adapted to the uniform actuation of an airfoil to produce camber change. This exploration builds on significant work of other researchers studying negative pressure actuated systems, and serves primarily to expand the known morphospace for this technology.

1.4 Biological Precedent

This thesis investigation into the design and production of compliant, semi-rigid, negative-pressure actuated surfaces is based upon the motion of plants. This mechanism takes inspiration from the basic principles that govern the motion of desiccating plants—namely, that geometrically imposed anisotropy in the bending material allows an otherwise reasonably rigid material to become compliant, and that a desiccating form bound by a semi-flexible vacuum chamber produces motion as pressure changes. For plants, the boundary skin would typically be a cell wall or the surface tension of water. In this soft robotic actuator, the bounding material is a plastic or cloth bag. In studies on the geometry of desiccation, there is a high degree of variable morphology that governs the bending motion of herbaceous structures (Rafsanjani et al. 2015). These morphologies serve as inspiration for the geometric study conducted in this work. Plant seed pods, famously including pinecones, acuate by this method in which one layer remains relatively rigid while a surface section of the material is made more compliant than the underlying substrate, thus generating actuation when a force is applied uniformly to the surface of the structure (Rafsanjani et al. 2015).

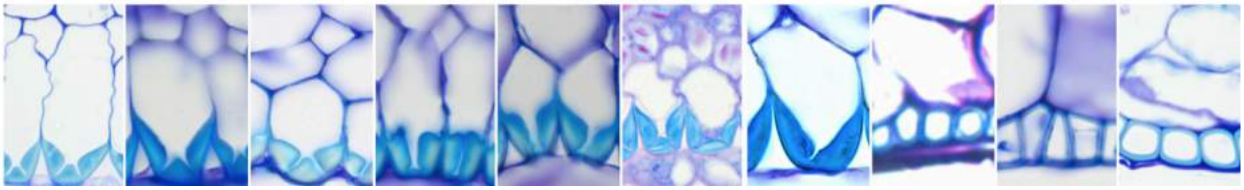


Figure 2: Plant cell walls, adapted for desiccation. (Hofhuis et al. 2016)

A second biological example that has been closely studied for this property of shape-change through desiccation is the sporangia of ferns, the pods that release fern spores by catapulting them into the air (Noblin et al. 2012). The fern sporangium actuates by means of a compliant, semi-rigid spine which possesses an anisotropic geometry with ridges along one edge (Figure 3). When wet, the surface tension of water between the ridges keeps the pod closed, but upon drying out, the surface tension of the water pulls the ridges closer and closer until the form snaps back to release the spores, and when water in the plant is replenished, the sporangium returns to its original conformation (Noblin et al. 2012). In the case of the fern, shape change is accomplished by a specific, morphological compliance in the system, which takes advantage of the "pull" generated by desiccation (Figure 4).

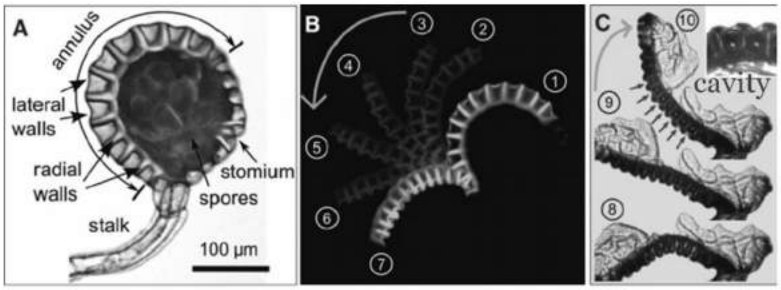


Figure 3: Fern sporangium precedent. (Noblin et al. 2012)

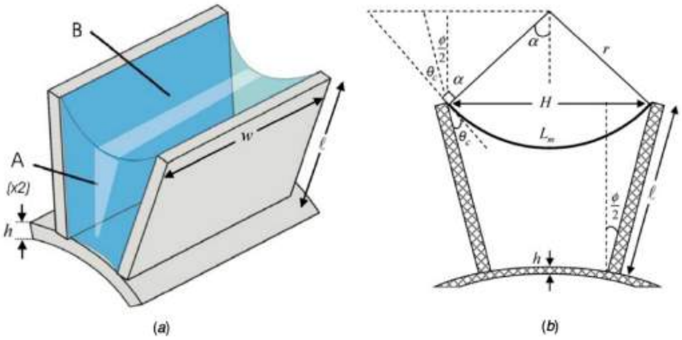


Figure 4: Model of fern sporangium. Note the surface tension of water provides the resistive skin that promotes actuation (Borno, 2006).

CHAPTER 2: ***Background and Literature Review***

2.1 Digital and Material Relationships

There is a significant debate occurring in the field of architecture and design around the expression of formalism in practice. Namely, *what comes after formalism?* Formalism is described slightly differently by each critic: an "emphasis on meaningful shapes" (Kwinter 2007), a focus on shape and container that is "divorced of [the] context" of matter (Oxman 2010), shapes informed by Euclidean mathematics used to achieve form (Lynn 1994). There are many, many interpretations, but in the most basic terms, all center around an emphasis on shape, container, and defined boundaries. Here, it is crucial to understand formalism as the current age of architecture and design, the predecessor of which is still being defined. Of this, some of the loudest voices call for a material-focused approach to design. I will highlight three writers as a cross-section of this debate, Kwinter, Oxman, and Menges. This is by no means an exhaustive review, but it serves as an introduction.

In his work "Who's Afraid of Formalism?" Sanford Kwinter proposes the next age within formalism, which he calls "extended formalism" (Kwinter 2007). This is in response to what he considers to be shallow examples of formalism, results of a "sloppy conflation of the notion of 'form' with that of 'object.'" He discusses the difference between form and formation, where information is the "process by which discernable patterns come to dissociate themselves from a less finely-ordered field" (Kwinter 2007). He argues that when taken from the perspective of formation, form is understood to be directing an action. The old formalist techniques, which

Kwinter takes issue with, are those which he describes as static, not “knowing what they are” (Kwinter 2007). His new proposal for a way forward in design practice is a re-defining of formalism as something active, everchanging, and enacted with the intent of proliferating “fundamental resonances.” His “extended formalism” should demonstrate how these properties, or fundamental resonances, “accumulate in figures, order, and shape” (Kwinter 2007). He asserts that only paying attention to form, divorced of its context, is not an appropriately deep assessment. Instead, one must consider the rules at the center of the object that point to its prescriptive formation (Kwinter 2007). He concludes by comparing this proposed movement from static to active formalism as a move from generic to genetic, generic being likened to structured Linnean models of biological organization, and genetic being likened to a model of the biological world as ever-changing, with blurry boundaries between classes. His assessment leaves an open question as to what the physical manifestation of “extended formalism” is and how it is put into meaningful practice in the world. His new brand of “extended formalism” is challenged by Oxman, who instead proposes an entirely different “age” in architectural practice (Oxman 2010).

Neri Oxman also challenges old formalism in her work, “Performative: Toward a Post-Formal Paradigm in Architecture.” In contrast to Kwinter, who merely *extends* the definition of formalism, Oxman proposes to entirely cast off formalism as an identifier, instead of defining a new paradigm in design and architectural practice that she deems “new materiality” (Oxman 2010). In her writing, she refers to this “new materiality” as “form’s other,” and juxtapositions the concept of form against matter. She defines form as being comprised of matter, but separate from it; as for her, form is a focus on shape at the expense of context. She traces the path of formalism through various styles, noting its evolution from “semantic, to geometric, to informed morphological expressionism" (she provides the Beijing Water Cube as a key example of this) (Oxman 2010). All of these styles, for her, continue within the outdated framework of formalism. Her proposed new paradigm, *new materiality*, is practiced with experimental approaches and is marked by a strong integration of design, engineering, scientific, and architectural practices. Form, she writes, is the consequence of manipulating matter, and not the container of it (Oxman 2010). As such, she considers new formations to arise through a "morphogenetic" process, which is contingent on aspects of the ecology of site and program. This approach of "new materiality" is focused on the matter that makes up form, and focuses on opportunities for materials to become dynamic. She proposes looking to biology as a model for understanding how complex material systems can be constructed, defined, generated, and understood.

Oxman's alternative paradigm of design is not just based on adopting the visual language of biological systems, as this would be too shallow—she suggests a practice in which "materiality becomes an a *prior* condition of design rather than a product of *a posteriori* effects." Oxman later writes that "new materiality begins where formalism ends" (Oxman 2010). This materials-driven lens on design practice brings materials science squarely into the conversation of architecture and is expressed through the creation of artificial (designed) materialities of increasingly refined control. In practical terms, this is expressed through "material computation," generative and evolutionary design processes, and materials with gradients of performance. She traces the history of this notion from its roots in the space of natural and ecological design, once concerned with the impact of architecture on the planet, now taking new directions in the production of naturally derived, artificially designed materials. Oxman leaves a number of open questions in her bold assertion of the death of formalism in architecture. What is the practical expression of this concept? Where is form-focused production relevant in this space of new materiality? Oxman states that this new methodology asks "how can we become digitally transcendental?" Indeed, how might her proposed paradigm shift in architecture take us beyond the realm of digital integration? What are the new end goals of "new materiality" if not to achieve a bounded shape as formalism might dictate?

Menges reflects the assertions of Kwinter and Oxman in his writing "Material computation: higher integration in morphogenetic design." Menges's writing is not intended as a philosophical appeal to the heart of architectural design practice, but is instead as an outline for how, in practical terms, we might reframe it. He writes that "the production of architecture is under significant change," due to the increased role of computational design in architecture, which allows for the embedding of complex design information previously unattainable without digital tools (Menges, Achim 2012). He posits that this revolution in design and architecture will be facilitated by the introduction of digital fabrication in robotics, large scale construction, and manufacturing (Menges, Achim 2012). Of particular note, is Menges' focus on computation not only as a means to deposit materials, but as something intrinsic to the material. He writes: "computation, in its basic meaning, refers to the processing of information. Material has the capacity to compute" (Menges, Achim 2012). He argues that material is often considered an afterthought in the process of design, instead of key to the structure. As with Kwinter and Oxman, Menges likens the process of computationally generating materials to an evolutionary process. "Simple, local materials" he writes, interact and give rise to material self-organization in what he refers to as "physical computation" in nature (Menges, Achim 2012). The same can be applied to the process of designing materials, systems, and structures in architecture, in which materials perform "material computation."

The goal of creating tangible interfaces, as previously outlined, is to bring the digital world into a physical manifestation that is interactive and responsive. Similarly, work on responsive materials focuses on the creation of matter that is reactive and changes based on external stimuli. Currently, the integration of electronics and circuitry into these objects and materials is crucial to achieving responsiveness. By integrating electronics into materials, designers embed computational intelligence into the material system. These connected, integrated materials and objects are granted state-changing behavior through the use of electronic systems.

Michael McEvoy and Nikolaus Correll offer an example of this process in a bio-inspired design context, in their paper entitled “Shape Change Through Programmable Stiffness” (McEvoy and Correll 2016). In this work, material-based actuation is achieved using thermoplastics that swell and release based on electrical stimulus. When combined into a series of units, this behavior results in a highly controlled material that can bend, change shape, and act as an appendage in a similar fashion to muscular hydrostats found in nature (for example, an elephant’s trunk) (McEvoy and Correll 2016). Here, the responsiveness of the object is dependent on the organization of the units and the material property of the thermoplastic, but it is *dependent* on instruction from electrical signals. This strategy of material systems design removes the need for motors by relying on material properties for bending actuation, and so it is more highly integrated than an entirely stiff robotic arm. However, electrical wiring and environmental sensing elements, in this case, are still necessary and separate from the material architecture. This piecewise composition of computationally enable machinery is rudimentary when compared to the seamless integration of function, sensitivity, and form found in biological systems.

