Exoskin

Pneumatically Augmenting Inelastic Materials for Texture Changing Interfaces

Basheer Tome
B.S., Georgia Institute of Technology, 2013

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences at the Massachusetts Institute of Technology.

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Abstract

Programmable materials have the power to bring to life inert materials in the world around us. Exoskin, provides a way to embed a multitude of static, rigid materials into actuatable, elastic membranes, allowing the new semi-rigid composites to sense, react, and compute.

In this thesis, we give an overview of our motivations, design space, and molding architecture that together answer the when, where, and how of Exoskin's use. We then use Exowheel, an automotive steering wheel, as a case study illustrating the concrete benefits and uses of texture change as a multi-modal, bi-directional interface. By incorporating Exoskin, Exowheel is able to transform its surface dynamically to create a customized grip for each individual user, on-the-fly, as well as to adapt the grip during the drive, as the car moves from congested city driving to rougher rural roads.

Finally, we introduce the idea of membrane-backed rigid materials as a broader, more versatile platform for introducing texture change and sensing into a variety of other products as well. By deeply embedding soft materials with more-static materials, we can break down the divide between rigid and soft, and animate and inanimate, providing inspiration for Human-Computer Interaction researchers to design more interfaces using physical materials around them, rather than just relying on intangible pixels and their limitations.

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Contents

"The 19th century was about the control and manipulation of energy. The 20th century was about the control and manipulation of information. The 21st century will be about the control and manipulation of matter."

~ Tom Knight

1. Introduction

In my first week of studying industrial design in college, one of my professors turned to the class, and while holding and pointing to a hammer, he said "form follows function." That was the first time I heard the phrase but certainly not the last. Form follows function is one of the first rules or "laws" of design that all product design & architecture students learn and they pretty much carry it with them throughout their entire professional careers.

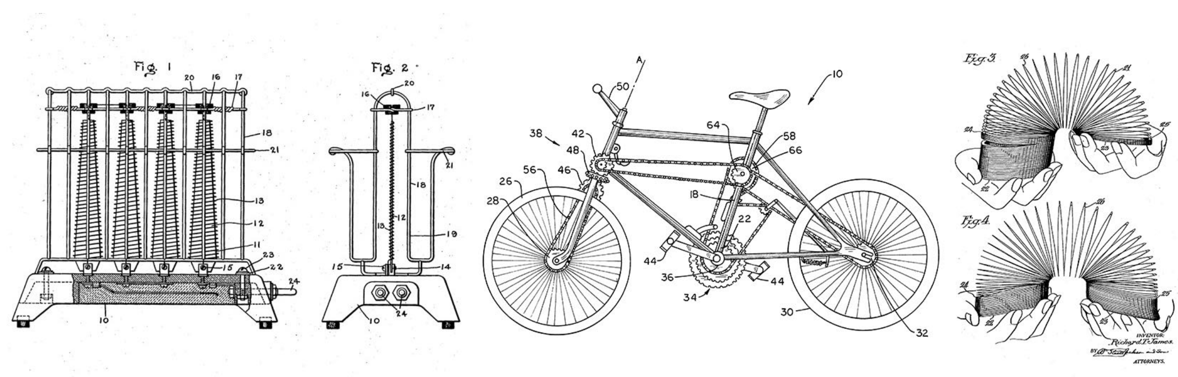

Figure 1. Patent drawings of an early General Electric toaster, a bicycle, and a slinky.

For early purely mechanical products such as the bicycle, toaster, or even a slinky, their function is evident in their form. The physics and ergonomics of the mechanics demand it, almost with the promise of an ultimate form – a holy grail beneath all the design. Granted you follow the function, you can find the ultimate form of an object. This of course, is utopia, but feels graspable. Along the way, you hope to reach affordance: what you see is how it works. The less information your audience will have to remember (about things that are not central to the experience you want to offer) the better. For every little piece that needs to be learned, it takes some workload that could be used for something else. And what needs to be learned will need to be remembered.

Figure 2. Variety of modern-day computing devices mobile and desktop

However, the rise of digital computing has simultaneously created a new opportunity and rift: form and function are now separable as function has become infinite. New features and abilities can be re-programmed, downloaded, and distributed. And as the complexity of our digital products has grown, the form of our devices has driven towards a ubiquitous, unassuming minimalism — plastic rectangles with touch screens.

With an entire body at your command, why should the future of interaction be limited to just the fingers?

1.1. Motivation

One of the most inspirational visions we've come across while doing our work is from Mark Weiser, chief scientist at PARC:

> *“For thirty years most interface design, and most computer design, has been headed down the path of the "dramatic" machine. Its highest ideal is to make a computer so exciting, so wonderful, so interesting, that we never want to be without it. A less-traveled path I call the "invisible"; its highest ideal is to make a computer so imbedded, so fitting, so natural, that we use it without even thinking about it. I believe that in the next twenty years the second path will come to dominate. But this will not be easy; very little of our current systems infrastructure will survive.” (Weiser, 1999)*

Our research hopes to help achieve that vision by creating materials where physicality and tactility are not at odds with reconfigurability. We want to make form as malleable as function, in order to break down that divide between physical & digital and make digital computation & data intrinsic components of the world around us. With that, the assumption and hope is that we're not only expanding the palette of technology and design for interfaces, but also allowing people to leverage the years of experience of interacting with the physical objects & world around them.

1.2. Contributions

By designing a way to embed a multitude of static, rigid materials into actuatable, elastic membranes, we enable the new semi-rigid composites to sense, react, and compute.

In this thesis, we give an overview of our motivations, design space, and molding architecture that together answer the when, where, and how of Exoskin's use. We then use Exowheel, an automotive steering wheel, as a case study illustrating the concrete benefits and uses of texture change as a multi-modal, bi-directional interface. Finally, we introduce the idea of membrane-backed rigid materials as a broader, more versatile platform for introducing texture change and sensing into a variety of other products as well.

1.3. Aims

This thesis aims to push forward the field of programmable materials and increase their interoperability to more directly integrate them into our static materials and ultimately our environment in order to showcase new affordances, animations, and utilities. By deeply embedding these soft radical materials into the more static materials around us we can break down the divide between rigid and soft, animate and inanimate, in order to inspire future Human Computer Interaction researchers to design and manipulate the atoms around them as they have been with bits for decades.

2. Background

With each great digital user interface leap, we've brought the worlds of digital and physical one step back closer. When Doug Engelbart presented the mouse, we made our first huge jump from mere visual representation of words to a digital arrow intrinsically linked to a physical puck in our world (Engelbart, 1968). Thirty years later, Hiroshi Ishii and the Tangible Media Group developed Tangible User Interfaces (TUI) which made a similar leap in that negotiation between computation and physical materials. They more intimately link a variety of inert physical objects to a sea of glowing pixels projected beneath, thus giving physical form to digital information — the core concept of "Tangible Bits". (Ishii, 1997)

Today, we are standing at a point where "Tangible Bits" has transformed into "Radical Atoms" (RA) (Ishii et al., 2012). It is a vision that questions our fundamental experience with physical materials:

- What if inert materials became as dynamic as pixels on screens?
- Will they allow us to take advantage of the richness of multi-modal human senses

- Will they allow us to take advantage of skills developed through our lifetime of interaction with the physical world?

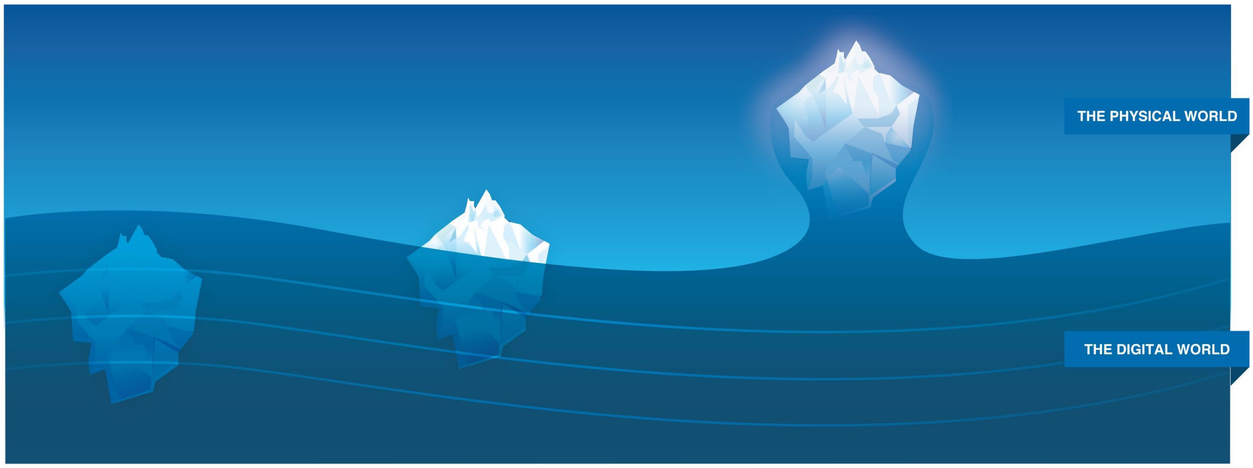

Figure 3. Diagram depicting a TUI like an iceberg: there is a portion of the digital that emerges beyond the surface of the water into the physical realm. With RA, all digital information has physical manifestation as if the iceberg had risen from the depths to reveal its sunken mass.

At its core, Radical Atoms seeks the deep integration of, rather than the mediation or supersession of atoms to bits. As we pursue this vision, we are encountering a new range of design problems: how do we *prototype* and *integrate* such physical processes of transformation?

2.1. Programmable Materials

Programmable materials have the real power to bring to life those inert materials in the world around us by enabling control of their properties using digital information. They 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. One key category of these materials are Organic

User Interfaces (OUI), which leverage the advantages of soft materials and allow interfaces to be deformed and adapted to any non-planar surface.

2.1.1. Jamming

Stiffness-changing material and mechanisms have been explored in mechanical engineering to construct robotic manipulators, such as medical robotics, gripping arms (Cheng. et al., 2012).

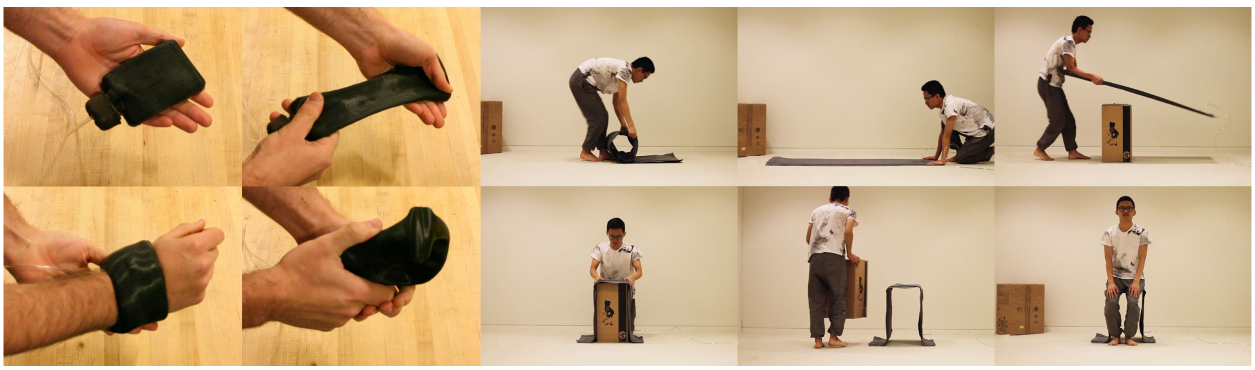

Figure 4. On the left, is a variety of applications for Jamming User Interfaces in the context of mobile shape-changing interfaces: from phone, to remote control, to watch, to game controller. On the right, a deformable piece of furniture using Jamsheets.

Jamming is the most popular of those methods, which changes the stiffness of a material through pneumatic air pressure. Most prominently, particle jamming allows for free form change of volumes that then can change their stiffness. Prior work in the Tangible Media Group shows some applications of particle jamming as well as layer jamming. The Jamming User Interfaces (Folder et al., 2012) project shows malleable interfaces on tabletops, for haptic feedback, and for mobile shape-changing interfaces (Figure 4). Further development incorporates the use of layer jamming as a simple, low-cost way of switching between rigid and soft to give more control of stiffness for thin layer interfaces.

2.1.2. Pneumatic Inflation

In the field of HCI, pneumatic inflation has been explored as an approach for shape change before. Volflex (Iwata et. al, 2005) is a volumetric display consisting of independently controlled balloons. Deformable convex or concave hemispherical membranes with rims can be used for an inflatable multitouch display (Stevenson, 2011). Inflatable Mouse (Kim et. al, 2008) is a shape-shifting mouse that can change the volume by using an air balloon and a built-in pump. Harrison explored dynamically changeable physical buttons on a display, with a variety of different materials for creating soft and ridged buttons, and integrated multi-touch sensing on the surface through diffuse illumination, pressure sensing for input (Harrison and Hudson, 2009).

Much in the same way that jamming utilizes pneumatic bladders to drive physical changes, PneUI (Yao et al., 2013) from our research group is an enabling technology to build shape-changing interfaces through inflating soft composite materials rather than hyper-deflation. The composite materials integrate the capabilities of both input sensing and active shape output. This is enabled by the composite's multi-layer structures with different mechanical or electrical properties. The shape-changing states are computationally controllable through pneumatics and a pre-defined structure (Figure 5).

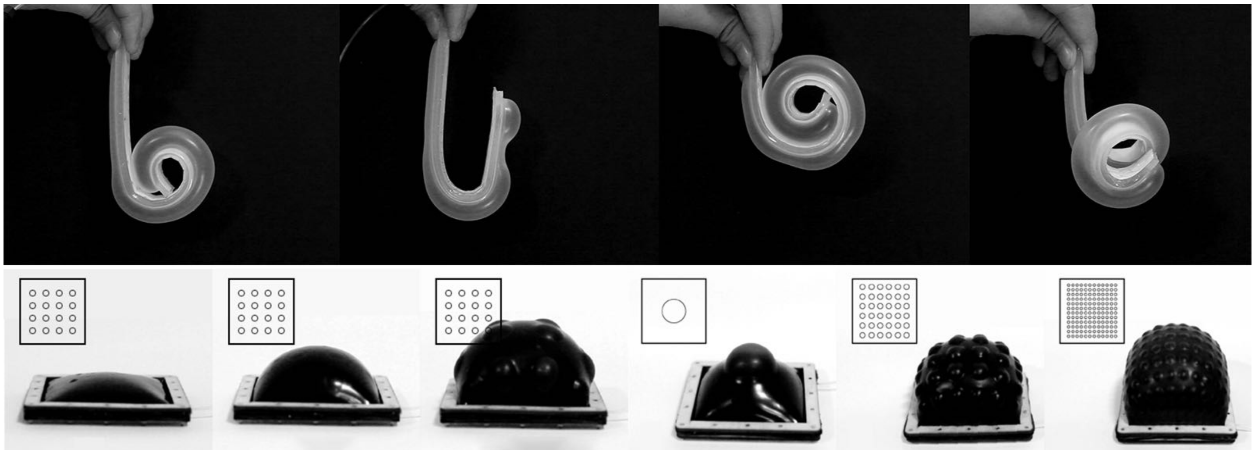

Figure 5. Top: Pneui bending shape primitive. Bottom: shape primitive of multi-stage texture change

This technology affords for a variety of cheap, simple, and effective fabrication methods to prototype these kinds of organic shape-changing interfaces.

2.1.3. Optielastic

While Pneui presents its own deformation sensing methods using either barometric pressure or liquid metal, I worked with Lining Yao and Jifei Ou from our research group and many others to develop a third method using optical fibers. By adding them, one can unify the input sensing and new visual output functionalities in one material which simplifies the design and fabrication of the PneUI material.

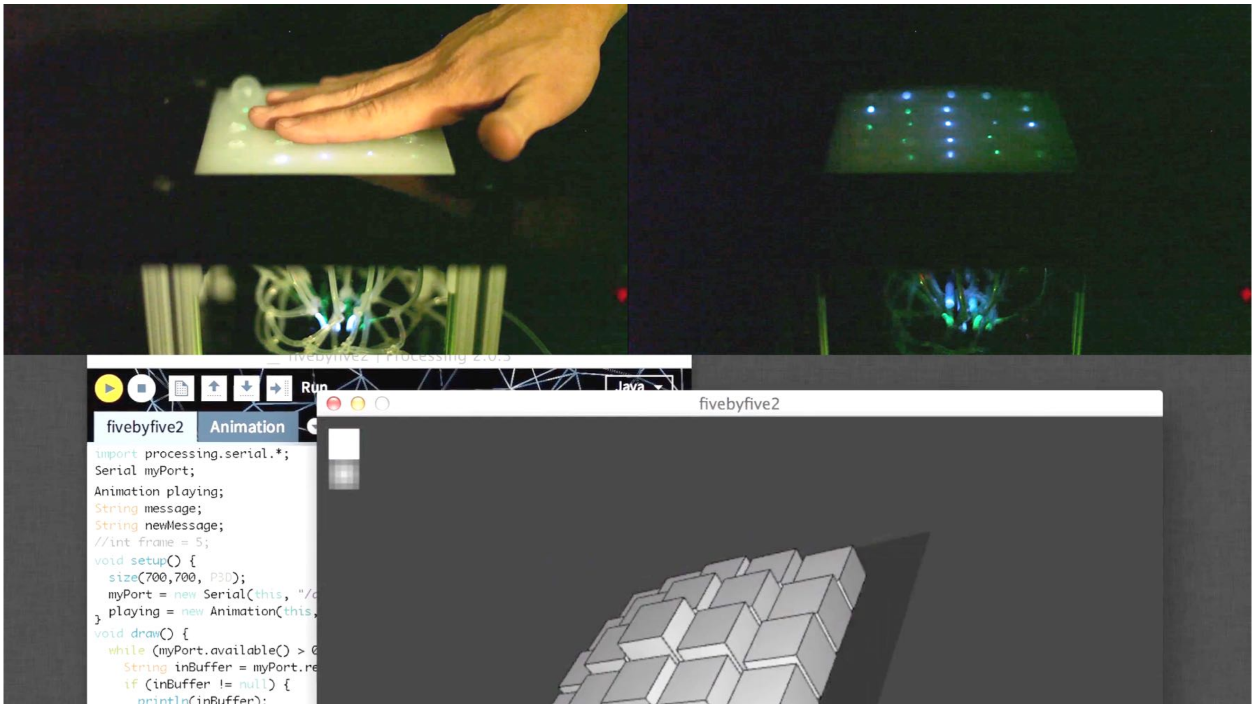

Figure 6. Pneuxel is made of five by five individually controllable cells that can light up through an optical waveguide composite. It can simulate variable degrees of expansion and contraction through pneumatic actuation. Shown here is the device and software implementation.

Inspired by the method introduced in PneUI to create a dynamic texture display, we developed Pneuxel to unify both a dynamic haptic and visual display in one, as seen in Figure 6.

2.1.4. Biologic

Biologic, on the other hand, takes an entirely different approach to programmable materials both in terms of the effect as well as the actuation method. Nature has long engineered its own actuators, geometry, and structures to achieve functional transformation. Based on the natural phenomenon of cells' hygromorphic transformation, Biologic introduces living cells as nanoactuators that react to body temperature and humidity change (Yao et al., 2015). These living nanoactuators can be controlled by electrical signals and communicate with the virtual world as well.

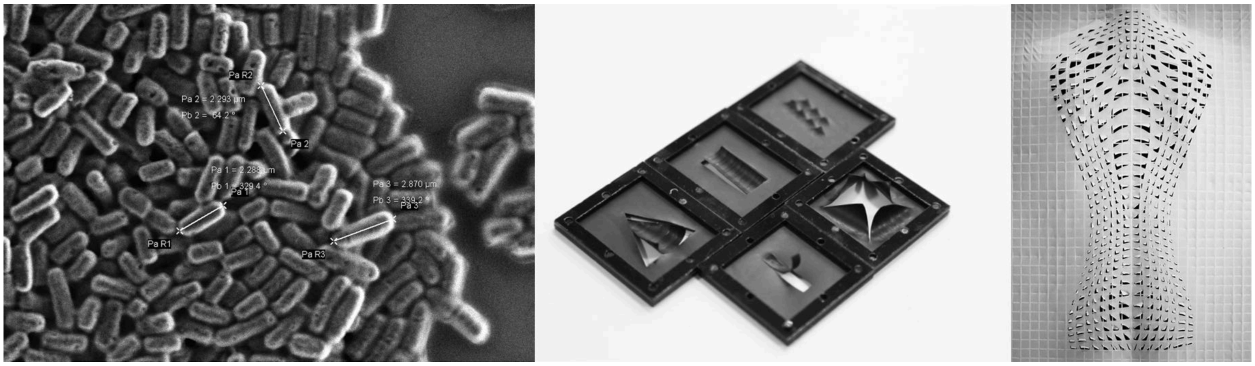

Figure 7. Left: SEM image of the nanoactuators, natto cells. Center: Actuated Kapton-backed samples. Right: Second Skin latex-backed breathable shirt

By placing those actuators on Kapton or Latex, they're able to create a subtle, thin, and organic shape transformation of the surface. While the cells cannot apply much force, in the right context such as the shirt seen in Figure 7, they're able to create a breathable skin that you can wear.

