Materials of Interaction

Responsive Materials in the Design of Transformable Interactive Surfaces

Marcelo Coelho

B.F.A. in Computation Arts, Concordia University, May 2005

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

Materials that embody computational properties are reshaping the ways in which we design, interact and communicate. This thesis looks at the topic of form transformation and how to bring the programmability and versatility of digital forms into the physical world. The focus is placed on the relationship between materials, form and interaction, in particular how the behavior and properties of shape-changing materials can support the design of transformable interactive surfaces.

Three design implementations are presented, each addressing a distinct subject area in the design of form transformation, namely topology, texture and permeability. *Surflex* is a composite that uses active and passive shape-changing materials to undergo large surface deformations. *Sprout I/O* implements small shape deformations and co-located input/output at a surface boundary to create a dynamic texture for communication. *Shutters* uses shape change to regulate a surface's permeability and control environmental exchanges between two distinct spaces. Drawing lessons from these projects, a soft mechanical alphabet and language for form transformation are derived, providing new formal possibilities for enriching human-computer interactions.

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Initial Remarks

What you are about to read describes my efforts towards a future vision: the inevitable coalescence between matter and computation. Within this corollary, this thesis attempts to shed light on the topic of *form transformation*. This quest is a combination of two intertwining research threads. The first – the 'how' question – deals with the development of appropriate material technologies for making programmable shape change a reality. You will find that the answer is sometimes convoluted, if not quixotic, in its effort to harness the physical properties of materials which are not yet fully understood or compliant (it is 2008, and only recently are materials being comprehensively used for their dynamic properties and ability to change under controlled stimulus). The second thread – the 'why' question – looks at three different case scenarios in which *form transformation* can be applied to support human-computer interaction. The complete answer to these questions is far from definitive and the rough picture sketched here will take years to fully form. Hopefully these pages will inspire ideas, suggest new directions and guide the development towards a future where computers are as rich and enticing as the material world.

1 Introduction

Designing Fluid Forms

New materials impose and invite new ways of building by transforming the boundaries of what is possible and imaginable. In the last century, developments in material science, fabrication processes and electronic miniaturization have dramatically altered the types of objects and environments we can construct. More recently, materials that exhibit electromechanical properties are paving the way for the seamless integration of sensors and actuators into the environment, expanding the limits of where computation can be found and reshaping the ways in which we interact and communicate (Trivedi, 1998).

This thesis looks at the topic of form transformation in the design of interactive systems. The focus is placed on the relationship between materials and form, in particular how the behavior and properties of shape changing materials can guide the design of ubiquitous and transformable interactive surfaces. The objective is not to invent new materials per se, but to map possible application areas, understand what are the limitations and interaction metaphors leveraged by new material technologies and, most importantly, inspire future developments in this area.

Materials, Surfaces and Form Transformation

In 1963, Ivan Sutherland's Sketchpad turned drawing into a dynamic synergy between humans and computers by combining the expressivity of a pen with object oriented programming and line constraints (Sutherland, 1963). Since then graphical user interfaces and computer-aided design have become incredibly versatile, and their virtual dynamism is slowly being matched by advances in material science and 'programmable matter' (Knaian, 2008). However, while a lot of headway has been made in controlling light to deploy information all around us, there is still a lot to be done to make physical form equally mutable and controllable.

The question this thesis tries to raise is: can we give physical surfaces concurrent transformational and computational capabilities, similarly to what Sutherland did to the digital line? And if we can, what expressive capabilities and applications do they enable?

Today most of the objects we use and own are created in a virtual environment and built by digitally controlled tools, but end up relegated to a physical existence of static analog matter. In the future, physical form could be as mutable as its digital equivalent, deriving its shapes, movements and behaviors from a continuous and dynamic relationship with its users and environments.

The goal of this thesis is not to develop the ideal technology for form transformation but to show it is feasible today and, as a potentially interesting alternative for designers, it is a direction worth pursuing.

To understand how form transformation can be achieved, I started by looking at the materials available today which can inherently change shape. Weighing the advantages and constraints of each one of them, I have primarily settled on using shape memory alloys (SMAs).

After developing several techniques for shape setting, controlling and embedding SMAs into composites, I started exploring ways to generalize and amplify their properties to the scale of larger shape changing surfaces. Imagining future possibilities for this technology, I stepped back from the engineering problems to sketch an alphabet and language for the transformation of physical forms and consider how they can be used to create enriching user experiences.

Finally, looking at topological limitations and how users could interact with these surfaces, I developed three design probes which explore important facets of the form transformation problem.

Design Probes

No technological exploration is complete without real prototypes that can give form to abstract ideas, push the limits of what is technically feasible today and capture people's imagination. With that in mind, I have developed three design probes – *Surflex*, *Sprout I/O* and *Shutters* –; each addresses a distinct subject area in the design of form transformation, respectively *topology*, *texture* and *permeability*. Their distinction is derived by considering form transformation from the perspective of a user and by looking at the material and topological limitations imposed by transformable surfaces. Moreover, the lessons taken from these prototypes can help open the floor for a discussion on a language for form transformation and potential applications for these technologies.

Surflex

Surflex is a transformable and programmable physical surface for the design and visualization of digital forms. It combines active and passive shape memory materials, specifically SMAs and foam, to create a surface that can be electronically controlled to deform and gain new shapes without the need for external actuators.

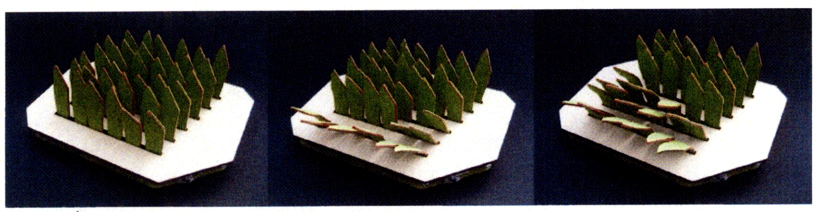
Surflex's surface deformation in three steps

Surflex's hardware architecture is inspired by the way draughtsman used the intrinsic properties of wood and rubber rulers to draw symmetric curvatures, which eventually led to the use of spline-based curves in computer-aided design.

Sprout I/O

Sprout I/O is a haptic interface for tactile and visual communication composed of an array of soft and kinetic textile strands which can sense touch and move to display images and animations. It is built from a seamless textile and SMA composite to render a dynamic texture which is responsible for both actuation and sensing, as well as the surface's visual and tactile qualities.

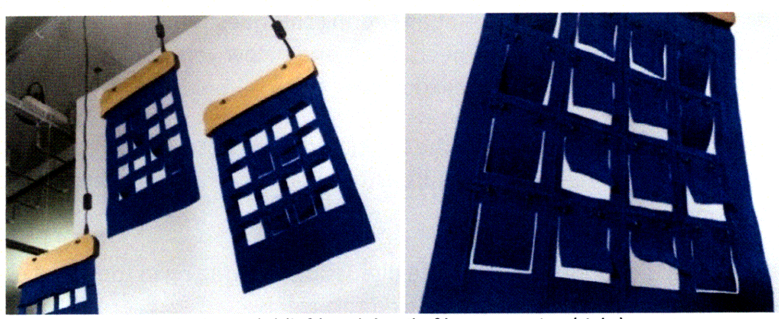
Sprout I/O uses a shape changing texture to explore how small shape deformations on a surface can be perceived as a whole and used to communicate. As consequence, this exploration also sheds light on the relationship between the overall shape of an object and its changing surface properties.



Sprout I/O animation

Shutters

Shutters is a curtain composed of actuated louvers (or shutters) that can be individually addressed for control of ventilation, daylight incidence and information display. By embedding SMA into a textile membrane, the curtain allows for a finer and dynamic control of environmental exchanges, such as light and ventilation, creating living environments that can better respond to its inhabitants' activities.



Shutters displaying the letter 'A' (left) and detail of louver motion (right)

Shutters explores another facet of form transformation, where perforations are introduced in a continuous surface and their aperture controlled to regulate permeability. Form transformation in this case controls the boundary between two distinct spaces, examining how kinetic membranes can be used to blur their physical boundary, rather than just modulate their spatial relationship.

Contribution

It is my hope that this work can help pave the way for merging computation and materiality, seeding some of the conversation about form transformation and directing these technologies towards the development of new interaction metaphors and ways to enhance human-to-human communication. With that in mind, this thesis hopes to provide a contribution in two main ways:

(1) Advancing and making accessible to designers the knowledge for making programmable shape change and multifunctional materials a reality;
(2) Beginning to devise a language for talking about *form transformation* in interaction design vis-à-vis how it can be applied to support communication, manipulation and visualization of digital information.

Thesis Overview

Few people these days are able to find the time to read a document of this length. In order to facilitate matters, this subsection provides a reading guide and chapter breakdown that can be used to skip directly to the most relevant parts. Hopefully, they will be captivating enough to persuade you to continue reading the rest.

For the reader pressed with time, the connection between physical and virtual transformable surfaces is addressed in chapters 5 and 6. For those interested in what shape changing materials are available today and how to use them, chapters 3 through 8 will hopefully answer some of your questions. Finally, for the readers interested in how form transformation relates to human-computer interaction, chapter 5 and the succeeding design probes are my attempts at answering this question. Related work is spread out across the different chapters and below you will find a more detailed chapter-by-chapter breakdown.

Chapter 1: Introduction reveals the big picture and loosely ties a common thread between materiality, form transformation and human-computer interaction.

Chapter 2: Motivation opens up the discussion by bringing in the ideas and previous work that have influenced this thesis.

Chapter 3: Responsive Materials attempts to understand how physical materials are rapidly becoming more like computers by inherently supporting interactivity and shape change.

Chapter 4: Designing with Shape Memory Alloys focuses on generic and practical techniques for using SMAs. This chapter is probably the most technical one and will mostly likely interest designers who want to get practical information on how to use shape changing materials.

Chapter 5: Soft Mechanics picks up the discussion where *chapter 3* left off by looking at how shape changing materials provide new ways to build mechanical systems. The primary goal here is to extend the properties of shape changing materials to the scale of surfaces, devising an alphabet and language for designing and interacting with shape changing materials, as well as setting the background for the design probes that will come in the following chapters.

Chapter 6: Surflex is the first design probe and it proposes a composite material architecture for building physical surfaces that can be digitally manipulated with the same versatility as virtual NURBS.

Chapter 7: Sprout I/O examines the scale of textures and looks at form transformation which is co-located with tactile input.

Chapter 8: Shutters wraps up the design explorations by investigating the topic of permeability in form transformation, particularly addressing the architectural need to control environmental exchanges and regulate a space to multiple conditions of use.

Chapter 9: Conclusion and Future Forms concludes by looking towards the future and envisioning the probable progenies that could evolve from the technologies developed here.

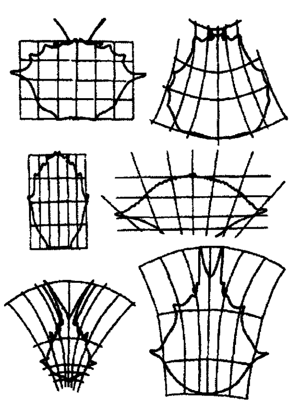
2 Motivation

"Of bodies changed to other forms I tell;
You Gods, who have yourselves wrought every change,
Inspire my enterprise and lead my lay
In one continuous song from nature's first
Remote beginnings to our modern times."

— Ovid, 8 AD

This thesis was born from a frustration with the inability of physical things to adapt in response to our needs and desires. Through a process of design and iteration, we continuously saturate the world with new objects and painstakingly improve on the ones which fail to meet our expectations. Nevertheless, the ability of objects to physically transform themselves is still in its infancy and remains in the realm of myths and storytelling. Drawing parallels with a number of different fields and disciplines, I will attempt to bring together some of the bigger ideas that have served as motivation for this thesis.

As computers shrink to nano scales, and *programmable matter* becomes a reality, our capacity to manipulate physical form is drifting away from the limitations of fabrication processes and becoming a lot more like manipulating pixels on a computer screen. For the most part, this means that *matter* could become the ultimate instantiation of programmatic control; but while this future is still uncertain and transformable forms remain trapped in the domain of bits, it might be valuable to consider what forces could ultimately guide the transformation of physical forms.



The transformation of crustacean carapaces through the deformation of a flexible grid Image from *On Growth and Form*, by D'Arcy Thompson

The natural world offers compelling examples of how physical forces have led to the progressive form transformations that generated the uncountable species populating this planet. In *On Growth and Form* D'Arcy Thompson elucidates how the transformations we see in animal forms are the evolutionary result of forces, such as gravity or surface tension, acting upon the material properties of bones or skin. With this work, Thompson compels us to move the concept of form giving from its "statical aspect to its dynamical relationships" by considering how the continuous forces enabling and constraining material behaviors might impel the search for more advantageous forms (Thompson, 1992).

Nature provides another interesting example of how animals engage in building and iterating the design of elaborate forms. In an eternal struggle for survival and reproduction, some animals have evolved the skills and 'tools' to build intricate structures from the materials locally available to them. Male weaverbirds, for instance, have developed beaks for holding, cutting and manipulating small twigs and leaves, which they use to lure their mates by weaving complex nests. Young birds start practicing these construction skills from an early age, by building and rebuilding nests which will never be used, in the hopes that more refined skills will later increase their chances of reproduction. The building skills developed by these birds, which are so tightly coupled to their morphology and the materials available to them, are the result of a long evolutionary process. However, design iteration does not always need to happen over such long timeframes.

Black Headed weaverbird
Image from Jay Berkeley

Traditional crafts, which borrow most of their techniques from the natural world, are our early design practices for iterating and engaging with external forces in a quest for optimizing and perfecting forms. Iteration, in this case, is supported by a deep understanding of material behavior, experience with different techniques for processing them, and ultimately intimate knowledge of how the designed forms are used and behave in the real world. Due to our capacity to document and communicate our design improvements, as objects change, the skills we learn are passed down from generation to generation in tandem with our social practices and cultural values. Quilts are a symbolic example of this iteration and transmission process. Traditionally built from leftover fabrics, an individual quilt can be passed down across several generations, and continue to be improved and built upon, forming an intricate patchwork of materials, techniques and personal histories.

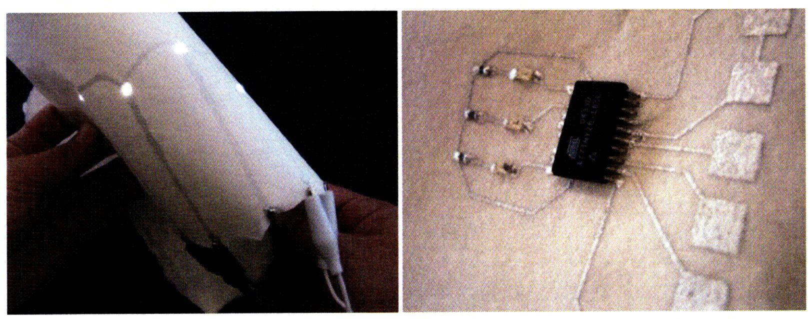
Basket weaving
Image from Buddhasits

Far from advocating craft as a viable manufacturing alternative today, I am trying to bring attention to the distinction between designs which change across different reproductions and designs which evolve during the lifetime of a single object. While the first has already gained digital momentum through the development of rapid prototyping and open-source practices, the second is still struggling to catch up with our digital tools. In an age when the turnaround of new products leaves little time for iteration and refinement, one might wonder what alternatives we have for building physical things which can adapt and grow with their users.

I believe that a potential solution can be provided by materials which are 'naturally responsive' and behave more like the digital tools or embedded electronics which define their form and behavior. Materials which are capable of changing their properties in response to different input stimuli can play this role by overcoming the material constraints which would normally make objects and spaces immutable things.

In interaction design, electronic textiles have spearheaded this material revolution by looking for new aesthetic and electromechanical possibilities for building computers and electronics which are more adequate for the shape, movements and interactions of the body. These electronic textiles not only create a new class of human-computer interactions, but also introduce a wide range of material affordances to the way we design and interact with computers.

In my own work I have pursued this approach by looking at how different material affordances can become computationally dynamic and influence how we manipulate information and communicate. *Pulp-Based Computing* are electronic circuits built out of paper and responsive materials which can leverage the interaction affordances of paper, such as folding, ripping or crumpling (Coelho, Hall, Berzowska, & Maes, 2007). Rather than perpetuating current interaction metaphors with an 'electronic paper' that mimics a computer screen, my interest is in unleashing new ways to deliver information and interact with the world by capturing the rich and implicit knowledge we have of how things look, feel and behave. While the first approach reduces every surface around us to the same interaction metaphors, the latter combines the richness of the physical world with the versatility of digital information to create new ones. As we progress towards a future where surfaces will be capable of sensing and displaying information, the need will arise for them to not only portray information through light changes, but also through adaptable topologies, surface properties and permeability.



Pulp-Based Computing
Image from XS Labs

As this thesis looks at how shape changing materials can be used to design new interactive systems, it takes inspiration from Thompson's work to explore how human interaction can serve as the primary force driving form transformation, and hopefully bring to the physical world the same versatility for manipulating forms that we find in the digital world.

I believe part of this quest comprises of looking at how we perceive and interact with the forms and material affordances we encounter all around us. However, this is an enormous task and I will focus here on a small slice of it, specifically how surfaces can be transformed through topological, textural and permeability changes, to support new modes of interaction and communication.

3 Responsive Materials

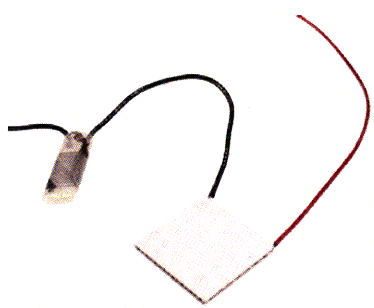
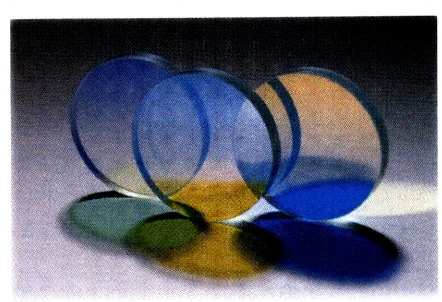
"The hybrid or the meeting of two media is a moment of truth and revelation from which new form is born.
The moment of the meeting of media is a moment of freedom and release from the ordinary trance and numbness imposed by them on our senses."