How will this divide between digital and physical materials be resolved? Sanford Kwinter frames this question in his essay, “The Computational Fallacy,” and proposes a path forward (Kwinter 2003). He beings by asserting that “mechanical” and “electronic” are not distinct categories as they are often treated, and that treating them as such hobbles the progress of technology. Instead, he proposes considering the “mechanical” and “electronic” as expressions of two connected modalities: “matter” and “intelligence” (Kwinter 2003). In this context, the modality of “matter” possesses some form of innate, embedded intelligence, in much the same way that we might consider natural objects to possess a raw material intelligence (Kwinter 2003). Design processes, in this framework, are the means by which this embedded intelligence is refined, added to, and incorporated so that the program or performance of the matter becomes like a memory (Kwinter 2003). He summarizes this process, stating “all matter, even totally disorganized matter, possesses some degree of active intelligence, and the refinement of matter is always the refinement of intelligence embedded within it” (Kwinter 2003). Kwinter proceeds to suggest that for a time we have been in an age of valuing quantitative information out of our matter, single-directional and highly mechanical outputs. He encourages the consideration of qualitative information, which manifests itself not as a single function, but as many functions. Kwinter’s argument breaks down the notion that there is a dichotomy between the mechanical and electrical manifestations of computation in material settings, instead proposing that they are part of a continuum of matter and intelligence interactions given physical form (Kwinter 2003). This work knits together digitally controlled materials and non-digital, programmable materials into a single expression in the arc of design and engineering advancement.

2.2. Bio-Inspiration in Design Practice

Bio-inspired design takes many forms across the fields of design, engineering, and architecture. Once an entirely informal practice of drawing inspiration from objects in nature, bio-inspired design has, in the last few decades, become a design phenomenon in its own right. Many authors have synthesized it and described it through popular books, and there is even a website entirely dedicated to flagging natural phenomena as sources for solutions (Benyus, n.d.). However, the future impact of this work is still unclear. To date, only a modest number of designs, architectural works, and technologies have made it out of the studio or lab and into the everyday world (Zari, 2019). This begs the question: in what ways is bio-inspired design practiced as a design methodology, and how might it be understood in the context of information and material? Is the practice subject to limitations that restrict its proliferation into mass production? Does it have more substance than a catchy title?

In a comprehensive survey of bio-inspired works, Maibritt Pedersen Zari outlines the common practices that fall under the category of "bio-inspired design." She notes that, as the interplay between any source of inspiration and subsequent application goes, there is both a problem-driven and a solution-driven approach to bio-inspired design (Zari, 2019). In the problem-driven approach, described by Zari as "design looking towards biology," a problem is identified, and a selective search is conducted to find natural models that might inform the final product (Zari, 2019). The solution-driven approach, which Zari refers to as "biology influencing design" naturally begins with the study of biological systems in a purely academic context, which is then reimagined as a technology, and later, as a technology made useful through creative design (Zari, 2019).

The world of biology is incredibly complex, and so the applications of “bio-inspiration” across academic fields, organismal scales, and emergent properties are nearly infinite. Zari helpfully categorizes this complexity into three areas of focus: organism level (mimicry of a specific organism), behavior level (mimicry of organism behavior in context), and ecosystem level (mimicry of an ecosystem) (Zari, 2019). Each of these categories is used in design practice at the level of form, material, construction, process, or function (Zari, 2019). Through this categorization system, Zari draws a map for pinpointing the biology-level positioning of each source of inspiration in all design applications. This model meshes nicely with established uses of bio-inspiration terminology in design practice. Zari’s categories of form— material, construction, process, and function—can be understood as the underpinnings of biomimicry, bio-fabrication, biological computation design, and bio-inspired design.

There exists a highly described pathway for conducting bio-inspired work in science and engineering, but in the realm of design, this discrete pathway breaks down. As described in their paper on legged robotics, authors Daniel E. Koditschek, Robert J. Full, and Martin Buehler outline a stepwise approach to arriving at bio-inspired, engineered solutions (Koditschek, et al. 2004). It begins, in their approach, with purely academic inquiries into biological phenomena. It then proceeds to an abstraction of the mechanism of the biological phenomena, usually by means of a mathematical model. Next, the mathematical model is put to the test with the creation of physical, artificial models of the *function* of the biological system, but not the form (Koditschek et al. 2004). Finally, their physical models are tested against the performance of the biological system, to determine if the isolation and application of the originally biological phenomena holds merit as an engineering solution (Koditschek, et al. 2004). This highly structured approach is common in science and engineering, but creative spaces in architecture and design often take more liberties, adopting a less-structured approach contingent on the focus of the investigation.

2.3 Current Approaches and Applications of Negative Pressure Systems

Pneumatic soft robotic actuators are a wide field of study, with a plethora of proposed applications in literature. Most commonly, these pneumatic actuators rely on positive pressure, as illustrated by the PneuNet actuator (Ilievski et al. 2014). This form has since been adapted in a host of bio-inspired grippers and actuators.

Of specific interest here are negative-pressure actuators, of which the research field is slightly less developed. Laminar jamming is a strategy developed by both researchers at Harvard and MIT, in which sheets of material, paper or otherwise, are vacuum sealed in a bag to stiffen the material and laminate the form. This has been proposed for the production of variable stiffness actuators, dampers, and form-changing furniture (Narang et al. 2018). A similar method, granular jamming, also uses negative pressure, but instead applies it to granular materials such as coffee or sand. This has been employed as a gripper with great success, and is particularly well suited for applications which require one form to deform and stiffen around another (Brown et al. 2010). Artificial muscle is the term given to negative-pressure actuators which rely on the compliance of the vacuum-sealed substrate to produce motion. Applications have included origami forms that produce shape-changing materials and grippers, as well as foams coated in rubber that contract when negative pressure is induced, resulting in a remarkably strong actuation (Shuguang Li et al. 2017). In one method, researchers created a gripper out of foam blocks and hinges sealed inside an airtight nylon bag. The gripper was capable of lifting

100 times its own weight, demonstrated by lifting a tire (Shuguang Li et al. 2017). In yet another example, researches coated foam with rubber and created units that could control depressurization, creating a modular system of shape-changing robotic objects. When these units were assembled in a chain, the robot moved like an inchworm (Robertson and Paik 2017).

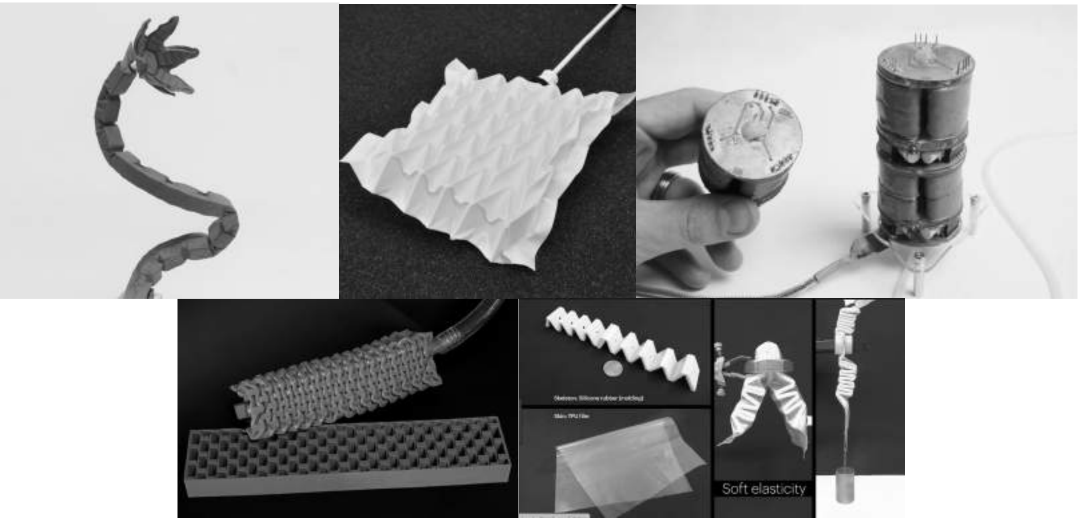


Figure 5: Soft robotic precedents. [Top row] (Shuguang Li et al. 2017), (Shuguang Li et al. 2017), (Robertson and Paik 2017) [Bottom row] (Yang et al. 2016), (Shuguang Li et al. 2017)

2.4 Analogous Negative Pressure Systems in Nature

Nature is full of examples of negative pressure actuating systems, but they are perhaps nowhere more prevalent than in plant architectures. Plants adjust the turgor pressure within their cells, generated through the pressure exerted from osmosis of water and from desiccation, to actuate their bodies (Allaby 2019). This thesis investigation will pay special attention to those plant forms that remain rigid throughout all stages of actuation. An outstanding example of this can be found in the sporangia of ferns, which contract under sizable negative pressure forces until the pressure becomes too great, the compliant spine of the sporangium snaps back, and fern spores are catapulted into the air. In each state of the soprangium's confirmation, from snap back to launch, the plant material remains semi-rigid and upright (Noblin et al. 2012). A similar mechanism can be found in the seeds of many other plant clades, in which the process of desiccation causes a confirmation change based on the microstructure of the plant tissue (Rafsanjani et al. 2015). This functionality is also present in plant bodies that are exposed to extreme drought, with the specific anisotropic patterning of the plant structure lending itself to curling. These plants use a change in shape induced by negative pressure to curl into a shape with a smaller surface area, protecting the rest of the plant from drying and damage until rains return (Rafsanjani et al. 2015). Common examples of this are the resurrection plant (Figure 6) and the resurrection fern. These properties of plant bending have been put to use in architecture and design research which relies on the digital fabricated anisotropic properties in simple materials to produce compliant bending and pressure-driven actuation (Schleicher 2015).

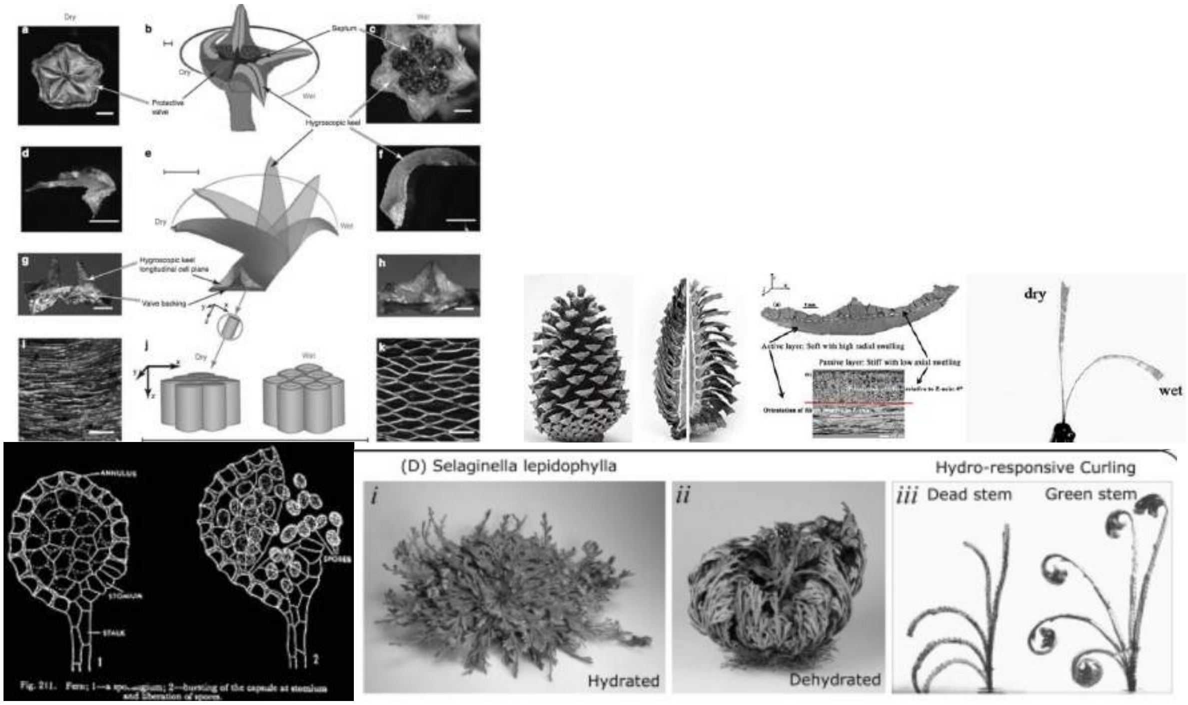


Figure 6: Desiccation in plant systems. [Top row] Plant bending structures (Suyi Li and Wang 2016). Pinecone actuation and anisotropy in tissue organization (Le Duigou et al. 2017). [Bottom row] Fern sporangium ("Ferns..." 2016). Resurrection plant (Rafsanjani et al. 2015).