2.2. Limitations

Due to their fabrication and bonding qualities, most current programmable materials used in interface & product design simply propose these materials as wholesale substitutes for more conventional, inert materials. However, very few of the materials, products, and environments we're surrounded with everyday are made of elastic, squishy, and/or soft materials. Furthermore, Color, Material, and Finish trends (often referred to as CMF) are the most widely tracked trends in the creative field. The form or a style, or an image that comes from the appearances may be vivid and easy to conceive. However the

Figure 8. Materials library exhibit by Material Connexion displaying a variety of samples

sense of comfort of a product, the quality of a product that make you feel you want to use the product, or the textile, the agreeable touch of your affectionate items that derives from the perfect balance of the weightiness, the prevention system for the malfunction, the resistance against the damage, all these elements have to be the essence of the product design. Thus, by narrowing down the material choices to purely silicone, latex, or other elastomers, we severely limit the contexts and use cases for programmable materials. If we are able to better integrate these programmable membranes into more rigid materials, we can enable industrial designers, architects, and more to consider these values when designing shape & texture-changing products:

- **Functionality**: Different materials have different functional properties. Ceramics are particularly heat resistant and hard. Plastics can be easily formed into an infinite range of shapes and colors. Glass is hard and has some outstanding optical qualities. Wood is easy to work without necessarily using expensive machinery and is also naturally highly decorative.

- **Emotional Quality**: While it is easy to consider materials only from the perspective of obvious functional attributes, the emotional qualities should also help define the product as much as the form and function. The surface texture, the translucency, the softness or hardness all have an effect on the way a product is perceived and used for different product characteristics, i.e. wood can be warm and nostalgic while metal is cold, clean, and precise.

Figure 9. A sample inspiration board from Bengt Brummer, CMF specialist, arranged by hues and tones.

- **Aesthetic Quality**: Whole organizations are devoted to predicting what will be next year's hot colors or pattern. In the housewares and fashion industries, for example, the Color Marketing Group meets yearly to coordinate what the next year's palettes will be. This is incredibly useful for a brand that manufactures for a retailer like Target, who wants to coordinate vast quantities of varied products into a cohesive color scheme. Treating CMF in new and fresh ways is critical for creating differentiated products.

3. Related Work

This thesis aims to push the envelope of radical atoms such that programmable materials can be intrinsically embedded into our products, buildings, and environment. It draws upon the literature of Human-Computer Interaction, Robotics, Programmable Materials and interaction techniques. In this chapter, we hope to reference and synthesize this rich body of work we build from. Though we try, it is in no way as comprehensive and complete as it could ever be, especially as new technologies are invented each day.

3.1. Actuated Tabletops

To overcome the static limitations of passive objects in the past, systems like Pico by James Patten (Patten, 2007) utilize an array of electromagnets underneath a tabletop to computationally move tokens. Madgets by Weiss (Weiss, 2010) extends this approach through actuatable tokens that can be moved, rotated and have part of their physical state altered through an internal magnet array. Festo Wave Handling proposes object movement through shape actuation for factory automation (Rolf et al., 2012). MoleBot (Lee, 2012) actuates small objects across a table surface through a moving molehill-like shape.

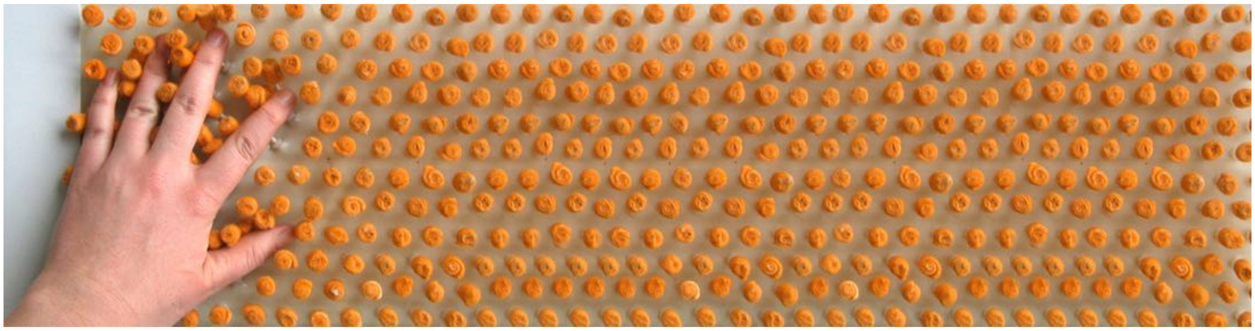

Figure 10. Super cilia skin is a tangible interface which responds to touch. Like our skin, it is a haptic I/O membrane that can sense and simulate movement and wind flow.

However in terms of this thesis, the most important iteration of the magnet-driven grid table is Hayes Raffle's Super Cilia Skin. Super Cilia Skin is a tactile and visual system inspired by the beauty of grass blowing in the wind. It consists of an array of computer-controlled actuators that are anchored to an elastic membrane. These actuators then represent information by changing their physical orientation. Despite limitations in only being able to induce lateral movement (orientation) in the cilia, those deformations are still easy to see or feel because humans have an acute ability to identify moving objects. By moving past the tabletop, scale, & complexity limitations of electromagnetic actuation, the hope is that Exoskin can use the pneumatic actuation and a larger variety of materials to extend this tactile-visual skin interface even further.

3.2. Shape Displays

Even within the confines of the tabletop form factor, there have been huge leaps in capability. Shape displays jump from 2d to 2.5d by creating a dense, actuatable surface of pins that focuses on rendering content, user interface elements through shape output, and dynamically changing UIs.

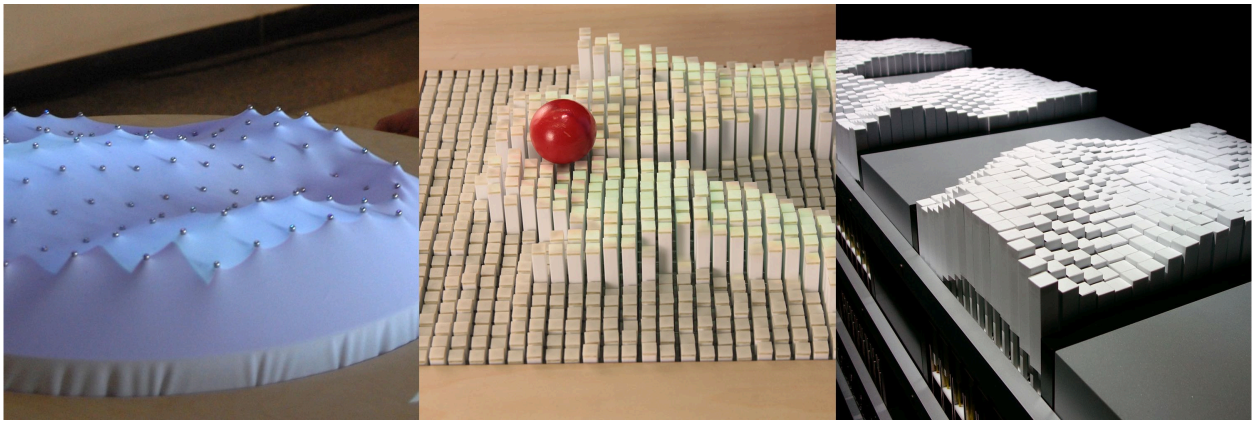

Figure 11. From left to right: (1) Relief: low-density shape display with latex sheet covering, (2) inForm: higher-density display capable of representing human-scale features, and (3) TRANSFORM: design-lead piece able using motion to depict waves & other non-rigid modalities

Relief, inForm, and TRANSFORM (Figure 11) look at how we could interact with a 2.5D shape display. Users can use gesture or direct manipulation to change the shape of the surface. As the physical 2.5D model is synchronized with its digital model, the surface actively deforms itself, too. inFORM also investigates moving various inert physical objects through shape change (Follmer, 2013). Physical telepresence enables the remote handling of objects through the users shape (Leithinger, 2014). However, while these tools enable rapid prototyping using 3d modeling tools, such interfaces require a large set of complicated motors, which limit their conformability, scalability and integrability. That said, the motion design of the wave machine in TRANSFORM has been a huge inspiration for designing and creating materials that look, feel, and move like others.

3.3. Smart Materials

A smart material refers to a highly engineered material that responds intelligently to their environment (Addington & Schodek, 2005).

Figure 12. A variety of iconized smart materials: ferrofluid, aerogel, metal foam, nanotubes, and shape memory alloy

Due to the popularity of smart materials like shape memory alloys (SMA) in the field of robotics, there's emerged interest to bring them to the HCI field. However, due to their complexity in both use and fabrication, most current attempts to implement smart materials in interface & product design simply propose smart materials as replacements or substitutes for more conventional materials or actuators. They then are typically patched atop an existing structural system, isolated. If we want to construct more complex and embedded transformation, we need to more deeply intertwine our active and passive materials

3.4. Soft Robotics

Soft robotics is an emerging domain that is dedicated to robots comprised of soft components including soft actuators, flexible sensor/circuits, and soft bodies. This contrasts other techniques for shape-change, such as actuated modules, self-foldable chains, and self-foldable surfaces. A team of Harvard University researchers led by George M. Whitesides use networks of channels in elastomers that inflate like balloons for actuation as seen in Figure 13. Through this, they achieve complex motion that requires only a single source of pressure and movement that can be designed by appropriate selection of the distribution, configuration, and size of the embedded pneumatic network. (Ilievski et al., 2011)

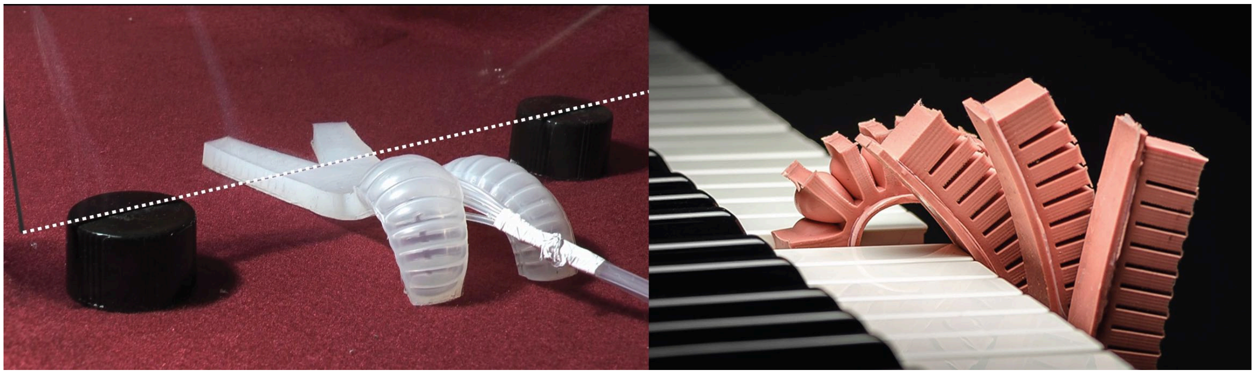

Figure 13. Left: The soft robot can wiggle its way underneath a pane of glass just three-quarters of an inch above the surface. Right: Four soft robotic fingers progressively curl to play notes on a keyboard.

While a primary focus of soft robotics is the improvement of the robot's performance and the exploration of the bio-inspired mechanism itself, there is still room to popularize soft robotic technology for driving shape-changing interfaces. Its using these techniques we can now design interfaces can change their curvature from convex to concave, act as compliant grippers for handling fragile objects without damaging either, or create various modes of locomotion.

3.5. Art & Design

> *"Art at its most significant is a distant early warning system that can always be relied on to tell the old culture what is beginning to happen. ~Marshall McLuhan*

Art helps us express our desires in a physical world that's rapidly changing while architecture & design then help define how we should live, work, play, and learn. Through the combined disciplines of art, design, science, technology, and architecture, we hope to understand how these key scales below can not only be emphasized to convey meaning, but be a departure point for creation:

3.5.1. Human Scale

TurtleSkin Metal Flex Armor (Warwick Mills, 2015) is a platform technology which combines high-performance textiles with solid metal elements to provide the protection of a steel plate with the flexibility of a textile. It achieves protection against knives, spikes, and hypodermic needles while remaining a thin, flexible, and lightweight panel.

Figure 14. Left: Early "wood skin" experiments. Right: Great Rose artisanal wood clutch.

Tel Aviv design studio Tesler + Mendelovitch transforms wood into a “skin” through diagonally-oriented crosshatches that allow the wood veneer to arch and fold like a textile and a separately composited leather backing. Cutting into the wood helped uncover the material's weak spots, and bending it gave them insight into how it behaved in its new panelized format.

3.5.2. Furniture Scale

In furniture, there’s often the decision of choosing a strong, robust, yet rigid material that must be carved or sculpted or choosing a weak, delicate, yet pliable material that hugs the body. Annie Evelyn, founder of New Colony Furniture, began experimenting with that hybrid middle to create concrete upholstery in graduate school and expanded to other hard materials like wood metal and even crystals when she received a Windgate Grant for furniture in 2011 (Werbler, 2015). Now, working with wood, concrete, metal, and crystals, New Colony Furniture presents a whole series of soft/hard upholstered chairs.

Figure 15. Left: Scotty Graphite Chair by New Colony Furniture. Right: Soft Bench by Daniele Lago

In similar vein Daniele Lago, in her piece called “Soft Bench”, used wooden panels and foam rubber paired in an innovative way to create a mosaic that looks rigid yet shapes itself under the weight of your body (LAGO, 2004).

3.5.3. Environmental Scale

Benjamin Boré’s Soft City questions the harshness of the city through a variety of installations (Jobson 2011). As seen in Figure 16 below, he embedded a water-filled pouch beneath the city streets to transform the perpetually rigid and static brick pavement into a liquid mound. It’s part of an exciting trend of architects becoming more and more conscious of the relationship between individuals and their environments, and realizing ways in which to explore and apply it in their practice. Onlookers can walk across this piece of road and jump on it, causing the bricks to ripple and form pavement waves.

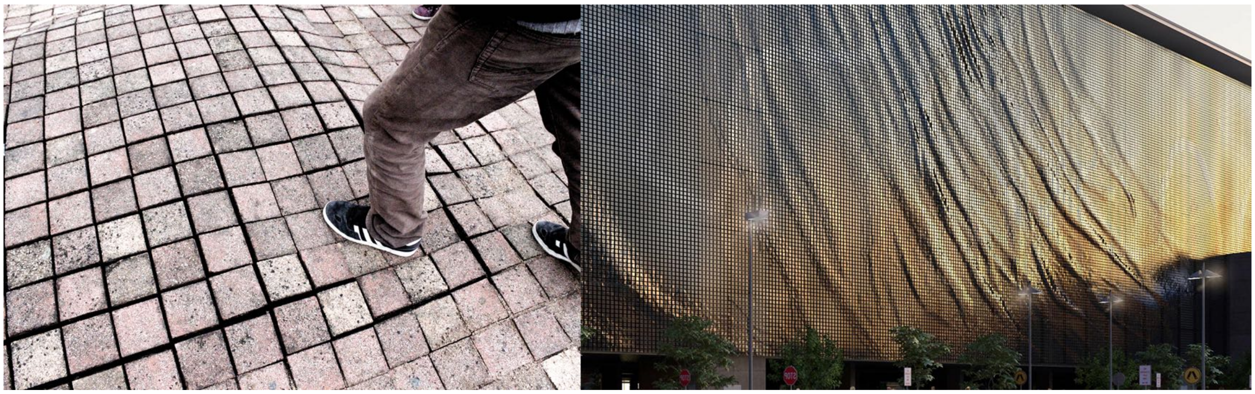

Figure 16. Left: Liquid Bricks installation by Benjamin Boré. Right: Turbulent Line Kinetic Façade that ripples fluidly with the wind

Environmental artist and sculptor, Ned Kahn, created the Turbulent Line, a new facade at Brisbane airport's domestic terminal car park (Ned Kahn Studios, 2012). The work of art cloaks the entire side of the eight-story car park with a lightweight, permeable screen made of 117,643 hinged aluminum panels bolted to a steel substructure. Viewed from the exterior, the car park's entire eastern side will appear to ripple fluidly as it responds to the ever-changing patterns of the wind and creating a direct interface between the built and natural environments.

4. Explorations

Leading up to the main contributions of this thesis work, described in the chapters following this, two relevant exploratory projects will be discussed: Focal Wheel and Anima. It was the frustrations, discoveries, limitations, and opportunities encountered during these projects that incubated what would later become Exoskin and Exowheel.

The first project, Focal Wheel, is relevant to this thesis since it serves as the initial test for using soft programmable materials in the automotive context. It was through the design, building, and presentation of the project that we were able to both validate the use of these new materials in this environment but also to find its limitations after seeing how people interacted with it during our test run throughout the fall 2014 members event.

The second project, Anima, grew from an extended collaboration with Jaguar Land Rover. With the goal to make the car feel alive, this project iterates on the concepts from Focal Wheel and explores the use of a variety of other programmable materials throughout the rest of the car.

4.1. Focal Wheel

We found that our senses are overloaded while driving a car. The current automotive interaction model overloads people with expensive visual interactions that chew up active processing cycles in the brain and cause longer delays between action and reaction. Furthermore, traditional research into the area has relied on haptic feedback to create a tactile interface. Shape & texture change have a greater ability to create more perceivable, understandable, and intuitive stimuli. Because of that, we explored this more tactile, shape-changing approach to taking advantage of the hands

4.1.1. Project Background

Collaborating with colleagues from my research group Felix Heibeck and Lining Yao, we brainstormed a variety of materials and target areas for tactile interfaces in the car. Pneui, a recent development from Yao et al., provided us with an enabling technology to build the shape-changing interfaces we sought through a pneumatically-actuated soft composite material. Furthermore, its ease of molding and prototyping became critical for the project on its tight deadline.

Our general approach was driven by an enduring paradigm for car drivers: anyone who is driving a car should keep their eyes on the road and their hands on the steering wheel. In accordance with this paradigm we envisioned a concept where the output modality is directly integrated into the steering wheel. This creates the opportunity to design a safer non-visually reliant interface. It also is able to take advantage of the fact that the hands and fingertips, which have some of the densest areas of nerve endings on the body, are in constant contact with it.

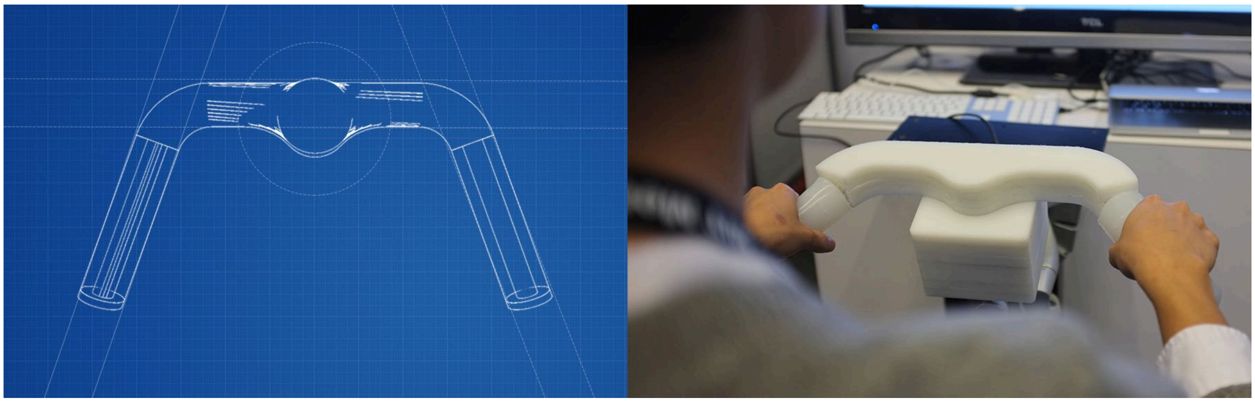

Figure 17. Left: Technical sketch of Focal Wheel design showing overall form factor and bladder placement. Right: Final Focal Wheel prototype during member's event

4.1.2. Implementation Details

The system has three main components: fabrication, hardware, and software. Each of these components contains significant design choices, tradeoffs, and features that contributed to the overall experience.

4.1.2.1. Design & Fabrication

Focal Wheel is built from layered HDPE plastic sheets and pipes. These provide an easily-fabricated hollow skeleton that guides and encases the internally-routed tubes and circuitry. Silicone is then molded with air bubbles inside the elastomer, layer by layer. We can vary the density, frequency and sequence of texture by pumping and vacuuming air in separate columns at different times.