— Marshal McLuhan, 1964

Materials of Interaction

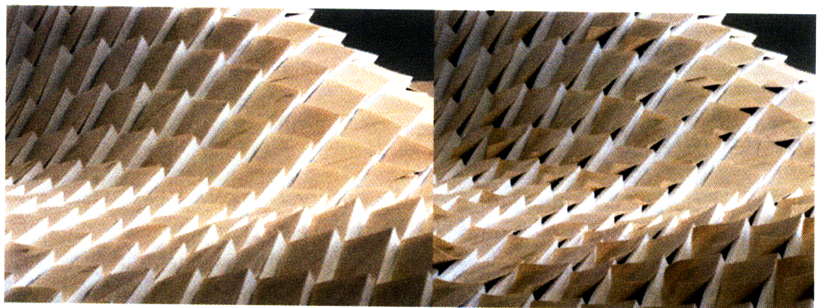
In his article *The Computer for the 21st Century*, Mark Weiser envisioned the day when computing would become an integral and invisible part of the way people live their lives by vanishing into the background (Weiser, 1991). Since then, a multitude of approaches and implementations have emerged from this vision but have for the most part ignored the material behaviors and affordances that dictate how we perceive and interact with the physical world. In order for computers to be seamlessly embedded into our environments, it is crucial that they preserve their capacity to leverage input, output, power storage, communication and processing, while simultaneously conveying a wide range of material properties that can engage our intuition about the behavior and affordances of the material world.

Smart materials and their composites are strategically positioned to fulfill this desire by transforming input stimuli into controlled materials responses, while presenting a wide range of material properties and behaviors. Nonetheless, the term 'smart material' is somewhat misleading and, with little regard for how materials are made, used or behave, it tends to encompass a wide range of technologies which are neither 'smart' per se, nor related to one another (Addington & Schodek, 2004) (Ritter, 2006).

Examples of 'smart' materials: thermoelectric junction and dichroic glass

To complicate matters, most materials, smart or not, are capable of changing their properties due to different input stimuli, but remain largely unexplored for these responsive properties. Steffen Reichert's prototype for an adaptive membrane provides an interesting example. Built from small wooden strips, it takes advantage of wood's natural capacity to expand and shrink in response to different humidity levels. Under prolonged exposure to humid environments, the wood curves opening small apertures on the membrane; however, when brought back to a drier environment, the curvature is reversed and the apertures close (Menges, 2008).



Responsive surface of veneer composite components with the capacity to adapt porosity in response to changes in humidity
Image from Achim Menges

Under these circumstances, how can we identify the materials which are suitable for the design of interactive systems? Three material characteristics are of particular importance in designing human-computer interaction and can help us sketch an answer to this question:

Computational Control

In order to interface with the world of bits, materials need to respond to stimuli that can be computationally controlled. This process can happen *directly*, as in the case of electronically controlled thermoelectric junctions, or *indirectly* through a secondary process, as in the case of thermochromic inks activated through the resistive heating of an external element.

Scale Shift

To support meaningful interactions, material changes need to operate at a scale in which stimulus and response can be perceived and acted upon. In most cases, this simply means the amplification of the natural material responses we already encounter in the physical world, so they can be brought to a scale where people can interact with them. Even though wood can change shape in response to humidity levels, the time scale in which it changes removes the possibility of a fluid dialogue with a user.

Reversibility and Repeatability

Although these are essentially two separate properties, they occur together. Reversibility is the capacity of a material to change to a new state and return to its original condition, and repeatability is its capacity to repeat the transformation process innumerous times without considerable performance decay.

Although these properties are in no way exclusive and are most likely to find counterexamples which contradict this categorization, they can help us narrow down the scope of relevant technologies. Moreover, in order to address the capacity of smart materials to support human-computer interaction, it is more appropriate to narrow this discussion with the term *responsive materials*, putting aside unrelated technologies and bringing old ones back to the table. Responsive materials are understood here as materials and composites that can leverage input and output capabilities, and which under different stimuli are capable of altering their own properties or transforming energy from one form to another.

The focus in this case is placed on transformations – transformation of the material itself or the energy applied to it – which can support the design of ubiquitous interactivity while cohesively integrating sensing, actuation, power distribution and communication. The following table illustrates these transformations by comparing the relationship between input stimulus and output response in different materials.

Response / ***Stimulus***	Electrical	Magnetic	Optical	Thermal	Mechanical	Chemical
Electrical			Electroluminescent Wires	Resistive Inks	Piezoelectric, Electrostrictive, ER Fluids, Dielectric Elastomers	
Magnetic			Magneto-optic		Ferrofluid	
Optical	Photoconductor		Photochromic Dyes			
Thermal	Peltier Junction		Thermochromic Inks		Shape Memory Alloys	
Mechanical	Piezoelectric, Electrostrictive	Magnetostrictive	Mechanochromic		Negative Poisson Ratio	
Chemical						

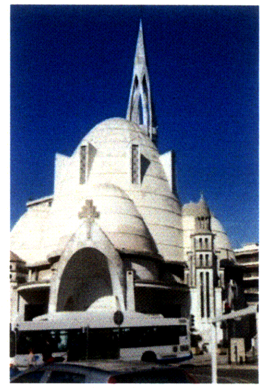
Stimulus-response matrix for selected materials
(ER – electro-rheological; MR – magneto-rheological)
Source: modified from Textiles Future

Responsive Composites

Designers looking to explore more refined interaction scenarios and material affordances can combine these materials into composites rendering a greater variety of transformations and catering to more specific needs. Composite materials are engineered combinations made from two or more constituent materials with significantly different physical or chemical properties. These materials remain separate and distinct on a macroscopic level within the finished structure, but together create unique material properties.

Composites for Performance

Traditionally composites are made from fibers embedded in a matrix or substrate and are designed to achieve specific performance goals, such as higher stiffness, strength or low density. Reinforced concrete is a good example in which reinforcement bars ("rebars") or fibers are incorporated to strengthen concrete, a material that would otherwise be brittle. Typical concrete mixes have high resistance to compressive stresses, but any appreciable tension (e.g. due to bending) breaks the microscopic rigid lattice resulting in cracking and separation. If a material with high strength in tension, such as steel, is placed in concrete, the composite material becomes capable of resisting compression as well as bending and other direct tensile actions. A reinforced concrete section, where the concrete resists the compression and steel resists the tension, can be made into almost any shape and size, opening new design possibilities for engineers and architects.



Reinforced concrete at Église Sainte Jeanne d'Arc, by architect Jacques Dror, 1926–1933

Composites for Interaction

The same approach that aims to improve concrete's performance can also be used to give new interaction possibilities to a host of materials which would normally only be considered for their static properties. Moreover, responsive materials come in every form imaginable, such as powders, liquids, fibers, etc, and can therefore be combined through different fabrication techniques, such as sewing, weaving, casting, silk screening, papermaking, etc. This synergy between material property and fabrication technique inevitably leads to their responsive behavior as well as visual and tactile qualities.

The main challenges in creating responsive composites are three-fold: (1) finding the appropriate material combinations; (2) developing the fabrication techniques for putting them together in a way that takes advantage of their properties; and finally (3) interfacing them to the logic circuitry that can control their behavior.

These composite design processes have been extensively explored in the development of electronic textiles, where traditional textile techniques are combined with responsive materials. The core technical challenge in electronic textiles lies in finding the appropriate methods and techniques for coupling soft and hard materials. While textiles are traditionally soft, smooth and malleable surfaces which can easily rest on the body, electronic devices are enclosed in hard cases and shells which need to maintain a certain degree of rigidity to preserve the electrical and structural integrity necessary in circuit design (Berzowska, 2005). In order to find alternatives to the challenges posed by Wearable Computing (Mann, 1996), Rehmi Post et al. set forth a technical and conceptual framework for matching the material impedance of electronics to those of textiles (Post, Orth, Russo, & Gershenfeld, 2000), thus providing an alternative approach to Weiser's vision of transparently imbuing our physical world with computation.

Ultimately, rather than focusing on ubiquitous computing approaches that employ sensors and actuators as discrete add-on components, these responsive composites allow computation and interaction to be seamlessly embedded into materials themselves opening new possibilities for the deployment of computation into the environment. Two recent

Physical Heart in a Virtual Body by Amit Zoran

Chronos Chromos concrete by Chris Glaister et al.

examples include: Amit Zoran's guitar, *Physical Heart in a Virtual Body*, which uses a wood and piezo composite to determine the different acoustic properties of a wood centerpiece embedded in a digitally fabricated guitar (Zoran & Maes, 2008); and *Chronos Chromos* which uses concrete dyed in thermochromic ink and embedded with resistive wires to create a color changing wall display (Glaister, Mehin, & Rosen, 2006).

Shape Changing Materials

This thesis intends to address the topic of form transformation in human-computer interaction and as a prerequisite places particular emphasis on materials which undergo a mechanical deformation under the influence of direct or indirect electrical stimuli.

Current materials science literature is replete with examples of shape changing materials which promise one day to revolutionize the way we build motors, solenoids and other traditional actuators. Nonetheless, the future is not fully here yet. Most of these materials are at their early research stages and only a few are sufficiently mature today to be reliably implemented. As a result, the techniques for fabricating these materials are not fully disclosed or their power and mechanical constraints are still too difficult to overcome.

But before this promise realizes itself, it might be informative to consider what intrinsic properties shape changing materials should have and how they can limit, guide and support new designs. Below are a table and a list of properties which have become critical to me when selecting what materials to use. Some are fairly obvious and self explanatory, such as speed or strength; on the other hand, other properties are unique to shape changing materials, such as their ability to learn new shapes after fabrication. It is also important to note that these properties are explicitly connected to each other and to design a material that maximizes one of them will most likely affect other properties. In the future, we will hopefully be able make more informed trade-off choices when shopping for new shape changing materials.

Shape Changing Material Properties

Deformation strength and ***power requirement:*** These properties are inversely proportional and play an important role in limiting things such as size or mobility, much like in the design of traditional actuators. For instance, shape memory alloy (SMA) wires drawn in large diameters are incredibly strong, but their power requirements increase considerably as their size goes up, making their untethered use impractical. Power requirements also determine how the material should be interfaced to electronic circuitry and controlled.

Speed and resolution: These properties determine the frequency and precision with which a material can be controlled. Materials with a linear response, such as piezoelectric films, can be controlled with fine precision and be used in microscopes or small linear actuators, while electrostrictive material are considerably fast, but non-linear, making it harder to control finer movements with precision.

Number of memory shapes and ***transition quality:*** Not as clear as the relation between deformation strength and power requirement, these properties determine what makes a shape changing material an effective actuator. The *number of active memory shapes* determines how many physical configurations a material can take and if it requires a counter-actuator to return to its original shape. Certain electroactive polymers (EAP) for instance have two deformation shapes and can be controlled to cycle from one to the other, while an SMA only has a single, usable shape memory and requires an external actuator to return to its original shape. Moreover, materials that *transition* from a malleable to a rigid memory state, such as SMAs, are capable of actuating other materials without requiring any external force. However, materials that transition from a stiff to a malleable memory state, such as shape memory polymers (SMP), become too weak when active to exert any relevant force on other materials. As a rule of thumb we could say that effective actuators can be made from (1) a transition from a resting malleable state to a rigid memory shape; or (2) a transition from a resting rigid state to a rigid memory shape; while a transition from a resting rigid state to a malleable memory shape requires an external force for the material to actually change shape. These relationships will be better explained and become clearer in *Chapter 5: Soft Mechanics*.

Trainability: The capacity to give a shape changing material new memorized shapes after it has been fabricated.

Reversibility: The capacity of the material to fully recover from the shape memory transitions without considerable decay. This is closely related to the concept of *fatigue*, where a material can progressively wear over time until it loses its shape changing properties. For instance, SMAs can repeat their memory cycles numerous times, but under considerable stress eventually start gaining a new memory shape and 'forgetting' the previous one.

Input stimulus: The nature of stimulus required to trigger the shape change, such as a voltage potential, pH change or heat. This also deeply influences the power efficiency as well as the infrastructure needed to actuate the material.

Bi-directionality: The capacity of the material to change shape under a stimulus but also to generate that same stimulus when physically deformed. This is an important property, especially in the design of interactive systems, where it might be interesting to gather feedback on how a user modifies or offers resistance to shape change. Several materials are capable of doing this, such as piezoelectric ceramics which can be used as vibration sensors or power harvesting and SMAs which increase temperature when physically deformed.

Environment compatibility: The material's capacity to operate in the same environment as their application. For most cases, this means dry environments at ambient temperature, however, some ionic EAPs, for instance, need to be immersed in an aqueous media containing ions, such as saline solution, blood, urine, plasma or a cell culture medium, which makes them ideal for medical applications but impractical for use in everyday situations.

Consistency: A material's physical state (rather it is a solid or liquid) plays a role in the kinds of application it enables and infrastructure required for using it. Liquid shape-changing materials for instance, such as ferrofluids and magnetorheological fluids, need to be encapsulated inside other solid structures that can prevent them from leaking or coming in contact with other substances.

Material Name	Direct or Indirect stimulus	Keep shape when stimulus is removed	Displacement	# of 'memory' states	Force	Consistency
Shape Memory Alloy	heat	no	large	1 (potentially 2)	high	solid
Magnetic Shape Memory Alloy (Ni_2MnGa)	magnetism		large	2	high	solid
Shape Memory Polymer	heat	yes	large	1	weak	solid
Piezoelectric Ceramic	electric	no	small	2	high	solid
Dieletric EAP (e.g. Dielectric Elastomers (DEs))	electric	yes	large	2	high	solid
Ionic EAP (e.g. Ionic Polymer Metallic Composite (IPMC))	electric	no	large	2	high	solid
Magnetostrictive (Terfenol-D)	magnetism		large	2	high	solid
Electrostrictive (Lead Magnesium Niobate (PMN))	electric field	no	small		small	solid
Thermoplastic	heat	yes	large	1	weak	solid
Ferrofluid	magnetism	no	large	indeterminate		viscous

Relating the more important properties back to the materials which are available to designers today, we can create the comparative table above. There are several materials that can change shape and transform under stimuli. This list is in no way extensive and I am only listing here a few of the more common materials to compare their main properties. I have also purposefully omitted from this list materials that are pH or light controlled, and whose mechanical properties cannot be triggered by a direct or indirect electrical stimulus.

SMAs and specifically Nitinol are currently the most versatile of the shape changing materials. Due to its market presence, many years of practical use, wide range of applications, strong shape memory effect and the possibility of purchasing it in small quantities, SMA is the ideal material for the work developed in this thesis. The following chapter takes an in depth look at shape memory alloys, outlining the mechanical and electronic techniques I had to develop to make this material easier to use.

4 Designing with Shape Memory Alloys

A shape memory alloy (SMA) is an alloy that, once treated to acquire a specific shape, has the ability to indefinitely recover from large strains without permanent deformation and remember its original geometry.

As I briefly described in the previous chapter, SMAs are the most versatile of the shape- changing materials and have many years of practical use. Due to their shape memory effect and superelastic properties, SMAs can be currently found in applications as diverse as eyeglasses frames, medical stents, hydraulic connectors and MEMS actuators (Gilbertson, 2005).

The research literature on SMAs is also quite extensive and covers anything from detailed descriptions of thermal and electromechanical properties to manufacturing and processing techniques (Funakubo, 1987). Nevertheless, a lot of this literature presents techniques, processes and even terminology which make this knowledge inaccessible to designers at large or impractical for anyone primarily interested in SMAs for the kinds of applications they enable.

In this chapter, I will describe some of SMA's main properties and some of the techniques I had to develop to build the projects described in chapters 6, 7 and 8. The emphasis is placed on the practicality of some of these techniques with the intent of making shape change a more accessible design tool.

Overall Properties

There are several kinds of SMAs, however the most commonly used ones are made primarily of a combination of nickel and titanium. Nickel and titanium formulations are more expensive to melt and produce than copper alloys for instance, but their ductility, stability in cyclic applications, corrosion resistance, biocompatibility and higher electrical resistance (used in resistive heating actuation) makes them a more desirable alloy. Most nickel-titanium formulations contain nearly equal amounts of nickel and titanium. Differences of less than one percent or contaminants such as carbon or oxygen can radically change the temperature in which the material changes shape to as much as 200 °C. SMAs are also manufactured in many different forms: drawn as a round and flat wire, tubing, rolled sheet, sputtered thin films and shaped components targeting specific applications (Humbeeck & Stalmans, 2002).

SMAs, however, are not for all applications, and it is important to take into account the forces, displacements, temperature conditions, and cycle rates required of a particular actuator. The advantages of SMAs become more pronounced as the size of the application decreases, since there are few actuating mechanisms which produce more work per unit volume than SMAs (Johnson A. D., 1998). In conditions where mechanisms, such as solenoids, motors or electromagnets, are a not a viable alternative due to their large size, SMAs can be used as thin films, embedded into composites or single-wire linear actuators (Introduction to Shape Memory Alloys, 2003).

For the design of *Surflex*, *Sprout I/O* and *Shutters*, I have primarily used 0.2 mm SM945 Nitinol wire produced by Nitinol Devices and Components (NDC) with a composition ratio of 54.5 wt.% nickel, 0.05 wt.% oxygen, 0.02 wt.% carbon and balancing titanium. The material datasheet indicates the following properties:

Physical Properties

Melting Point:	1310 °C
Density:	6.5 g/cm^3
Electrical resistivity:	76 μΩ-cm
Modulus of elasticity:	28 x 10^3 MPa (M_f) and 41 x 10^3 MPa (A_f)

Mechanical Properties

Ultimate Tensile Strength (min. UTS):	1100 MPa
Total Elongation:	10%

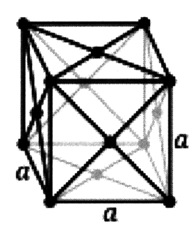
Shape Memory Properties

Loading Plateau Stress @ 3% Strain (min):	100 MPa
Shape Memory Strain (max):	8%
Transformation temperature (A_f):	60 °C

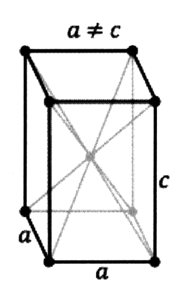
Shape Memory Effect

The shape memory effect (SME) refers to a material's capacity to be deformed or strained at low temperatures and, when heated, to reverse this strain and remember its original (pre-strain) shape.