2.5 Morphing Airfoils

Morphing wings have long been an active research space in the design of aircraft and drones. Decades of NASA funding has gone towards the design and deployment of materials and engineering approaches that allow for greater control over the camber, angle of attack, and chord height of wings. Attempts to create these shape-changing structures range from the smallest of drones to the largest of commercial airliners.

Continuing to the specific case study around which this research is focused, it is pertinent to review previous attempts at the creation of a lightweight, highly controlled method for varying the confirmation and stiffness of the wings of light aircraft. Current aircraft wings tend to be fairly rigid, and, if they contain actuating components, these components are typically rigid as well, and have a limited range of achievable wing shapes as compared to some natural structures (Figure 7) (Pagitz, Pagitz, and Hühne 2014).

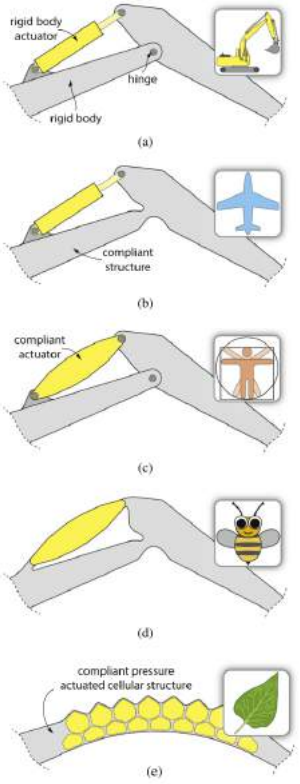


Figure 7: Image taken from "A Modular Approach to Adaptive Structures," demonstrating the space of actuator designs for a mechanism with one rotational degree of freedom. (Pagitz, Pagitz, and Hühne 2014)

Winged aircraft are typically well designed for efficiency in long range, uninterrupted flight, but make up for this with severe inefficiency in takeoff and landing. If one requires agile flight, for instance, to navigate rough terrain or through dense cities, helicopters and helicopter-style drones are the logical choices, though these options lack long-range and high-speed capacity. In contrast, fliers in nature are particularly good at flexible, adaptive flight in a range of conditions. Bats, for example, are among the most agile fliers known in nature, able to turn on a dime and navigate through the air by shifting the shape, angle, and balance of their wings (Bergou et al. 2015). Birds are shining examples of efficiency and robustness in flight, able to take off at a near vertical, with some species staying aloft in the air without food for a year at a time. How can we begin to consider these flight efficiencies in biological models, and use new material paradigms to construct an adaptive wing form?

Previous attempts at morphing wing structures have relied on a number of different approaches to achieving a highly controlled programmable material. In some cases, only existing hydraulics are used, on planes of average size, an approach first spearheaded by the company FlexSys (“FlexSys” n.d.). A second and sizable avenue of research in this area is the production of a deforming wing mechanism that is reliant on shape memory alloys inside the wing structure, as detailed in the paper “A Review on Shape Memory Alloys with Applications to Morphing Aircraft” (Barbarino 2014). This approach is intriguing because of its ease of reversibility and minimal chance of system failure, although the response time of such materials could limit their usage (Barbarino 2014). At MIT, researchers have proposed a third, mechanistic way of achieving a morphing wing, by constructing the entire wing structure out of a series of repeating mechanical fasteners and joints, arranged in a repeating, organized, cell-like pattern that can articulate in upward and downward configurations with a high degree of control (Figure 8) (Jenett et al. 2017). This approach is also exciting because of the repeating pattern of mechanical linkage “blocks” used across the wing structure. However, this complexity of organization and assembly, while highly responsive, begs questions as to how it might stand up to harsh conditions and turbulence in all possible applications, whether as an adaptive facade, movable roof, or articulated wing.

Investigations into the wing and fin-shape morphologies have not been limited to aircraft structures. J. Lienhard and coauthors apply organizational and structural bio-inspired principles to wing design in a paper titled “Flectofin: a Hingeless Flapping Mechanism Inspired By Nature.” (Lienhard et al. 2011). While the goal for many streamlined, hydrodynamic wing structures is **not** to integrate flapping behavior into the material, flapping behavior, however, can in some situations be a useful. The Flectofin is designed for use in architectural and built settings to act as a deployable structure for temporary shelter or adaptive regulation of building temperature (Figure 8). By employing biomimetic principles isolated from the study of the bird-of-paradise flower, the research team created a tuned, pliable structure with kinematic capabilities intrinsic to the material composition of the fin. This study is of particular note for its scale-jumping success. The flowers are small, but the first principles of hingeless kinetic movement can be applied to large pliable structures. While it was successful in this case, the scale can often be an overlooked factor in the success of certain biological structures. For example, the ability of insect wings to take advantage of turbulent air currents, even though they have a relatively small wing to body ratio, is dependent on their small size.

Concerning insect wings, there are a number of studies point to the use of principles defined through the study of their wings that are applicable at larger scales. One such paper is “Flexural Stiffness in Insect Wings: Scaling and the Influence of Wing Venation”, which describes the relationship between wing venation and flexural stiffness of insect wings, a key component to the success of the wing (Lienhard et al. 2011). Through a phylogenetic study, flexural stiffness testing of biological samples, and modeling, it was determined that specific patterns in wing venation (namely, spanwise veins) played a crucial role in the stability and efficiency of insect wings (Lienhard et al. 2011). These principles have since been applied to a number of small scale robotic wing applications (Finio 2012).

Of the subset of morphing wing research that employs soft robotics, a commonly cited failing of designs is their inability to maintain shape and rigidity under high wind speeds. In the following work, this low rigidity of soft robotics approaches will be addressed.

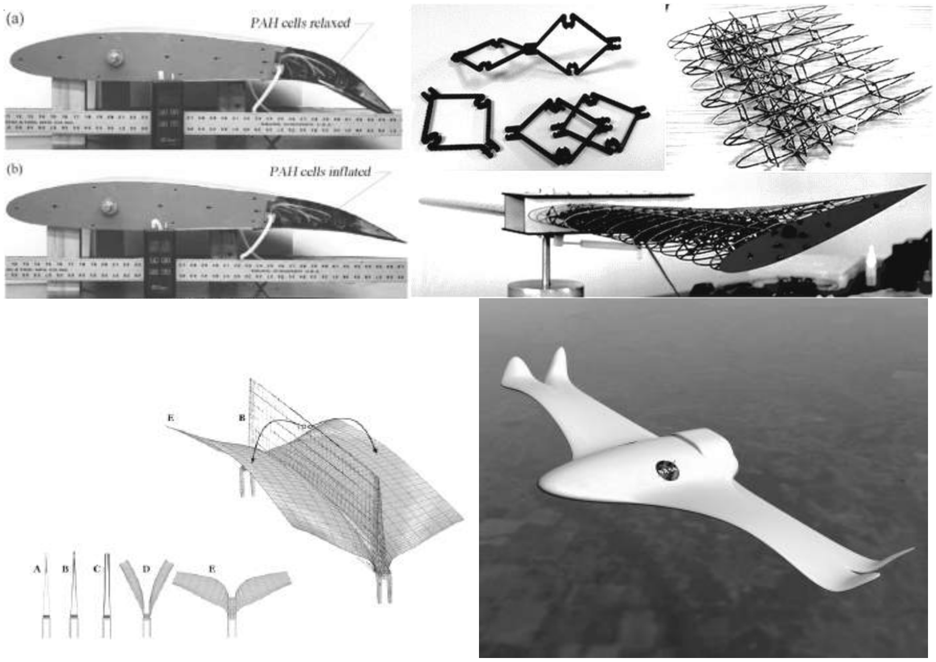


Figure 8: Examples of morphing wings and airfoils. [Top] (Vos and Barrett 2011), (Jenett et al. 2017), [Bottom] (Lienhard et al. 2011), (Abdulrahim, n.d.)

CHAPTER 3: *Study of Substrate Geometry in Semi-Rigid Actuators*

3.1 Objectives

This thesis work investigates the use and functionality of soft robotic techniques as applied to semi-rigid materials. Such actuating surfaces may be employed in load-bearing capacity, architectural settings, or semi-rigid interfaces. Currently, similar robotic negative-pressure systems have been employed as large-scale grippers, that can achieve a high degree of strength and resistance to bending. Li {et. al} demonstrated this capacity in their 2014 paper on negative-pressure-driven grippers by using this technique to design a gripper capable of lifting a heavy load (Suyi Li and Wang 2016). This approach to creating a negative-pressure actuator produces a strong gripper, beam, or surface when vacuum systems are turned on and air is removed from the surrounding bags, but it does not maintain the same rigidity and strength when vacuum systems are turned off and air is allowed to flood the bag.

The ability to stay rigid in all conformations, both bent and unbent, in which vacuum systems are turned on and off, would expand the utility and application space of negative pressure systems. To achieve this effect, the flexural capacity of the material substrate must in all conformations be balanced with the rigidity of the overall surface. Negative-pressure actuated structures that remain semi-rigid in both bent and unbent states are common in nature. Plants use turgor pressure as the primary driver of movement as they change and grow, all while maintaining a semi-rigid composition. Many species of plants have adapted rigid structures that actuate with extreme negative pressure imposed by desiccation. It is these structures that serve as the inspiration and basis for this exploration into the underlying geometry for semi-rigid substrates, actuated by negative pressure.

For this initial series of small geometry studies, the main objectives are [1] to find a void geometry for the study material that actuates well but maintains a high degree of flexural stiffness in both “on” and “off” conformations. [2] determine the most crucial parameters that control the degree of curvature in each sample, and [3] compare flexural stiffness to the degree of curvature to determine which geometries produce the highest degree of curvature and which maintain the greatest material resistance to bending.

3.2 Material Selection

Material selection is crucial to the performance of this system. For this study, the material substrate had to be semi-rigid; a material that could be used in a small load-bearing capacity, and that resists bending, but that still had a high degree of elasticity. Many commonly used plastics possess these properties, and so were a good candidate for the substrate used in this study. Many rubbers and certain composites would also have been sound choices for this application. Here, HDPE (high-density polyethylene) was used for the majority of the material studies. Polyethylene foams, silicones, and rubbers were initially tested as potential substrates but proved to be too soft to achieve the goal of a self-supporting actuator in this case. These materials may be applicable in other contexts.

Outer skin material choice for the creation of a pneumatic chamber is also essential to the functionality of these systems. This covering must be pliable, but resist stretching, in order to create the tension necessary for actuation (Suyi Li and Wang 2016). In similar structures, this is typically achieved with a vacuum-sealable bag or rubber coating.

3.3 Methods

To test the bending properties of a semi-rigid substrate in a negative pressure actuated system, many test samples were created with differing void geometry. Each test sample was a beam 15 cm in length, with a depth of 1.27 cm and an active bending section of 10 cm. The dimensions of the test samples are indicated in figure 9 below.

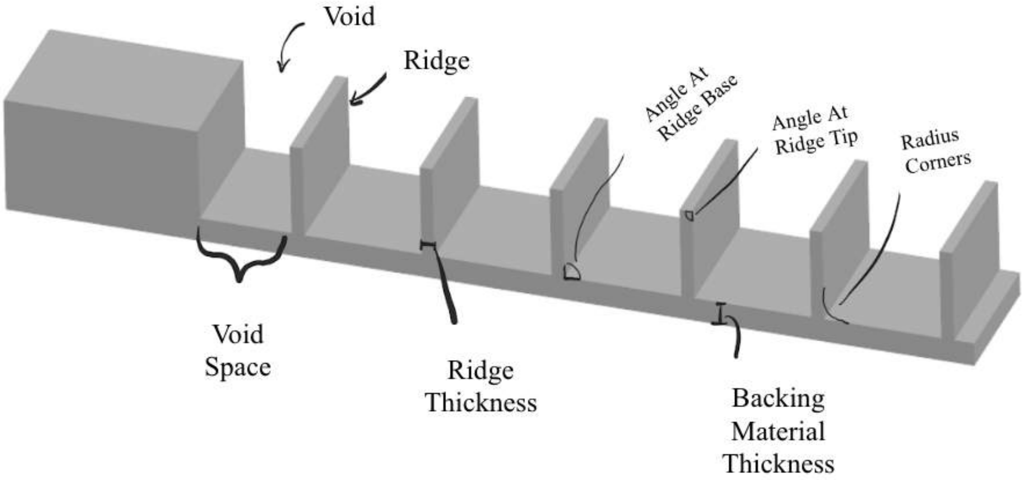


Figure 9: Diagram of test beam design, annotated with the primary variables tested in each trail of the geometry study.