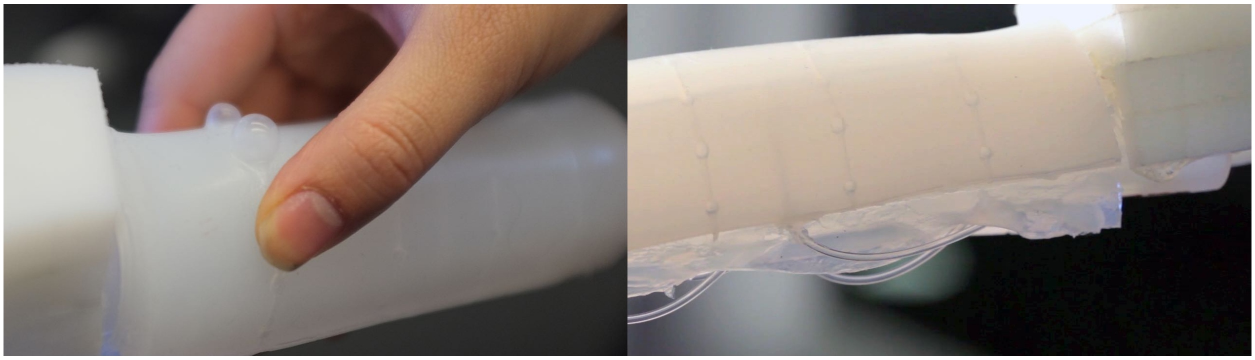

Figure 18. Over-actuated smaller air bladders in top layer in order to better show the tactile shape change happening underneath the palms during GPS turn navigation

The combination of the three factors is capable of communicating different types of information, such as directional signals and speed. Also, by compositing a second silicon layer with bigger airbags, we combine deformation on both macro and micro level, to create texture patterns on a deformable, 3D surface.

4.1.2.2. Hardware

The hardware pneumatic control system powers the soft composite material as the wheel pivots & the system senses pedestrians. Air can be either injected into air channels inside the elastomer, or introduced into the space wrapped around the composite material. There are three modes to control the airflow in and out of the material: supply, exhaust, and close. The supply/exhaust is the mode to inflate/deflate an air bag. The close mode stops the airflow to air inside the composite. Our pneumatic control circuit consists of nine 3-port solenoid valves, an Arduino-inspired micro-controller board designed by Felix, and an external air compressor / vacuum pump. These then connect directly to a computer equipped with a Microsoft Kinect for Windows 1.0 device for sensing.

With this system, we were able to actuate the bladders roughly 2cm/s with a 1.5-second relaxation time to the zero state with around 1N of force. Smaller actuations had proportionally smaller actuation and relaxation times.

4.1.2.3. Software

We then connect all the hardware & shape-changing materials together using the vvvv software, a hybrid visual/textual live-programming environment for easy prototyping and development. It is designed to facilitate the handling of large media environments with physical interfaces, real-time motion graphics, audio and video that can interact with many users simultaneously. We then wrote the final demo through the use of a machine-vision-based tracking algorithm running on the data obtained from the Kinect, as well as some pre-scripted driving sequences.

The wheel's larger air bladders greatly inflate to directionally alert users of danger, including: oncoming collisions from other cars, cyclists approaching from a blind spot, and/or pedestrians crossing close to the front and rear of the car.

The wheel's smaller lines of air bladders ripple cyclicly in order to give users a subtle heads up to start shifting lanes before taking a turn while also giving them a gradated metric of how soon the turn itself needs to be taken.

Because the bladders are layered in descending order in size from bottom to top, we're able to actuate both the smaller and larger bladders simultaneously. This enables the wheel to inform users of an upcoming turn without sacrificing the perpetual nor the technical ability to alert the user of any immediate danger.

Lastly, we implemented a rough concept of HUD integration tied to our sensory input and tactile output. This is important because while tactile feedback is immediate and well-perceived, it is unable to precisely communicate in true xyz world space what the system sees and understands. Thus, we paired a color overlay that identifies and highlights perceived threats to the user as they enter the car's sights.

4.1.3. Implications and Criticism

We presented this project during the Fall 2014 Members Event at the Media Lab. On top of being able to watch, study, and discuss how a large variety of users interacted with the system over the span of a few days, we were also able to receive critical feedback from experts at automotive companies like Jaguar Land Rover and the Volkswagen group.

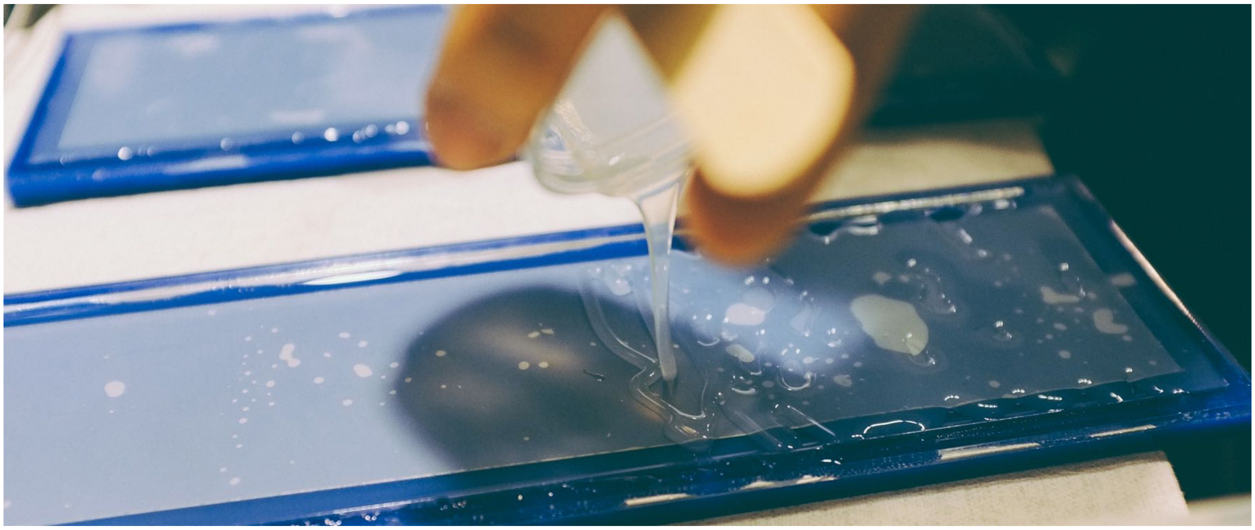

Figure 19. Pouring the uncured silicone into a mold to create the actuating bladders

Being able to visually perceive the tactile stimuli helped set expectations for the wheel's shape-changing output and kept the interface predictable and helpful. Current limitations in the sheet-like molding process of the silicone prevented us from creating a more traditionally-styled wheel shape. The straight bars held by the hands looked more like a cruiser bicycle than an automotive steering wheel, which confused a handful of users.

However, much of the negative feedback about the device centered around the silicone material itself. Despite it being the enabling technology and the pneumatic technology relying on an elastomeric material, many people could not cope with its visual aesthetic, surface feel, or compliance. Designers from Toyota told us that no matter the benefits, the silicone's inability to visually pair with their leather and metal-based interior designs made the technology a non-starter. We heard similar complaints from other companies as well.

Furthermore, after a few hours being handled by dozens of people, the surface became even slimier than its initially fabricated state after absorbing the oils, moisture, and heat naturally covering users' palms. We found that those changes can affect the electrostatic interactions between the polyisoprene strands in the rubber and make it act more fluid-like to become sticky. We attempted to alleviate some of the issue by intermittently applying baby powder to the composite, which did improve the feel but did not return it back to its original state and is not a sustainable strategy in a non-demo context.

Moving forward with the project would require either a change in material entirely or another in-between solution. Exoskin, presented in the following chapter, would eventually become our solution to this issue as well as create new opportunities for the use and contextualization of programmable materials.

4.2. Anima

As the UK's biggest investor in manufacturing research and development, Jaguar Land Rover is leading the way in developing innovative new solutions in several key areas. Major advances are currently being made in powertrain development and the use of hybrids, electronics and entertainment, and further into the future with technologies such as driverless cars. However, less of their research has been focused on creating more tactile, physical interfaces within the car. So, when Simon Thompson, an ergonomist and (Human Machine Interface) HMI specialist from Jaguar Land Rover joined us, we decided to revisit our earlier concept of pairing programmable materials with an automotive interior, now with the goal of making the car feel alive. To do this, we expanded our exploration of both materials and contexts within the car, investigating applications like: dashboard and console use, safety belt systems, ambient dynamic interior paneling, and even exterior bodywork augmentations.

4.2.1. Project Background

Project Animus is a dynamic texture interface, able to immerse the driver into the driving experience, and enabling them to develop a stronger experiential connection with the vehicle. In this project, we wanted to make the car feel alive while also offering an engaging, involved drive, rather than just performing a robotic function. Like an animal wakes and stretches, the vehicle comes to life around them accentuating cues that enhance excitement. We explored this across three contexts:

Illustrative Panels

Project Animus is able provide an impression of control and response from the vehicle through texture. Imagine using the electric window switch and seeing a texture rippling and emanating towards the window glass on the door panel. Project Animus aims to make the once static vehicle interior come alive through dynamic texture, reactive to the vehicle occupants. This creates a new level of transparency for electronic controls. By having the texture travel from the locus of input towards the area of output, users can easily see the connection and better understand the interface.

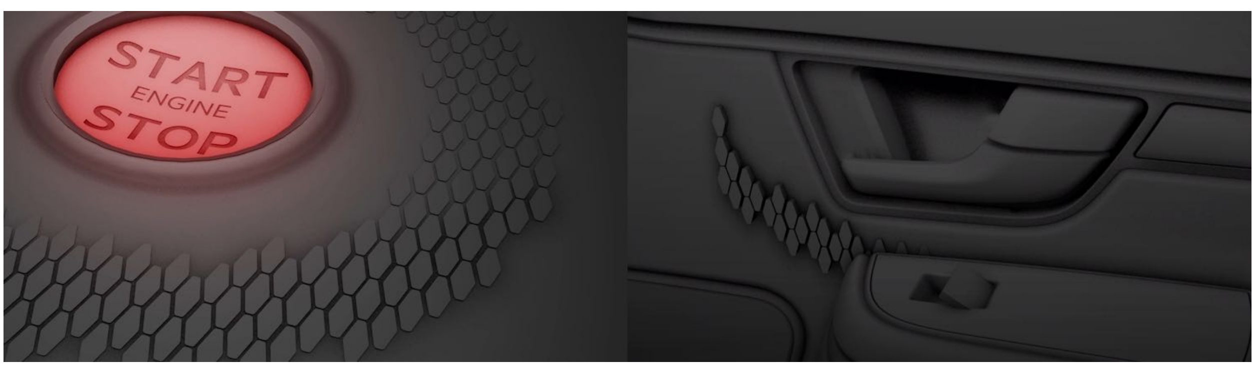

Figure 20. Left: Illustration of the texture change emitted from the start button to show a visual awakening of the vehicle. Right: Illustration of texture traveling from the window open/close switch towards the actuating window pane

Visual Awakening

Inspired by the current theatrical opening and closing of the console when starting the car, the driver sees a visual awakening of the vehicle through a texture that travels through the interior cabin when the engine is started, that embodies the story that the car comes alive. Whilst vehicles generally become more sophisticated and cosseting from the task of driving, Jaguar has an ethos to make the car feel more existent, active, and aware.

Figure 21. Illustration of the reactive dashboard actuating with the high speed movement of the car

Reactive Dashboard

Project Animus can be used to connect the driver to the external environment. Today's vehicles cosset the driver and can leave them feeling disconnected, creating a false feeling of safety. Texture can add an impression of vehicle speed or serve as a means to highlight movement as the vehicle drives past infrastructure such as bridges or other vehicles. A cat's hair stands on end in response to an emotional trigger, called the fight-or-flight response. Animus could mimic this behavior, alerting the driver to possibly unseen events such as another vehicle alongside in your blind spot. In another iteration, we use the metaphor of water underneath the surface. With high velocity changes in speed or moving objects passing quickly nearby, the surface emits ripples. This can compliment the aggression and excitement of a professional driver or serve as an ambient display for the average consumer to monitor the smoothness and safety of their driving.

4.2.2. Implementation Details

Collaborating as well with Felix Heibeck, Lining Yao, and Clark Della Silva, we decided to work with Yao et al.'s recent Biologic development to achieve the texture changes we sought. Nature has long engineered its own actuators, geometry, and structures to achieve functional transformation. Based on the natural phenomenon of cells' hygromorphic transformation, Biologic introduces living cells as nanoactuators that react to body temperature and humidity change. By placing those actuators on latex, we were able to create a subtle, thin, and organic shape transformation of the surface. While the cells cannot apply much force, in the right context such as the dashboard or the interior paneling, they provided us with the output we were looking for.

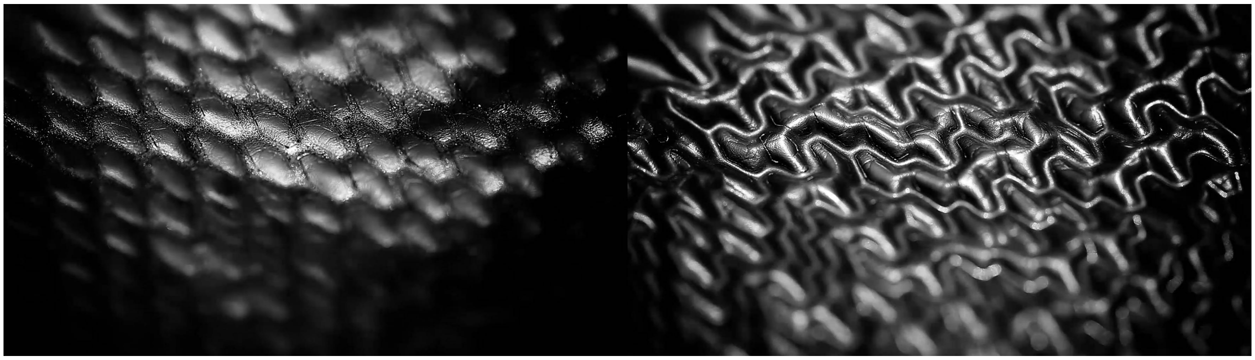

Figure 22. Macro photographs showing the texture change using the Biologic natto cells on latex. The left photograph shows their humid state, while the right photograph shows the arid state.

In order to make the texture actively respond and react to human interaction, we designed & built an Arduino-inspired micro-controller board coupled with 8 computer fans, a humidity sensor, and a steaming wand. Embedded and sealed within an acrylic box and mounted to the back of the latex, we were able to create a closed-loop humidity control system that can activate and de-activate the natto cells.

4.2.3. Discussion

While the system was able to roughly visualize and prototype the texture-changing interactions we were seeking, we ran into a few issues:

1. The actuation strength of the natto cells is extremely weak. This is not an issue in some applications, but in many of the automotive contexts we're interested in, it's a deal breaker. This is especially true in any sort of contact-based situations like a steering wheel's surface.
2. The control system that we implemented exhibits a large amount of hysteresis. By using off-the-shelf assemblies like the steamer wand, our entire control

task could only address humidity *removal* rather than being able to control the rate of steam creation as well. Thus, adding humidity was as simple as turning off all the fans, but removing it required just cycling in entirely fresh air.

3. The nature of applying these cells to an elastomer severely limits our material choices down to rubber and latex, neither of which are common materials found in the user-facing portions of a car interior.

These issues that we encountered during and after building the prototype, combined, also made this execution path unfeasible for any usage in production-level cars. In order to be able to incorporate these elastomer-based programmable materials in challenging, high-touch, and aesthetically-driven environments, we need to be able to transfer the actuating materials away from the surface and have them act more as an engine driving more rigid materials.

5. Exoskin

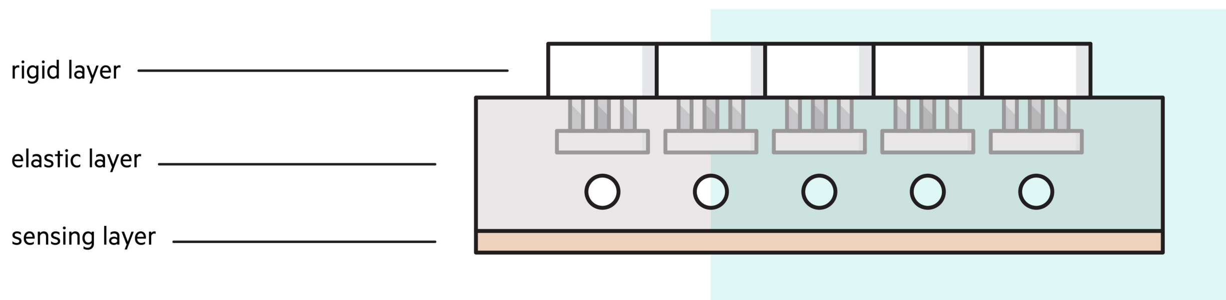

Figure 23. Simplified illustrated diagram showing the three key layers in Exoskin

Due to their fabrication and bonding qualities, most current programmable materials used in interface & product design simply propose these materials as wholesale substitutes for more conventional, inert materials. Thus, by narrowing down the material choices to purely silicone, latex, or other elastomers, we severely limit the contexts and use cases for programmable materials.

Exoskin, provides a way to embed a multitude of static, rigid materials into actuatable, elastic membranes, allowing the new semi-rigid composites to sense, react, and compute. It is comprised of three key layers:

- **rigid layer**: external “skin” controlling the perceived, tactile, and material qualities of the final composite

- **elastic layer**: underlying driver to actuate system
- **sensing layer**: provides capacitive feedback loop to sense interaction & deformation

By being able to better integrate these programmable membranes into more rigid materials, we significantly expand the design space and palette by enabling industrial designers, architects, and more to consider these material values when integrating shape & texture-change into their products: functionality, aesthetic quality, and emotional quality.

Figure 24. Left: Soft Glass Table by Nendo. Center: Two-toned Ceramic Pitcher by Heath Ceramics. Right: Nokia Universal Portable USB Charger

Examples of these qualities include ceramics' particular heat resistance, plastics' ease of formation into a range of shapes and colors, glass' optical & refractive qualities, and more. Their surface textures, translucencies, and softness / hardness all have an effect on the way a product is used, perceived, and remembered. i.e. wood can be warm and nostalgic while metal is cold, clean, and precise.

5.1. Design Space

At each layer of the composite, there are a myriad of design decisions that greatly affect the final performance of the material depending on the intended context and use case. In this chapter, we will outline what those decisions are, what they can enable, and what their limitations are.

5.1.1. Rigid Layer

The rigid layer acts as the externally-facing interface between Exoskin and the world. It is key to controlling the perceived, tactile, and material qualities of the final composite.

5.1.1.1. Material Choice

Because the elastic layer is relied upon for actuation and a separate sensing layer can be composited, the choice in rigid material does not rely upon its functional aspects with regards to digital input and output.

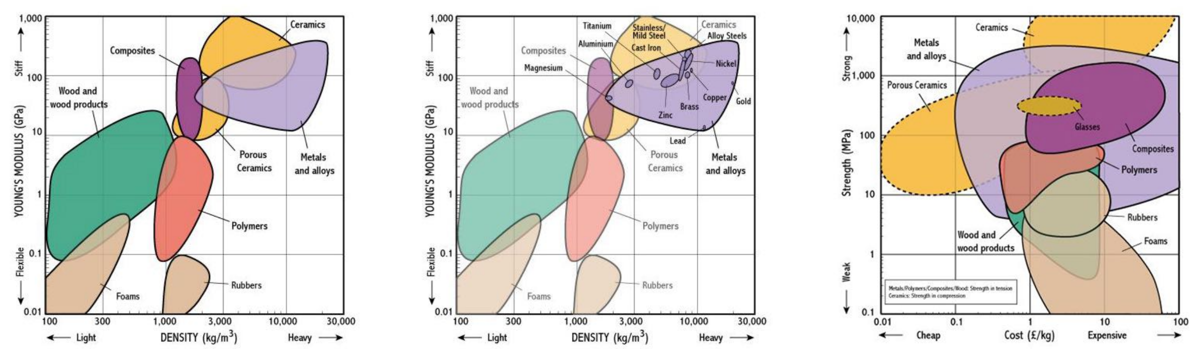

Figure 25. Charts by the University of Cambridge Department of Engineering used to identify the best classes of materials, and then to look in more detail within these classes (Lovatt and Shercliff, 2002).

Instead, we can use more traditional means of material selection to best match the properties to our use cases. The charts above as seen in Figure 25 are an example of how an engineering department, like that of the University of Cambridge, might select a material for their products. As designers, however, the aesthetic, emotional, and tactile qualities serve as our motivating factors driving decision as well as their ease of prototyping, manufacture, and availability.

Figure 26. Comparative visualization of Exoskin using wood, leather, and metal (from Left to Right) as the triangularly panelized rigid layer.