The shape memory effect was first described by Dr. Frederick E. Wang (Kauffman & Mayo, 1993) and is a result of phase changes that take place while the material remains a solid. Normally, these phase changes occur when an alloy is heated to its melting point; however, in the case of SMAs, the phase transformation occurs below the melting point through a rearrangement of the position of particles within the crystal structure of the solid. Thus, the alloy can retain its shape without melting.



FCC austenite

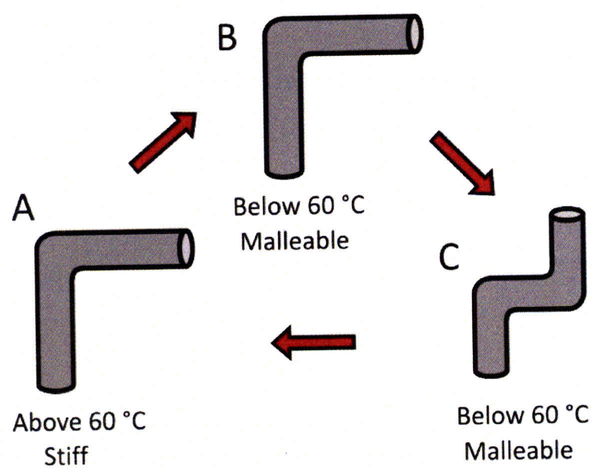


BCT Martensite

This solid state phase transformation is a transition from a martensite to an austenite crystal structure. In austenite, the atoms of SMA are arranged in a face-centered cubic crystal structure (FCC), while in martensite they are arranged in a body-centered-tetragonal (BCT) crystalline structure.

These structural changes at the atomic level are the source of the unique properties of these metals, in particular the changes in elasticity and shape memory. In the martensite phase, an SMA is malleable and can be bent into various shapes, while in austenite it becomes rigid and remembers its memorized shape.

To fix its memory shape, the alloy needs to be held in position and heated to about 500 °C. The high temperature "causes the atoms to arrange themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase (Kauffman & Mayo, 1993). Following this training process, whenever the alloy is brought back to its transition temperature (around 60 °C), it will revert back from its martensite to its austenite atomic arrangement and memorized shape. However, if during this heating and cooling process no forces are applied to the SMA, the microstructure of the alloy will change without visible macroscopic changes. This cycle can be repeated millions of times (Jackson, Wagner, & Wasilewski, 1972). The following illustration explains these transformations in more detail:



In this example, a strand of SMA is controlled to present three different material and shape properties:

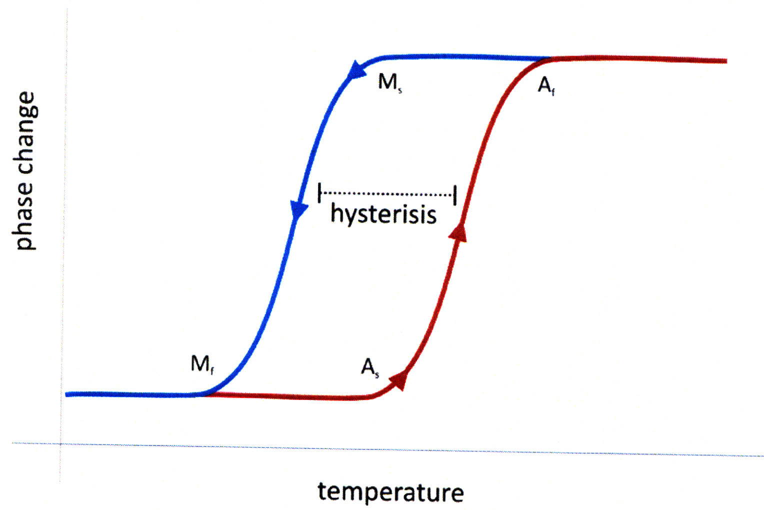
(A) *High temperature, austenite phase*: SMA is heated above its transition temperature of 60 °C. In its austenite phase it becomes stiffer and recalls its memorized L-shape;

(B) *Low temperature, martensite phase:* SMA cools down back to its martensite phase and becomes malleable, but remains in the same memorized L-shape since no external force has been applied to it;

(C) *Low temperature, martensite phase:* While in its martensite phase, an external force can make the SMA bend into a completely new shape, in which it remains after the force is removed.

Hysterisis

Hysteresis in SMAs is the temperature difference between a material's phase transformation upon heating or cooling. This spread is typically around 20-30 °C for Nitinol superelastic alloys used in medical applications. In the case of the 0.2 mm SM945 Nitinol wire, the transistion temperature is centered at approximately 60 °C; however, the full transformation to the austenite phase occurs over a 20 degree range, beginning at 50 °C and ending at 70 °C. Several heat treatment sequences, temperature and heating times can shift the hysteresis higher, lower, or widen it. A typical SMA hysteresis curve is shown below.



A_s: temperature where material starts to transform to austenite upon heating
A_f: temperature where material has finished transforming to austenite upon heating
M_s: temperature where material starts to transform to martensite upon cooling
M_f: temperature where material has finished transforming to martensite upon cooling

Superelastic Effect

Another important property of SMAs is their superelastic effect, also known as pseudoelastic effect, which describes the ability of the alloy to recover from large strains isothermally. When in its austenitic phase, a martensitic phase can be induced by stressing the metal, making it considerably more flexible. With the removal of the stress force, the material prefers to returns to its austenite phase at the operating temperature and the strain is instantly recovered.

The superelastic effect is commonly used in reading glasses, which allow the frame to completely deform under stress and perfectly return to its original shape when the stress is removed. This phenomenon is essentially the same as the thermal shape memory effect, but in this case at ambient temperature the alloy is in its austenitic, rather than martensitic phase. This gives the impression of the material being extremely flexible, since no amount of bending or stretching can permanently deform it.

Fabricating 3D Actuators

This section looks at different techniques for training, controlling and building actuators with SMAs. I purposefully drifted away from an extensive material and actuator characterization towards a more hands-on and practical design approach in order to make this knowledge more accessible to designers at large.

Shape-Setting

In order to take advantage of an SMA's superelastic or shape memory effects, it is necessary to train the material into a new "memory" shape. This is done by firmly constraining the material into its new shape in a fixture or mandrel and then performing a heat treatment. The specific heating method can vary considerably, as long as it can keep a stable temperature around 500 °C. Two shape-setting heating methods which are easy to control are the use of a high temperature furnace with a thermostat or resistive heating (joule heating) (Case, Kreiner, Redmond, & Trease, 2004). The advantage of a furnace over resistive heating is that it is safer, since the alloy is not exposed while hot, and it also provides even temperatures across the whole extension of the alloy. Cooling should be done with water quenching at ambient temperature and should be rapid.

The exact timing and temperature needs to be determined experimentally since they depend on the processing history of the material and the heating method used. Variations in the temperature range (outside of 500 °C) and shape-setting times can also lower or increase the A_f temperature. For instance, the alloy used in *Sprout I/O* and *Shutters* was shape set at 515 °C for 15 min in a temperature controlled furnace, lowering the A_f temperature to approximately 54.7 °C. Even though this seems like an ideal technique to reduce the SMA's transformation temperature and lower its power requirements, it is not completely reliable and results are sometimes inconsistent and hard to replicate. Moreover, higher shape-setting temperatures, resulting in lower A_f temperatures, makes the SMA slightly stiffer at ambient temperature and harder to use.

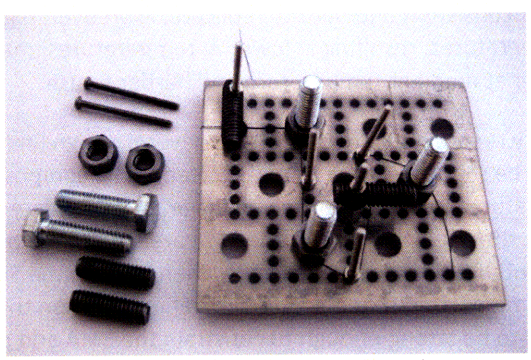
This 'memory recording' process imposes several design limitations. The SMA cannot be shape-set after it is integrated into a composite, since the high temperatures would most likely damage the secondary material. Additionally, the size and shape of the SMA are limited by the strength of the fixture and the size of furnace used. When heated, the SMA tries to revert to its memorized shape and applies large forces on the fixture, which needs to be strong enough to constrain the SMA and prevent it from moving. The fixture also needs to be made of an alloy which can withstand temperatures above 515 °C without considerable deformation.

Multiuse Fixture

Designing a fixture for constraining the SMA during shape-setting needs to take into account the desired actuation shape, the amount of force required in actuation, how those forces are biased (by gravity or other forces and actuators) and how the SMA is interfaced to the control circuitry. Most SMA applications use a spring to generate linear actuations, since springs allow for large linear displacements. Springs are shape-set by wrapping an SMA wire around a screw and crimping both ends with nuts. However, in order to move linearly, springs need to coil orthogonally to their actuation axis and cannot be embedded flat into composites. In order to address these requirements, I have designed a generic shape-setting fixture which allows for quick experimentation of new actuator shapes.

Example of SMA spring and screw fixture

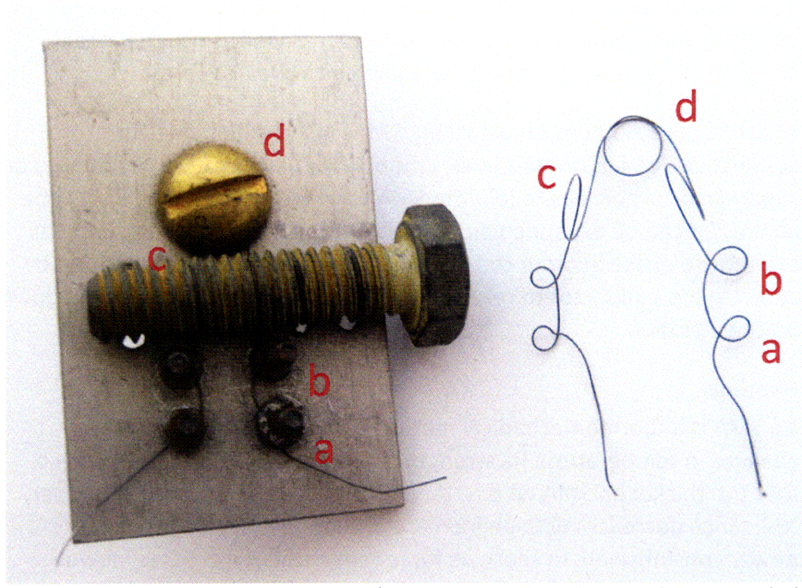
The generic fixture is primarily limited by the size of the furnace used and is composed of four different parts: a perforated plate; headless horizontal screws with an orthogonal hole; regular vertical screws; and nuts. The perforated plate is a metal sheet with intercalated equidistant holes through which it is possible to affix the vertical screws. This creates a grid of vertical screws for tying the SMA into different two-dimensional shapes. By attaching orthogonal screws to the vertical ones, it is possible to add a third-dimension for quickly designing and testing three-dimensional actuator shapes. The grid resolution and screw sizes can also be changed to allow for the design of smaller actuation loops or enhance the detail of certain elements. The image below illustrates this design.



Generic fixture for shape setting SMA wires

Anchor Points

The different screw sizes in the generic fixture were chosen because the SMA needs small loops that serve as anchor points to prevent it from spinning within a composite. When actuated, the SMA changes shape and moves towards the path of least resistance to accommodate its crystal transformation. The anchor points help focus the movement where the actuation is most desired and can also be used to solder or crimp the SMA to a circuit board or wires.



Fixture and shape set SMA used in *Sprout I/O*. Loops **A**, **B** and **D** indicate anchor points which prevent the SMA from moving within its composite. Loop **C** is the section of the SMA strand actually responsible for the composite's actuation

Multiple Actuation

A single SMA wire can also be shape set to contain multiple actuation points. By individually heating different sections of the wire, multiple parts of it can be heated and actuated without affecting others. In the image above, power wires attached to loops A and D would only heat the right half of the SMA strand and leave the left side in its martensitic phase.

Bias Force Compensation

When strained, SMA loses part of its memorized shape and actuation strength; additionally, the rigidity of the composite in which the SMA is embedded provides a bias force and can sometimes prevent it from moving. Both of these problems are overcome by wrapping the SMA around a screw multiple times to create a large shape change transition where the actuation needs to be stronger. In the image above, loop C only generates a 90° bend on the fabric, but needs to be shape set at 360° to account for the stiffness of the fabric.

Soldering and Crimping

SMAs have a strong oxide layer and are therefore harder to solder than other alloys. This oxide layer causes solder to bead up on the surface and roll off. An aggressive flux, such as the Indium Corporation Indalloy #2, is required to remove the oxide layer, making complete surface wetting more favorable, before a standard Sn-Ag solder can be used. The liquid flux must be removed thoroughly after soldering is complete, or it will continue to corrode the nickel titanium and surrounding materials. Practically speaking, SMAs are still not easy to solder and tend to move when heat is applied. To ease fabrication, I have found it necessary to apply the flux, solder and heat concurrently, as well as use the actual shape of the SMA wire as a way to attach it to circuit boards.

Alternative techniques for attaching SMAs include: bonding with conductive epoxies or adhesives; crimping; or using the shape memory or superelastic properties to join the SMA to other materials. An SMA tube connector can be expanded either mechanically or by cooling during its martensite phase in order to be inserted over another element, then by allowing the connector to return to its austenite phase, it can clamp down on the element.

Heating

An SMA is a thermomechanical material which changes shape with changes in temperature. Its strength is a result of its size and shape, so that the thicker an SMA wire is, the higher its actuation force. However, resistance decreases with an increase in thickness, leading to higher power consumption. In short, as force requirement increases, power consumption increases as well. Any design using SMAs should take into consideration the amount of force required, the thickness and shape of the SMA strand used to achieve that force and how much power it requires to reach its transformation temperature.

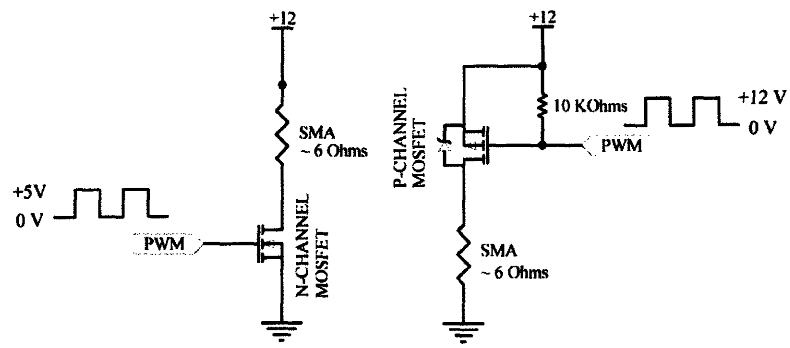
Inductive or External Resistive Heating

Even though it seems like external heat sources, such as nichrome wires or resistive films, are efficient techniques for heating SMAs, they have important disadvantages: thermo coupling is difficult since the SMA is constantly changing shape and being deformed; it is hard to prevent heat loss to the rest of the composite where the SMA is embedded; and they add extra bulk which counteracts the advantages of using SMAs as actuators in the first place.

Resistive Heating (aka Joule Heating)

The most common technique for heating SMAs is using the metal's own resistance to generate heating. When an electric current is passed directly through the wire, it can generate enough heat to cause a phase transformation and shape change. In most cases, the transition temperature of the SMA is chosen such that room temperature is well below the transformation point of the material and only with the intentional addition of heat it can exhibit actuation.

Measuring the specific heat capacity of an SMA sample – the heat energy required to increase the temperature of a unit quantity of a substance by a certain temperature –, it is possible to determine how much current is needed to the heat the material to a particular temperature over a particular time scale. However, I have found more efficient to determine heating times for different SMA composites experimentally, since several factors affect how fast heat is generated, such as variations in mechanical coupling, length and size of wires, the length and width of the SMA strand itself, ambient temperature and the composite's thermal conductivity. The following schematic shows the basic power circuit I have used:



Basic circuit designs for actuating an SMA wire through pulse-width modulation

In this illustration, the wires connected to the SMA increase the overall line resistance enough to bring the current under 1A. By slowly increasing pulse width and frequency at the control line it is possible to determine heating times, as well as control to a certain extent the degree of actuation and its speed. A more detailed schematic with a complete circuit is included in the appendix.

Fatigue
Since SMAs are 'trained' through a combination of heat and physical stress, it is possible to overheat the wire while attempting to move it, which makes the SMA lose its shape. While there are techniques which describe ways to detect a phase transformation and prevent overheating, they require a considerable amount of characterization of an individual SMA sample which makes an impractical technique to use (Ma, Song, & Lee, 2004). I have found that once the heating time for an SMA composite is determined, temperature variations around human comfort levels have very little impact on how the material fatigues.

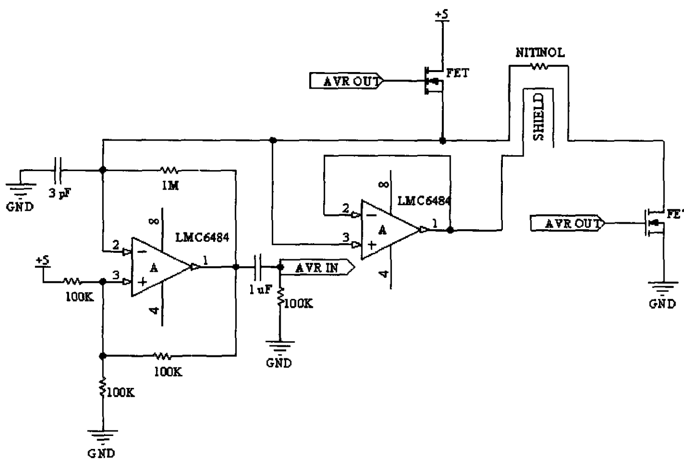
Two-Way Shape Memory
SMAs can also be trained to exhibit a two-way shape memory effect. Similar to the more conventional shape memory effect, two-way shape memory is achieved through a thermomechanical training process which imparts the alloy with a memory in both its austenitic and martensitic phases.