The geometric relationship between the void and ridge spaces in each of the test samples was investigated through a series of short studies in which one variable was adjusted in each trial. The test apparatus remained constant for all samples tested. Negative pressure applied to each sample was in the range of -0.6 bar. The variables tested are listed in figure 10 below.

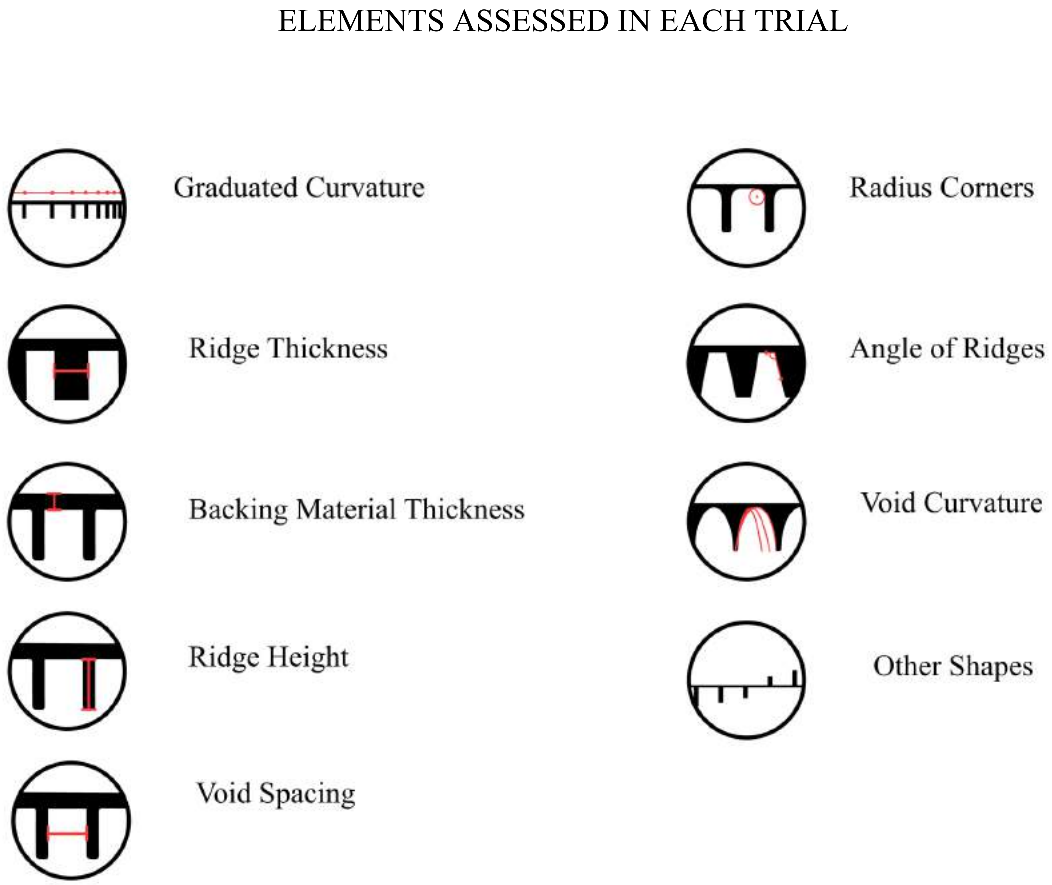


Figure 10: Independent Variable for Each Trial

The test beams were designed using a CAD program and milled from half-inch thick HDPE using a CNC. Below, figure 11 shows an example of the types of forms created for each test, visualized in a CAD program. The following figure 12 showcases the breadth of geometries tested, and depicts some of the physical pieces used.

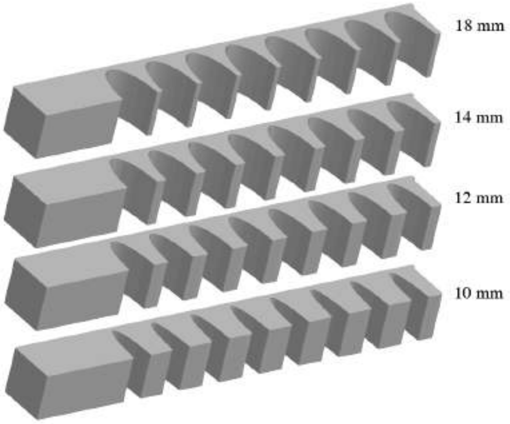


Figure 11: Sample illustrations of beams tested. Here, the units on the right indicate the width at the base of each curved void space.

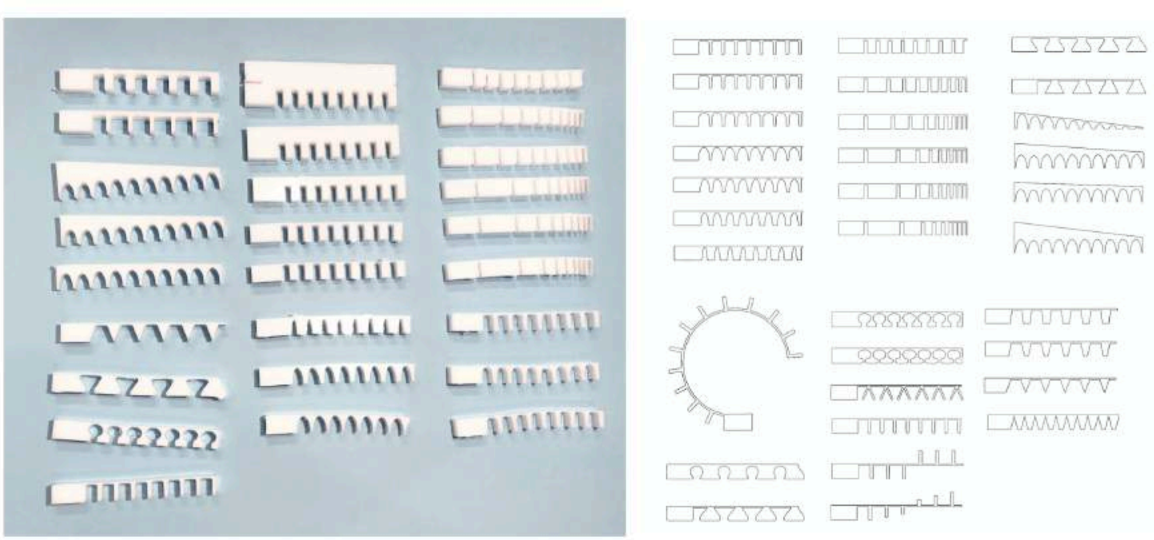


Figure 12: [Right] milled prototypes, [left] cut files

each sample was clamped to a flat bending plane, and was subjected to the following tests. Figure 13 offers a visual representation of the image analysis performed on the samples.

TESTS

> ***[1] Bending with no loads applied.*** Here, the vacuum system was turned on and the sample was allowed to curl to the highest degree with no additional loads applied.
>
> *[2]* ***Deflection when a load is applied in the direction of curvature.*** Here, with the vacuum system turned on, weights of 50g, 250g, and 500g were progressively applied to the end of the beam.
>
> *[3]* ***Deflection when a load is applied in the opposite direction of curvature***. Here, the sample was turned upside down and weights of 50g, 250g, and 500g were progressively applied to the end of the beam.

In addition, a separate analysis was performed on samples designed to test the ability to produce curvature with varying radius of curvature along the length of the beam.

Figure 13: Example of image analysis protocol. Deflection from negative-pressure-induced bending, radius of curvature, and deflection of the vacuum sealed beam with additional weight, were all assessed using imageJ.

A 3D model of each sample was analyzed to determine the moment of inertia for each, which was then used to generate the flexural stiffness value for each sample. This value was compared to the deflection achieved with the weights, and with the radius of curvature for each of the samples. All analyses of the radius of curvature and deflection were performed using ImageJ (Schneider, Rasband, and Eliceiri 2012). Radius of curvature measurements were taken specifically with the radius of curvature extension by Marco Brugnara (Brugnara 2008).

3.4 Results

For each of the variables tested, 4-6 samples were produced of each, with slight changes to each parameter being tested. These samples were then compared to their subgroup in terms of both radii of curvature and flexural stiffness. For example, if the parameter being tested were the base angle of the sample, the base angle of each sample would be plotted against the radius of curvature for that sample, and then would be plotted against the flexural stiffness. An example of this process is shown in the figure below, for samples in which a radius corner was added to the location where the a ridge meets the backing material of the beam prototype (figure 14).

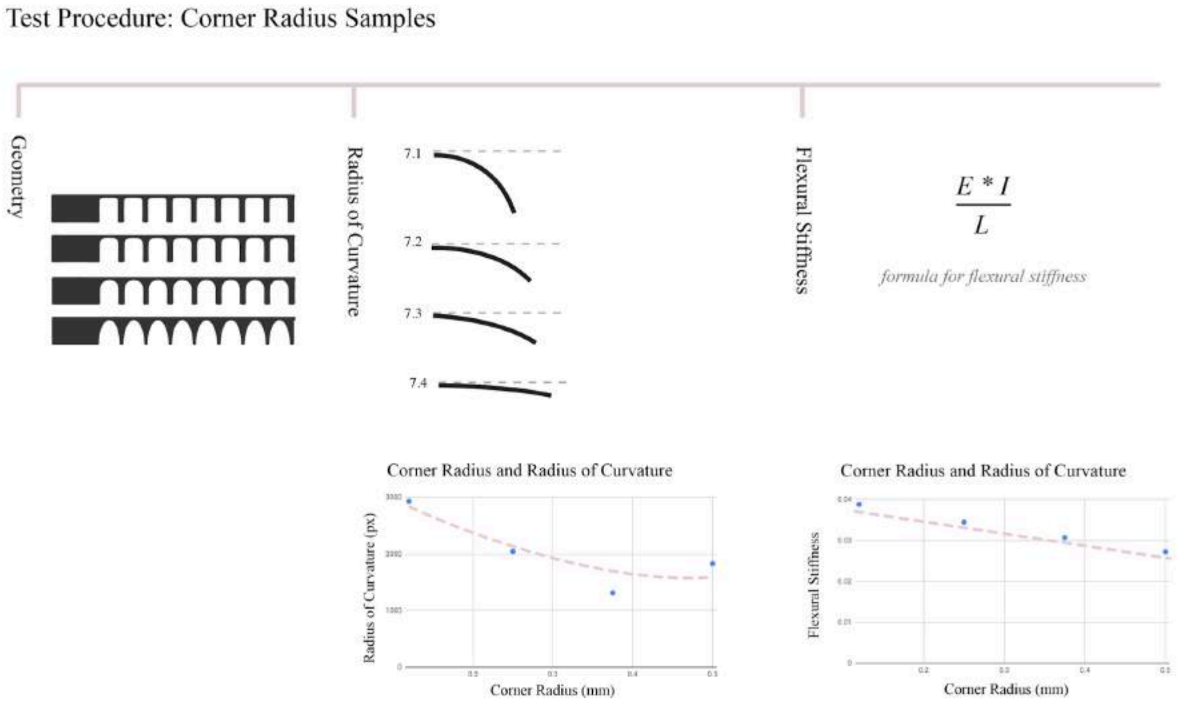


Figure 14: Example test procedure for individual trial. This trial assessed the effect of adding radius corners to space where ridges met the spine of the prototype. Please note the equation for flexural stiffness, which includes second moment of inertia as one of the terms. The second moment of inertia was derived from a computational model.