Plastic is the most versatile material ever invented. In fact, the word "plastic," which derives from the Greek word plastikos, meaning to mold or form, has come to be used as a general description for anything particularly adaptable or flexible. Since the first plastic, celluloid, was developed as a replacement for elephant ivory in the 1860s, many different types of plastics, including ABS, PLA, acrylic, and polystyrene have revolutionized the manufacture of commercial goods. Utilizing plastic in Exoskin has 3 key advantages:

- Varieties such as ABS & PLA are the most common materials for 3D printing, enabling extremely rapid prototyping
- They are available in a near infinite array of colors, textures, and finishes
- They are lightweight and inexpensive

Metals, on the other hand, have traditionally been used in many markets for their material properties high mechanical strength, dimensional accuracy, heat and UV resistance, perceived high quality, low thermal expansion, and good thermal and electrical conductivity. Metals, like aluminum, steel, and titanium, suggest quality and durability, and meet consumer expectations for high-end, traditional appliances and automotive vehicles. While they *can* be 3D printed, the sintering process involved is prohibitively expensive in the DIY market and historically, cheap metal fabrication & prototyping revolves around stamped, cut, and bent sheets. Waterjet cutting of softer metals like aluminum is popular for 2D shapes.

Figure 27. Left: 5-axis CNC milling of a wooden block using a KUKA Robotics arm to create a complex form. Right: Antwerp-based design studio Unfold 3D printing ceramic using their proprietary method.

Wood provides a warm, rich look and feel with distinctive natural grains. Over 100,000 different species of trees have been identified worldwide. However, only a very small portion of these species is harvested and dried for use, but that 'small portion' still comprises over 500 species such as walnut, bamboo, maple, etc. They still can vary widely in appearance and physical properties, with colors ranging from pale yellows and grays to vibrant hues of purple, red, and green. Because of its organic grain and non-moldability, wood can be quite hard and unreliable to work with without the correct tools and experience. Typically, engineered woods like plywood are easier to work with due to their sheet-like form and can be cut into 2D shapes. However, on a piece by piece basis, individual blocks can be shaped into more complex forms with mills, sanders, and other traditional machines.

Masonry materials such as concrete, stone, ceramic, and glass are common in architecture as well as some product design. They are particularly heat resistant and hard and some exhibit outstanding optical qualities. While a bit harder to work with in prototyping due to their brittle nature, the processes for 3D printing these materials have greatly progressed in the past few years. Furthermore, 2D computational routing using a waterjet cutter is possible.

Figure 28. Left: Wool felt. Center: Two pieces of raw leather hide Right: Blue neoprene rubber fabric.

Fabrics, especially on the thicker side, are actually a distinct possibility with Exoskin. Examples include 10mm-thick wool felt from Filz Felt, 10mm-thick full grain vegetable tanned leather, and neoprene which is available in a variety of thicknesses. All of these materials, while compliant, are quite inelastic and thus without composition into Exoskin are quite difficult to actuate as a soft interface.

5.1.1.2. Panelization

Because fundamentally, the material needs to be able to stretch, articulate, and transform, it cannot be applied as a singular, monolithic structure. Over the past two decades, the architecture and design industry has undergone a digital revolution. CAD, 3D modeling, and script driven design programs are commonly used in most major design offices around the world. Modeling technology is now so advanced that it is possible to produce extremely complex geometrical forms from minimal design input. Still, the implementation of freeform and complexly-curved shapes is an area which encompasses great challenges in engineering. Traditionally however, panelization has been used in architecture to solve cost and fabrication issues when otherwise the surface part would be too big, be too complex with too many undercuts to manufacture on the majority of tools, and require too many intermediary processes that prevent a single-stage build.

Figure 29. Left: Armadillo roaming in the wild. Right: Frightened armadillo rolled up into a ball while being held in hand.

The armadillo and its unique armor system served as the inspiration for using *panelization instead as an enabling technique for rigid materials to flex & transform*. It has a unique protective bony armor, called the osteoderm, which enables its shell-like skin distinctive mechanical properties. The top layer of the shell is made out of a dark-brown, extremely rigid keratin layer with bimodal size scales. Beneath the keratin layer, the osteoderm consists of hexagonal or triangular tiles having a composition that is the same as bone. In other animals, these tiles fuse together as they age but in the armadillo, they don't. Those tiles are then connected underneath by flexible collagen fibers, with no direct link to the internal skeleton.

However, panelization is not merely a binary choice of whether or not to utilize it. The choice of geometric tessellation has a huge impact on the design, feasibility, and transformation range of the rigid material for application within Exoskin. Furthermore, there's an even bigger impact when designing Exoskin for non-linear surfaces. There is an inseparable link between the panelization scheme and the geometry of the smooth surface. Meshes are the discrete analogues of smooth surfaces and will give the basis for the panelization scheme.

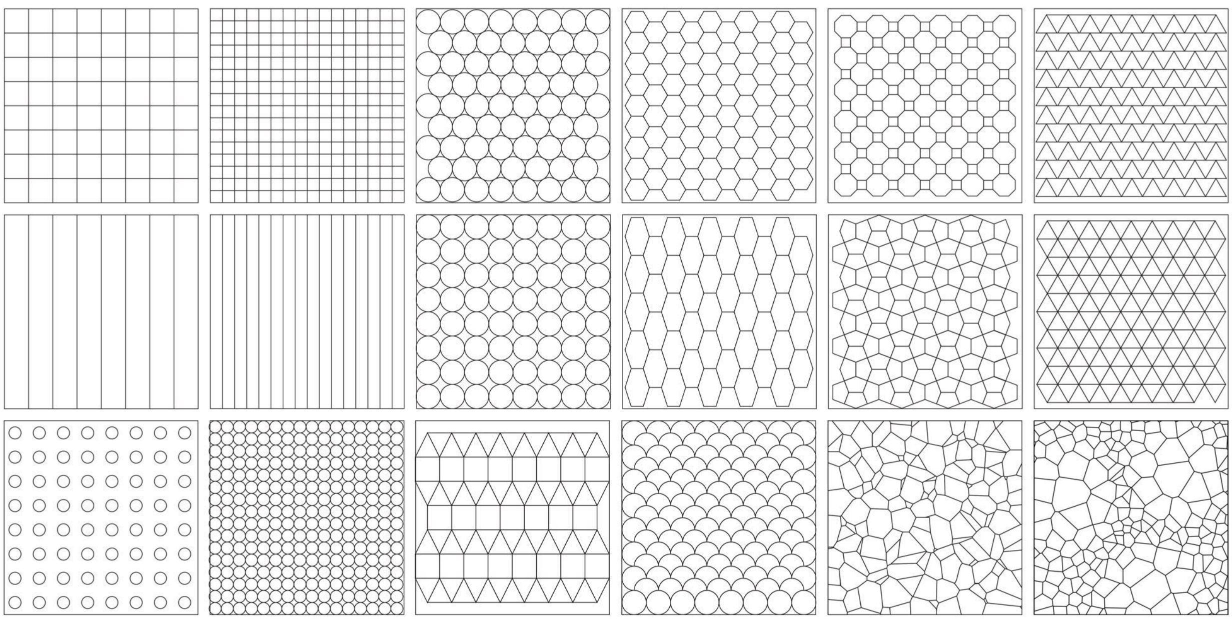

Figure 30. Variety of 2D panelization methods explored in early Exoskin samples including quad meshing, triangular, hexagonal, voronoi, and more.

Hexagonal

From the economic point of view, hexagonal meshes are an interesting solution. With minimized structural elements hexagonal meshes appear lightweight and structurally ideal. From the design point of view, hexagonal meshes have a strong aesthetic impact on the design, which might not always be wanted.

Figure 31. 3D visualization of the panelization methods from Figure 30 including quad meshing, triangular, hexagonal, voronoi, and more. Shown here are the default and actuated states of each.

Planar Quadrilateral

A planar quadrilateral (PQ) mesh is a mesh whose faces consist of four, coplanar, vertices. Planar quadrilaterals fit their bounding box more efficiently than triangles and reduce node complexity. PQ meshes have many desirable properties, but since four random points almost never lie on a plane, they are quite difficult to apply to an arbitrary surface. That said, PQ meshes have general aesthetic advantages: they do not run the risk of exhibiting an ornamental character; they stand back for the benefit of the overall form and motivate aesthetically pleasant freeform facades from the inside and outside alike.

Triangular

Approximating a smooth surface with triangular elements is the oldest and still most popular way of panelization. It is particularly well-suited for panelization with glass or other 2D materials, since it is always possible to construct a flat element through three points. However, a discretization into triangular elements has a number of specific attributes to consider. Such schemes have the highest panel count of any scheme, resulting in the highest number of overall cuts. A triangular scheme also means that six edges meet at a typical node, which implies high node complexity and low structural transparency.

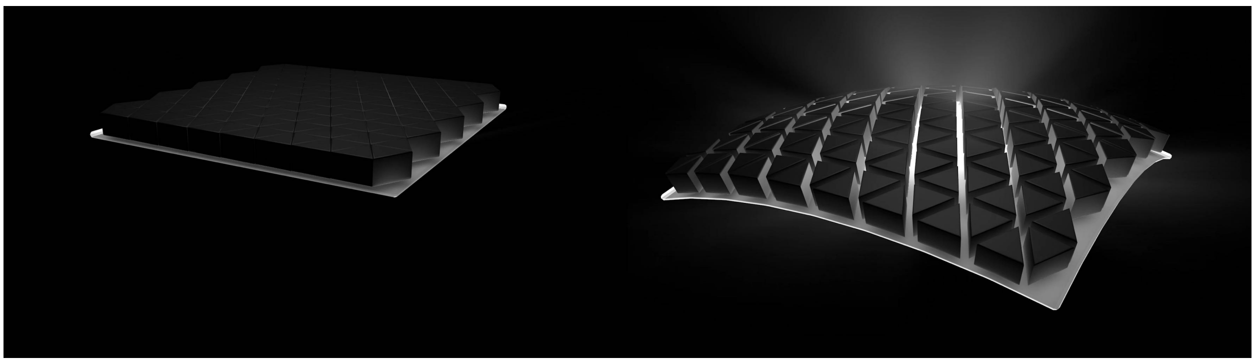

Figure 32. Visualization of triangular panelization scheme applied to an opaque rigid layer embedded in Exoskin. Placing a light source below reveals the high control of permeability this scheme enables.

As seen in Figure 32 above, however, this can be taken advantage of with an opaque material to design a rigid layer whose light permeability is controlled by the Exoskin's actuation; it is highly opaque in the default state and becomes quite porous when inflated.

Tessellation

Tessellation works on the intersection of numerous tangent planes of the selected surface. If the tangent planes of a smooth surface are positioned in a certain way, it is possible to obtain patterns such as convex voronoi panels. This is achievable if the observed surface is positively curved. If the surface is negatively curved, we get butterfly-formed panels. If tangent planes are selected at consecutive points near the principle curvature lines, it is possible to predict the orientation of the intersecting edge between two adjacent surfaces.

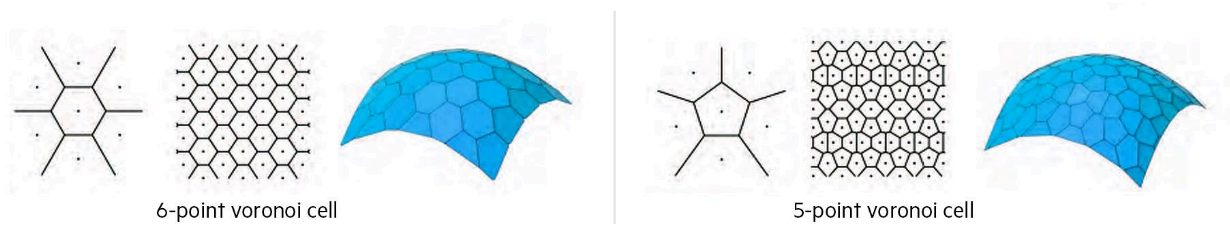

Figure 33. Voronoi cell panelizations on positive curved surfaces by Stavric et al.

Stavric et al. show in their paper, Discretization of Free-form Surfaces, examples (Figure 33) of how one might use that tangential mapping system to fit a voronoi cell mesh to a curved surface.

5.1.2. Elastic Layer

Because this dynamic, pneumatic layer relies on the deforming material to be quite pliable and be able to stretch many times its size, we quickly narrowed down our material selection to two products by specifically looking at two values: *shore hardness* and *elongation at break*.

5.1.2.1. Material Choice

The hardness of plastics is most commonly measured by the Shore (Durometer) test. This method measures the resistance of plastics toward indentation and provides an empirical hardness value that doesn't necessarily correlate well to other properties or fundamental characteristics.

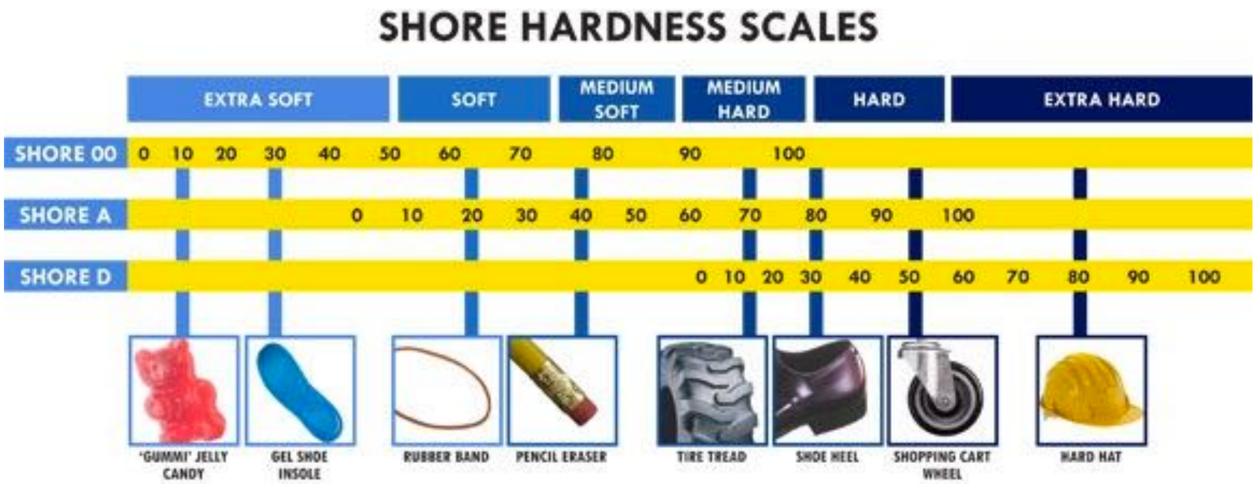

Figure 34. Chart from Smooth-on Inc. showing a range of various everyday objects along the scale.

Shore Hardness, using either the Shore A or Shore D scale, is the preferred method for rubbers/elastomers and is also commonly used for 'softer' plastics such as polyolefins, fluoropolymers, and vinyls. The Shore A scale is used for 'softer' rubbers while the Shore D scale is used for 'harder' ones. Many other Shore hardness scales, such as Shore O and Shore H hardness, exist but are only rarely encountered by most people in the plastics industry. Due to their availability and cost, the majority of the materials tested are available from Smooth-on, Inc. They make a large variety of epoxies, urethane rubbers & plastics, and foams.

The Dragon Skin silicones are high performance platinum cure silicone rubbers traditionally used in many special effects applications, especially animatronics where repetitive motion is required. However, we found it just a bit too rigid (Shore hardness 10) for our use compared to their Ecoflex rubbers.

Their Ecoflex Rubbers are platinum-catalyzed silicones that are versatile, easy to use, and softer. They're mixed 1:1 by volume and cure at room temperature with negligible shrinkage and the low viscosity ensures easy mixing and deairing. The cured rubber is very soft (Shore hardness 00-30), very strong (38 pli) and very "stretchy", stretching many times its original size without tearing (up to 900%) and will rebound to its original form without distortion. This is why they by far performed the best for our purposes and we chose EcoFlex 00-30, specifically, for our final samples.

5.1.2.2. Bladder Design

Although Ecoflex won't stick to much and has great release properties, it may stick to surfaces with open pores (open grain wood, very dry plaster, concrete, etc.). It will also bond to glass, surfaces coated with shellac and itself (which is an advantage if you need to add new silicone to already cured silicone). That said, in practice, those cases appear to be edge cases and rarely become an issue.

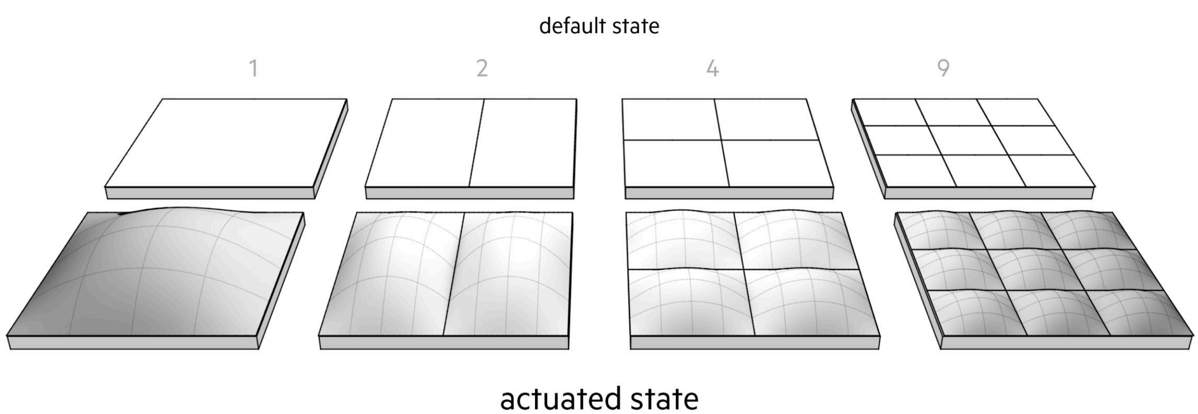

Figure 35. Illustrated diagram showing the tradeoffs between discretization of the bladders and overall actuation amount

Thus to create bladders, we simply insert a piece of mylar, paper, or any non-porous sheet-like material designed into any 2d shape we desire. The silicone will avoid adhering to either side of this foreign material and naturally leave an air pocket.

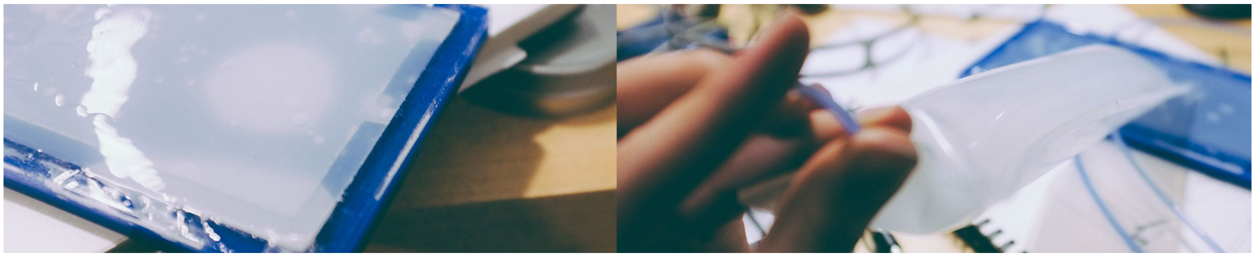

Figure 36. Left: Newly molded silicone bladder showing inserted mylar sheet. Right: That silicone bladder after tube insertion and inflation.

The bladder design has the largest affect on the actuation abilities of Exoskin. The design itself must take into account the degree of panelization of the rigid layer as well as the intended discretization of control. Furthermore, those levels of control are not necessarily mutually exclusive through the use of multiple layers of bladders. The bladders act precisely like balloons, thus segmentation and spacing have greater effects than the particular shape of the bladder.

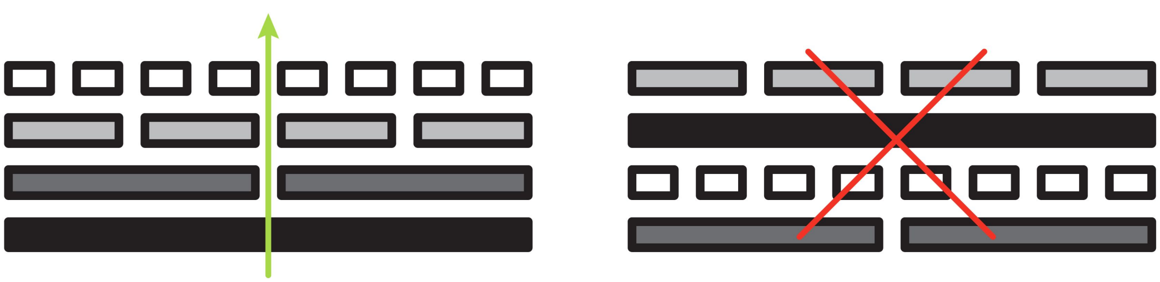

Figure 37. Illustration showing the correct, ascending order for actuated bladders in the elastic layer

One key parameter to factor in when layering however is that the bladders *must* be sorted in ascending order from the exterior surface, more discrete to the largest bladder. By doing this, we're able to have a large uniform, organic deformation of the surface while still having the ability to individually actuate single rigid scales in order to create texture patterns on a deformable, 3D surface.