After a two-way shape training process, an SMA in its austenitic phase reverts to its second shape upon cooling, allowing the material to be cycled between two different shapes without the need for an additional external force (Humbeeck & Stalmans, 2002) (Perkins & Hodgson, 1990).

The ability to train SMAs into two different shape memories makes it the ideal shape changing material for many applications, however two-way shape memory is a somewhat unstable behavior which requires a complex thermomechanical training process, making it difficult to obtain consistent results (Wang, Zu, Feng, Zhu, Bao, & Wang, 2004) (Wang, Zu, Dai, Fu, & Feng, 2003). Additionally, the force generated by the SMA's second memory is considerably smaller than its regular shape change transformation making it impractical to use a single SMA strand to generate both a primary and bias actuation.

Kinetic Coincident I/O

Another important characteristic of smart materials is their capability to concurrently support multiple functionalities. For instance, SMAs can be used as: actuators, capacitive sensing electrodes, wires for power distribution and communication, and on top of its electronic functionalities, they can provide structural support, form and behavior to an object.



Square-wave relaxation oscillator for coincident I/O

In order to develop a texture strand for *Sprout I/O* that could sense touch and shape change, I combined an SMA's resistive heating circuitry with a relaxation oscillator, creating a capacitive sensor electrode that can also be heated to physically change shape. The circuit schematic above shows the basic layout.

In this circuit, the LMC6484 op-amp generates an oscillation on the SMA electrode which is watched by a microcontroller at 'AVR IN' (not seen in the circuit). Variations in the electrode's capacitance, such as the ones caused by touch, change the oscillation frequency and trigger the microcontroller to turn both MOSFETS on, actuating the SMA. Since no sensing is being done while the SMA is actuated, the two systems can operate without affecting each other. One of the disadvantages of this design is that the overall oscillation frequency is diminished by the capacitance of the two MOSFETS, diminishing the sensor's range.

5 Soft Mechanics

"Ligament and membrane,
Muscle and tendon,
Run between bone and bone;
And the beauty and strength of the mechanical construction
lie not in one part or in another,
But in the harmonious concatenation which all the parts,
Soft and hard,
Rigid and flexible,
Tension-bearing and pressure bearing,
Make up together."

— D'Arcy Thompson, 1917

Form and its ability to transform in nature are the result of a harmonious orchestration between elements with disparate physical properties. The human body, as illustrated in Thompson's quote, is neither hard nor soft, but a combination of muscles, bones, tendons and ligaments which make up the complete load-bearing actuation structure that allows us to walk, resist the pull of gravity or write this thesis (Thompson, 1992).

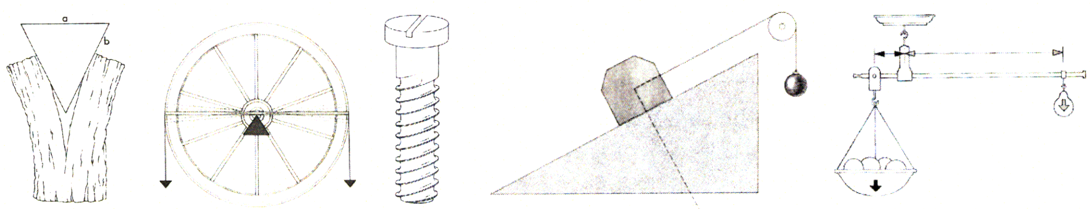
Shape changing materials, sometimes referred to as artificial muscles, are unique in their capacity to 'remember' different physical properties or shapes and transition between them in response to controlled stimuli. This ability allows us to blur traditional distinctions between malleable and soft materials, and look at mechanical systems in a new light, where kinesis and transformation happen through changes in material properties, rather than changes in how different mechanical elements, such as gears or joints, come together.

For designers at large, this shift brings about new challenges, but also the potential to overcome stasis and some of the traditional assumptions we make about mechanical systems, in exchange for a more holistic approach where elements can assume different roles according to their received stimulus. For instance, structural components which rely on external actuators for movement can now become the actuators themselves, and conceptual distinctions between structure and membrane are made irrelevant by surfaces which can transition from providing structural support to enveloping a space or object. But before looking at how to build dynamism from the dynamic properties of materials, it is valuable to consider why traditional mechanics came to depend on static elements for generating kinesis and transformation.

Hard Mechanics

Mechanics has been around since at least Archimedes' times and in spite of having evolved considerably up to now, benefiting from revolutions in materials, power and miniaturization, the machines we use today are still very similar to their predecessors. There is a good reason for this: mechanical systems are inherently constrained by the materials from which we build them.

In the 18th century, the Swedish engineer Christopher Polhem invented a *mechanical alphabet*, which consisted of a large collection of mechanical devices. Polhem believed that with just five *vowels* – the lever, the wedge, the screw, the pulley and the winch – and more than 70 *consonants* he could construct every conceivable machine. He went on to identify and fully describe the entire mechanical design space of his day. His work had a strong and direct impact on the training of engineers which is still influential to this day (Johnson, 1963).



Simple Machines such as the wedge, wheel, screw, inclined plane, pulley and lever were primarily constructed from wood and metal
Images from *A History of the Machine*, by Sigvard Strandh

A century later, building upon Polhem's work, the German engineer Franz Reuleaux, who is often called the father of kinematics, developed a compact symbolic notation to describe the topology of a wide variety of mechanisms. He believed that machines could be abstracted into chains of elements constrained in their motions by adjacent parts in the kinematic chain. Reuleaux showed how they could be classified and eventually lead to the invention of new useful mechanisms.

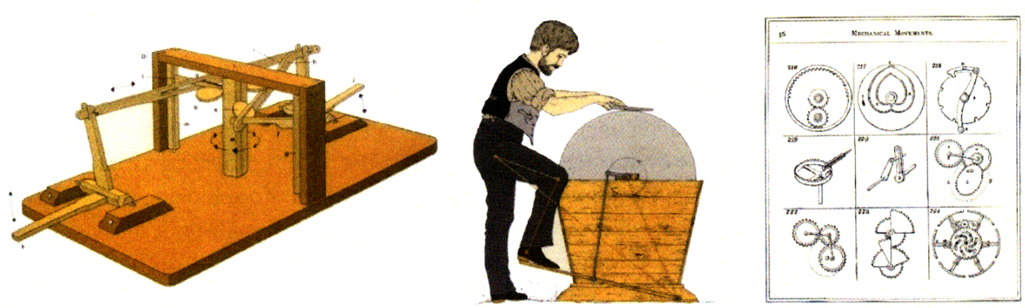


Illustration of Polhem's machine elements (left and center) and Reuleaux's mechanisms (right)
Images from *A History of the Machine*, by Sigvard Strandh

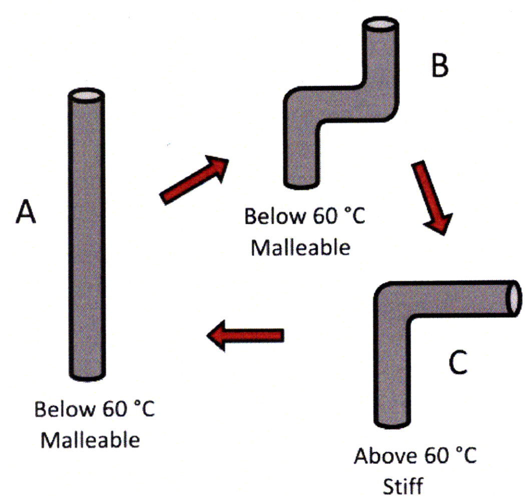
In an attempt to create an encyclopedia of machine elements, which could support and guide the design of more complex kinetic systems, these engineers tried to exhaust all the possibilities in which simple machine elements could be combined to transform forces from one form into another. However, Polhem and Reuleaux's machines were designed to be primarily constructed from materials such as wood or steel, where material rigidity and strength are desirable qualities (Strandh, 1988). Building upon the ancient s*imple machines*, their designs were predicated on the assumption that its mechanical elements are rigid, and that variations on their flexibility and shape will hinder their functionality by adding unnecessary friction or stress where they are not desired. However, this material restriction is no longer relevant and inherently constrains alternative actuation possibilities. Shape memory alloys (SMAs) and polymers allow machines to be built out of soft and malleable components, driving their actuation from changes between different shape memories and elasticity states. As a consequence, by inventing new shape changing materials and new ways to control and use them, we can dramatically alter the ways in which we design kinetic systems.

Soft Mechanics

Soft mechanics is a new research area in the field of developmental robotics, which encompasses flexible structures, control and information processing. In the context of this thesis, *soft mechanics* refers to mechanical systems based on the use of shape changing materials and their composites, which generate kinesis via transitions through different shape memories and elasticity states (Yokoi, Yu, & Hakura, 1999).

The following diagrams provide a brief illustration of how the elasticity and *active memory* of an SMA can be used in combination with other materials' *passive memory* to create composites with different shape changing properties.

Shape Memory Alloy and Silicone Composite



In this example, an SMA strand, which has an *active shape memory,* is embedded within silicone, which has a *passive shape memory,* to create different shape change configurations:

> (A) During the SMA's martensitic phase, silicone gives the composite the straight shape in which it was originally cast, controlling the composite's shape. Silicone is a polymer and, in spite of its low elasticity modulus, its cross links give it a memory shape;
>
> (B) While the SMA remains in its malleable martensite phase, an applied force can modify the composite into different shapes but needs to remain in place to hold this shape configuration;
>
> (C) The SMA is heat activated, making the composite stiff and bringing it to the SMA's memorized L-shape; finally, when the SMA is cooled back to its martensite state, the silicone springs it back to the initial straight shape.

Besides taking into account these memory and elasticity properties, designers working with shape changing materials also need to consider how external forces, such as gravity, might affect materials kinesis and shape transformation. Although these are not explored in detail in this thesis, the discussion on *Surflex's* limitations in chapter 6 explains how gravity can severely limit the scalability of a transformable surface which relies on material properties to change shape. Additionally, the composite techniques and materials used can considerably affect shape change and I will discuss these in more detail in *Sprout I/O's* engineering section in chapter 7.

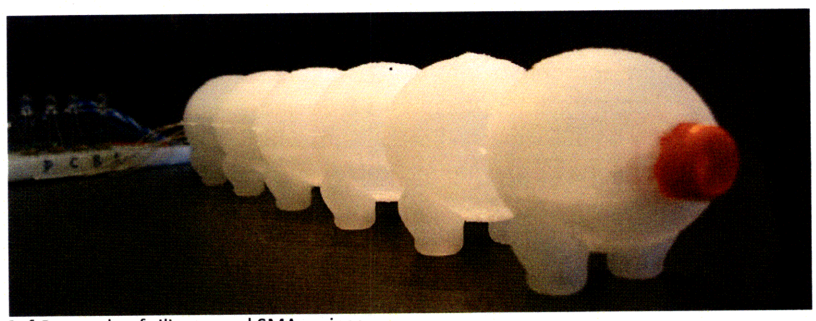
Soft Mechanics Applications

Soft mechanics is a naturally occurring and powerful design approach for situations where physical adaptability and malleability are necessary. Sea cucumbers, for instance, like other echinoderms, have the ability to rapidly and reversibly alter the stiffness of their inner dermis by secreting a substance which regulates the stress transfer between adjacent collagen fibrils. This change occurs within seconds and serves as a defense mechanism which increases their survival advantages. This ability has inspired the development of a family of polymer nanocomposites, which recreate a similar chemoresponsive mechanic adaptability and could eventually come to support promising biomedical applications as adaptive substrates for intracortical microelectrodes (Capadona, Shanmuganathan, Tyler, Rowan, & Weder, 2008).

Traditionally, research into the mechanical control of flexibility was limited to the fields of flexible manipulators and structures. This eventually grew to include control and information processing, opening up novel possibilities for the construction of soft biomimetic robots that can be squeezed flat to reach inaccessible places and then regain their shape.

Sea cucumber in a relaxed (left) and stiffened (right) state
Images from Capadona et al.

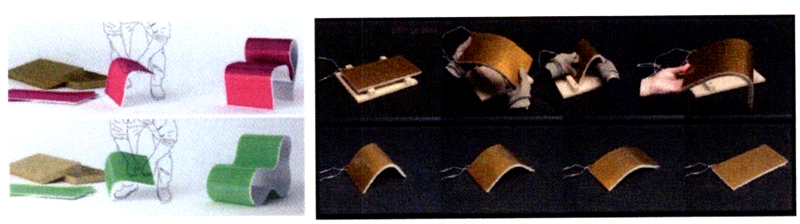
A compelling example is *SoftBot*, a robot inspired by the tobacco hornworm caterpillar and composed of silicone rubber segments lined with SMA wires which cause the rubber to bunch up and then return to its original shape, thus moving the robot forward. In designs such as this, joints do not restrict movements, but rather allow soft-bodied animals and robots to crumple, compress and rotate body parts to move in complex and confined three-dimensional structures such as tubes and branches (Trimmer, Takesian, Sweet, Rogers, Hake, & Rogers, 2006).



SoftBot made of silicone and SMA springs
Image from Barry A. Trimmer et al.

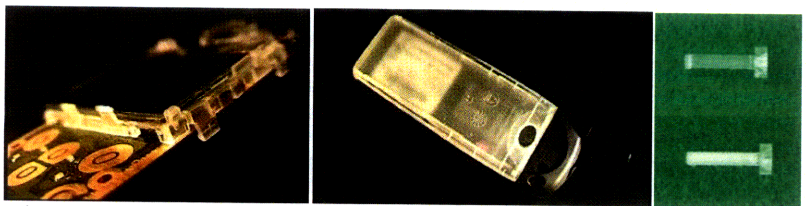
More recently, the application of soft mechanics has been leaving specialized fields and getting closer to the needs of end users by supporting applications such as adaptive furniture, active disassembly in cell phones and kinetic clothing.

In furniture design, shape memory polymer has been used to create an adaptable chair which is purchased as a flat sheet, saving on transportation and assembly costs, and once delivered to a customer can be electrically controlled to gain different shapes (Fan & Schodek, 2007).



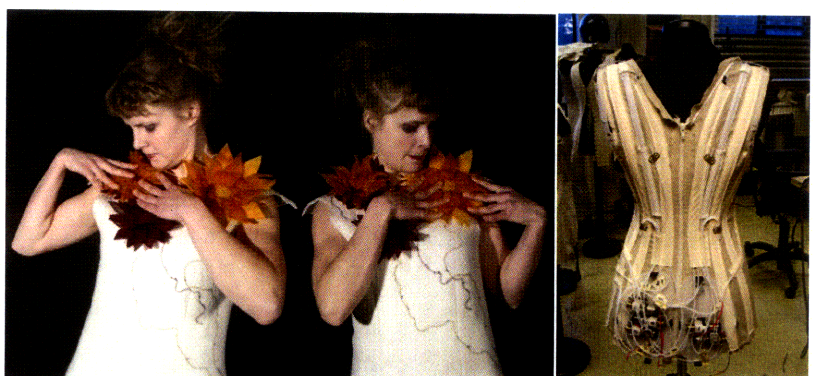
Reconfigurable chair design concept and SMP composite tests
Images from Jeng-Neng Fan and Daniel Schodek

Nokia has used a similar approach to develop cell phone components which can change shape to disassemble without any external actuators, using only a battery's residual charge. On the left and center images below, the cell phone hinges open when heat activated and, on the right image, the screw threads disappear when heated making them easier to remove. Active disassembly can not only eliminate the need for extra labor during recycling but also facilitate the reuse of components which can repeatedly transform into different shapes (Chiodo, Billett, & Harrison, 1999).



Nokia SMP prototypes for active disassembly
Images from Nokia Research

Finally, Kukkia is a garment which implements soft mechanics as a way to generate kinesis and preserve the softness and malleability of textiles, supporting more appropriate affordances for our soft skins while allowing for additional functionalities (Berzowska & Coelho, 2005). Alternative approaches rely on bulky mechanical systems which make kinetic garments uncomfortable and impractical for everyday use.



Kukkia's kinetic flowers (left) and Hussein Chalayan's 'animatronic couture' (right)
Images from XS Labs and Technology Review

But how can shape changing materials and soft mechanics provide the underpinnings of physically transformable interactive systems? In the next section I will begin to sketch an answer to this question by looking at how we perceive and interact with physical forms through their surfaces and how these surfaces can physically transform from one shape into another.

From Materials to Surfaces

> *"We are drawn to surfaces for their reality.*
> *Surfaces define form;*
> *Form reflects utility and history."*
>
> – Felice Frankel and George M. Whitesides, 1997

Ever since Donald Norman introduced the term affordance into the HCI community – a term originally coined by the perception psychologist James J. Gibson in 1979 -, it has been seen as a concept which can lead to improved usability and the inevitable enrichment of our interactive experiences. Norman defines affordances as action possibilities which are readily perceivable by an actor and, while many other interpretations have derived from his, they have in common the idea that affordances invite, guide and limit users to particular actions (Norman, 1990).

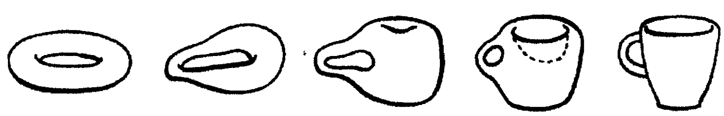
When we interact with the physical world, affordances are a product of properties, such as form, texture or color, which we extract and interpret from the surface properties and topologies of things. Most of the discourse on the nature of surfaces focuses on two aspects: surfaces as theoretical abstractions and surfaces as physical entities, grounded in our experience of the physical world. In general, a person's idea of a surface develops through a process of visual and tactile observation and interaction, making itself clear only in contrast with things which are *not* a surface. As Mark Taylor points out "surface of a lake generally means the uppermost layer of water; a shadow has a boundary and an edge, but no surface; and we withhold surface-talk from water that does not lie smooth, such as when gushing or spraying" (Taylor, 2003). Surfaces are also discussed relative to the operations performed on them – painting, carving, finishing, etc – as well as the materials manipulated by these operations. We can also identify surfaces through their haptic qualities – soft, smooth, cold, etc – or their spatial relationships – surfaces on the wall, floor or enveloping objects.