Below are figures detailing measurements from the sample group in which the radius-corner geometry was tested for the void space. These figures serve as an example for the calculations that were performed on each test group. For this sample test group in which radius-corners were tested for the morphology of the void space, the diameter of the void space ranged from 15 mm to 18 mm across. The flexural stiffness (figure 16) and radius of curvature (figure 15) were compared to test the independent variable in each.

There is a slight trend towards a smaller radius of curvature as the corner radius for the void space increases, though the relationship is not strong (figure 15). Similarly, the flexural stiffness drops as the corner radius increases (figure 16).

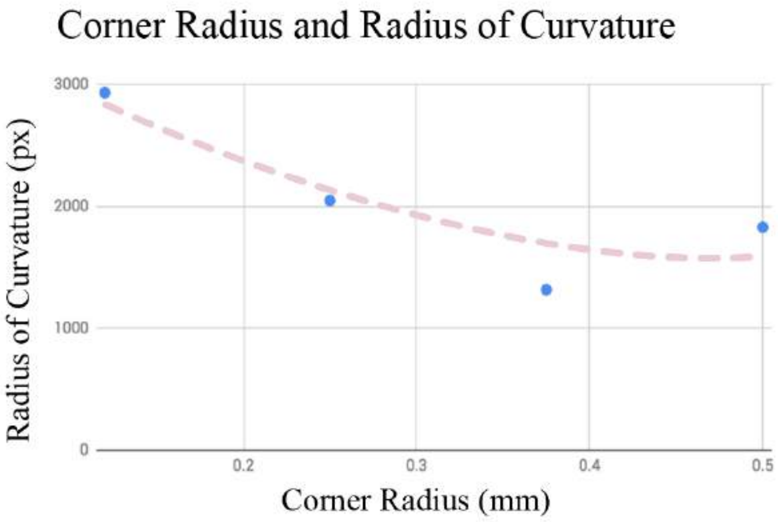


Figure 15: *Radius-corners and overall radius of curvature.*

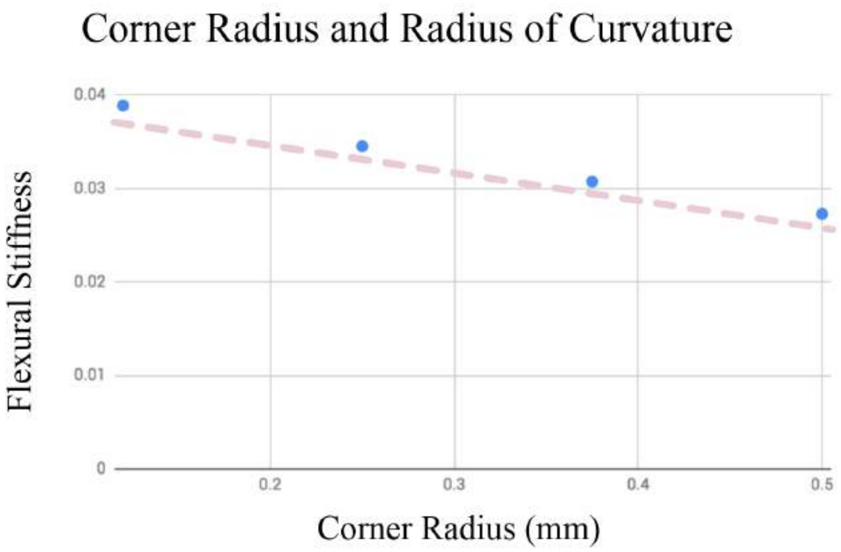


Figure 16: *Radius Corners and Flexural Stiffness*.

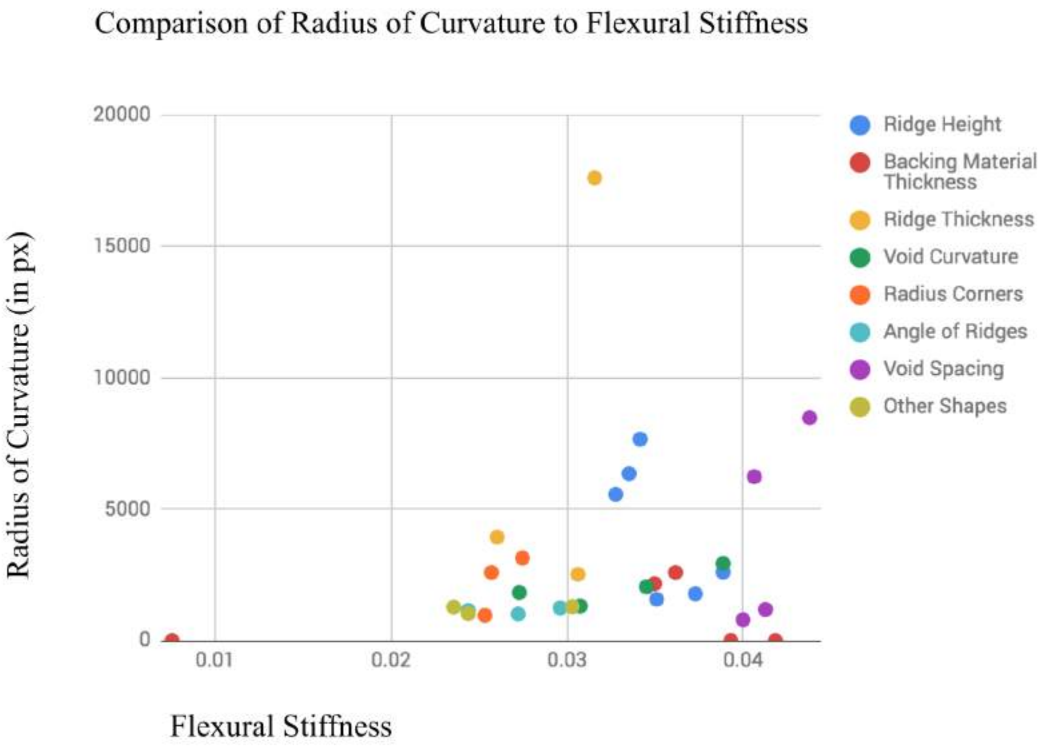


Figure 17: Radius of curvature (in px) plotted against flexural stiffness. This serves to map out the morphospace of this geometric study.

One of the main objectives of this preliminary study was to identify beam geometries that produce a predictable range of radii of curvature while remaining semi-rigid, i.e. maintaining a relatively high flexural stiffness. To determine which tests performed best under these conditions, the radius of curvature for each prototype was plotted against its flexural stiffness. Some tests proved to afford no radius of curvature at all, as with the trial labeled “top thickness.” Other tests, however, performed well on both counts, particularly those samples with narrower spacing between ridges. A visual analysis of curvature was also complied to map out the range of potential curvatures and forms generated by the varying geometries tested (Figure 18). Though not explored in depth in this work, of particular interest was the generation of an “S” curve achieved by putting ridges on both the top and bottom of the beam, adjacent to each other. This S curve pattern can be seen under “Other Shapes” in the curvature analysis in Figure 18.

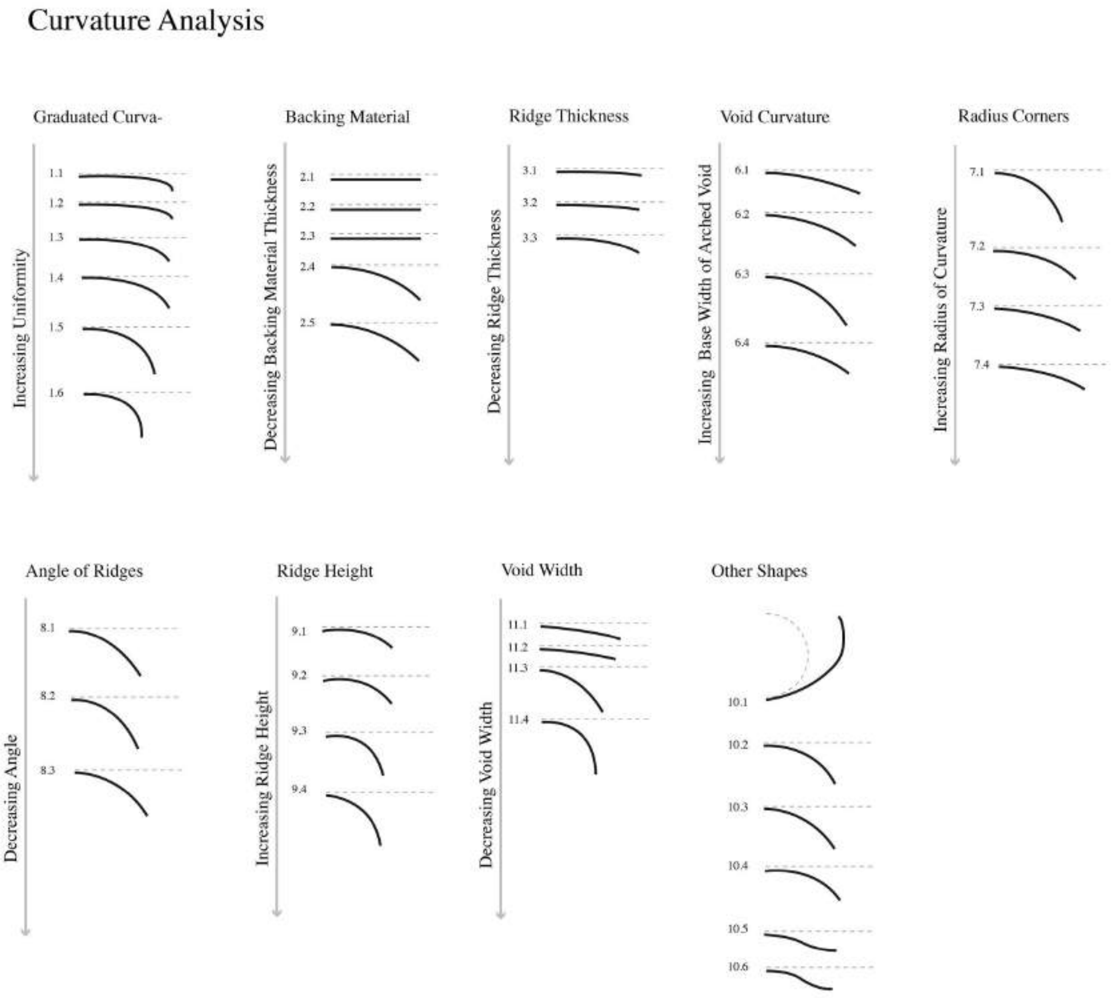


Figure 18: Assessment of curvatures achieved with various geometries.

3.5 Discussion

This study of void geometry was not intended to solve any singular objective in terms of strength or radius of curvature, but rather to survey the morphospace of this basic form and determine the most crucial variables controlling strength and curvature. Of these many small tests, some parameters stood out as having an important relationship to the performance of the overall system.

01
Backing Material Thickness

02
Void Spacing

03
Ridge Height

04
Void Curvature

Figure 19: Important elements controlling bending in semi-rigid soft actuators.

3.5.1 Backing Material Thickness

The thickness of the backing material, that is, the material which joins the ridges in this material system, is crucial to the flexural stiffness and achievable curvature of the system. For this particular material, HDPE, the thickness of the backing material needed to be thin enough to bend given the forces applied. However, the backing material also needed to be thick enough to maintain rigidity in the unbent state, thick enough to return to its unbent state once the vacuum was turned off, and thick enough to resist fracture. For this system and series of trials, the best backing material thickness range was between 2-5 mm. This value is dependent on the properties of the material substrate used as a bending surface, and on the forces applied through inducing negative pressure.

3.5.2 Void Spacing

Test prototypes with narrower void spaces overall performed better than those with larger spaces, achieving both greater curvature and a relatively high flexural stiffness, the two goals for this material study. This held true regardless of the geometry of the spaces, whether squared or curved.

3.5.3 Void Space Curvature

Curved edges in void spaces, in addition to performing well under the criteria of this study, were useful in preventing fracture in the thinner HDPE flexible backing material. In a situation in which this structure might need to undergo hundreds of cycles of bending, this is a crucial element to the overall design.