5.1.2.3. Actuation

Actuation is enabled through a combination of a post-fabrication procedures on the elastic layer in tandem with additional, externally located hardware.

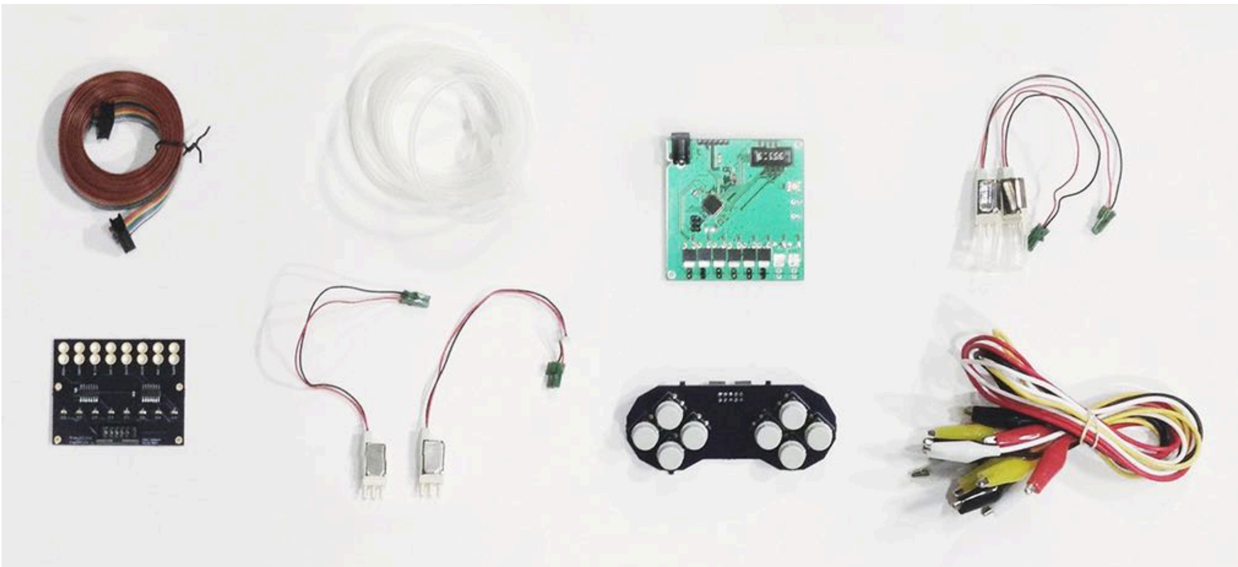

Figure 38. Pneuduino prototype system components deisgned by Felix Heibeck

To prepare the material for actuation, we create a small incision in each bladder and insert a tube. This is then connected to a solenoid valve and an air compressor. To increase speed of actuation, a second solenoid valve can be connected to the tube and vacuuming portion of the air supply. Then, to drive each valve, we require an h-bridge controller to apply current in both directions. Felix Heibeck, my colleague in the Tangible Media Group, developed an electronic hardware system to help deal with & control an n-number array of these valves, called Pneuduino.

Pneuduino is a toolkit for fast prototyping of inflatable structures. Currently developed for workshops with kids or students of different ages, we've already seen great results with novices achieving surprisingly complex results in short amounts of time. The kit has a motherboard to drive valves and pumps at its core and multiple extension boards including capacitive sensing, a gamepad and air-pressure sensing.

Air can be either injected into air channels inside the elastomer, or introduced into the space wrapped around the composite material. There are three modes to control the airflow in and out of the material: supply, exhaust, and close. The supply inflates and the exhaust deflates a bladder, while the close mode stops the airflow both in and out.

5.1.3. Sensing Layer

A variety of sensing techniques on flexible surfaces have been explored in HCI. Bend sensor composites (Balkarishnan, 1999) and flexible capacitive sensing (Gong, 2014) are among common approaches to sense human interaction as well as the material topology itself. Especially capacitive sensing through conductive material creates an interesting opportunity, as it is able to sense human interaction (Gong, 2013) as well as its own surface deformations (Yao et al., 2013) while possibly providing the architecture for other electrical components.

In Exoskin, we have found that depending on the context, sensing can be integrated at each layer of the composite: integrated into the rigid layer, passively through the elastic layer, or actively below as a separately layer. We also found that separating sensing into its own foundational layer to be the simplest, cheapest, and most robust method. In some circumstances, when sensing is needed in a variety of contexts and across many different deformation stages, employing multiple overlapping methods of sensing can cover the full range needed.

5.1.3.1. Sensing Integrated into Rigid Layer

Because the composited rigid layer can be composed of any material, our options are quite open for how to directly integrate sensing by considering integrating 3rd party components and by considering the material choice itself.

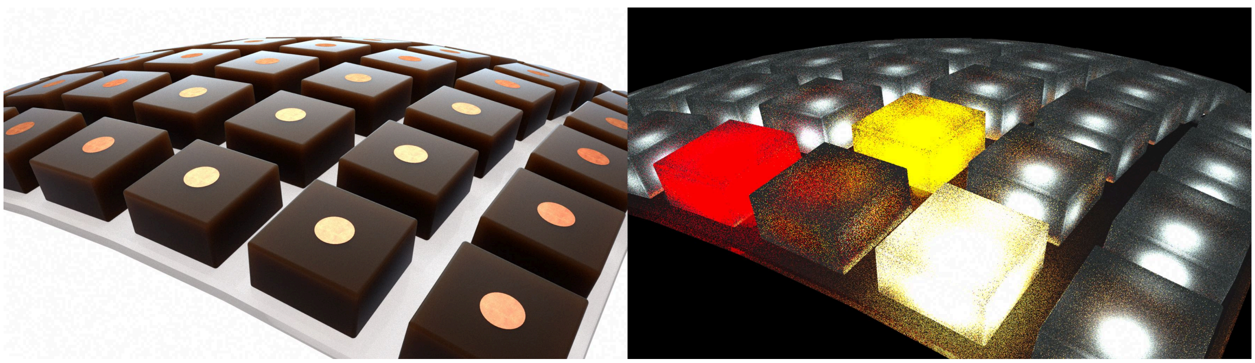

Figure 39. Rendered illustration depicting integrating into the rigid layer, metal capacitive sensors (Left) and integrating LED's for input & output.

Material-Native Sensing

There are a variety of materials that are electrically conductive and thus conducive to sensing nearby objects and simple touch interactions. Furthermore, depending on the panelization method of the rigid material, sensing using this method can be quite precise. Copper, aluminum, silver, gold, and high-carbon organic compounds are among the most popular materials for this method of sensing. More recently, and expensively, transparent conductive polymers and composites like indium tin oxide (ITO) have also become feasible. With Exoskin, these materials can be used as whole-substitutes of the rigid material, fixed on top, patterned in-between, or embedded inside as seen in Figure 39.

However, one also needs to understand the environment the device will operate in, such as the full operating temperature range, what radio frequencies are present, and how the user will interact with the interface. With no additional moving parts, this direct sensing method is moderately durable, but has low resolution, is prone to false signals from parasitic capacitive coupling, and needs calibration post fabrication. Therefore, it is most often used in simple applications.

Photoelectronics

We can directly embed LED's intro the rigid scales. Not only can LED's be used to sense light, but by clever use, they can function as both light detectors as well as emitters. This happens because a small amount of parasitic capacitance when connected in reverse. Thus, when this capacitor is charged, it will leak and lose its charge in proportion to the amount of light falling on the LED. So by alternating between having the LED's emitting and "receiving", we create that dual functionality. This can be harnessed to achieve a capacitive-like multi-touch system for touch & grip input or used to sense ambient light.

Force Resistive Sensors

Force-sensing resistors (FSR's) consist of a conductive polymer, which changes resistance in a predictable manner following application of force to its surface. They are normally supplied as a polymer sheet or ink that can be applied by screen printing. The sensing film consists of both electrically conducting and non-conducting particles suspended in a matrix. This means that they can be integrated into Exoskin in three ways:

- during the fabrication process of the rigid material itself, the FSR ink material can be injected and infused within if the rigid material has a minimum amount of compliance
- fixed as panelized sheets post-fabrication on top of the rigid material
- embedded as sheets directly below the fabricated rigid material scales during the Exoskin molding process

Figure 40. Left: variety of pre-fabricated force resistive sensors available off-the-shelf from sites like Sparkfun and Adafruit. Right: Applying FSR ink to a surface using an airbrushing system.

Thus, following that integration, applying a force to the top of the rigid layer causes those new particles to touch the other particles, changing the resistance of the film and/or ink. As with all resistive based sensors, force-sensing resistors require a relatively simple interface and can operate satisfactorily in moderately hostile environments. Compared to other force sensors, the advantages of FSRs are their size, low cost, and good shock resistance. A disadvantage is their low precision: measurement results may differ 10% and more.

5.1.3.2. Sensing using Elastic Layer

As Yao et al. have shown in their Pneui paper, there are a variety of worthwhile sensing methods to consider in the elastic layer. The two primary techniques that most naturally embed sensing into the elastomer involve:

1. Embedding liquid metal in the elastomeric air channels for sensing deformation of soft surfaces
2. Externally placing barometric pressure sensors on tubes connected to the air bladders

Neither of these methods will enable the ability to sense light touch nor gestures, but they do enable Exoskin to sense externally applied deformation from a user as well as sense its own deformation. In particular, sensing barometric pressure is key to being able to respond to and react to user input in the inflated state where sensing methods in the layers above or below might be disrupted from the state change. The Pneuiduino platform we work with directly gives us this ability.

5.1.3.3. Sensing as a Separate Layer

For ease of prototyping, speed, cost, and robustness, we found that separating sensing into its own foundational layer to be best, by using flexible capacitive sheets of copper, but can be implemented with rigid copper as well as other conductive materials depending on the intended context.

There are two types of capacitive sensing systems: mutual capacitance, where the object (finger) alters the mutual coupling between row and column electrodes, which are scanned sequentially; and self or absolute capacitance where the object loads the sensor or increases the parasitic capacitance to ground. In both cases, the difference of a preceding absolute position from the present absolute position yields the relative motion of the object or finger during that time.

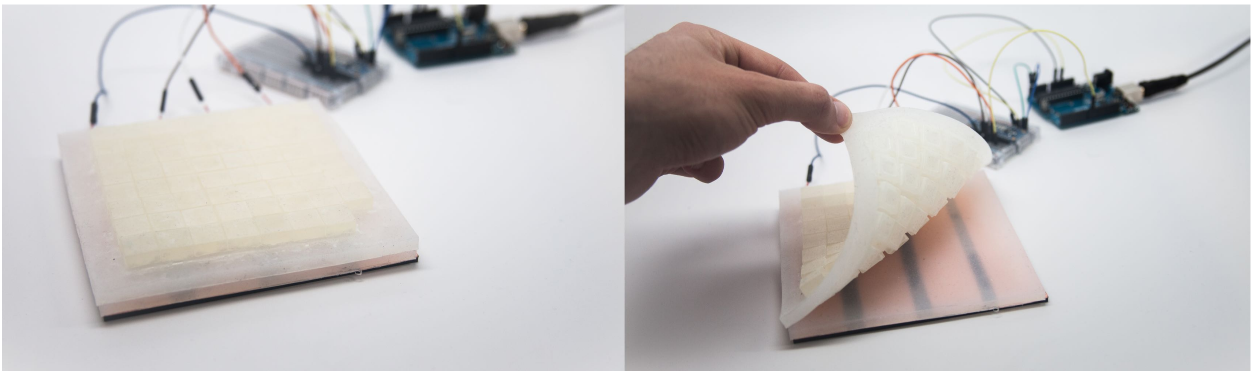

Figure 41. Copper-based capacitive sensing layer prototype with Arduino platform

In this instance, we use projected capacitance, which allows more accurate and flexible operation, by etching (or cutting) the conductive layer. An X-Y grid is formed either by etching one layer to form a grid pattern of electrodes, or by etching two separate, parallel layers of conductive material with perpendicular lines or tracks to form the grid. The greater resolution allows operation with no direct contact, such that the conducting layers can be placed below further protective insulating layers, like the elastic and rigid layers.

5.2. Fabrication

Fabricating Exoskin is a multi-step process requiring both analog and digital fabrication processes. The rigid layer must be fabricated prior to final compositing of each of the other two main elastic and sensing layers; the material must be either printed or cut from a larger substrate and pre-panelized. In the sub-chapter following this, we will discuss the various molding architectures available for the rigid material and how each option impacts the degrees of freedom, stability, and deformation of the rigid material.

5.2.1. Process Steps

Before beginning fabrication, design and fabricate a simple rectilinear mold to contain the silicone once poured. Then roughly follow the steps below:

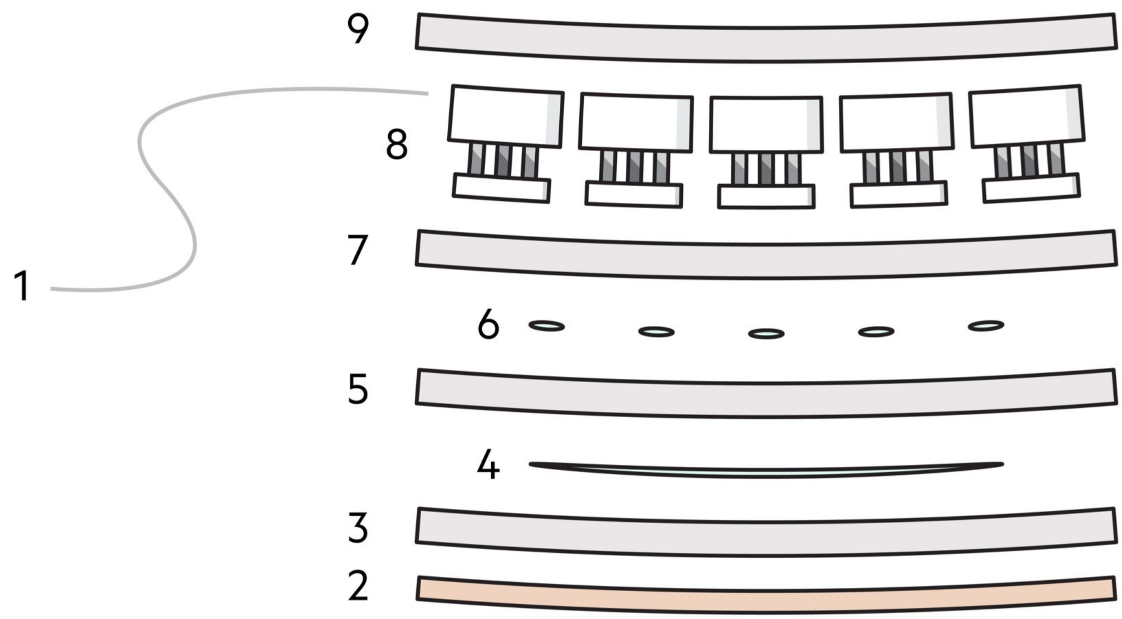

Figure 42. Illustration depicting the order of fabrication for Exoskin layer by layer

1. Design and build the panelized rigid scales.
2. If using separate sensing layer, cut, solder, and paste copper sheets to surface Exoskin will be applied.
3. Mix Smooth-on Ecoflex 30 silicone and pour first thin layer. Bake in oven to set more rapidly.
4. Place mylar 2-dimensional silhouette cutout for largest pneumatic bladder

5. Pour second layer of silicone directly on top and set.
6. Place mylar cutout sheets for smaller bladders.
7. Pour third layer of silicone directly on top and set.
8. Arrange rigid scales on the surface of the silicone.
9. Carefully pour final layer of silicone around the rigid scales, making sure to fill any and all gaps.

By directly pouring each additional layer of silicone on top of the previous, rather than using an adhesive, the layers bond directly to each other and form a much stronger, more uniform, and robust composite.

5.2.2. Molding Architecture

Silicone will not adhere to most materials and thus has great release properties for molding. However, it does stick to surfaces with open pores (open grain wood, very dry plaster, concrete, etc.), glass, surfaces coated with shellac and itself. These factors must be taken into account when designing how to integrate the rigid layer into the elastic.

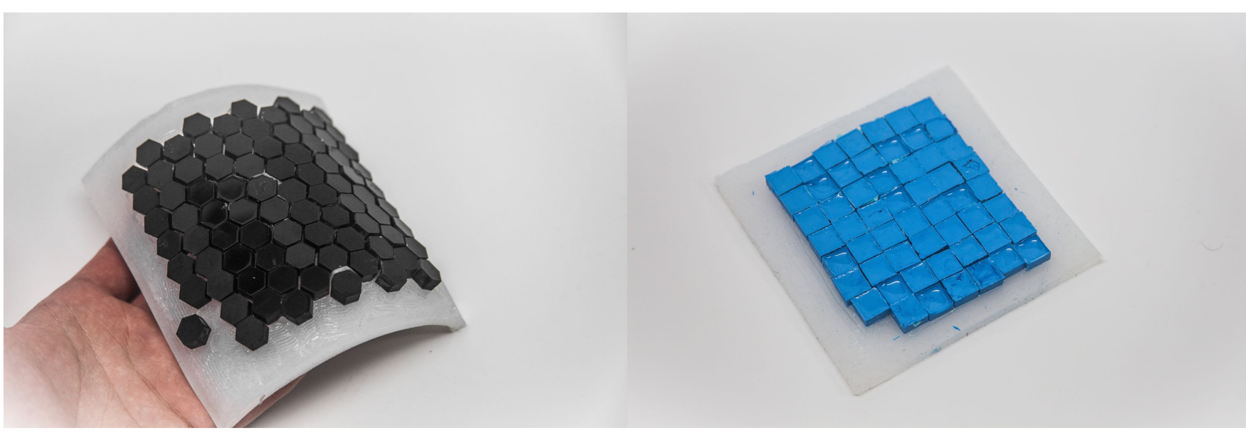

Figure 43. Left: Lasercut acrylic scales epoxied to silicone sheet. Right: Hand-molded urethane-based resin plastic square scales epoxied to silicone sheet.

Figure 43 shows two types of 2-dimensionally formed rigid scales affixed to silicone sheets using an adhesive. Despite the urethane-based resin bonding better to the silicone than the more oily acrylic, both materials failed rather rapidly with only a few flexures of the material. The only robust and reliable method for integrating the rigid layer into the elastic is through architectural trapping of the silicone, which due to its low viscosity in its uncured state flows freely through open pockets.

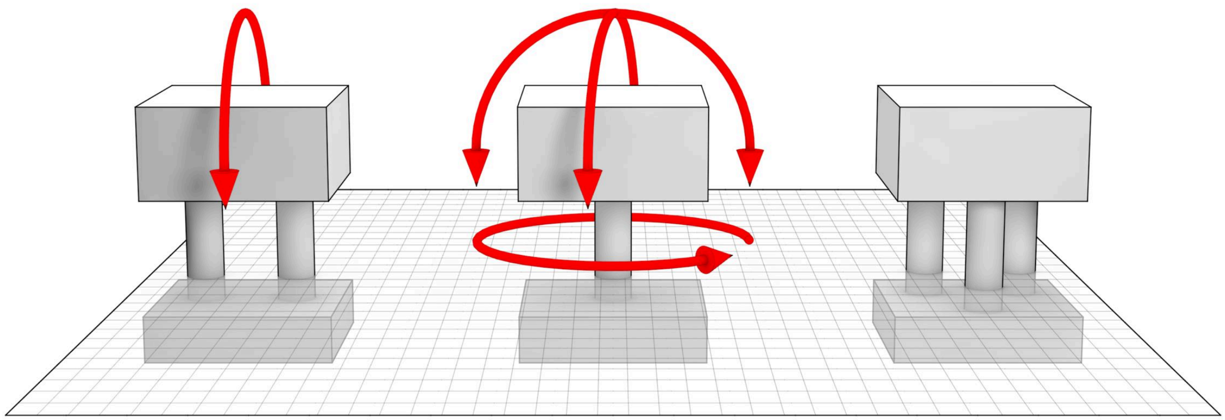

Figure 44. Illustration showing the degrees of freedom of movement for an individual rigid scale depending on the number of pillars.

The number of pillars impacts the degrees of freedom, stability, and deformation of the rigid material. With a **singular pillar**, the scale is able to have minor pivots on both the Y and Z axes, while also complete 360° rotation along the X axis. This can be valuable leeway in contexts with more dramatic texture change where the individual scales might need to accommodate complex surface changes. With **double pillars**, motion along either the Y or Z axis is now fixed, and with **3+ pillars**, most lateral and rotational motion is fixed.

However, pillars are not the only architectural choice for integration into the silicone. So long as the silicone is encapsulated in some way that it creates a small connective tissue in-between the scales, the materials will fuse together.