Without diving into the philosophical problem of perception through a discussion of how we define and perceive surfaces, they are relevant here as the boundaries through which we interact with things, where things end and begin, separating them from space, other things and ourselves. Ultimately, surface boundaries define physical forms and how we perceive and interact with their transformation. But how can we extend beyond simple material changes to build complex transformable surfaces? A place to start looking at this is at how surfaces can be deformed to make up complex shapes.

At a basic level, surfaces are very simple and only have four distinct shapes: flap, convex, concave and saddle-shaped (a combination of concave and convex). At a convex point, a surface curves like an egg, at a concave point it curves like the inside of an egg and at a saddle point it curves like a horse's saddle providing a smooth transition between convex and concave regions (Hoffman, 2000). Combining these four surface types and manipulating their direction of curvature, we can create any physical form and transform it, as long topological equivalences are preserved.

Surfaces shapes: flat, convex, concave and saddle-shaped

In mathematics, surfaces capable of transforming into one another are considered to be homeomorphic or topologically equivalent. Intuitively, two spaces are topologically equivalent if they can be continuously stretched and deformed into another without cutting or sticking distinct parts together. A common example is the topological equivalence of a donut and a mug. A sufficiently pliable doughnut could be reshaped to the form of a coffee cup by creating a dimple and progressively enlarging it, while shrinking the hole into a handle, without the need for cuts or gluing parts together. Homeomorphism places a considerable limit on the number of possible transformations a surface can support, but it also reveals the physical constraints we encounter when designing transformables surfaces without having to resort to constructive or destructive processes, such as punching holes or stitching surfaces together.



A pliable doughnut can be reshaped into a cup in a homemorphic transformation
Image from *Animate Form*, by Greg Lynn

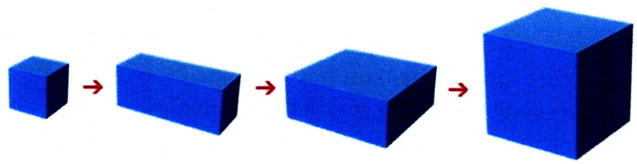
In the digital realm, these limitations do not exist and a surface is generally regarded as a two-dimensional programmatic field without thickness or bulk: an "immaterial and pliable two-dimensional datum with no depth or internal structure" (Taylor, 2003). Digital surfaces are unconcerned by gravity, construction and traditional oppositional distinctions between surface and structure, but in reality things are quite different, and physical surfaces need to account for their topological and material limitations, as well as external forces.

Based on these constraints and in a similar fashion to how Polhem and Reuleaux extrapolated their mechanical alphabets from the *simple machines*, form transformation can be derived from the two basic ways in which materials deform: *compression* and *elongation*, which can take place in any three-axis configuration and can be combined to create complex curvatures.

Soft Machine Alphabet

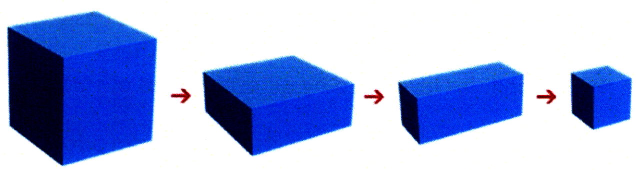
The following examples are an initial sketch for a *machine alphabet* for form transformation. They show several variations of how compression and elongation lines can be combined to build simple shape changing elements.

Single Elongation



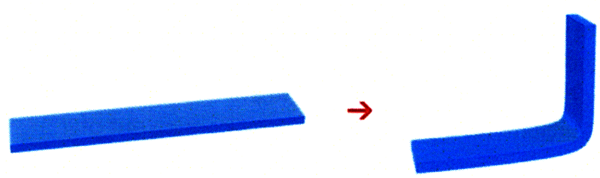
Cube consecutively elongated in one, two and three dimensions

Single Compression

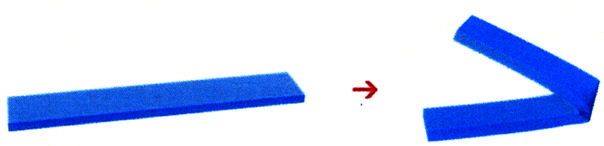


Cube consecutively compressed in one, two and three dimensions

Combined Compression and Elongation

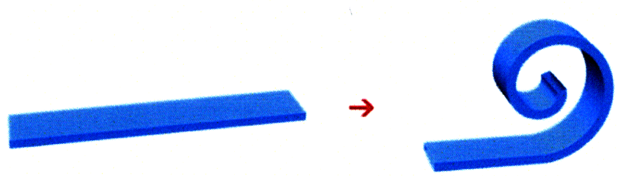


A single orthogonal line of compression and elongation makes ribbon bend

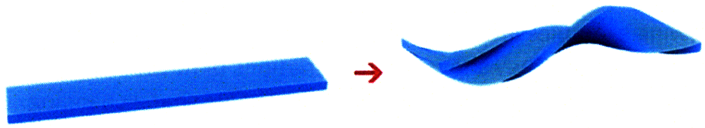


A single diagonal line of compression and elongation makes ribbon twist

Series of Combined Compression and Elongation Lines



A series of parallel orthogonal lines of elongation and compression
make the ribbon curl



A series of parallel diagonal lines of elongation and compression give the ribbon a helical shape

These transformations can be easily and quickly scaled to support the design of more complex surface changes. It is not difficult to imagine a future where designers will be able to create three-dimensional transformable surfaces by digitally drawing their initial and final states. Specialized morphing software will then pick the simplest compression and elongation elements required for building a single surface capable of physically transforming between the two states. However, due to material and homeomorphic constraints, there might still be limitations on what transformations might become possible one day. The design of *Surflex*, *Sprout I/O* and *Shutters* are partially motivated by these constraints and the possibilities leveraged by different *types* of surfaces.

Surflex proposes a material architecture in which a surface can adopt different topologies by combining compression and elongations in the principal directions, much alike NURB-based digital surfaces. Its design is limited in two particular ways: the actuation strength of its materials and the fact that it cannot break its homeomorphic continuity.

Sprout I/O, on the other hand, focuses on changing the tactile and visual qualities of the surface through a shape changing texture, rather than its overall topology. The lines of compression and elongation in this case are not on the surface itself, but on small protrusions coming out of it.

Finally, *Shutters* breaks the surface continuity by using small controllable perforations to modulate the permeability between two spaces. Similar to *Sprout I/O*, it can be used as a kinetic display, but one which uses the negative space of apertures to show images.

These topological distinctions are relevant here in so far as they hint at how homeomorphic deformations can hinder or support the design of shape changing surfaces that foster new interaction possibilities. The application of shape changing materials is still crude and the transformation of physical forms still needs to develop an expressive language of its own. In the next section, I describe how the physical properties and interrelations of soft mechanical elements can be pierced together into an expressive language for designing with form transformation.

A Language of Transformation

> *"Ignorant of the fact that the photographs of all the various forms were in fact pictures of the same thing – a single lump of material metamorphosed into different forms – they imagined variety and difference where there were none."*
>
> — Vik Muniz, 2005

Today, state of the art technology for form transformation is embodied in the special effects and parametric design tools of computer animation. In these virtual spaces, form can be created, destroyed and transformed to tell stories or solve dynamic engineering and design problems.

In recent years, tangible interfaces have started to make use of shape change as a way to communicate and allow users to manipulate digital information. While most of these interfaces provide interesting interactive possibilities, we have just begun to scratch the surface of how to use form transformation as a tool for communication and expression.

Far from falling into the mistake of trying to develop a framework to define and encapsulate the use of form transformation, I am particularly interested in identifying some of the elements that make up shape change and how they provide new and unique properties for the design of tangible interfaces. A complex language of transformation will eventually emerge over the years. As Rikard Stankiewicz points out in *The Concept of Design Space*:

> *"There has always been a considerable tension between engineering science and practical engineering, which has always included a strong element of craft. But that is not the whole story. The creation of an effective design language requires a different type of conceptual development -- one that is capable of reducing the vast complexity of technological design spaces to manageable forms. "First principles" modeling of complex systems tends to be quite impractical. Effective design work requires 'high level' languages which cannot be logically deduced from lower ones, and must be allowed to evolve in their own right."*

Systems are in their essence a unified set of related and interdependent elements which operate under certain principles and help create a relationship among the parts. While in the sciences, principles may take the form of physical laws and mathematical prepositions, in the arts they oscillate between cultural conventions and formal limitations.

A key principle in form transformation is that for physical things to change shape, they need to transition from an initial to a final state over a certain period of time.

Additionally, these forms need to be composed of individualized transformable elements which, acting in unison, allow the transformation to advance from an initial to a final state. This is akin to building a conventional machine where the individual mechanical elements are put together into cohesive whole working towards a common goal. When put together into a temporal sequence, the individual elements serve specific functions and can advance or deter the development of a transformation towards its final state.

This dichotomy between the elements and the whole and their unraveling over time forms the basis for advancing physical transformations and developing meaningful interactions. By extensively exploring how these elements can act together, we can start to understand how they can be used to express ideas and communicate. According to their temporal relations, the elements of form transformation can be manipulated through:

Temporal order: The sequence in which an element's transformation precedes, follows or parallels another. Different sequences lead to different transformations, conveying new meanings or interaction possibilities.

Temporal duration: The transformation of every element, as well as the overall transformation of a complete system, happen in a certain time span and eventually end.

Temporal frequency: Since transformations exist within a timeframe, they can also be repeated at a specific frequency and intervals. Moreover, they can be unidirectional — shape goes from one state to another — or multidirectional — shape oscillates between two or more states.

One constraint of these temporal relations is their physical limitation. Transformable forms which exist in the physical world need to progressively transition from one shape to another, and cannot simply 'jump' from a state to the next. This raises an interesting formal question: how could forms hint at future forms without necessarily becoming them? Or to phrase it in another way, how can forms do flashbacks and flash-forwards to create suspense, hide or reveal information from a user without breaking their main 'narrative thread' of transformation?

Another important aspect to consider is how the physical transformation of individual elements can be combined to form a cohesive whole.

Similar to how scenes in a movie propel a story towards an inevitable conflict resolution, every soft mechanical element can advance or hold back the progression of a physical transformation, either directly or indirectly, by supporting other elements that do so. According to their developmental relationships, the elements of form transformation can be grouped under:

Similarity and Repetition: Similar to beats in music or meter in poetry, repetition and similarities establish a pattern of development and satisfy a user's expectations. Moreover, through recurring motifs and parallelism, they can bring temporal cohesion to a transformation (either physical or narrative).

Difference and Variation: A transformation made only of repetitions would hardly engage any user. Difference and variation advance a transformation by introducing changes, distinguishing elements and creating side-by-side juxtapositions or large scale patterns. Repetition and variation are two complementary artifices and by shuffling between the two it is possible to develop motifs and parallelism, as well as reinforce crucial variations.

Unity and Disunity: Unity and disunity are a matter of the degree to which elements support the overall transformation or narrative being told. A system of transformation is created from all elements acting together and if certain elements appear to behave in disagreement with others this gives the impression of disunity and incoherence. Unity and disunity are formal choices that can confuse, suggest external elements, break diegesis and generate expectation or surprise.

Form Transformation in HCI

In this section I look at the different ways in which users can interact with form transformation and how it can be used as a tool to enrich human-computer interaction.

As far as interaction affordances are concerned, form transformation can be described as shape changes which occur in an object or space and can be perceived and acted upon by a user. Therefore, users can *perceive* shape changes in four distinct ways:

(1) The overall shape of an object or space is transformed and a user can perceive these changes by seeing or touching them, as in the case of *Surflex*;
(2) Only the external surface quality is transformed affecting its tactile and visual properties while preserving its overall form, as in *Sprout I/O*;
(3) A transformation can affect external elements, such as shadows or airflow, through which the user perceives changes, as in *Shutters*;
(4) Any permutation of these possibilities can be combined to create different effects.

Additionally, users can *act upon* an object or surface to cause them to change shape. In response to a deformation exerted by a user, transformable shapes can develop the following kinds of interaction with a user:

(1) Objects can gain a new physical shape and the transformation mapping between input and output can be amplified, dampened, modulated, or simply remain the same;
(2) Objects can respond with force-feedback and counteract the user's deformation;
(3) Objects do not respond at all, recording the user's action and applying it in some other place or context;
(4) Objects can constrain and limit the deformation imposed by the user.

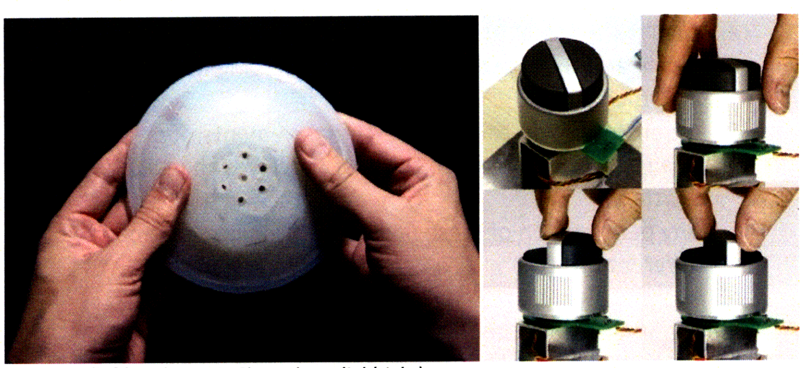
Finally, while developing this work, I have identified three ways in which shape changing interfaces can be used to support more intuitive human-computer interfaces.

Dynamic Forms Reveal Dynamic Functions

As previously discussed, surfaces and form play a great role in how we construct an object's affordances, telling a user how to touch, hold and use an object or a space. But as forms become dynamic they start to reflect dynamic functionalities.

A relevant example is *SpeakCup*, a voice recorder in the form of a soft silicone disk with embedded sensors and actuators, which can acquire different functionalities when physically deformed by a user (Zigelbaum, Chang, Gouldstone, Monzen, Ishii, & Hiroshi, 2008). When molded into a cup, *SpeakCup* becomes a vessel for recording sound; however, when deformed into a convex shape it replays the recorded sound, releasing it back to the user. Form in *SpeakCup* not only communicates different functionalities, but it is also used to trigger different events, in this case, recording or reproducing sound.

By changing shape, an object can also adapt to changing tasks and goals, gaining personalization or new functionalities which could have not been predicted a priori, as in the case of Fan and Schodek's shape memory polymer chair described earlier in this chapter.



SpeakCup (left) and *Haptic Chameleon* dial (right)

Dynamic functionalities do not always need to be complex. *Haptic Chameleon* is an example of a dial for navigating video content which can change shape to communicate different functionalities to a user. For instance, while a circular dial advances a video continuously (frame-by-frame), a rectangular-shaped dial advances it scene-by-scene (Michelitsch, Williams, Osen, Jimenez, & Rapp, 2004).

Dynamic Forms as a Physical Representation for Dynamic Data

Another example of the use of form transformation in human-computer interaction is the case of physical shape as representation for dynamic data. Shape changing interfaces can communicate and be used to manipulate information in three main ways: (1) acquiring new forms which in themselves carry some kind of meaning; (2) using motion as a way to communicate change; and (3) providing force-feedback to a user.

Although not a direct example of form transformation, *Actuated Workbench* uses electromagnets to move physical tokens across a table reflecting changes in the digital information these tokens are supposed to represent. Co-located input and output in this case is important to approximate and prevent disconnects between data and their physical representation (Pangaro, Maynes-Aminzade, & Ishii, 2002).

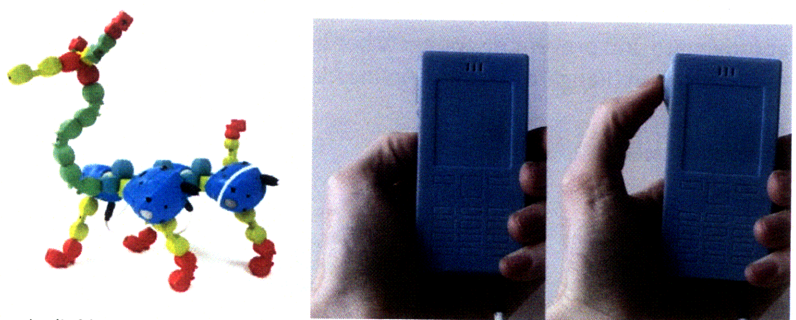
Actuated Workbench revealing the array of electromagnets (left) and *Source* displaying the word 'London' (right)

Moreover, form can be used to communicate the current state of an object or some external information completely unrelated to the form and context of the object. *Source* and *Lumen* are examples of displays that use kinesis as a way to simulate shape change and display information. *Source* allows direct creation of low-resolution 3D objects hanging in space by controlling the position of 729 balls suspended on metal cables and forming a 9×9×9 spatial grid (Source, 2004). In the particular case of Lumen, discussed in chapter 6, shape change can communicate data to a user visually or through tactile feedback (Poupyrev, Nashida, & Okabe, 2007).

Dynamic Forms Guide and Limit Dynamic Physical Interactions

The last scenario in which form transformation can support user interaction are situations in which controlled shape changes can guide and limit physical interactions. Physical constraints are sometimes pointed out as being the greatest drawback of tangible interfaces when compared to the more versatile graphical UIs (Michelitsch, Williams, Osen, Jimenez, & Rapp, 2004). However, these constraints can help a user learn an interface or system; they can also be catered to support specific tasks or goals; and, as explained above, physical limitations in shape and movement can portray limitations in digital data.

Topobo is an example of a construction toy which uses motion, kinetic memory and the constraints and relationships of its parts to teach children about balance, relative motion and coordination (Raffle, Ishii, & Tichenor, 2004). Another example is *Dynamic Knobs*, a cell phone prototype whose button can change size to indicate the length of a voice message or simply disappear when no message is available, guiding and limiting how a user interacts with the device (Hemmert, Joost, Knörig, & Wettach, 2008).



Topobo (left) and *Dynamic Knobs* (right)

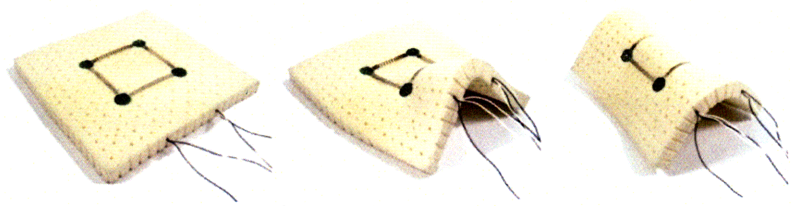
These scenarios are in no way supposed to exhaust all possibilities in which form transformation can be used in human-computer interaction. They are used here to give examples of how, in spite of their tangibility and inherent limitations, transformable physical forms present great advantages over their digital counterparts or similar physically static equivalents.