3.5.4 Ridge Height

Taller ridges clearly resulted in a greater curvature, a result in line with the expected outcome in a kinematic model of this system. Ridge height must also be considered in terms of preventing fracture, as taller elements of the structure could be prone to breakage. Additionally, it was observed that bending which is too severe, that is, too great a radius of curvature localized in one part of the beam, may result in permanent deformation.

3.6 Study Limitations

In this series of studies, a single material was used for the entire substrate of the bending structure. This use of a single material was intentional. An overall aim of this geometric and material investigation is to better define the boundaries of what can be achieved using a single material substrate and a bag envelope. A uniform material is given anisotropic properties in this study through a subtractive digital manufacturing process, requiring little to no post-processing and assembly.

More optimized performance for specific applications could probably be achieved by complicating the design space with additional composites. For instance, the backing material of the curving structure could be carbon fiber, while the ridges might be foam or polyethylene rubber. These modifications would depend on the target performance criteria for future studies, and would likely be tailored to specific use-cases. This work begins to flesh out the use and requirements of more rigid soft robotic substrates, but much is left to be explored.

CHAPTER 4: *Form Exploration and Early Prototypes*

Figure 20: Curling form.

The production of semi-rigid actuating surfaces, milled here from HDPE, affords a number of interesting properties which may be useful in a wide range of design applications. In particular, the ability of these surfaces to support their own weight and hold shape is a useful and uncommon trait in most soft robotics applications. Four prototypes were creating using lessons from the initial geometry study to further explore the potential of this morphospace. Though these forms were not assigned to a specific task aside from a showcase of the system's properties, they hint at tactile interfaces, curvature-controlled live hinges, and artistic displays.

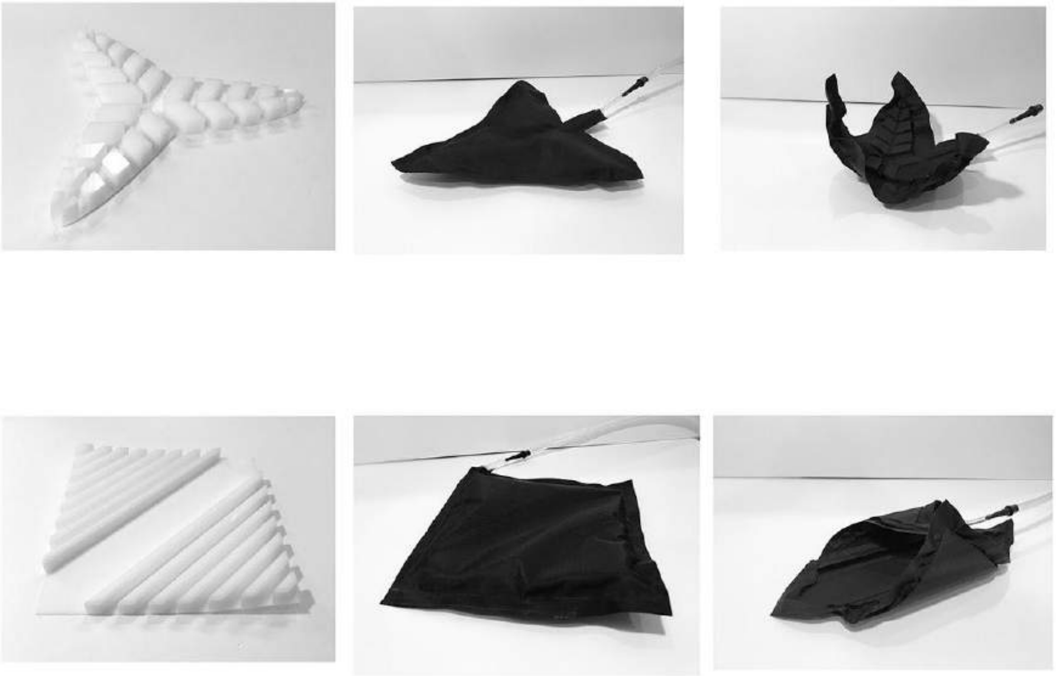


Figure 21: Form exploration prototypes

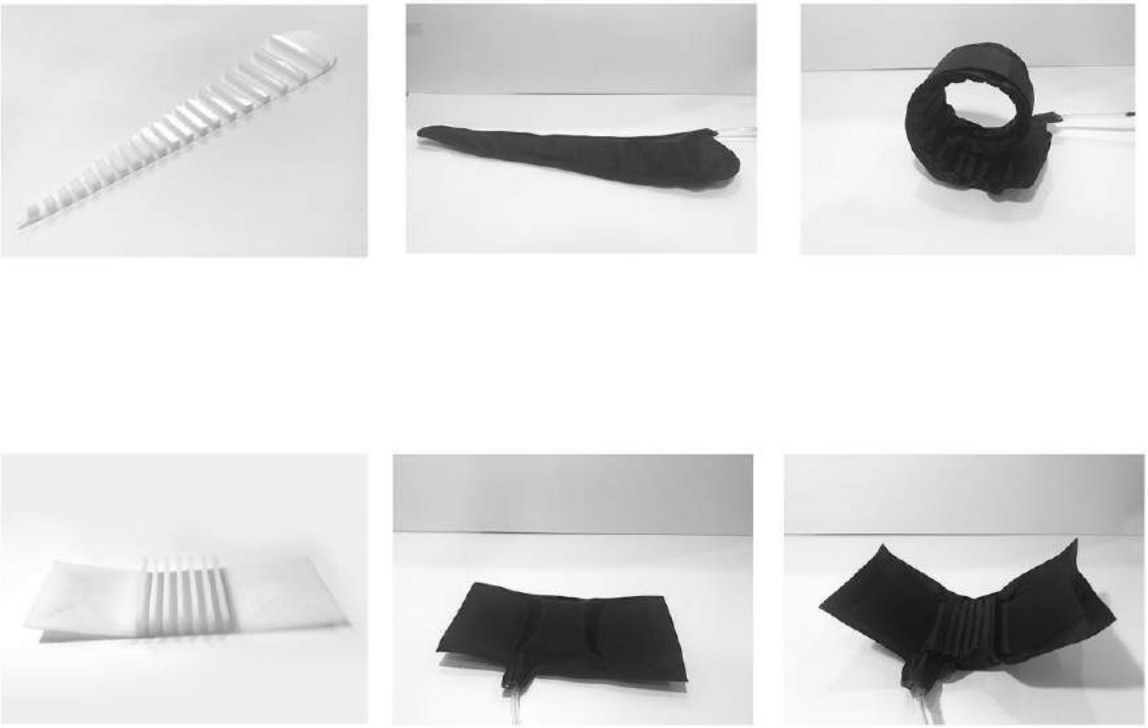


Figure 22: Form exploration prototypes

Figure 23: Curling form in action

CHAPTER 5: *Application Study for Wings and Other Adaptive Surfaces*

Figure 24: Morphing airfoil prototype

5.1. Context

The semi-rigid negative pressure soft robotic system explored in this thesis work has been proposed as a new and beneficial design due in large part to its rigidity in all conformations (both bent and unbent), and due to its high degree of strength despite the use of flexible materials. In order to test this claim, the semi-rigid actuating surface has been adapted to the shape of an airfoil and tested in a wind tunnel.

There are a number of clear benefits to using this method of whole-surface, negative pressure driven actuation described in this paper. It can be designed to be lightweight, it provides a high degree of control over curvature while remaining reasonably rigid in all states, and it is far simpler than the enormously complex mechanisms used to control wing shape on most airplanes and drones. There are also, as one might expect, many potential drawbacks. The largest of the possible drawbacks is the high risk of bag failure. If the bag or other encasing skin fails at any point along the wing, actuation is no longer possible. it also still requires a vacuum, which, while lighter weight than many plane systems, is still not insignificantly heavy (it is notable that most planes, some drones, and a number of different vehicles already have a vacuum system on board). With these considerations in mind, this initial test was conducted with a specific and limited set of objectives. Further studies and prototyping are needed to explore the full potential of this system for flight applications. Despite its limited scope, this test application is well suited to defining the functional range of semi-rigid soft robotic surfaces. Because airfoils must withstand enormous forces and because a large number of specific parameters must be met, any system which can withstand these harsh conditions and requirements can be adapted to less demanding settings. Therefore, an airfoil is an ambitious, but deeply practical, application to test.

While this airfoil was designed with some requirements for aerial vehicles in mind, it is by no means only applicable to flight. Robust airfoils are also essential to wind turbines, as well as some features of buildings, namely shading structures, exterior facades, and temporary deployable structures.

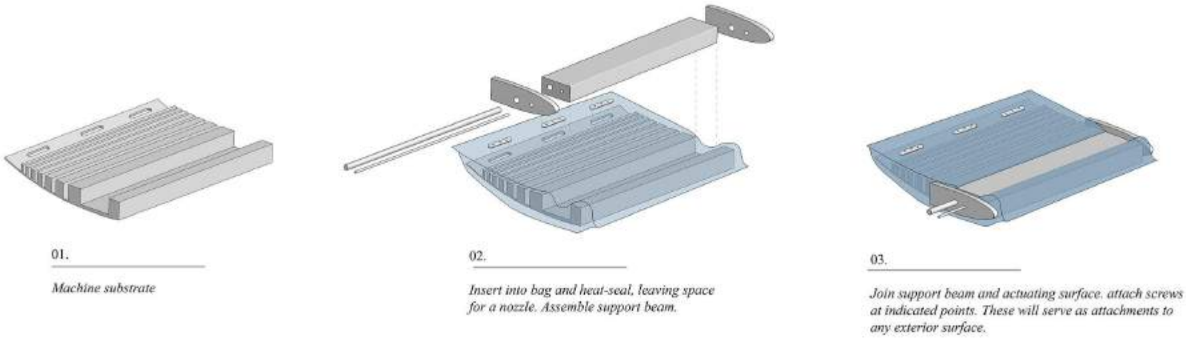
5.2. Objectives

The primary objective for this study was to determine whether a semi-rigid actuating surface could withstand the high forces exerted on an airfoil in use. This includes high wind speeds, the pressure force underneath the wing, and the resonance of the material that might require dampening. The secondary objective of this study was to ensure that the system could continue to actuate and change shape in a controlled way at high wind speeds. Finally, the third focus of this study was to determine the ability of this design to generate lift and drag, without an attempt yet to optimize the production of lift, as that would be best suited to a combination of a change in angle of attack of the wing, in addition to a change in the camber of the wing. Lift production potential may be explored in future studies.

5.3. Design

The overall design of this prototype centered around changes to the camber of the airfoil, which contributes to both the production of drag and lift. In future prototypes, to stretch this technology to the fullest, it would also be pertinent to design a mechanism which could change the angle of attack of the wing, in addition to changing the confirmation of the ends of the airfoil. However, for this initial test, camber suffices to test the durability and lift production value of the airfoil prototype.

As an initial test, it was not essential for the design of this airfoil to be performance-ready; that is, it did not need to be able to fly independently of the test set-up. It was essentially only that the airfoil maintains its shape, has a relatively smooth surface for testing, and maintains its angle of attack in the face of high wind speeds.



01.

Machine substrate

02.

Insert into bag and heat-seal, leaving space for a nozzle. Assemble support beam.

03.

Join support beam and actuating surface. attach screws at indicated points. These will serve as attachments to any exterior surface.

Figure 25A: Fabrication process

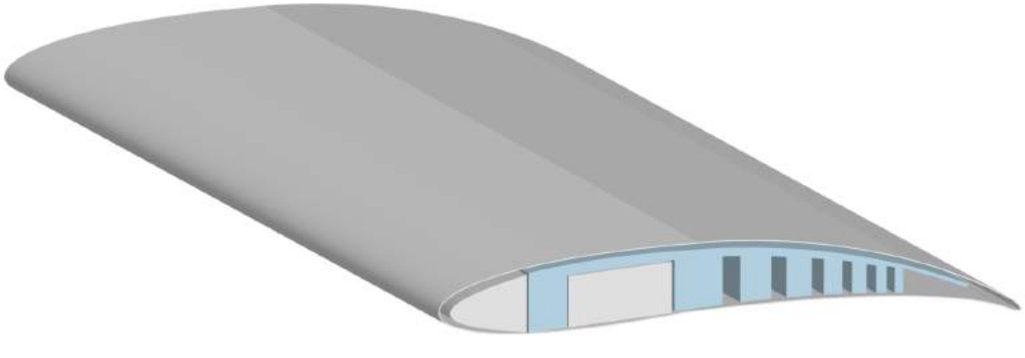


Figure 25B: Airfoil with styrene exterior shell.