Figure 45. Exoskin composite prototype photographs showing the thin silicone connective tissues in-between the scales.

In Figure 45 above, we've 3D printed PLA plastic rigid scales with a rectilinear closed loop architecture that forced the silicone to create a regular grid of connections. This created an isotropic deformation across the Y and Z axes when stretched. With higher precision and more intricate modeling, the closed loop architecture can be utilized at a smaller scale more closely resembling a sponge or foam.

5.3. Implementation

For the implementation of the test prototype samples created for Exoskin, we began with a variety of panelization methods for the rigid material layer, but quickly narrowed down to using a matched triangular mesh pattern as seen in Figure 46 for its aesthetic value, ease of fabrication, and to explore its light permeability control.

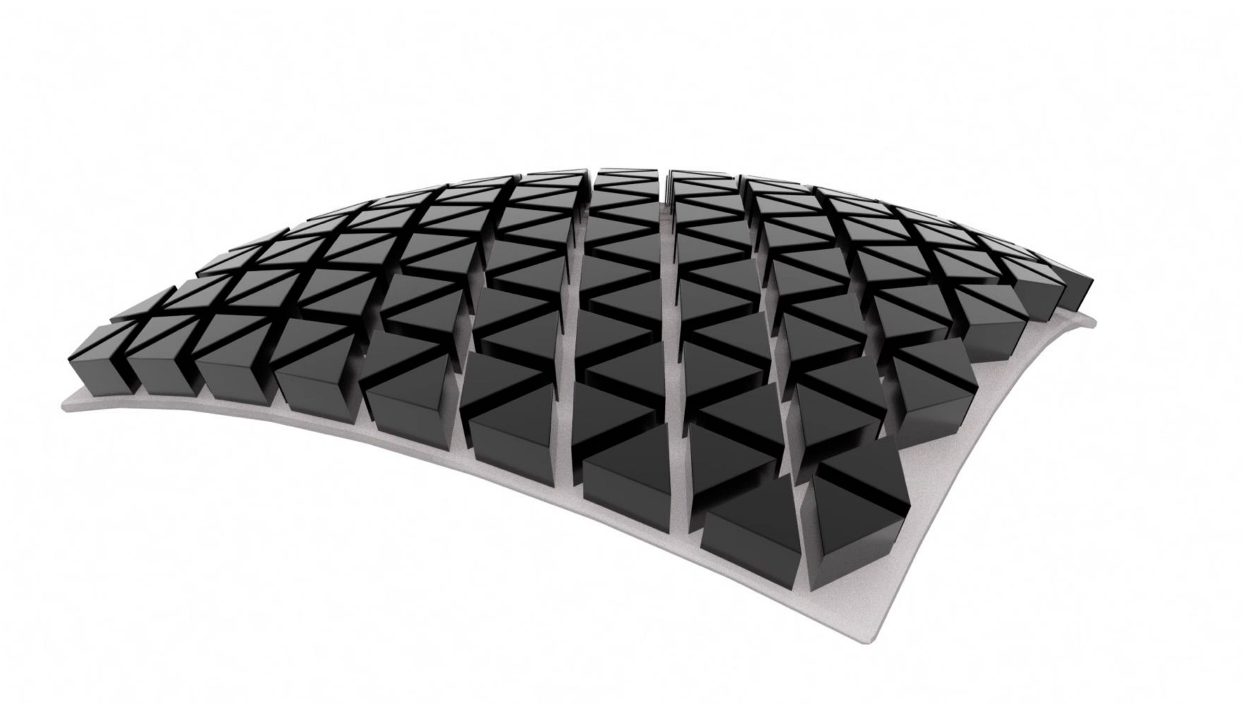

Figure 46. Rendering of the matched triangular panelization pattern on a stretched elastic layer

For the final panelization design and modeling, we used the Grasshopper graphical algorithm editor for Rhino. Grasshopper is a node-based visual programming language primarily used to build generative algorithms. Changes made to the design are instantly propagated through all parts of the model, avoiding the need for repetitive redrawing with each iteration.

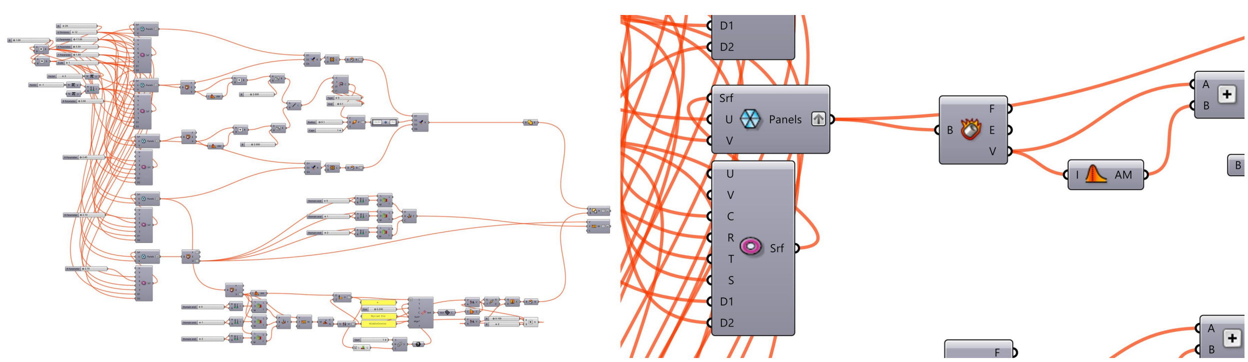

Figure 47. Screenshots showing Grasshopper script written to create the triangular panelization architecture on a given surface

By parametrically modeling the design for the panelization, we can adapt the output to whichever input surface necessary and enable us to create bespoke Exoskin rigid scales that nest perfectly at a default state around any curvature from atop spherical surfaces, to conical, and more. We then used this method to create three prototypes:

The first prototype, which cured its large air bladder with too thin of a bottom wall, is shown below in Figure 48 encased in an acrylic frame for stability.

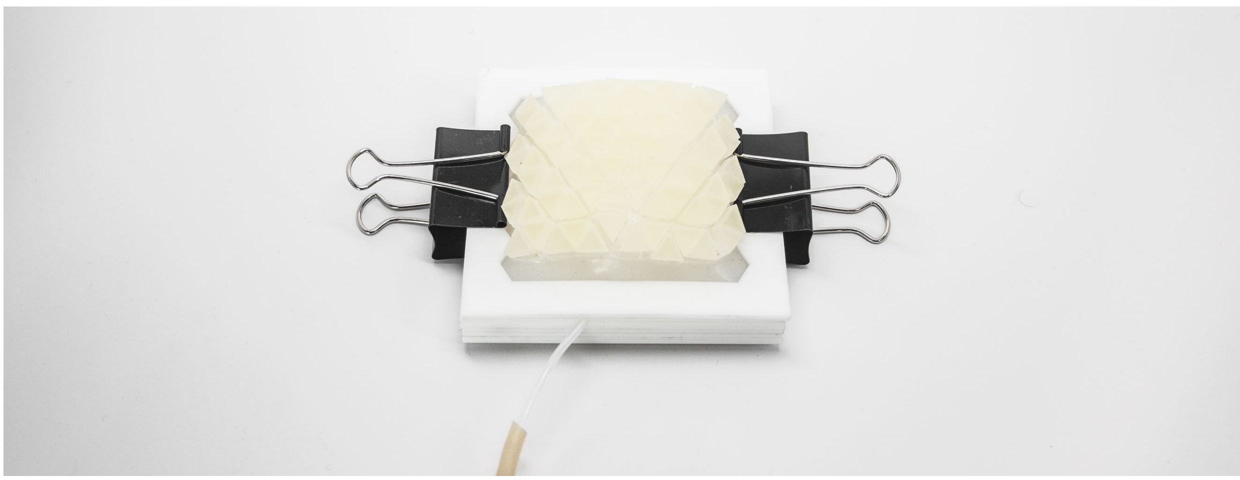

Figure 48. Initial Exoskin prototype inside of acrylic frame

Despite that setback, we were still able to insert a tube into the singular large bladder post-fabrication and achieve deformation by manually blowing into the tube.

Upon closer inspection of the surface, the scales show some physical separation near the extreme ends of the actuation range. However, tactily the change is felt much sooner than the visual change is perceived.

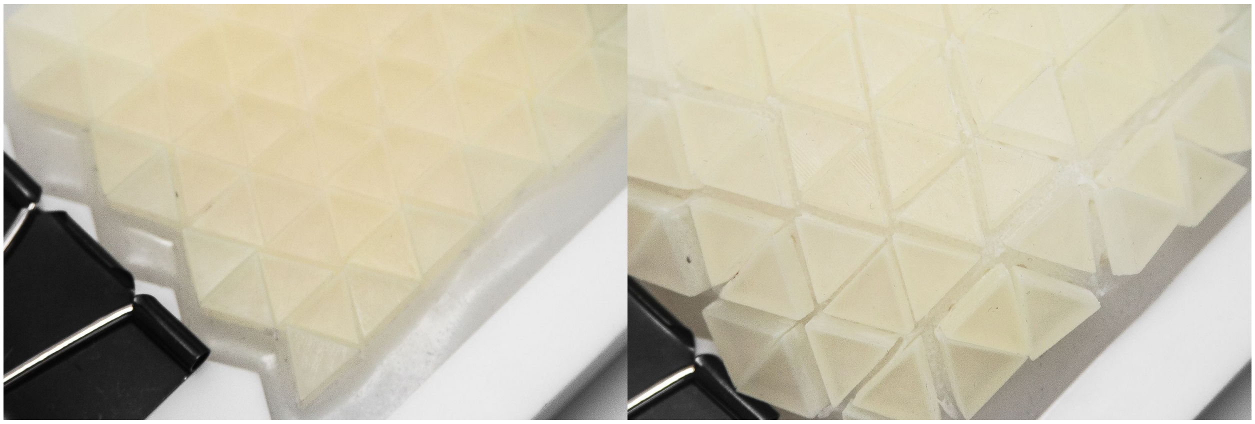

Figure 49. Close up photograph showing the default un-actuated (Left) state of the initial Exoskin prototype and (Right) the actuated state

One interesting discovery found during this implementation process was anisotropy in the flexure deformation of the material using this triangular panelization method. Flexure in the Y axis caused the scales to group like diamonds while flexure in the Z axis caused them to group in rows.

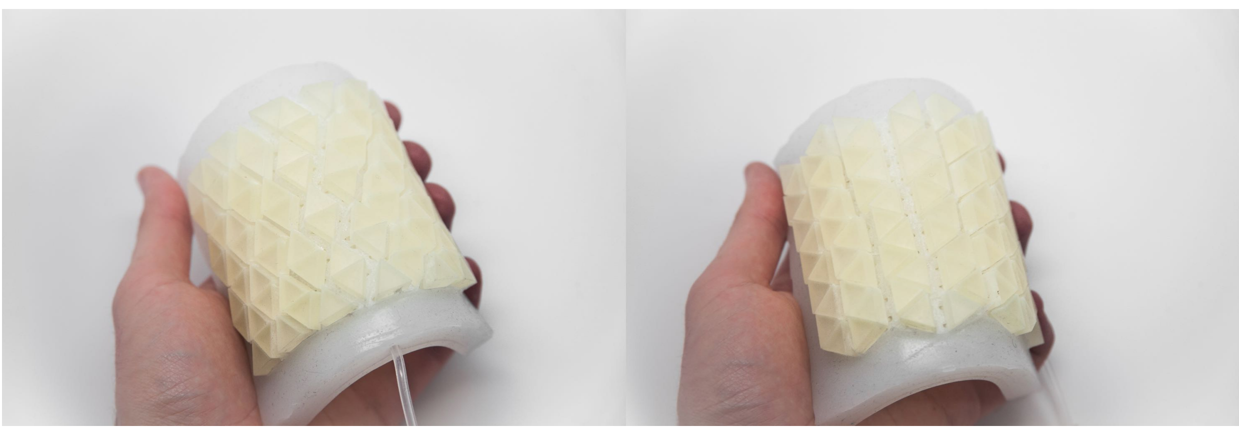

Figure 50. Anisotropy seen in deformation. Flexure in the Y axis caused the scales to group like diamonds (Left) while flexure in the Z axis caused them to group in rows (Right).

With more experimentation, this anisotropy can be greatly harnessed not just passively through the material design, but actively actuated through the air bladders by designing two layers of long & thin bladders at 90° angles from each other.

The second prototype utilized the same triangular panelization method and instead explored more discrete bladders (4 parallel rows vs. 1 large) in efforts to control the anisotropy.

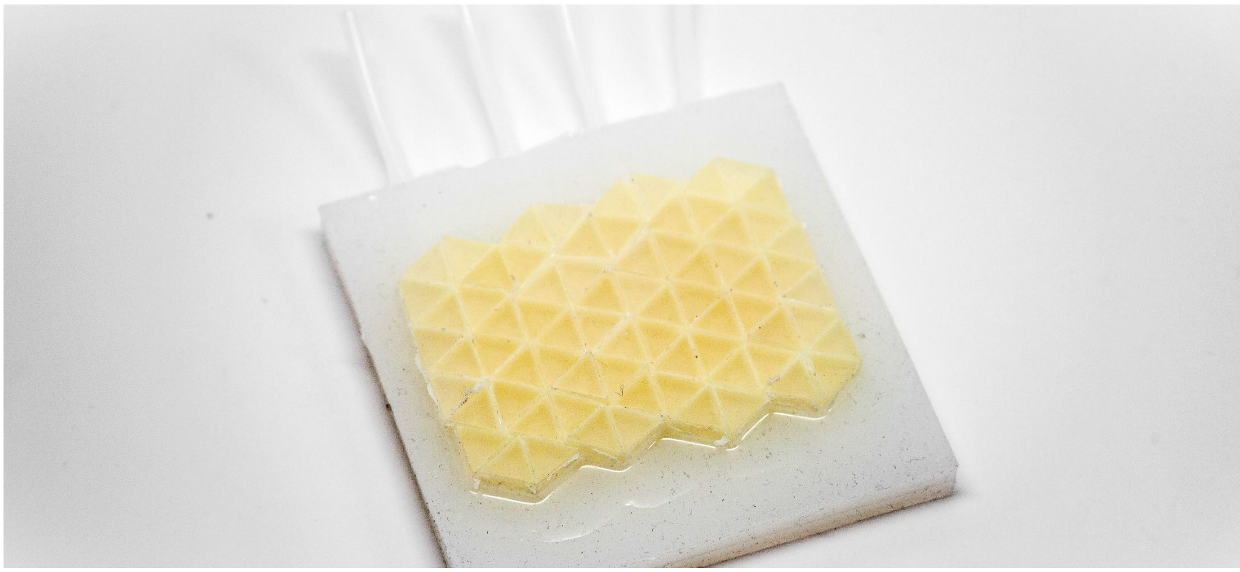

Figure 51. Same triangular panelization method now with 4 discrete bladders in rows

By actuating bladders 1 & 3 or 2 & 4 simultaneously, we were able to split the rigid mesh along its rows. However, without sensing directly implemented, we relied upon manual & scripted transformations to test actuation.

Thus, in prototype 3, we explored integration of the sensing layer with a more simplified quad-based panelization structure. We applied 1" strips of copper foil tape in rows of four to an acrylic sheet, soldering wires directly to the copper leading to the CAP1188 8-Key Capacitive Touch Controller from Adafruit. This then communicated with an Arduino micro controller sending serial commands to a Processing visualization.

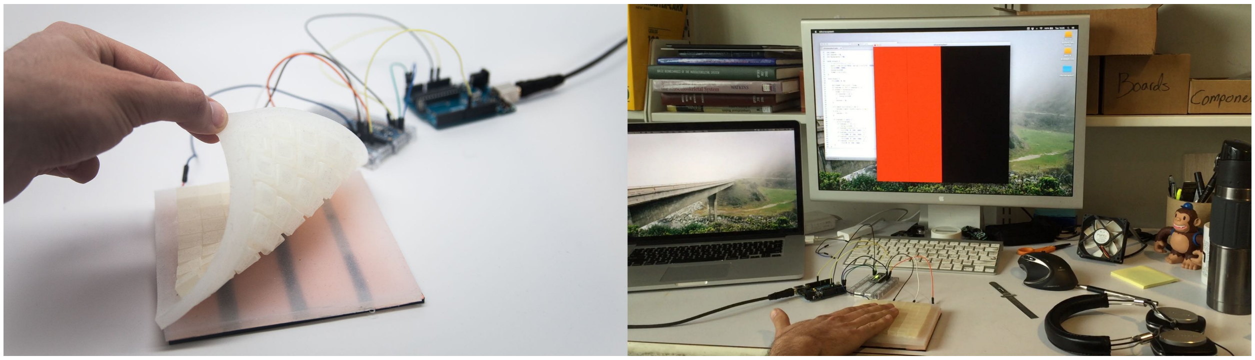

Figure 52. Copper-based capacitive sensing layer prototype with Arduino platform

By reading the analog values from each of the capacitive pads, setting a threshold, and temporally smoothing the input, we are able to visualize the sensed input in real time. Plus despite being placed beneath the silicone and plastic rigid layer, we not only were able to sense touch input but also reliably sense hover & gestural input above the surface of the entire composite.


Figure 53. Combined prototype with capacitive sensing, embedded LED, and actuation all on dynamic feedback loop controlled by both an Arduino and Pneuduino.

Finally, we produced our last iteration that combined many of the actuation and sensing features we wanted to explore in a single prototype. Through parallel use of the Pneuduino platform and an Arduino, we were able to actively and dynamically drive the actuation of the air bladder as well as an embedded led. These both then responded to active capacitive input from copper pads below. This combination helped show how the composite's light permeability is changed through the actuation and resulting separation of the panels in the rigid layer.

5.4. Technical Evaluation

This section describes some examples of empirical tests that have been carried out to characterize Exoskin composites. The aim of presenting these examples is to help think about what types of tests are needed to perform to help the design once localized to a specific context.

Material stiffness affects how much pressure is required to make the actuator bend. High strain/low durometer (stretchy) materials will deform more for a given pressure than low strain/high durometer (rigid) materials. There is a wide variety of both types of material available.

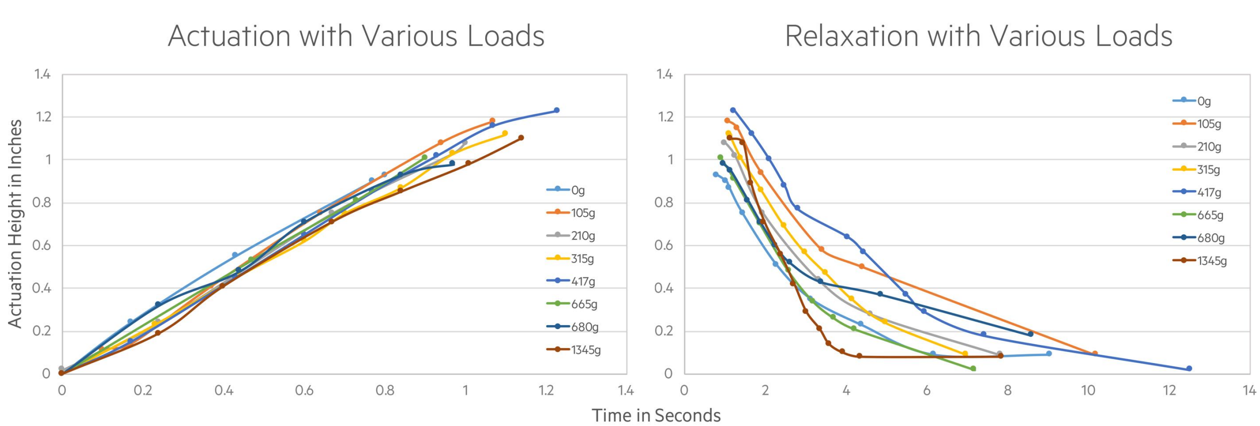

Figure 54. Exoskin composite actuation and relaxation tests under various loads up to about a kilogram.

We tested an Exoskin composite with triangular panelization under a variety of loads to understand how both actuation speed and actuation range change. We tested a distribution of 8 loads spanning 0g to around 1.3kg.

The graph on the left shown above shows this data compiled for the actuation (inflation) of the composite to the bladder's maximum capacity. We were able to inflate at a rate of about 1" of deformation height per second linearly, with smaller deformations proportionally taking smaller amounts of time. We also noticed how despite loading the material with various weights, there was no significant change in either the actuation height or speed. With a sufficient pump powering the composite, this holds true for even larger loads as well.

On the right-side graph in the figure above, we show the data compiled for the relaxation speed of the composite under those loads. Here we did in fact see a change across each test. Unloaded, the composite took about 10s to deflate back to its initial state while at the maximum load it only took about 4s. With active deflation, more intake / outtake tubing, and other changes, many of the relaxation speed issues can be surmountable making Exoskin a quite fast and strong actuator in tight spaces.