In this chapter, I have described how shape changing materials can provide new opportunities in human computer interaction. In the following three chapters, I will describe *Surflex*, *Sprout I/O* and *Shutters* and how they implement some of the soft mechanics ideas described so far.

6 Surflex: Topology

Designers and engineers have always struggled to ease the transition between their ideation and fabrication processes. With the advent of computer aided design, a great deal of this effort has focused on overcoming the material limitations and idiosyncrasies imposed by the physical world while preserving the programmability and volatility of digital forms. However, as long as materials are considered for their static nature and behaviors, this problem will continue to exist.

In an effort to address this issue, I have applied the soft mechanics concepts discussed in the previous chapter to develop *Surflex*, a transformable and programmable physical surface for the design and visualization of digital forms. *Surflex* combines active and passive shape memory materials, specifically shape memory alloy (SMA) and foam, to create a surface that can be electronically controlled to deform and gain new shapes. Moreover, by examining how topologically equivalent transformations can be recreated in the physical world, it will hopefully help pave the way for making form transformation a reality.



Surflex's surface deformation in three steps

Surflex is still at an early prototype stage, but the development of its hardware architecture has so far provided insightful information on the material, electronic and topological limitations that need to be overcome in order for programmable tangible surfaces to become a ubiquitous reality.

In this chapter, I will discuss related work, the design principles and motivations behind the development of *Surflex,* its architecture, some of the material and electronics challenges encountered, and I will speculate on future applications and possibilities for this technology.

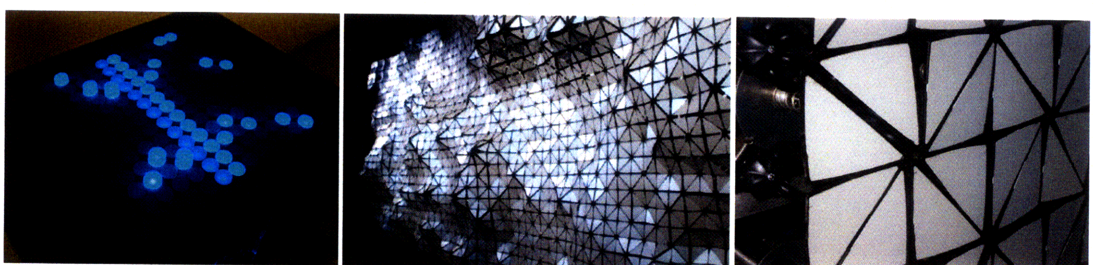
Related Work

The paradigm of ubiquitous computing has for some time strived to blur the boundaries between computation and materiality. While digital information can be copied, deleted and transformed innumerable times without decay or expense, designers and researchers are faced with the electromechanical constraints of kinetic systems and finite physical resources which break and wear over time.

Nonetheless, our form giving practices have come a long way in overcoming the limitations imposed by physical materials. Today artists and designers have at their disposition a variety of additive and subtractive fabrication techniques, such as laser sintering or CNC milling, to visualize and physically create virtual objects at high resolutions. These techniques rely on computationally controlled additive or subtractive processes, which either add or remove successive layers of materials to give form to an object. While these fabrication processes can support almost an unlimited control over the fabrication of digital forms, once objects are materialized they lose their digital and computational possibilities. They cannot be easily modified to accommodate revisions or reuse of materials and, most importantly, physical changes in a printed model are not directly updated in its virtual correlate.

Marcel Wanders' Snotty Vases: a 3D scan of the fluid droplets emitted by someone sneezing

To address this issue, researchers have sought to create kinetic surfaces and interfaces for physically manipulating and visualizing digital information, with the goal of creating tangible objects and spaces more akin to the transient nature of digital objects. One striking example is Mark Goulthorpe's *Aegis Hyposurface*, a kinetic wall-sized surface constructed out of interconnected metallic plates and actuated by an array of pneumatic pistons, which can display evolving patterns or texts three-dimensionally and at a high refresh rate (Goulthorpe, 2000). Another example at a smaller scale is *Lumen*, a kinetic display consisting of plastic rods embedded with LEDs, which can be raised and lowered to display kinetic and visual images (Poupyrev, Nashida, & Okabe, 2007).



Lumen by Ivan Poupyrev (left) and *Aegis Hyposurface* by Mark Goulthorpe (middle and right)

In spite of the possibilities they offer, these technologies are inherently limited by the fact that they mimic surface deformations with an array of linear actuators mounted on an external plane, rather than embedding the actuation in the moving surface itself. This choice limits the shapes and angles of curvature they can create to a small set of topological transformations making it impossible, for instance, to wrap the surface around objects and bodies.

Another example is the shape changing composite developed by Robert J. Lind and Charalabos C. Doumanidis. By embedding a parallel array of SMA wires into neoprene foils, they controlled the degree of deformation of a surface; however, their design only implemented a one dimensional deformation rather than the two necessary to make a complete shape changing surface (Lind & Doumanidis, 2003). Similar implementations have also have also made their way into airplane wings and helicopter blades, which morph to reduce drag and improve their efficiency (Mabe, Calkins, & Ruggeri, 2007).

Surflex is unique in that the hardware necessary to make the surface change shape is embedded in the surface, rather than being attached to a separate structure. Additionally, *Surflex* uses the changes in the physical properties of its materials to generate kinesis and generates deformations in two dimensions. Being reversible and electronically controlled, *Surflex* is a step forward towards creating an interface for manipulating surfaces with the same fluidity we have when designing virtual objects and spaces. More importantly, it can sustain a direct link from the digital to the physical world and back, without giving away computation precepts in exchange for physical affordances.

Design Principles

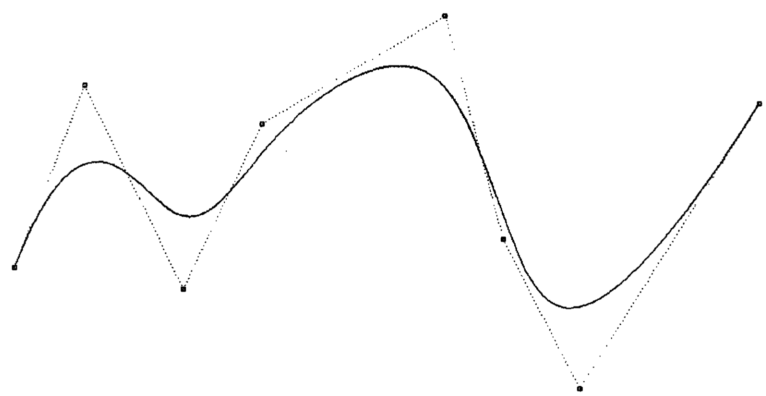
Before diving into the engineering details behind *Surflex*, I will revisit some of its guiding principles and how the properties of digital surfaces correlate to the behavior and constraints of real world materials.

Points, curves and surfaces are the basic geometric elements used to create and manipulate three dimensional objects on a computer. Today most modeling softwares use primarily two different approaches for creating and manipulating these three-dimensional surfaces: NURBs and polygons. Both geometries start from connecting points in a three dimensional space but radically differ in how they make up and control these surfaces. Polygons are shapes defined by vertices that create three, four or n-sided surfaces which appear flat. Polygonal objects are made up of many polygons and the normals across adjacent faces are interpolated to make the object appear smooth. To deform a polygonal object, it is necessary to modify the angle connecting different surfaces while stretching and contracting them to account for the topological changes. *Hyposurface* compensates for this problem by permitting small gaps to increase and decrease in between its triangular tiles. The drawback of this approach is that it does not map well to the reality of objects which need to maintain their physical integrity while being deformed.

Boeing draughtsman (left) and spline ducks (right)

NURBs on the other hand are based on splines, which are piecewise polynomial parametric curves manipulated by control vertices located outside of the curve. Splines originated from the wood and rubber rulers used by draughtsman, which due to their intrinsic properties created perfectly symmetric curves under tension. These rulers were held in place by weights called spline ducks and by manipulating their position and rotation it was possible to draw different complex curvatures.

In computer-aided design, three-dimensional surfaces are made from a combination of splines oriented in opposing U and V directions and their curvature is manipulated by pulling and tilting the spline's control vertices.



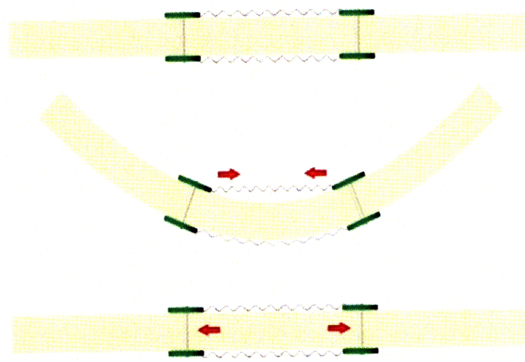
Curve with external control vertices which define its shape

In order to build a physical spline-based curve, these control vertices cannot float autonomously and need to be either located on the surface itself or embedded inside of an object wrapped by the surface. To avoid some of the same limitations encountered in previous work, *Surflex* takes the first approach and uses an array of compressions and elongations to change shape, as explained in the previous chapter. SMA strands arranged in opposing U and V directions pull the surface's vertices together, which in this case are small circuit boards attached to the surface itself, while the foam's passive shape memory pushes the SMA strands back to their original shape. Their combination allows for a range of surface deformations similar to the ones we find in virtual surfaces. The following section covers *Surflex's* engineering aspects in more details.

Engineering Surflex

Surflex is constructed from 1" foam which can return to its original shape after being compressed. This substrate is pierced by 4 assemblies of 2 printed circuit boards (PCB) each, which are connected to each other through 8 SMA springs arranged on an x,y grid.

Surflex works by counteracting the contraction force of the SMA strands with the ability of the foam to return to its original shape. Through resistive heating, it is possible to electronically control the temperature of the SMA springs to make them contract. Since the boards on both sides of the foam are attached to each other, they cannot move in relation to the foam, and the contraction of the SMA springs cause the surface to warp.



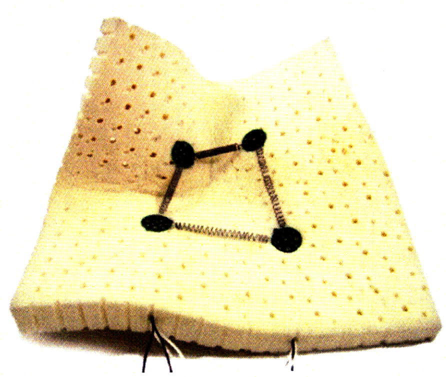
Deformation process: (Top) *Surflex* at its initial state when the SMA springs are malleable and the foam gives *Surflex* its shape; (Center) Upper SMA springs contracts through resistive heating, pulling the PCB assemblies together and curving the surface; (Bottom) After the SMA spring is unpowered and cools down, it becomes malleable again and the foam pushes it back to its original shape.

Combining horizontal (x) and vertical (y) compressions, it is possible to bend the foam composite into any shape in the z-plane. When the SMA cools down to ambient temperature and reaches its 'malleable' martensite (M_f) state, the foam becomes stronger than the SMA and forces the composite back to the foam's 'memorized' state.

This surface deformation architecture can also be applied to materials other than foam, dramatically increasing the range of materials properties, textures and surface qualities from which we can build tangible interfaces.

Morph Units

In this prototype, I implemented an array of 8 SMA springs which can generate a virtually unlimited number of surface deformations from 256 combinations of actuation.



In this arrangement the display unit is described by the amount of deformation it can cause on a surface, rather than by the wavelength, luminosity and viewing angle of the individual pixel.

Detail of circuit board and SMA spring

In the case of *Surflex*, every *morph unit* is composed of two horizontal and vertical SMA spring on each side of the foam, totaling four strands, and its display range is a measure of the angle of bend of the substrate – from 0 to 360 degrees in both x and y planes. For example, by combining small angular bends of sequential units, *Surflex* could create a curve with a large radius, while a series of sharper bends could cause the surface to wrap around itself.

Power and Control

Passive Control Nodes: To deliver power to each one of the SMA strands, *Surflex'* current design uses a multiplexing grid embedded in the foam and diodes placed on the PCB nodes to prevent the SMA grid from acting as a resistor network. This approach reduces the complexity of the connecting nodes, but increases the amount of connections between the controller circuit and the surface nodes.

Active Control Nodes: Another approach for the construction of *Surflex,* that I plan to explore in the future, is the use of 'smart' power distribution nodes that can communicate with each other wirelessly or through the actual SMA. This would require a sandwich of foam, power and ground electrodes, and nodes outfitted with a microcontroller, current controllers and radio communication. This set-up simplifies the power distribution considerably, but the bigger nodes would limit the surface's miniaturization.

Sensing and Control: *Surflex* is at an early prototype stage and its control circuitry is programmed to cycle through a series of shape-changing animations. Future designs will most likely include some way of sensing the surface's topology and more interesting interactions will become feasible.

Application Scenarios

Currently, I envision two main applications for this technology: the real-time computer modeling of objects and surfaces, and the construction of adaptable interfaces.

Tabletop and Architectural Modeling

As an alternative to subtractive or additive 3D rapid fabrication processes, *Surflex* could be used as a tool for displaying computational models in real time. Designers could make their models in a CAD program and have that design instantly sent to a tabletop *Surflex*, which could reconfigure itself to represent any curve or shape, at different scales and degrees of resolution. Another possibility is modeling at a room-size scale, where a large *Surflex* could serve as walls to a room and quickly update to reflect different space arrangements or acoustic profiles.

Adaptable Interfaces

One application domain for programmable surfaces that also seems promising is the design of physical interfaces that can change shape to accommodate different uses and contexts. By looking at body language, gestures and our human interactions, objects and spaces can learn to adapt to their different conditions of use and respond with *just-in-time affordances*, ultimately supporting more relevant interactions which could not have been predicted by their original designers.

Adaptable Spaces and Acoustics

Programmable acoustics is another possible application, where a person could easily modify the shape of a room according to the sound characteristics they want to amplify or dampen. The acoustic profile of a room could be updated overtime to reflect changes in its usage or it could even be 'played' in a similar way to how a musician plays an instrument.

Design Limitations and Usability Implications

Surflex is still at an early stage, but its current design already reveals certain limitations and the need for additional functionalities.

Shape and Accuracy Limitations

Resolution in this kind of display can be measured as the amount of deformation per surface area that it can generate. In this prototype, *Surflex* has 2 *morph units* per 4 square feet. Shape changing displays with high resolution could be used for modeling small objects, such as a cell phone or a chair, while low resolution ones could be used for large scale architectural models where details are not a requirement.

Gravity

Another important factor which cannot be ignored is the role played by gravity in this design. If *Surflex* were to be hung on a wall, the top SMA strands would have to be strong enough to lift the whole structure, while strands at the bottom would only have to account for the weight of the lower part of the structure. Increasing the actuation force of the SMA would solve this problem, but this would also increase the power requirements and require stiffer foam. Depending on the application requirements, *Surflex* could be hung at different points so that the weight of the whole structure would be evenly distributed.

Topology

Due to its topological configuration, *Surflex* is limited to homeomorphic shape changes and could not create perforations on its surface or stitch any of its edges together. However, actuating two parallel SMA strands compresses the foam without making it bend, which could allow other uncompressed parts of the surface to bulge out and protrude.

Lack of Feedback

Finally, *Surflex'* current prototype has no feedback system that can sense its shape and preserve the correlation between the real physical shape and its virtual representation, if externally applied forces cause the two to go out of sync. A possible solution for sensing deformation across the whole surface could come from embedding an array of optical bend sensors, similar to the ones used in the design of TWEND, an input surface for sensing bend gestures (Herkenrath, Karrer, & Borchers, 2008). This would prevent discrepancies between the real and expected shapes and also allow for more interesting interaction scenarios.

Conclusion

In this chapter, I have proposed a material and electronic architecture for the design of shape changing surfaces. *Surflex* draws its inspiration from the intrinsic properties of spline rulers and combines the shape memory properties of SMAs and foam to create an array of soft mechanical elements.

Surflex suggests a material model through which a surface can transition between different shapes by combining compression and elongations in the principal directions

Apart from solving some of the technical challenges described in this chapter, future directions for *Surflex* include: replacing the foam with an active shape memory material to preserve the surface's shape when it is not actuated; and combining *Surflex* control with a parametrics design software package for real-time virtual and physical modeling.

The next chapter discusses the design of *Sprout I/O* and looks at how a shape changing texture can modify a surface's external appearance and be used for sensing and communication.

7 Sprout I/O: Texture

Our perception of the world is highly informed by the textures and material qualities of the physical objects we interact with. Variations in pressure, shape and temperature are responsible for adding dimension, weight and material composition to the surrounding environment, and most importantly, they allow us to communicate and convey emotion where speech and words are inadequate or insufficient. The textured strokes on a canvas might reveal an artist's process or intentionality, while a friendly touch might provide comfort, support or portray affection. Some surfaces are very inviting to the touch and soothing, such as a rabbit's fur or silk, while others induce a sense of repulsion or emotional distress.

In order to examine the rich textural quality of surfaces and their potential for transformation, I have developed *Sprout I/O*: a haptic interface for tactile and visual communication composed of an array of soft and kinetic strands which can sense touch and move to display images and animations.

Sprout I/O is built from a textile and shape memory alloy (SMA) composite to render a dynamic texture which is responsible for both actuation and sensing as well as the surface's visual and tactile qualities. Rather than focusing on the transformation of a surface's overall topology, shape change in this case is responsible for controlling surface properties at an object's physical boundary with the external world (Coelho & Maes, 2008).

Sprout I/O animation

In this chapter, I will discuss related work, the design principles and motivations behind the development of *Sprout I/O*, potential applications for texturally rich interfaces, some of the challenges encountered in co-locating input and output in an SMA and textile composite, and I will speculate on future applications and possibilities for this technology.