As seen in Figure 25A and 25B, the surrounding shell for the airfoil was cut from a sheet of styrene, which was given shape through a combination of heat forming and mechanical attachment using Chicago screws. The styrene shell was folded in such a way that a sliding hinge was created at the end of the airfoil to allow the airfoil shell to bend freely. The shape of the prototype was based on a NACA 0012 airfoil. Earlier prototypes, shown in Figure 26, were moderately successful but indicated a need for taller ridges in the design in order to maintain the shape of the wing.

Figure 26: First prototype of actuating airfoil surface interior. Though this prototype was sufficiently rigid, the second iteration included taller ridges to improve the stability of the airfoil shape in high windspeeds.

The interior support was comprised of a 1/2 inch steel threaded rod. A foam and tapped HDPE block composite was attached to the rod and reinforced with mechanical fasteners. This support was clamped to the semi-rigid actuator using the shell of the airfoil. Support was also dependent on friction forces between the base support and the semi-rigid actuator. Because the bag must not be punctured for it to work, adherence to the support beam was a particular challenge. This iteration successfully weathered all tests without failure.

Figure 27: Prototype of the interior of the morphing airfoil.

The bag was comprised of heat-sealable ripstop nylon and was heat sealed using an exterior template. In the above figure 26, the screw details can be seen on the exterior of the bag, which were accomplished by heat-sealing through holes cut out in the substrate, and then pushing holes through the fabric for the chicago screws. Due to the high strength and rip resistance of ripstop nylon, it was possible to heat seal sections of the bag around the actuating form and push screws through the bag. Figure 27 shows the second prototype iteration, and is a shorter version of the interior of the final airfoil prototype.

Bag sealing is a particularly common point of failure in the production of soft robotic actuators. Some strategies employ mechanical attachments to tubing, which were initially tested in the design of this prototype. However, these mechanical fasteners proved ineffective when exposed to wear and tear. A second common approach to bag sealing, often used when creating laminar jamming structures, is to tie off the bag-tube interface with Teflon tape. At this scale, however, that strategy also proved ineffective. The winning strategy for the bag-tube interface was a combination of a number of different strategies. A pocket was first created in the sealed bag for the tube to be inserted. A heat-activated epoxy was then inserted between the tube and the bag opening, and allowed to cure. Finally, for added reinforcement, Teflon tape was wrapped on the exterior of the seal.

5.4. Methods

Figure 28: Airfoil prototype in the wind tunnel

The airfoil prototype was mounted to a plywood stand and elevated to ensure that the line of the airfoil was perpendicular to the ground (Figure 28). The prototype was then placed in a wind tunnel with a working section of 1.2 m x 1.2 m x 1.4 m. The windtunnel used is located at the Harvard University Concord Field Station outside Boston, and was used by courtesy of the Harvard Organismal Biology Department (Figure 29).

Figure 29: Harvard Concord Field Station Wind Tunnel

The airfoil was then put through a number of tests designed to determine its rigidity, resistance to failure in high winds, and actuation performance under conditions of high wind. The prototype was tested at maximum wind speeds of 18 m/s.

Figure 30: Airfoil prototype bending at various negative pressures.

5.5. Results

A number of short tests were conducted in the wind tunnel. They are as follows:

Test 1: *Uncurled prototype, high wind speeds*
Test 2: *Maximally curled prototype, high wind speeds*
Test 3: *Moderately curled prototype, high wind speeds*
Test 4: *Maximally curled prototype, variable wind speed*
Test 5: *Prototype curling back and forth in normal winds*
Test 6: *Prototype curling in high winds*

Test 7: *Streamlines over prototype when flat, moderate wind*
Test 8: *Streamlines over prototype when curled, moderate wind*
Test 9: *Variable prototype curling with streamlines, moderate wind*

Test 10: *Lift assessment in high-speed wind*

In all tests, the prototype performed well, holding up against high wind speeds and accompanying high pressure forces on the underside of the airfoil. The airfoil prototype achieved maximum curvature in both high and low wind speeds and maintained curvature for a number of minutes while at high speed. When streamlines were positioned on the leading edge of the airfoil, it was observed that there was little to no separation on the upper surface of the uncurled airfoil, even in high wind speeds. Increasing curvature was observed to drastically increase turbulence on the trailing edge of the airfoil. Though no direct measurement was taken, lift was observed in the uplifting of the airfoil testing apparatus at high wind speeds. The initial prototype is heavier than a version that would be set aloft, and so it is likely that even greater lift will be achieved in future iterations.

5.6. Discussion

This prototype demonstrates that semi-rigid soft robotic surfaces such as the one employed here can withstand gale force winds without failure. As evidenced by the displacement visible during testing, this prototype also successfully generated lift. In this series of tests, no recordings were taken for exact measurements of drag and lift, due to the limited resources of the testing unit. However, this would be a logical next step for future testing of this airfoil design.

During the tests performed in the wind tunnel, there was some wobble visible in the airfoil. This could be due to a number of factors and does not negate the results of this round of initial tests. However, in future work, it will be important to consider the resonance of the airfoil and ensure that steps are taken to dampen movement.

Of particular interest is the demonstrated ability of this system to achieve curvature despite being exposed to high winds. Despite high-pressure drag forces acting on the underside of the airfoil, curvature was still achieved in comparable time to when the airfoil is not exposed to wind.

Because the testing apparatus did not have smoke screen capability, streamlines were instead achieved with thread attached to the leading edge of the airfoil. This is a commonly used way to visualize streamlines and was effective here in demonstrating the performance of this airfoil. The airfoil was tested at three curvature states—the first, with no curvature, second, with middle-range curvature, which would be appropriate for a functional airfoil, and third, with extreme curvature, which would not be realistic for most airfoils but serves to demonstrate the capacities of this system. With no curvature, the streamlines stay close to the wing and show no separation from the top of the airfoil. There is only slight separation in high winds, verifying that this airfoil shape is functional. With the mid-range curvature activated, the streamlines begin to show more turbulent air behind the trailing edge of the airfoil, suggesting sufficient drag is produced to modulate the performance of the airfoil. During extreme curvature, the third setting tested, the streamlines move chaotically, and high turbulence is achieved due to the high amount of drag being produced by the extreme airfoil silhouette. Though this final shape would not be used in a traditional wing, it was intentionally chosen for this prototype and demonstration to illustrate the performance capacity of this system to produce large surface changes and to withstand high forces without failure.

5.7. Next Steps

This initial prototype test was a successful start to the extensive and necessary following tests to further explore the use of this semi-rigid soft robotic technology in airfoil design. Improvements to the shell design, production, and mounting structure would all be necessary for future tests.

Future tests might also integrate force sensors across the airfoil, to create a closed control loop between the force sensors and the vacuum actuator. By integrating force sensing capacity across the airfoil, a computer could read the local pressure along the span of an airfoil and make local adjustments in the curvature and camber to better generate lift, in a similar way that birds and bats read and adjust to the wind. Similar systems have been proposed for a morphing wing designed in the MIT Media Lab’s center for bits and atoms (Jenett et al. 2017) and could be employed in this system as well.

CHAPTER 6: *Application Explorations: Benefits and Utility of the System*

The approach presented in the present research, inspired by desiccating structures in plants, expands the scope of possible applications for soft robotic techniques to be employed throughout our built environments. Previously proposed applications for soft robotics are certainly not lacking in breadth, and encompass everything from medical technology to shape-changing pavilions. However, many soft robotic approaches are relegated to movements in objects that are not typically load bearing. Because of this, semi-rigid substrates in soft robotic actuators have the potential to expand the application space of soft actuators.

6.1. Benefits

Biologically-inspired, negative-pressure-driven actuating forms are unconventional, but there are many potential benefits to their employment. One such benefit is cost; in some cases, achieving a high range of curvature or bending in a form, especially at a larger scale (airfoil or otherwise), might require expensive and complicated mechanical linkages, gears, and components. For the semi-rigid actuator studied in this work, all that is required is a substrate, a bag or surrounding skin, and a means of creating negative pressure (which can be centralized). Though this approach is prone to its own failures, it may often be cheaper to employ, and possible to achieve with a wide array of readily available materials, in lieu of precisely machined parts. In addition, there are some circumstances in which it is desirable to induce uniform bending by apply forces across the entirety of a structure, as opposed to inducing bending through a single locus of kinematic motion. Another key advantage of this semi-rigid soft robotic approach is weight. Though the materials used in this thesis investigation are fairly heavy (i.e., HDPE), there are many other options with similar properties of elasticity and rigidity that are relatively lightweight. A semi-rigid actuator system with a single vacuum powering it would likely be lighter weight than many mechanical parts. Finally, this approach offers a key feature that many existing responsive architectural objects do not: control. Often, particularly in the world of responsive architecture, material shape change and actuation are achieved hygroscopically or thermally, relying on things like humidity, solar radiation, or other triggers that are difficult to precisely control. A negative-pressure system, in contrast, could be utilized in responsive and adaptive architectural settings, while still offering precise control over bending and actuation. One need only change the negative pressure being exerted throughout the system to change the shape of the object or objects, which can be accomplished with a digital signal. This allows the system to be particularly versatile, as it can be connected to any sensor input. As such, semi-rigid, actuating surfaces such as the ones explored here may be particularly well suited to use as an adaptive interface. One could imagine an object that changes based on thermal readings, density of people in a room, fluctuations in the stock market, air quality, or number of books checked out of a library.

The following proposals for the use of this semi-rigid actuator are intended to illustrate the broad application space in which it might be successfully employed.

6.1.1 Adaptive Shading

Shade Structures

Large shade structures with no mechanical components, in which the entire surface deforms when actuated by negative pressure. Lightweight, comprised of inexpensive materials, and responsive to solar radiation measured from light sensors on the surface.

Figure 31: Concept for an adaptive shading structure

Adaptive shading forms such as this one may be generated without a great deal of machinery, and with no moving parts to actuate the fronds, instead relying on the structure of the surfaces themselves to produce bending. A system such as this one may be beneficial because it is lightweight, can be made from readily available and inexpensive materials, and is compliant, meaning that it is safe to operate around people or animals that might get in its way.

6.1.2 Furniture

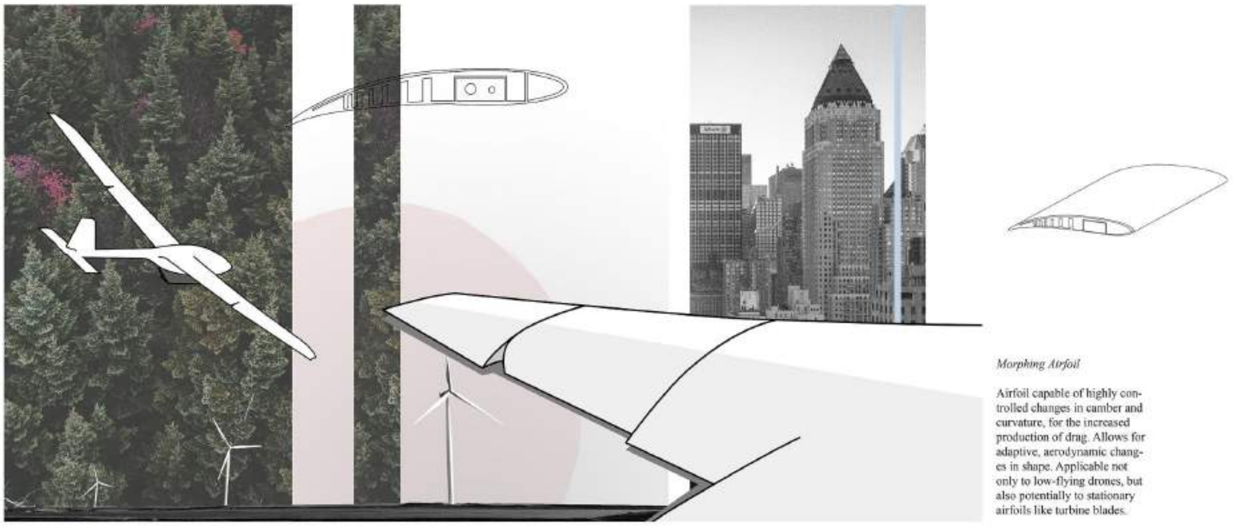
Transforming Furniture

Furniture with highly controlled curvature and shape, driven by negative-pressure actuation. Capable of flat packing and then taking shape, customizable to the user, and with the potential to become a responsive interface in the home.