5.5. Limitations

Our research hopes to help achieve our vision of creating materials where physicality and tactility are not at odds with reconfigurability. We want to make form as malleable as function and hope Exoskin is a step in that direction. That said, it does have limitations in its current state.

5.5.1. Single Sided

The present design for Exoskin has a single externally-facing rigid layer. This essentially limits the material to a single side for interaction which limits the contexts and uses cases for the composite. Expanding the number of layers to even just a second rigid layer on the opposite outer surface would enable actuation on both sides. We could then create full volumes actuated by Exoskin or use it as a wearable membrane cloth.

5.5.2. Actuation Source

The current system has limited mobility and is mostly stationary. Yao et al. have shown an untethered mobile pneumatic system, however the pumping and vacuuming speed drops significantly in that mobile system. Furthermore, the noise of the pump is also an issue but can be reduced with insulation.

5.5.3. Actuation Defined by Fabrication

Because of the need to cast the silicone layer by layer, the molding architecture plays a huge role and constraint in the size, shape, and range of Exoskin's actuation. It's possible that with more advanced fabrication techniques that we can "pixelate" the actuation and have variable bladders based on changes in air pressure. However, more opportunities are available through advances in multi-material 3D printing processes. These will allow fabrication in one uninterrupted job, seamlessly transitioning from rigid core components to a soft exterior in a single print session. Nicholas Bartlett and Michael Tolley at Harvard's Wyss Institute have recently employed this gradient material strategy in their newest jumping robot and greatly reduced stress concentrations typically found at the interfaces of soft and rigid components which has resulted in an extremely durable robot.

6. Exowheel

Despite its limitations, there are many applications for Exoskin in the driving environment. Driving a vehicle can be a stressful experience. Other vehicles, changing speed limits, cyclists and pedestrians can overwhelm the vision sense. Horns, air-hammers, conversation, children in the back seat and the radio can overwhelm the auditory sense.

Figure 55. 2012 Chevy Volt dashboard with display screen and instrument cluster

Furthermore, the automotive experience is increasingly being augmented with computerized devices. Cars come with built-in navigation and information systems, satellite radios, multimedia systems, and complex air conditioning and heating systems. For example, the BMW iDrive system controls over 700 functions. Drivers are also bringing complex devices into cars, including smartphones, tablets, smart watches, and GPS units. Not surprisingly, the increase in devices in automobiles has resulted in a need for users to interact with them while stationary or even while driving. Today, these devices are controlled using physical knobs, sliders, buttons, and virtual controls like on-screen keyboards and soft buttons. But these mechanisms often require users' visual attention and can be quite difficult, or even dangerous, to operate while driving and does not scale as the capabilities of our technology and automotive vehicles increase.

The current model overloads people with expensive visual interactions that chew up active processing cycles in the brain and cause longer delays between action and reaction. Looking down for even just a few seconds to check for the upcoming turn on your phone's GPS means being essentially blind for almost 100 feet of travel, which could be the difference between noticing the car ahead has slammed on its brakes.

classic dashboard **contemporary dashboard** **"state-of-the-art"**

Figure 56. The progressive digitization of the automative dashboard over time.

While classic car designs incorporated many physical knobs and buttons, the trend over the past 50 years has been to use bigger and more interactive touchscreens in lieu of tactile options. However, simply including a button for every feature is similarly overwhelming and unhelpful.

Traditional research into the area has relied on haptic feedback to create a tactile interface. Shape & texture change have a greater ability to create more perceivable, understandable, and intuitive stimuli and we seek to use recent advancements in programmable material prototyping to harness this.

6.1. Related Work

Haptic feedback is actually already available in some car systems, for example, Ford's Lane Keeping System, or Lane Change Assist systems used by Audi, Volkswagen, BMW, Porsche, and Mazda. These systems make use of state of art technology to check if the car stays on the lane or not, and warn the driver using haptic cues if the car crosses the lane line before the driver uses the signals or if changing lanes is not safe due to a car present in the blind spot. These systems build on nearly a decade of research in automotive user interfaces, which we will summarize here, specifically focusing on steering. Enriquez was one of the first to implement a tactile display in a vehicle context (Enriquez, 2001). Different types of warnings, e.g., errors on various gauges, are conveyed through pulsations of varying frequencies on the drivers hands by embedding inflatable pads in the steering wheel. User studies show a significant decrease in response time and demonstrate the feasibility of using frequency to convey different warnings. Van Erp et al implement a tactile display by embedding eight vibrotactors in the driver's seat (van Erp et al., 2001). Turning left or right is indicated by activating the vibrotactors under the driver's corresponding leg. The distance to a turn is conveyed using pulse length modulation.

User studies show a significant increase in driving performance over using visual feedback alone with a decrease in cognitive load.

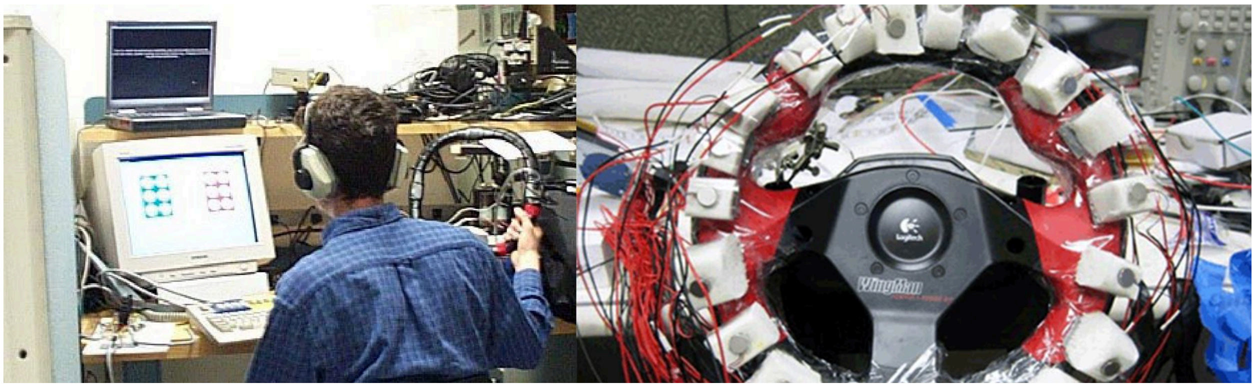

Figure 57. Left: Enriquez's tactile wheel that provides haptic feedback to alert the driver of a possible problem. Right: Haptic steering wheel developed by AT&T using 20 vibration motors.

Griffiths and Gillespie developed a driving simulator where the steering wheel is both held by the driver and motorized for automatic control (Griffiths and Gillespie, 2004). The motion of the steering wheel is a response to the sum of forces acting from the human grasp, from the automatic control motor, and from the steering linkage. Feeling the actions of the wheel, the driver can either comply with it or override it by applying more force. User studies show significant increase in the user's lane-keeping ability while decreasing the visual demand and reaction time.

However, the status quo of haptic feedback still remains quite limited in its ability to communicate a wide range of values and precisely to distinct physical locations. One of the most recent and prominent examples is AT&T's haptic steering wheel as seen in Figure 57 that utilizes 20 motors that vibrate one after the other in close succession to simulate motion in a counterclockwise or clockwise direction. The motion then becomes faster and stronger as the turn gets closer, thereby avoiding the confusion of “turn right at 200 feet.” Immersion's TouchSense solutions offer industrial strength haptics for

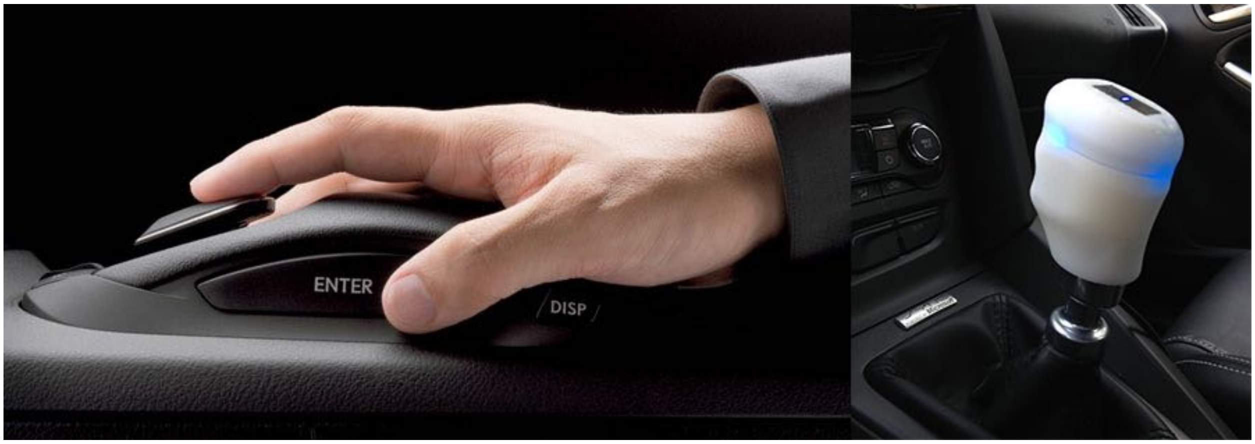

Figure 58. Left: Lexus' haptic Remote Touch Interface touchpad. Right: Haptic Feedback Shift Knob by Zachary Nelson that vibrates when it's time to select another gear.

touchscreens, touch panels, and touch surfaces. The latest version of Lexus’ Remote Touch Interface touchpad incorporates this by gently thumping and pulsing as the driver navigates menus and vehicle systems, helping the driver move through options intuitively. Ford too has jumped into the mix. Their Haptic Feedback Shift Knob is a replacement for a manual transmission shift knob that adds haptic and visual feedback to help drivers shift appropriately. An Android application monitors the vehicle's speed, RPM and accelerator pedal position. Based on this information, the application calculates and then indicates to the driver when he or she should shift by vibrating the shift knob. After feeling the haptic "pulse" the driver can then appropriately respond.

6.2. Rationale

However, despite praises sung about haptics, they come with a variety of limitations and unpredictable trade-offs. The hand-arm system has a complex dynamic response that varies between individuals and is dependent on the direction of vibration excitation, the grip force, muscle tension, and the position of the arm (Lundström, 1984). Because of this, haptics remain unreliable and low-fidelity in the constantly evolving automotive environment.

Evolving to shape & texture change can solve that amongst other issues. One of the many advantages of using them for relaying information is their inherent ability to allow fast reflexive motor responses to stimuli. In contrast to visual displays or haptic displays, Exoskin's stimuli are both highly tactily perceptible *and* visually interpretable. We classify these exchanges as a reflexive interface, which seeks to use a mixture of new visual, tactile, and shape-changing interaction methods in order to bypass the brain by driving our intuition, instinct, and reflexes.

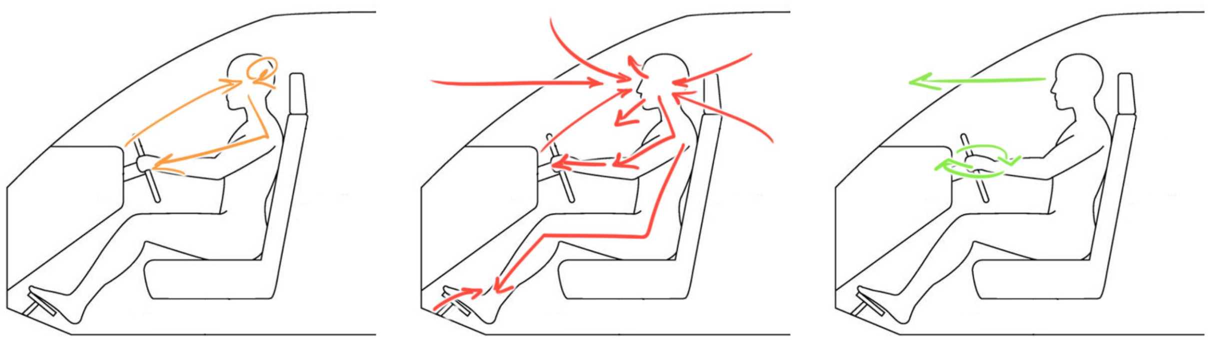

Figure 59. Diagram showing the progression from a typical automotive interaction loop requiring a glance at the dashboard to an evolved reflexive interaction loop allowing the hands to bypass the eyes.

Furthermore, by using pneumatic pockets, the tactile stimulus can be localized to a specific area instead of shaking the entire steering wheel. This allows multiple stimuli to be provided on the steering wheel, and minimizes extraneous disruptions. Thus among other uses, Exowheel is able to give you directions in an unobtrusive, natural way by taking advantage of the nerve endings in your palms. This also offloads some of your more overworked senses like sight and sound so that you're able to then stay focused on the world around you and the road ahead.

In the rest of this chapter, we present a texture-changing steering wheel that integrates GPS navigation directions among other information into your driving experience in an unobtrusive, natural way by driving your intuition through subtle, tactile feedback. We seek to increase spatial memory, reduce driver distraction, and simplify previously complex multi-tasking.

6.3. Design Criteria

As a part of research in this application, we identify four distinct goals for our dynamic tactile displays:

1. Easily and compactly actuated
2. Fast potential rate of transformation
3. Able to sense user input
4. Enable polynary tactile & visual expression

We then plotted more discretized versions of these goals in the chart below as shown in Figure 60 in order to gauge and compare the suitability of Exoskin for the automotive wheel context.

Figure 60. Chart comparing various input and output mechanisms used in automotive steering wheels

We found that by doing this, we realized the need for both the ability to define a narrow locality for the output, as well as the need for concurrency, where several independent types of information are conveyed by several modalities at the same time, which can speed up the interaction process.

6.4. Application Scenarios

After exploring a variety of ideas and potential applications for ExoWheel, we designed these key scenarios below to best showcase the right matching between opportunity, need, and utility:

6.4.1. Dynamic Ergonomic Grip

Traditional steering wheels, due to their static nature, have to make two general compromises and assumptions in their design: one generalized grip can mostly account for the large variety of hand sizes and placements, and one generalized design can mostly work for each speed and situation the car is in. Exowheel can improve on that in both ways. First, by directly embedding capacitive sensing in the composite, the wheel is able to directly understand where the driver is placing their hands as well as how hard they're gripping. This means that the grip can be adjusted as their pressure and hand placement changes during the drive—from a high-stress situation to a more leisurely roll into the driveway.

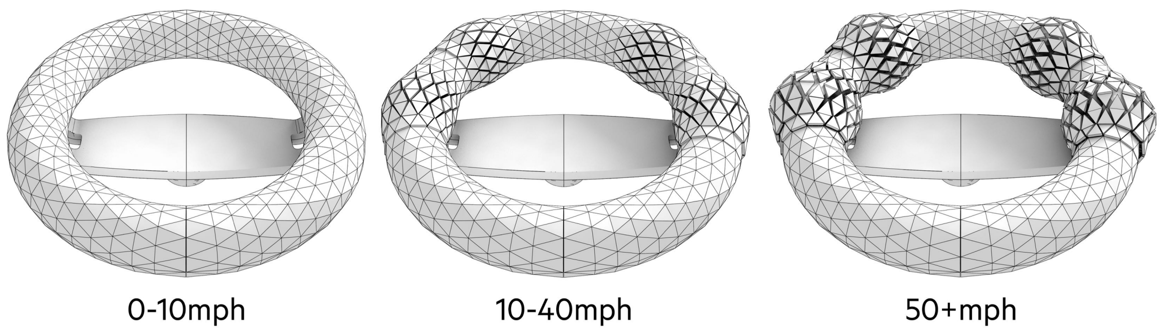

Figure 61. Illustration showing dynamic reaction to changes in speed and hand placement. As speed increases, the grip more tightly cups the drivers hands for safety and comfort.

It can, however, respond to input and data from the car itself as well. By changing the overall degree of cupping and grip on the wheel, Exowheel can positively reinforce safe habits such as preventing the hands from sliding across the wheel as the car corrects post-turn or keeping their hands in place during a high-speed turn and using a small degree of tilt.

6.4.2. Tactile GPS Navigation

GPS navigation is still an unsolved interaction in the most cars today, even so much as being distracting by relying on disruptive voice commands and prominent visual cues on a display. Exowheel can help alleviate these issues at the most important pain point: knowing which way to turn and how far away it is.

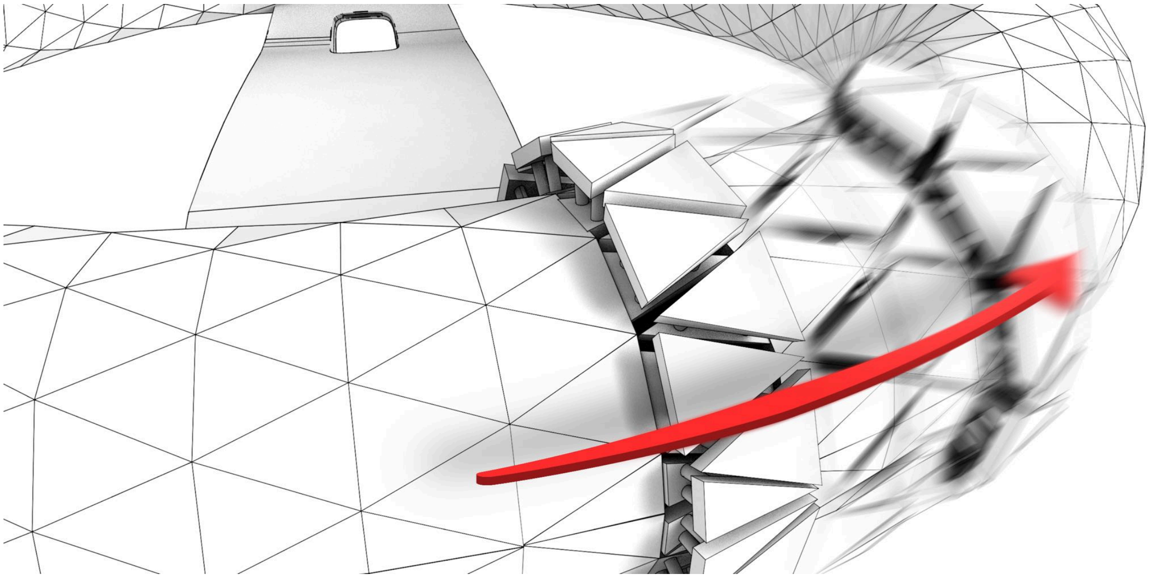

Figure 62. Illustration showing more fine-grain finger-by-finger actuation of Exowheel when communicating the next turn during navigation mode.

By utilizing more fine-grain finger-by-finger actuation, Exowheel can give discrete feedback on the corresponding hand when the turn is coming up, by pushing on the bottom hand and slowly rolling to the top. When the turn arrives, the animation begins to oscillate faster and faster. Lastly, by utilizing the barometric pressure sensors in-line with the bladders, Exowheel can sense user input such that when the driver squeezes the actuation back flat, the system stops actuation and lights the turn signal.

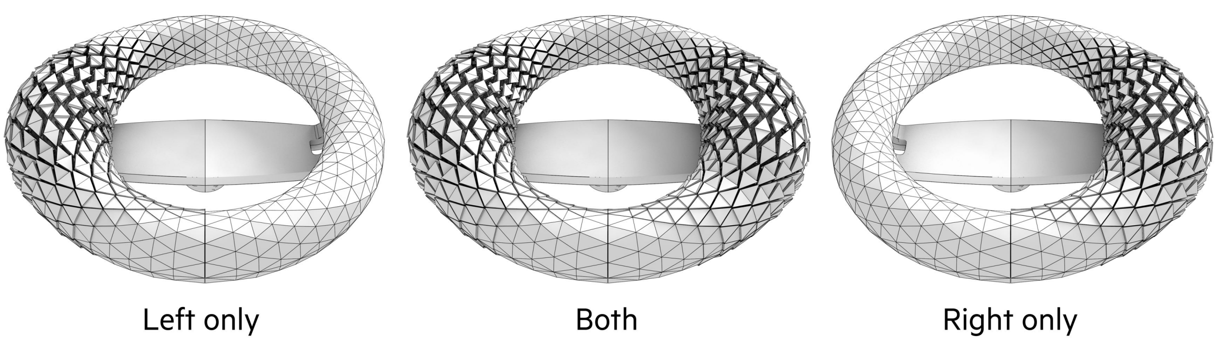

Figure 63. Larger deformations using the bulky air bladders nearest the bottom create an alarming and uniform inflation for alerting drivers of danger, pedestrians, and other potential collision hazards.

6.4.3. Directional Alerts

Lastly, larger deformations using the bulky air bladders nearest the bottom of Exowheel can be used to create an alarming and uniform inflation for alerting drivers of danger, pedestrians, and other potential collision hazards. Though the illustration above in Figure 63 might visually look a bit extreme, the tactile sensation of the expansion can be felt at a much earlier response time than can be perceived visually. Furthermore, because the largest air bladders are stacked in descending order, actuating the “alert” bladder does not impede on Exowheel’s ability to transform the more locally, minute bladders and vice versa—they’re concurrent.