Related Work

Sprout I/O's design has been influenced by a series of technologies, material practices and natural phenomena. Its primary inspiration is drawn from the footprints we leave on a shag carpet or a grass field. By dragging our feet or bodies over these surfaces we can reorient their fibers and light reflectance, creating images that are concurrently visual and tactile.

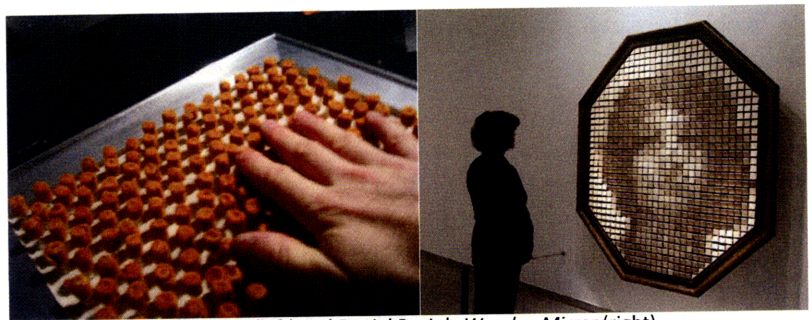
Haute lisse weaving loom at the Gobelin tapestry manufacture

Another source of inspiration, perhaps closer in spirit to *Sprout I/O*, is the long history of tapestry as a decoration and visual display medium. Tapestries have been used since at least Hellenistic times and their imagery ranges from coats of arms and hunting scenes to religious and mythological symbols to be hung for indoor decoration or as a symbols of status and authority. Similar in nature to the addressable grid of pixels on a computer screen, tapestries were traditionally woven by hand on a vertical loom, and unlike cloth weaving where both the warp and the weft threads are visible, their warp threads are hidden, allowing for colorful patterns or images to be created. The unique textural and material qualities of tapestries differentiated them from paintings and, besides their decorative purposes, allowed them to serve several other functions, such as furniture upholstery or wall insulation during the winter.

Texture as means to convey meaning has also been explored by the Surrealists. In the 1930s, artists, such as Salvador Dalí and Marcel Duchamp, were arranging found objects in bizarre combinations that challenged reason and brought together unconscious and poetic associations. The subtle perversity of Meret Oppenheim's fur-lined teacup makes it perhaps the single most notorious Surrealist object. By contrasting its furry surface texture with the insipid qualities of a regular cup, Oppenheim's *Object* "takes advantage of differences in the varieties of sensual pleasure: fur may delight the touch but it repels the tongue. And a cup and spoon, of course, are made to be put in the mouth" (Meret Oppenheim, 2007).

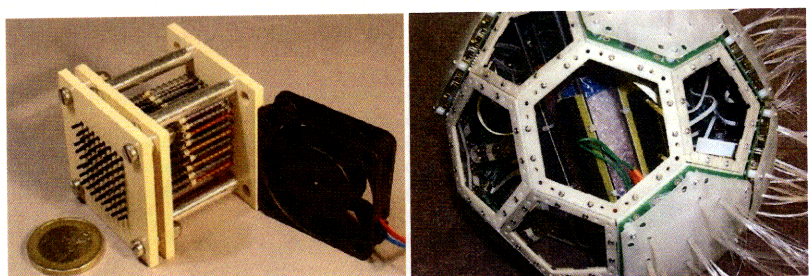
Smiley drawing on a shag carpet (left) and Meret Oppenheim's *Object* (1936) (right)

More recently, dynamic texture has been used as a compelling alternative to current display technologies. Hayes Raffle's *Super Cilia Skin*, for instance, is a texturally enhanced table top membrane that couples tactile/kinesthetic input with tactile and visual output, by moving small felt tipped rods controlled by an array of electromagnets (Raffle, Ishii, & Tichenor, 2004). Another example is Daniel Rozin's *Wooden Mirror,* which uses a grid of small wooden blocks to modulate the lights and shadows cast on them (Bodow, 1999).



Hayes' Raffle *SuperCilia* Skin (left) and Daniel Rozin's *Wooden Mirror* (right)

Another example is *Tribble*, a dense, multi-modal, peer-to-peer sensor network that acts as an electronic skin. *Tribble* is composed of a an array of tiles outfitted with vibration-sensing whiskers, sensors for local pressure, light, sound and temperature, as well as actuators for light, vibration and sound (Lifton, Broxton, & Paradiso, 2003).



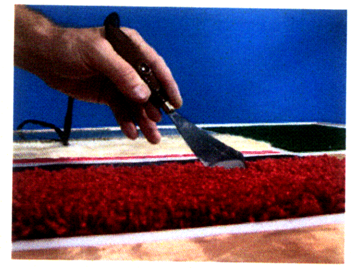
Ramiro Velázquez's SMA-based tactile display (left) and Josh Lifton's *Tribble* (right)

Interfaces that provide tactile output to the visually impaired or richer affordances for manipulating virtual objects abound in haptics research. One example is Ramiro Velázquez portable tactile display. Composed of a grid of 64 SMA actuated pins, which independently move upward and downward, it is connected to a vision system to provide haptic information about the physical configuration of a space indicating to a user where potential obstacles might be located (Velázquez, Pissaloux, Hafez, & Szewczyk, 2005).

While these systems enable a rich set of interaction scenarios, their level of kinesis and material affordances are very limited, since they rely on the use of rigid actuators and surfaces, moving away from the kinetic fluidity and aesthetics of fur or grass. *Sprout I/O* builds upon previous research by embedding an SMA actuator within the movable strand creating a soft and malleable surface that looks and feels like a textile, but behaves like a sensing grid and kinetic display.

Design principles

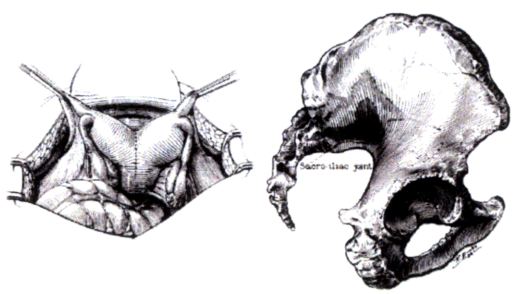
The design of *Sprout I/O* has been driven by the expressive potential of using texture as a way to kinesthetically overlap vision and touch. Additionally, since texture plays a crucial role in how the surface qualities of an object are perceived, it can also enhance or counteract the perception of form.



Sound of Touch, by David Merrill et al., produces sounds from the surface properties of physical materials

Rather than focusing on techniques which simulate different textures to provide information, I am primarily interested in how to build and control dynamic surface textures which preserve a wide range of material affordances and support multiple functionalities. Texture variations can modulate light reflectance, color, and give us audio and visual feedback of how objects react when in contact with one another (Merrill, Raffle, & Aimi, 2008).

In computer-generated images, photographs and directly viewed objects, it is often difficult to adequately perceive the full three-dimensional shape of surfaces. Light incidence, material quality and depth deeply influence how we perceive and interact with the surfaces of objects. Compelling evidence to this difficulty is the fact that medical and scientific disciplines continue to use multiple two-dimensional illustrations to convey the necessary information about a subject or scene (Interrante, Fuchs, & Pizer, 1997).

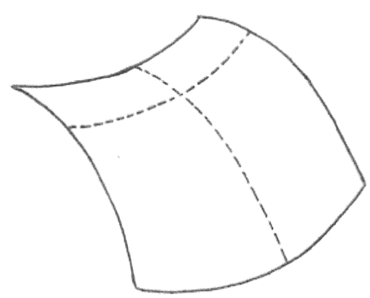


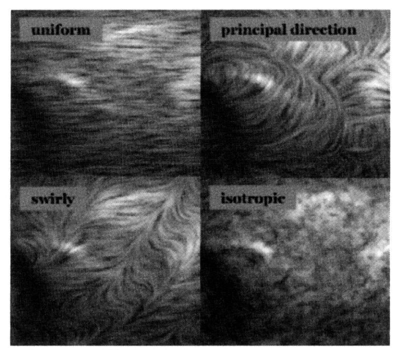
Surgical repair of septate uterus (left) and lumbosacral and sacroiliac fusion (right)
Images from Mayo Foundation

Artists have repeatedly emphasized the importance of texture and stroke direction in line drawings, bringing particular attention to how our perception of forms can be significantly altered by the direction of the lines used to represent them. Crosshatching, for instance, is the technique of laying down a "carpet" of pencil strokes, often crossing at different angles, to create a variety of shading cues in an image that can reveal the 3D shape of a curving surface, as well as enhance its expressive quality.

Cross-hatching
Image from *Drawing with the Right Side of the Brain*, by Betty Edwards

Although there seems to be no definitive agreement in the visual perception literature about the specific properties of a texture pattern that are most effective at conveying three-dimensional shapes, it is fairly recognized that the shape of a smooth curve or slanted plane can be conveyed much more effectively when the surface is textured rather than left plain. Researchers have found that a shape can be more easily identified when overlaid by a pattern with a strong directional component and when the texture is everywhere oriented in the direction of maximum normal curvature, also known as the first principal direction (Interrante, Fuchs, & Pizer, 1997). As explained by Victoria Interrante, "the first principal direction is defined as the direction in which the surface curves most strongly, at a point. The second principal direction is the orthogonal direction in the tangent plane. On an elliptical surface, this will be the direction in which the surface is most flat. On a hyperbolic (saddle-shaped) surface it will be the direction in which the surface curves most strongly in the opposite direction" (Interrante, 2003).



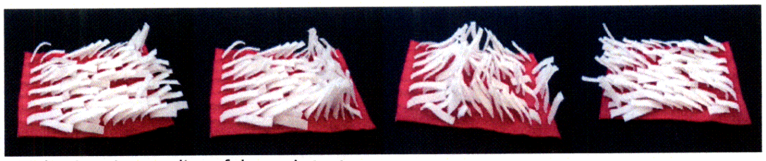


Curve with first and second principal directions (left) and different texture patterns applied to the same three dimensional shape, but rendering different visual effects (right)

In order to replicate some of these properties and support a large set of design possibilities, strands in a dynamic texture should be able to orient themselves in multiple directions as well as be made in different sizes, colors, materials and surface arrangements. The following section looks at different engineering alternatives for developing a dynamic texture and how different material properties affect shape change and a surface's overall dynamic qualities.

Engineering Sprout I/O

Most interfaces struggle to capture and convey the subtleties of human communication, but usually fail at supporting the textural affordances we encounter in the physical world. Part of this problem resides in the difficult electromechanical coupling between sensors, actuators and the materials they control.

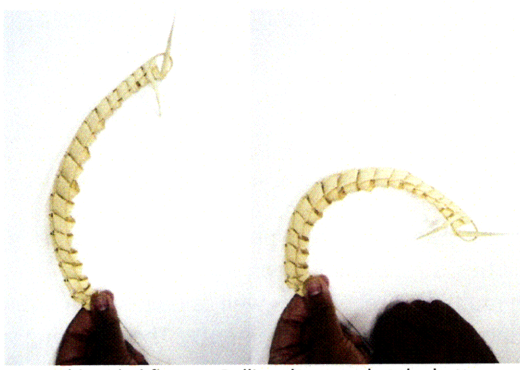


Initial animation studies of dynamic texture

The initial design goal for *Sprout I/O* was to create a soft interface that could sense, mediate and communicate touch in a subtle and non-intrusive manner, taking advantage of textural and surface changes, rather than light emitting techniques. The engineering challenge was to develop a shape changing composite with a small form factor and which, bundled into a large array, could use physical changes to display images or patterns, while preserving its soft properties. The design of *Sprout I/O* has gone through several iterations and implementations, and I will describe some of them here.

Single SMA Strand

An original source of inspiration for the design of *Sprout I/O* strands is a leaf braiding flexure constructed by the Javaés natives in northern Brazil. By slightly pulling one of its stems, this braided structure curves down; when we let go of it, its own structure forces it to bounce back into place, balancing the human actuation with the leaf's material strength.

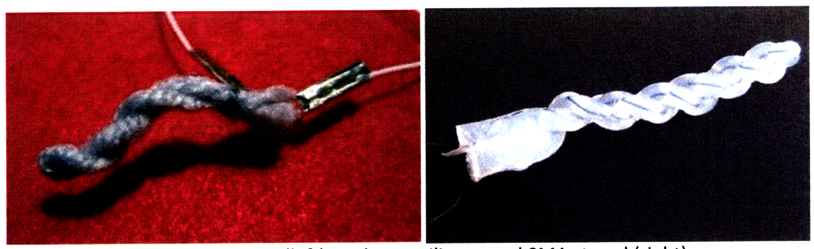


Javaé braided flexure: Pulling the strand at the bottom makes the braided structure curve

As an attempt to mimic this design, I experimented with different techniques where the SMA provides the main actuation force, while the composites' additional material provides the bias actuation force that brings the strand back to its original shape. This technique had proven to be successful in a larger gravity biased scale textile composite, but had not been tried at smaller scales (Berzowska & Coelho, 2005).

Spun Yarns

The first prototype was made from a combination a Teflon spun yarn and SMA. A spun yarn is made by twisting or bonding staple fibers together to make a cohesive thread. By twisting Teflon-wool yarns and a helical-shaped SMA wire, it is possible to create a shape changing yarn which is fire retardant and electrically insulated. Analogous to the Javaés' leaf flexure, this technique allows for a force and counter-force actuation mechanism, where the SMA is activated to curl the fur strand down, while its internal structure forces the strand back up to its original shape. In spite of its electromechanical advantages, this technology has its limitations. The Teflon yarn is affected by increasing hysterisis and over time it starts to 'learn' and retain the shape of the SMA, losing the possibility of counteracting the actuation force of the SMA.



SMA and Teflon-wool spun yarn (left), and spun silicone and SMA strand (right)

Knitting and Polyurethane

In an attempt to remediate the yarn's hysteresis, I also experimented with a knitted composite made of polyurethane, the Teflon-wool yarn and SMA. Knitting is a textile technique in which a thread or yarn is turned into cloth, by pulling loops of yarn through each other. Different knitting structures allow for the creation of cloths with different kinetic and tensile properties which could be used to make a complex, yet fairly soft actuator. The polyurethane was chosen because of its tensile strength and capacity to return to its original shape after deformation. However, this technique proved to be impractical, since the balance between the materials strength was hard to control and could not account for overall variations in fabrication and use.

Spun Silicone

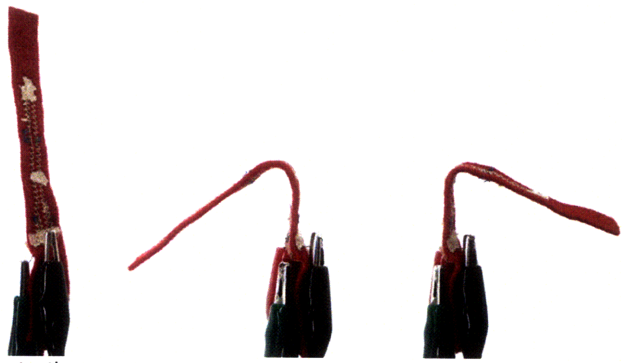
Finally, in order to homogenize some of the fabrication variables, I attempted to cast an SMA within a silicone tube. Silicone is a very malleable and heat resistant polymer, which can be spun like a regular textile and 'remember' its shape. Once a strand of SMA is embedded within a silicone tube, the composite is spun like a regular yarn. The SMA actuation worked well in this case but the silicone did not allow the SMA to cool rapidly, making for a slow actuator.

Multiple SMA Strands

Another solution was to combine two SMA strands to give the 'fiber' multiple actuation directions and avoid relying on a material's elasticity for the bias actuation. In this case the composite's principal material provides structure but is kinetically inert, depending solely on the SMA strands for actuation.

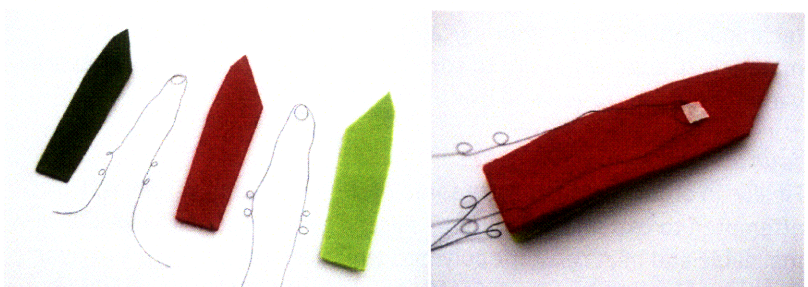
Laser Cutting and Bond Sewing

The final technique I developed uses two SMA wires embedded in a fabric sandwich of stretchy fabric and felt; while the SMA gives two-directional movement to this composite, the fabric provides structure, as well as visual and textural quality.



Two-way actuation

To create a strand that could move in two directions, I 'bond sewed' a complex SMA shape onto both sides of a grass blade-shaped piece of felt. Bond sewing is a technique in which an adhesive thermoplastic film is used for bonding two fabrics together. In this technique, an adhesive film is slit into tapes, applied in strategic locations and covered by a second substrate. Heat and pressure activate the adhesive and creates a bond between the two fabrics. To guarantee that shear between the different laminates would not hinder actuation, a stretchy fabric was used as the external substrate.



'Exploded view' of *Sprout I/O* strand (left) and assembly process (right)

By controlling the current running through each side of the SMA strand and localizing heat, it is possible to cause an orthogonal bend on the felt, as well as control its angle, speed and direction. This process proved to be the most reliable, since the SMA's actuation is independent of the felt's capacity to return to its shape. Moreover, this technique is more energy efficient, since it is only necessary to apply power to change the state of a strand, which remains in the same position after being actuated.

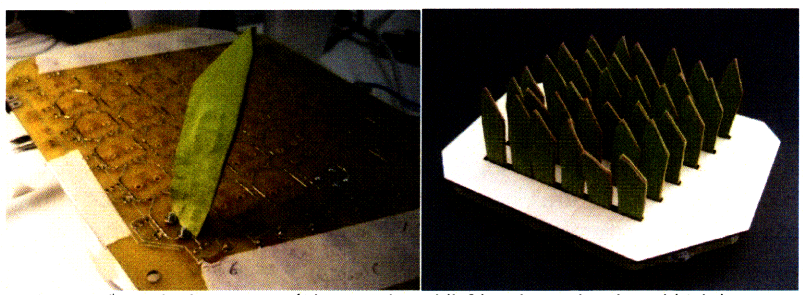
The only drawback of this technique is that fabrication is very time consuming, since the SMA is trained into a complex shape with seven different anchor points and actuation loops, which require a lot of alignment considerations during assembly. Moreover, heat bonding a material that is heat activated causes it to move, making it difficult to preserve equal tolerances among all strands.