Figure 32: Concept for shape-changing furniture, utilized as a tangible user interface.

A great strength of this technology is that it is highly controlled— the achievable bending with this actuating material system can be precisely coded to the pressure of the system, making it more highly controlled than some other proposed means of achieving responsive architectures and forms. Here, it is proposed as a tool for creating shape-changing furniture and walls, which change shape based on the user's movements, needs, and customizations. In this way, furniture could become a tangible user interface that we might passively or actively interact with. By making our dwellings more adaptable and form-changing, we increase the utility of our spaces. Additionally, encoding information into the environment in a way other than on a screen is beneficial to the human condition, and is a much needed avenue for displaying digital information as opposed to our screens, which many of us are so exhausted by. Brining a tangible user interface into the environment in this embodied way allows for signals that may exist in our peripheral vision, or may take advantage of our sense of touch, motion, and proprioception to communicate information. We now live in an information-dense world, and receiving all of it through screens is taxing. Brining functionality, computation, and information signals into a wider array of objects would serve to expand not only the utility of our spaces, but also our ways of collecting information from our digital environments.

6.1.3 Airfoils



Morphing Airfoil

Airfoil capable of highly controlled changes in camber and curvature, for the increased production of drag. Allows for adaptive, aerodynamic changes in shape. Applicable not only to low-flying drones, but also potentially to stationary airfoils like turbine blades.

Figure 33: Concept art for morphing airfoils on mid-range drone wings.

Here, this technology is proposed as an airfoil which can change shape as negative pressure is induced, but, unlike other forms of soft robotics, maintains its rigidity without any application of negative pressure or external supports. Both the strength and the potential for lightweight material usage in this system couple to make a promising form which could not only be responsive to human input but could also be integrated with pressure sensors to allow a control system to change the camber of the airfoil in a closed control loop, based on local air currents. As delivery drones become more common, there will be a need for longer-range drones, perhaps on the scale of 50 to 100 miles. Agile rotary drones, with which we are most common, are well suited to the task of navigating canyon-like cities and packed neighborhoods, but are not as efficient over long distances. Fixed wing craft are efficient over long distances, but are not agile enough to safety navigate around buildings and land without a runway. A fixed wing aircraft with morphing wings, however, might be well suited to most tasks. Like birds and bats, a fixed wing aircraft with morphing wings could be designed with the ability to change wing shape, allowing for agile movement in the air. This would also allow for near-vertical takeoff and landing, which animals excell at but humans have yet to master for fixed-wing aircraft. Vertical landing and takeoff would be particularly well suited for urban environments with densely packed populations, where fixed-wing craft might otherwise not be employed.

6.1.4 Wearables

Rigid enough to provide support, but flexible enough to conform around a body, and motion achieved without heavy machinery or cogs. Compliant, semi-rigid soft robotic surfaces and actuators may be employed in the creation of wearables designed to support the body and help in carrying heavy loads by dispersing the weight over a large surface, a feat achievable when the entire surface is the moving component. One can imagine this utilized in fashion, as shape-changing, “alive” armor around the body, but there are many practical applications as well. Supportive structures that wrap around the body, either for injuries or perhaps even for pregnancy back pains, would be widely useful. Clothing or bags intended to carry a heavy weight could be wrapped around the body, spreading out the surface area on the body which is responsible for taking the force of the weight applied. Spreading out these forces allows individuals to carry more weight, much more comfortably. There are a plethora of possible applications in the wearable space, and it is most certainly a fruitful space for studying the application of semi-rigid actuators in future work.

6.1.5 Building as an Interface

Figure 34: semi-rigid actuating surface, responding to the proximity of a user's hand.

Unlike forms of responsive architecture that deform in the presence of heat or water, this actuating surface can be highly controlled by a digital signal. As such, this technology could be adapted into a building surface or moving wall which takes in information from the surrounding environment and responds with deformation in structure. In a similar way to morphing furniture, this could be used as a tangible user interface. Shape-changing forms in buildings offer a passive way to connect users to the digital world around them, but signaling information through small movements, responsiveness, or some other confirmation change.

CHAPTER 7: *Discussion*

7.1 Impact

Soft robotics are often employed in, and proposed for, human-facing applications. Traditional robotics, with heavy moving parts and lots of mechanical components, are generally not safe to operate around casual users, or are simply too heavy to be worn. Soft robotics, in contrast, are just that— soft. Soft robotic technologies are excellent soft interfaces and wearables. They can serve as an adaptive gripper that can mold shape around many objects, and they are well suited, among other benefits, for producing fluid movements. Many soft robots, however, are only rigid or semi-rigid when pressurized or otherwise powered on. Dexterity and adaptability are commonly prioritized in soft robotics research over strength. Negative pressure actuators are one subset of soft robotics technologies which are both dexterous, adaptive, and strong.

Though extremely strong in comparison to other soft robotic techniques, soft robotic negative-pressure actuators lose their strength and rigidity when vacuum systems are turned off and the system returns to normal air pressure. This work expands the functionality of these negative-pressure-driven actuators by producing motion with semi-rigid materials instead of soft ones. Using semi-rigid materials, negative-pressure-driven soft robotic objects can maintain a level of rigidity and load-bearing capacity whether the system is at normal, low, or high pressure. This expansion in capability for negative pressure systems opens up possibilities for “soft” robotic surfaces, made with semi-rigid substrates, that change shape but remain load-bearing in any conformation. In a broad sense, the benefits of this semi-rigid soft robotic approach mirror the adaptive traits of the desiccating plant systems, which they emulate. This approach makes for objects and surfaces that can be adaptive but still support their own weight and the resisting forces imposed by the environment.

7.2 Application and Utility of Semi-Rigid Soft Robotics

The tests conducted on the actuating surfaces investigated in this thesis have indicated, as a first pass, that this approach is a promising avenue for expanding the application space of soft robotics (Figure 35). This plant-inspired approach, which marries a semi-rigid compliant surface with a constraining skin, results in a surface that is always rigid and capable of bearing small loads, which at the same time can bend easily. This approach is beneficial because it can be accomplished with lightweight materials, and so it is well suited to flight applications.

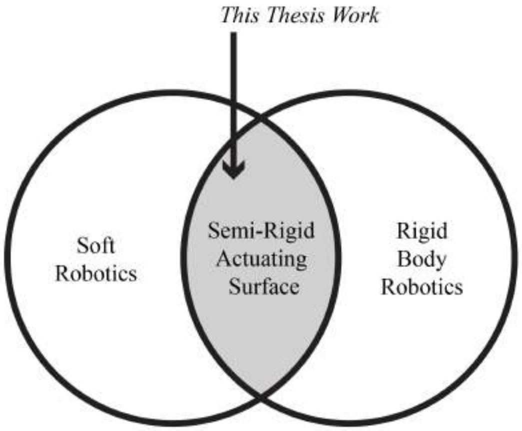


Figure 35: newly mapped morphospace

One major point of difference between an actuating, soft robotic surface and traditional modes of producing mechanical motion is that the force which spurs movement, in this case, is enacted uniformly across the entire surface instead of only at specific points. While unusual, there are some instances in which a uniform application of force and surface-wide deformation might be desirable. In instances in which shape change of an entire surface is desired, for instance, in the production of a sound wall which can adjust shape to reflect different frequencies of sound, one might want a full-surface shape change. T strategy of applying a uniform force to the surface to generate motion is also useful when generating a complex shape from simple materials. This functionality was not explored in the bounds of this thesis but is fertile ground for additional research. With greater definition to the geometric rules regarding surface actuation, surface geometry could be adapted to create complex shapes with twists, ruffles, and all manner of bends.

There are, of course, also important downsides to consider in the production of these forms, which may be solved by additional research and exploration of materials. Chief among these downsides is bag puncture—if the skin surrounding the actuating substrate is punctured, whether it is cloth, plastic, or a rubber coating, it will cease to be functional. Additionally, this system must be tethered to a vacuum pump. Though they can be fairly small, they can still be a heavy and ungainly piece of machinery. There are additional worries of material fatigue and breakage with compliant surfaces.

7.3 Benefits of Bio-inspired Design in Practice

This work was intended not only to explore the practical constraints and applications of plant-inspired negative pressure actuators, but also to investigate the boundaries of the larger framework of emerging practices in the realm of (and adjacent to) bio-inspired design. The successes of the airfoil prototypes in terms of strength and bending properties are due in part to their grounding in plant biomechanics. The plant models served as a guide for the production of compliant, negative-pressure-driven actuators that remained self-supporting and rigid throughout the entirety of their motion. This is quite different from many man-made forms that actuate, which are typically reliant on hinges and mechanical components. Here, designing a compliant structure specifically for negative-pressure actuation was key. Looking to natural systems, the first responsive networks, is an effective approach in reframing design thinking to encourage considerations around geometric, informational, and systemic integration within matter. The lens of biological organization and structure is a potent one to use when striving for the marriage of “matter” and “intelligence.” In this way, a bio-inspired, systems-focused perspective lends itself to the unique challenges of our new and emerging technologies.

7.4 Tangible Interfaces and Inspired Networks

Semi-rigid actuating surfaces might be utilized as a tangible interface in the production of a responsive wall, seating, vehicle interior, or other feature of our built environment that people inhabit. Because this responsive, plant-inspired system remains rigid throughout its motion program, it is an excellent candidate for expanding the traditional territory of tangible interfaces, generally relegated to small objects, screens, or surfaces on which to project. With this system, large surfaces could be made tactile and responsive. For now, most of our digitized information exists in our phones, TVs, and computer screens, seldom making its way into our personal environments in a way in which we can derive meaning from it. Bringing to life large swaths of our dwellings would put society a step closer to revisiting older ways of collecting environmental information, bringing back into use our senses of touch, peripheral vision, and motion tracking ability which have been long neglected by traditional electronics. Large tangible interfaces might allow us to design information-dense physical environments that we can read as easily as our ancestors might have read a forest.

CHAPTER 8: *Conclusions*

The first and most pragmatic objective of this thesis work was to establish the morphological paradigms for and strengths of the construction of compliant, semi-rigid substrates for actuation, as inspired by the initial plant models presented. This approach proved effective, yielding a number of geometries which afforded both a high degree of curling (a small resultant radius of curvature) and a high flexural stiffness to resist bending. In addition, a prototype airfoil using the same geometric principles and materials was shown to resist gale-force winds and produce lift in a wind tunnel test. As a proof-of-concept, this demonstrates that semi-rigid, negative pressure actuated soft robotic surfaces might prove to be a viable means of generating large surface deformations along with controlled curvature and bending, without the need for complex mechanics or heavy machinery.

The approach to the production of semi-rigid actuators explored in this thesis was grounded in an awareness of biomechanical principles governing the morphology of desiccating plant structures, which so elegantly balance rigidity with the production of curvature. Though this study deviated from employing the same bending principles in detail, it was nonetheless guided by the form and organization of many plant structures. The preceding meditations on the role and usage of bio-inspired design for thinking about information-dense systems of matter, as opposed to a tool only for discovering individual design solutions, suggest that nature may be a productive lens through which to study our designed relationship between matter and intelligence.

Figure 36: Compilation of thesis work. Left image component: (Suyi Li and Wang 2016)

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