6.4.4. Use in Other Vehicles

The use of the above features as well as more bespoke creations is not limited to the typical automotive experience people usually think of that involves your average consumer in a sedan or SUV. We can imagine using Exowheel across a large variety of vehicles and industries.

For example, we could use this new wheel in an excavator, a common heavy construction equipment consisting of a boom, stick, bucket and cab on a 360° rotating platform. Having an active actuated ridge in the wheel continuously track the direction of the rotating platform’s wheels, as well as having uniform inflation increase slightly as more pressure is put on the boomed bucket, would enable the driver to have an ambient tactile perception of which direction his vehicle is facing at all times and understand how hard he’s pushing the bucket’s strength.

We could also embed Exowheel into the chassis of a police car. By linking to data from the vehicle's external speed detectors, GPS receivers, and radio units, we can create an ambient tactile display that ripples as threats drive by and more directly creates a compass-based ridge during a high-speed chase to enable the officer to drive safer and out-maneuver the criminal without having to keep them in his or her line of sight.

6.5. Implementation

For the prototype that is currently in progress, we've gone through a series of design loops that considered our tradeoffs at each step.

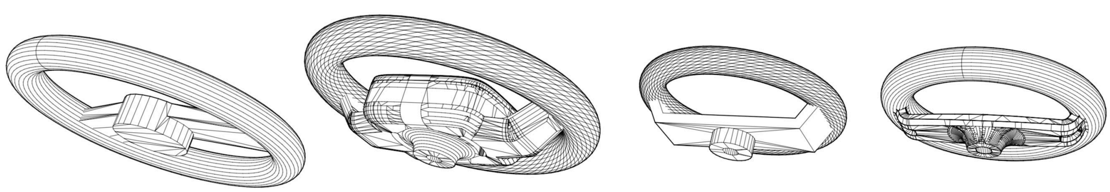

Figure 64. Illustration showing the iterative progression of the designs for Exowheel.

To begin with, we explored a variety of hub and spoke designs that would enable us to embed the tubing and hardware directly inside while also giving the impression of the new features and helping communicate to new users that this is for an automotive vehicle. That last issue is a specific sticking point because of the perceptive limitations we encountered in the prior Focal Wheel prototype.

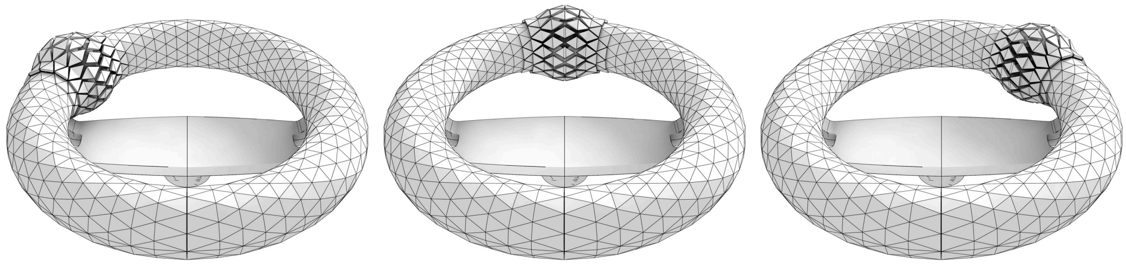

Figure 65. Illustration of final fully-panelized design for Exowheel showing the medium-sized bladders actuating clockwise around the rim.

For the final panelization design and modeling, we used the Grasshopper graphical algorithm editor for Rhino. Grasshopper is a node-based visual programming language primarily used to build generative algorithms. Changes made to the design are instantly propagated through all parts of the model, avoiding the need for repetitive redrawing with each iteration. Our generative program in this scenario used an accurately measured torus as the initial input. It then subdivides those surfaces into triangular panels, extrudes, and then connects them together.

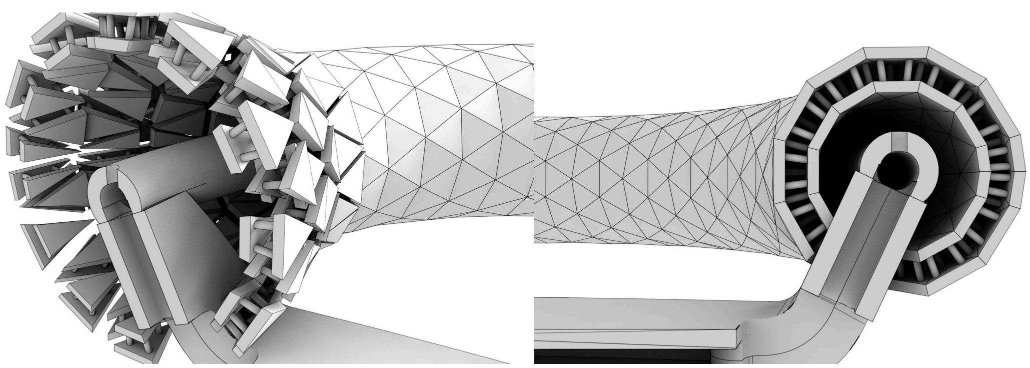

Figure 66. Close-up illustrated views of the molding architecture, panelization, and spoke structure of the prototype design.

As shown up close in Figure 66, the interior architecture of the panels are beveled allowing their exterior surfaces to meet flush and create a uniform face with no gaps.

6.6. Limitations

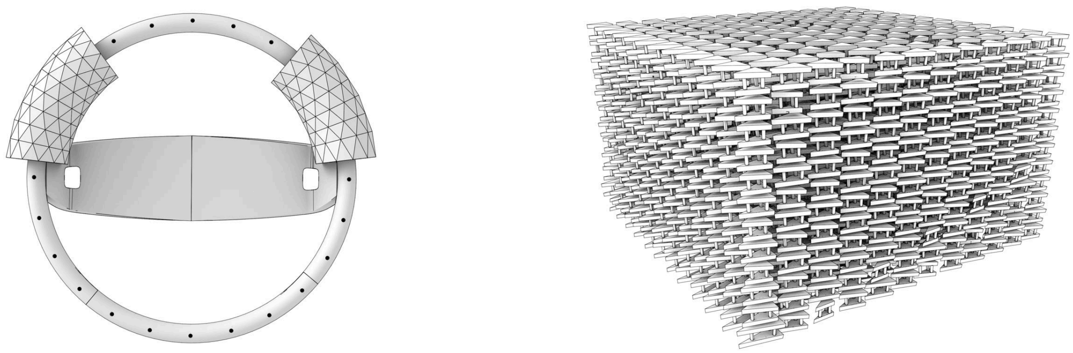

Figure 67. Right: Illustration showing stacked rigid 3d-printed panels ready for fabrication. Left: Those same panels applied to the wheel illustrating the quantities needed to fully cover the surface.

While the design of the prototype is complete, final assembly and programming is not. Because of the need to cast the silicone separately layer by layer, the molding architecture served as a huge barrier. In this case, we ran into many walls with being able to construct this closed loop that fundamentally cannot just be unrolled in any one linear direction.

The other huge constraint we keep running into is also in the fabrication stage. There is a direct tradeoff between surface contour and the density of panelization. Figure 67 on the right shows a stacked grid of over 600 panels ready to be 3d printed. Yet, those same panels once printed and put in place, still only account for 25% of the total surface area needed and it would take thousands of these scales to fully cover the entire prototype. We experimented in the design stage using a more coarse panelization method but the minimum number of panels to create an acceptably toroidal shape that can be actuated was still too high.

7. Exoskin as a Platform

We envision Exoskin as a greater, more versatile platform for texture change, rather than purely focused for the automotive market. Because of its conformability, offloadable locus of actuation, and its integrability, Exoskin can be used in situations spanning wearable, product, and even furniture.

By integrating different sets of inelastic materials and adjusting the overall scale of the composite, we can specifically tune Exoskin for each intended context.

7.1. Wearable Design

Adaptive Shoe Sole
Designing shoes, specifically the sole, requires considering a variety of factors that can drastically change depending on the context of the shoe's use: traction, comfort and absorption of mechanical shock, stability, and durability. The same design that might add control and traction on a turf soccer pitch might be unstable and dangerous on a smoother surface like

pavement. This forces designers to create a huge variety of shoes bespokely targeted to each use scenario.

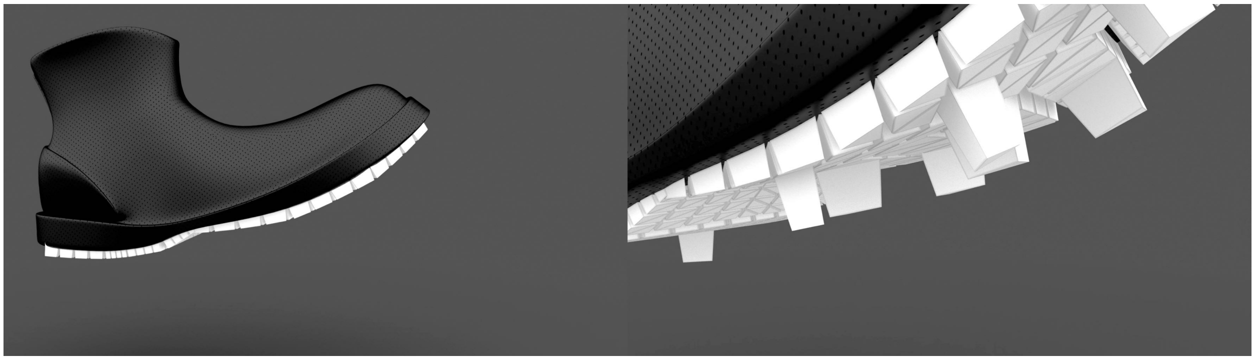

Figure 68. Illustration showing the application of Exoskin as the sole of an active shoe. Left: default state, Right: actuated state.

By instead using an Exoskin composite of thick polyurethane scales with an integrated force-sensing resistive sensing layer, we can create a dynamic shoe that can measure the pressure being exerted along the sole as the user steps. By using that data to actuate individual air bladders underneath the scales, the shoe can react to the variety of terrains a user might encounter on a run, hike, or during a game and improve their traction and stability.

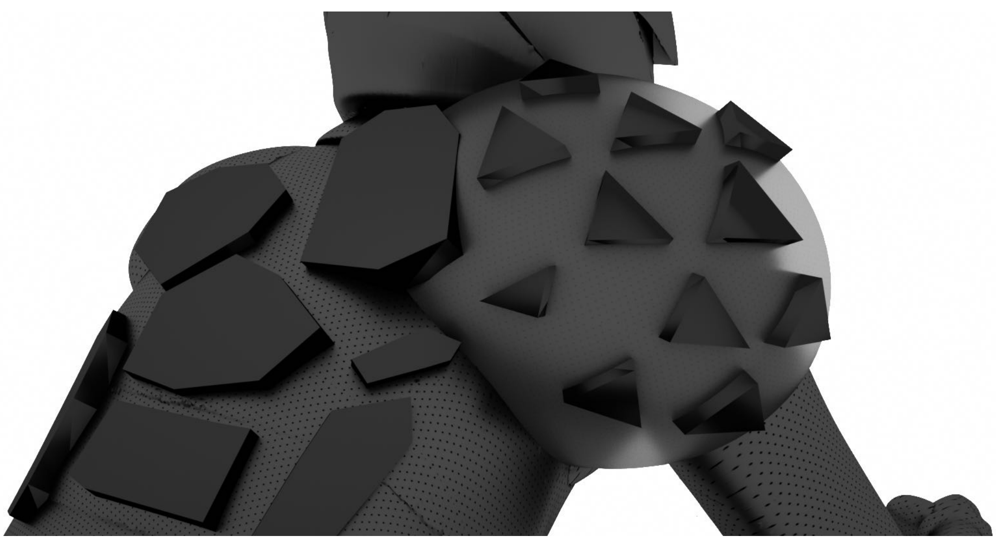

Figure 69. Illustration showing actuated safety airbag state of Exoskin when applied as a motorcycle jacket.

Dynamic Motorcycle Jacket

We can also apply the composite to the body in jacket form. Most riders know that protection is the most important safety aspect of motorcycle riding. However, many eschew wearing thicker motorcycle armor because of it can tend to be uncomfortable, unwieldy, and limit your range of motion.

Offering instantaneous, high-pressure inflatable actuation, Exoskin can be incorporated to give the rider comprehensive protection in a crash by covering the full back, shoulders, kidney areas and chest with thick rigid protective materials that still retain the ability to expand just before impact.

7.2. Product Design

On a different scale, we can also move smaller and look at the applications within handheld-sized product design.

Figure 70. Illustration showing the application of Exoskin embedded into a mobile phone case. Left: default state, Right: actuated state while watching a video.

Mobile Phone Case

For example, we can composite steel rigid panels into a thin version of Exoskin with two side-by-side air bladders to create a dynamic phone case. By submerging the silicone layer below the surface and instead having metal on the outside, we're able to establish a higher perceived quality & aesthetic value, we avoid the tackiness of silicone that would make it tedious to remove the phone from a purse or pocket, and we allow the case to change ergonomics depending on the usage scenario.

If the user begins watching a movie on the device and sets it down on a table, the case can inflate and adjust the viewing angle. If the user is holding the phone while running, the top bladder can inflate alone to provide extra grip.

Figure 71. Illustration of opaque Exoskin rigid material with interior light source and dense panelization method in order to create a dimmable lamp. Left shows the default state while Right shows the inflated, actuated state.

Dimmable inflatable lamp

Another example of Exoskin in product design takes advantage of the potential light permeability control. By using an opaque rigid material and a dense panelization method (such as triangular), we can create a lamp users can "“dim” in a more fun way. Figure 71 shows just how dramatic the change in light can become at the intersection of those two methods.

Automotive Wheel with Dynamic Traction

Similar in methodology to the adaptive sole shoe, an Exoskin composite of thick rubber scales with integrated force-sensing can be used to create a dynamic automotive wheel that can measure the pressure being exerted by the terrain on the car and use that data to actuate high-pressure inflatable air bladders underneath the scales to improve traction and stability.

Figure 72. Exoskin composite illustration of thick rubber scales used to actuate high-pressure inflatable air bladders that improve traction and stability. Left shows the default state while Right shows the actuated state.

7.3. Furniture Design

Many of us spend the majority of our lives sitting, which makes chairs, sofas, and beds all-important pieces of furniture to consider as both items that can become transformable as well as morphologically dynamic.

Convertible Wooden Ball Chair
Your body, when positioned on top of an exercise ball, is constantly making small adjustments, often imperceptible, to remain balanced and thus is constantly exercising a large group of muscles in doing so. By strengthening your body's core muscle group you help improve your posture, have better balance and guard against back injuries.

Figure 73. Illustration showing the use of Exoskin embedded with wood panels as a transformable chair from exercise ball (Left) to static stool (Right).

However, like switching to a standing desk, using an exercise ball requires moderation and switching back and forth between traditional seating to stay healthy. By utilizing Exoskin composited with wooden rigid scales and a single large inflatable bladder, we can create a singular seating solution that can transform from exercise to static stool. This takes advantage of a unique molding architecture to achieve locking in two distinctly separate states; using a single pillar design allows the rigid units to pivot & rotate around as the transformation happens and creating undercut angled edges that snap together.

Dynamic Soft Sofa

Couches are expensive and are supposed to last a long time, yet despite that usually come with design tradeoffs that consider comfortability opposed with case-specific aesthetic and functional features.

Furthermore, fabrics, especially on the thicker side, are actually a distinct possibility to integrate with Exoskin. Many of these materials are quite inelastic and thus without composition into Exoskin are difficult to actuate as a soft interface.

Figure 74. Exoskin illustration with thick wool felt panels integrated into an elastic layer embedded with an array of actuatable bladders, to form a dynamic soft sofa.

Using thick wool felt panels integrated into an elastic layer embedded with an array of actuatable bladders, we can imagine a new dynamic sofa that can ergonomically and functionally adapt to each situation that it senses. This means it can create an arm rest and cupholder in the center of the couch while watching TV solo, revert flat for a large group of users, or even create a larger headrest while lying down.

8. Looking Ahead

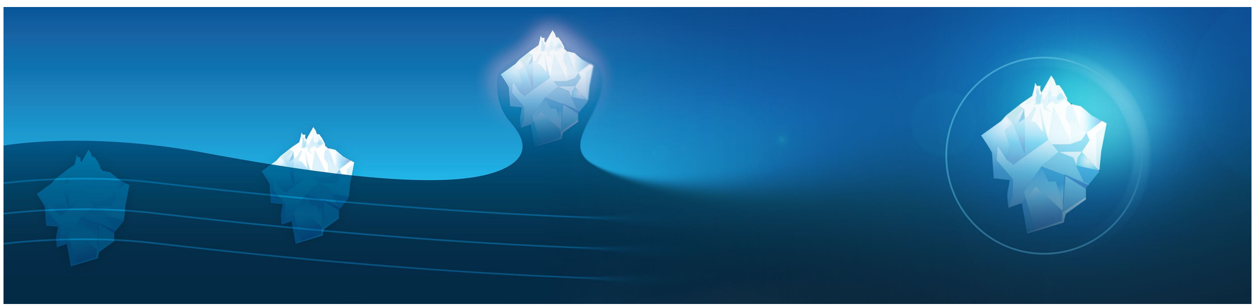

Figure 75. Modified TUI-RA diagram showing world state post radical atoms

We believe in a future where "programmable matter", "computational materials", and "radical atoms" shed their technology-centric prefixes and become simply just "materials" and "atoms".

With our vision for programmable materials set that far into a future where they're tightly and intrinsically integrated into the products and environments around us, we can recognize the gap between the steps we've taken in this thesis and that vision.

In this chapter, we outline promising methods, designs, and suggestions that might help overcome some of the limitations of this research and diminish the gap.

8.1. Composite Design

We can greatly expand the design of the composite by changing the sorting order, number, and orientation of the layers. Further exploration should also consider creating non-uniform layers. In revisiting these paradigms, we could begin by adding a second rigid layer on the opposite outer surface which would enable actuation on both sides.

Exploring changes in uniformity could yield more interesting surface topographies as well as creating more complex transformations. This means we could directly mix and match sensing, elastic, and rigid layers across the X and Y axes in patches to accommodate for localized specialization and needs. Portions of the outer surface could then be elastic for specific tactile qualities and even portions of the interior could be comprised of a rigid layer acting purely as a structural articulation control.

For example, we could use these new features to create a unibody automobile made of a singular, multifaceted Exoskin composite. The doors could, in addition to a typical rigid outer layer, incorporate an internal rigid layer that translates the inner elastic bladder inflation into flexion to open the door yet stay rigid when locked.

8.2. Fabrication

Furthermore, even greater advances in the composite design can be accomplished through the use of new fabrication processes. The current model relies on casting the silicone sheets by hand layer-by-layer, making anything but 2D casted

Exoskin sheets an extreme challenge. New multi-material 3D printing processes will allow fabrication in one uninterrupted job, seamlessly transitioning from rigid core components to a soft exterior in a single print session. This means that thinner Exoskin composites will be able to be manufactured by directly merging the rigid and elastic layers. Furthermore, this makes it possible to fabricate non-planar bladders for even more complex transformations.

For example, we could create an Exoskin soft robot inspired snake that can use an internal, scalloped tubular bladder to transform from a linear to a curled shape while also actuating individual scales to lock into each other like gears.

8.3. Technology

The third and final main opportunity to push Exoskin to a new level involves reconsidering the actuation method. While pneumatic pumping is robust, reliable, fast, and able to be offloaded externally from the actuator, it remains a mostly stationary, noisy, and power-hungry technology. Newer elastomer inventions might be able to improve on this by getting rid of the bladders and instead directly integrating actuation into the material itself.

Mora-Barrantes et. al at the Spanish National Research Council has developed an elastomeric material with shape memory effect which allows it to respond to thermal stimuli, due to the coexistence of ionic and covalent networks (Mora-Barrantes, 2012). The ionic network fixes the transitory shape whereas the covalent network enables the recovering of the initial shape.

Other possible successors for pneumatic actuation are dielectric elastomers (DEA), which are a type of electroactive polymers (Rogers, 2013). A DEA is a compliant capacitor, where a passive elastomer film is sandwiched between two compliant electrodes. When a voltage is applied, the electrostatic pressure arising from the Coulomb forces acts between the electrodes and squeeze the elastomer film.

9. Conclusion

Take a moment to pick up the objects around you. Use them as you normally would, and sense their tactile response — their texture, pliability, temperature; their distribution of weight; their edges, curves, and ridges; how they respond in your hand as you use them. This is how our tools talk to us.

Our research serves as a small step to help bring computing up to that level through this creation of a composite material where physicality and tactility are not at odds with reconfigurability. By deeply embedding soft materials with more-static materials, we can break down the divide between rigid and soft, and animate and inanimate.

With that, the assumption and hope is that we're not only expanding the palette of technology and design for interfaces, but also allowing people to leverage the years of experience of interacting with the physical objects & world around them.

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