Coincident Kinetic I/O

Another engineering challenge was to develop a strand that could change shape in response to touch, providing user input in *Sprout I/O*. To accomplish this, I used the SMA as an electrode for capacitive sensing, combining its resistive heating circuit with a relaxation oscillator and switching between sensing and actuation modes with a microcontroller. The specific details and circuit design are better explained at the end of *Chapter 5: Designing with Shape Memory Alloys*.

Power and Sensing Matrix

The final step in *Sprout I/O's* design was the construction of a matrix to deliver power and sensing to every one of its strands. An initial prototype used conductive threads embedded in between layers of fabric to deliver power while insulating every wire and retaining flexibility. While this proved to be technically feasible, it complicated considerably the mechanical connection between the texture strands and the power delivery grid, so I opted to use a PCB matrix instead and focus on the control and actuation of the strands.



Single strand attached to *Sprout I/O's* circuit board (left) and complete board (right)

Sprout I/O's final design is composed of a grid of 36 strands (6 rows and 6 columns), where every column is made of two power lines that separately control both faces of a strand allowing it to bend in two directions.

Sprout I/O uses an ATMEGA644 AVR microcontroller, which controls 6 2SK2231 N-Channel Toshiba MOSFETs for grouding the individual rows and 12 IRF5210PBF International Rectifier P-Channel MOSFET drivers for powering the columns on each side of the strands. The combination of sink n-channel and source p-channel MOSFETs keeps heat to a minimum by bringing the logic control line close to VDD (12V) and GND (0V), also preventing loss and dissipation in the circuit. This design also includes a USB connection for direct control of the images displayed. A circuit schematic and PCB layout are included at the end of this thesis in the Appendix.

Research still needs to be done to scale the coincident sensing and actuation from a single strand to a full grid and a possible solution might include using a 48-channel 'Qmatrix' IC from Qprox.

Control Software

The firmware behind *Sprout I/O* is similar to the logic used for controlling conventional LED grids, but with a couple of variations since it needs to account for the heating time of the wires and variations between different strands. The most important difference is that every 'pixel' in *Sprout I/O* is a strand composed of two SMA wires, which can move it in two directions. Frames are stored as signed 8-bit numbers and the most significant bit (MSB) represents the direction in which a strand moves, leaving 127 distinct values to control the degree to which a strand can curve. Before every frame is displayed a calibration array is added or subtracted from the frame to account for small resistance differences between strands.

Finally, since powering all strands in a row at the same time would require about 4 A, the multiplexing is done in two steps to cut power requirements in half. In short, the first 3 strands in the first row are powered and then turned off, followed by the next 3 strands in the same row; this sequence then moves on to the first 3 strands in the second row and so forth.

Application Scenarios

Apart from functioning as a new kind of soft and non-emissive display, applications for this technology could take many forms and, as implementation matures, it will also unleash a host of new interaction possibilities. I currently envision a series of different applications: display surfaces for the visually impaired which could take advantage of the textural qualities of different materials; carpets or grass fields for public spaces that could guide people to their destination or closest exit route, as well as display advertisement and information about a game of event taking place; a robotic skin that could sense the fine subtleties of touch and respond with goose bumps to create tighter emotional bonds with their owners; and interactive clothing that could record its history of interaction or simply animate to display the mood or personality of its wearer.

Coincident I/O in Form Transformation

Surface properties, such as texture, can play a great role in how people interact with digital systems and the kinds of information they convey. One of the greatest challenges of developing ubiquitous interfaces lies in finding the appropriate technologies for seamlessly integrating computers into the environment, without reducing our interaction modalities to the limitations imposed by the materials from which we build them. For instance, *Sprout I/O* is based on a composite that blends several functionalities: while SMA concurrently serves as an actuator and capacitive sensing electrode, fabric gives a *Sprout I/O* strand its structural support, as well as aesthetic and tactile qualities.

The immediate consequence of this amalgamation is a simplification of electrical connections and an approximation of sensors and actuators, facilitating the deployment of denser input and output grids which could potentially transform every surface into a computational device.

Responsive materials are not discrete systems, but continuous sensing and actuation substrates that can be cut, spliced and melded together. In fact, any surface that can become conductive can be used as a capacitive sensor, and the number of conductive materials available for designers has been dramatically increasing over the years.

By developing a composite material that co-locates kinetic I/O, while preserving the expectations that we normally have from interacting with physical things, we can more seamlessly embed computation in our surrounding environments and take into account the unique properties of a material to render its interaction affordances: an interactive textile fur, regardless of its digital mappings, should still drape, feel and conform to the body like a regular textile would.

Conclusion

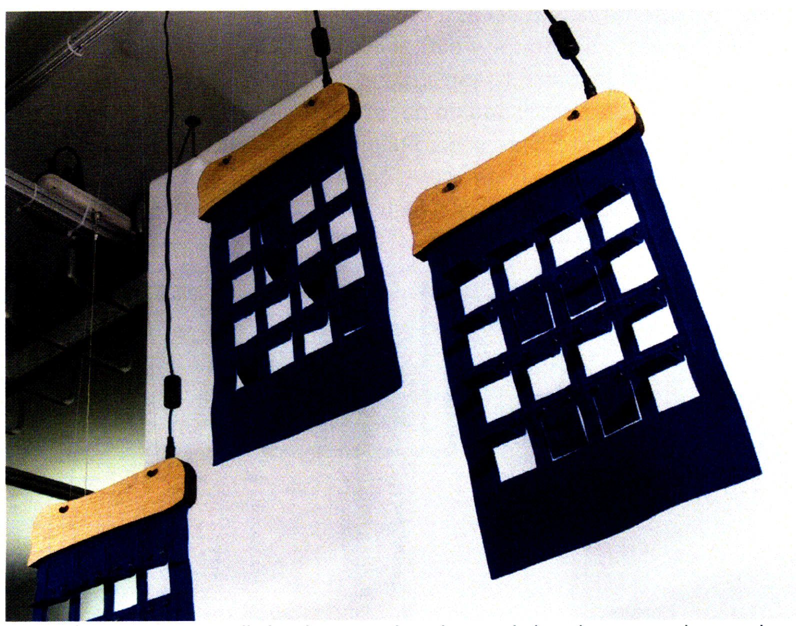
The development of *Sprout I/O* is still at a very early stage and, as such, there are many future challenges to address. The next step is to explore techniques for scaling the co-located sensing and actuation to a fully addressable grid, as well as optimize the size and shape of the strands, according to their physical constraints and ability to display images.

The next chapter discusses the design of *Shutters* and looks at how a shape change can be used to regulate a surface's permeability for environmental control and communication.

8 Shutters: Permeability

Textiles and architecture have a long intersecting history. Archaeologists date the first permanent construction and the first evidence of constructed textiles to approximately 7,000 years ago, and believe that the first building materials were textiles based on the form of wattle-and-thatch construction (Garcia, 2006). This intrinsic relationship highlights the overlapping roles that clothing and buildings have played in providing privacy, protecting the body from exposure to the elements, and serving as conduits for aesthetic and personal expression.

To create living spaces that are habitable and pleasant for its residents, a building needs to regulate and balance the exchanges between its internal and external environments, while efficiently using a variety of technologies to insulate and maintain an adequate temperature and quality of air. By carefully selecting materials and structures that can mediate the daylight intake and ventilation flow, it is possible to maintain, for instance, the building environment at a desired temperature range (usually based around human thermal comfort) throughout the sun's daily and annual cycles, while supporting lighting scenarios which are adequate for different activities. However, people's use of space is complex and changes frequently, raising the need for an environmental control system which is equally flexible, and capable of adapting to its users.



Shutters' louvers are controlled with a circuit board concealed on the top wooden panel. The *Shutters* on the left picture has its louvers arranged to display the letter 'A'

In an attempt to address this issue, I have developed *Shutters*, a curtain composed of actuated louvers (or shutters) that can be individually addressed for precise control of ventilation, daylight incidence and information display. As a shape-changing permeable membrane, *Shutters* improves upon previous façade systems by creating living environments and work spaces that are more controllable and adaptable, while also providing information to its users in a subtle and nonintrusive way. *Shutters* proposes an alternative for the deployment of pervasive computation in our environment through the use of a permeable surface that can support a range of different uses.

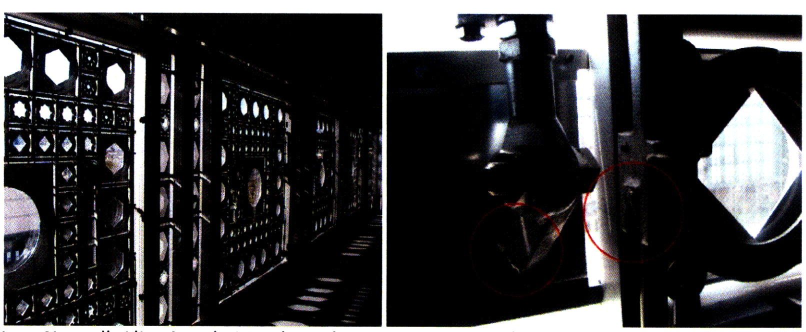
Alhambra palace in Granada, Spain

As in the previous chapters, I will discuss related work, the design principles and motivations behind the development of *Shutters*, its multiple iterations and engineering details, how it embodies multiple functionalities into a single system and, finally, I will speculate on future applications and possibilities for this technology.

Related Work

Most buildings present some form of adjustable sun-shading element or technique (also referred to as 'brise-soleil, from French, "sun break"). These can range from traditional methods, such as lattices, pierced screens or blinds, to more elaborate smart membranes that can filter out lighting and control ventilation at varying degrees with preprogrammed computerized behaviors.

The façade of L'Institut du Monde Arabe (Paris, 1987), designed by the architect Jean Nouvel, is an example of a structure carrying several motorized apertures that act as a brise-soleil to control the light entering the building according to the weather conditions and season of the year. In spite of their functionality and striking design, these façade panels are noisy, tend to break easily and do not provide a very scalable solution that can be easily integrated into other buildings or easily replaceable when they fail. Most importantly, they are fully automated, not allowing residents in the building to have a high granularity of control over their own space.



Jean Nouvel's L'Institut du Monde Arabe in Paris, France. The mechanical irises open and close in response to different light conditions over the course of the day (left) and broken actuator (right)
Images by David Merrill

The world of textiles is another area where precise and directional control of permeability is critical. For instance, high performance materials, such as Gore-Tex, can selectively let sweat and heat out of the body, while protecting a wearer from rain or snow. Moreover, shape-changing textiles have also already been successfully implemented. Kukkia and Vilkas, for instance, are two kinetic garments based on the use shape memory alloys (SMAs) which use shape change to develop an almost whimsical relationship with their wearers (Berzowska & Coelho, 2005). Borrowing ideas from the worlds of textile and architecture, I have developed a soft kinetic membrane that can be electronically controlled to regulate exchanges in a space and to communicate.

Design principles

Shutters is motivated by several design principles and architectural constraints. While *Surflex* and *Sprout I/O* respectively deal with shape-changing topology and texture, *Shutters* explores another facet of form transformation, where perforations are introduced in a continuous surface to break its homeomorphism and continuity. Focusing on shape-changing permeability, my intention was to create apertures for controlling the visual and environmental exchanges between two spaces, rather than just modulate their spatial relationships.

Architecture provides a compelling need for a permeable membrane that can physically transform itself to simultaneously accommodate multiple conditions and functionalities. Spaces are deeply affected by their exposure to the elements, which vary continuously, and 'one size fits all' louver approaches usually turn out to be inefficient or inadequate for individually regulating ventilation, daylight, or visual privacy.

A similar source of inspiration for the design of controllable louvers is a stoma. Found mostly on the underside epidermis of a leaf, stomata are pores which regulate the exchange of gases and water vapor between the outside air and the interior of a plant. The pore's aperture is controlled by a pair of specialized cells which elongate to open and close during the daytime in response to changing conditions, such as light intensity, humidity, and carbon dioxide concentration.

Electron microscope image of a stoma on the leaf of a tomato plant

Finally, as a result of daylight control, *Shutters* can also affect changes in external surfaces by casting shadows which can be controlled to project patterns and information as a seamless and pervasive display. Shadows have long been used as a technique for projecting images and providing information. Shadow puppetry is still a common form of storytelling and shadows on an illuminated backdrop.

Later in this chapter, I will specifically address how certain permeability properties, such as the pore's shape and its surface density, can affect the fidelity with which a permeable surface can display images and cast shadows.

Engineering Shutters

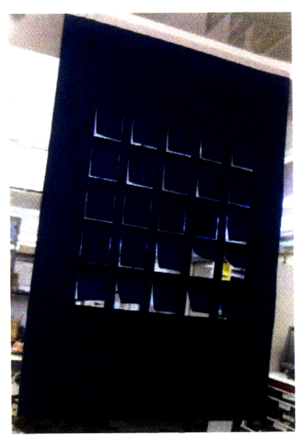
Shutters has gone through several design iterations, and I am currently working on its third implementation. The first two prototypes primarily address technical concerns, while the third iteration is more focused on improving its aesthetic design and scale, as well as optimizing some of the construction techniques. In this section, I discuss some of the main engineering challenges and how they were addressed.

Mechanical Design

Shutters is a fabric kinetic membrane composed of a grid of actuated louvers, which can be individually controlled to move inwards and outwards, regulating shading, ventilation, and displaying images and animations.

Shutters is constructed out of fabric so as to be flexible and easy to manipulate, while still embodying some of the functionality of external façade elements. In the initial prototypes, *Shuters* was constructed of fire retardant 100% wool felt, which is ideal for laser cutting and the integration of electronics, conductive threads and SMA strands. Nonetheless, felt favors the use of traditional craft techniques and, in the last design iteration, was replaced with Gore-Tex, a waterproof fabric, and the use of high performance construction techniques which are more efficient, reproducible and appropriate for *Shutters* application.

Laser cutting is a technique for cutting textiles which is becoming increasingly more common: it helps prevent fraying since the fibers fuse together when cut by the laser beam; it is also computer controlled making the design and cutting of unique and complex patterns more efficient and customizable; and, in the case of a textile actuator, laser cutting makes it possible to score hinges in the material to create precise points of actuation. In tandem with laser cutting, I opted for welded seams over traditional sewing techniques, since they are faster to assemble and remove the need of perforating the textile, which lets water in and weakens its overall structure.

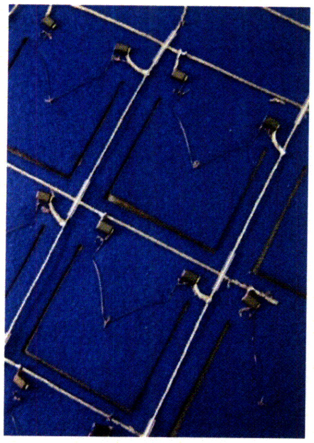


Laser cut felt without SMA and electronics

The mechanism for *Shutters* is based on the electronically controlled actuation of two strands of SMA per louver – for inward and outward movement – and through resistive heating, it is possible to electronically control the temperature of an SMA strand and generate the actuation to control the aperture angle of every louver.

The use of SMAs in *Shutters* is unique in that the SMA is shape set and optimized specifically for a two-way actuation and that it can lay flat against the felt, not requiring any extra physical space to move, as a helical shaped SMA wire would.

Another innovation is that previous SMA and textile composites require an external actuator, such as gravity, the wearer's interaction, or the rigidity of the material to provide a counter movement to the SMA's


Detail of SMA attachment loops and diode connections, before being completely sewed onto the fabric

actuation (Berzowska & Coelho, 2005). *Shutters*, on the other hand, combines the states of two different SMA strands to get a gradual shape change, largely increasing the possibilities for electronic control and the scope of possible applications for this smart material in textiles. Additionally, since there are no hard, moving parts, *Shutters* is a completely silent kinetic display.

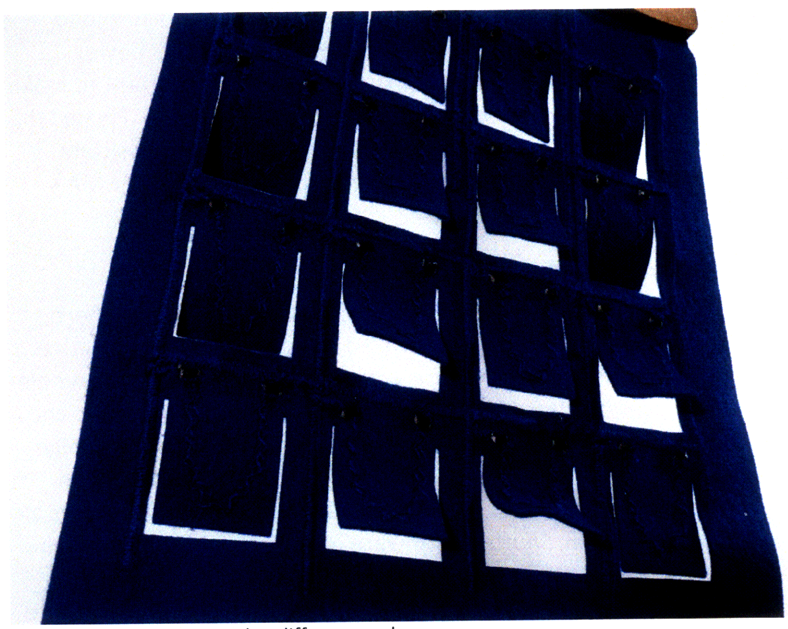
One of the greatest mechanical hurdles in *Shutters* was to devise a technique for attaching SMAs, fabric, the wires for power delivery, and diodes. The solution I found was to use the actual SMA to create mechanical loops from which to attach it to the textile, preventing the SMA from moving and speeding fabrication. In the initial prototypes, diodes were crimped to the SMA and to the conductive threads that deliver power to every louver, but in its final iteration, this connection was replaced by a small circuit board to which the diodes and individual louvers are soldered. There were two main motivations for this change: (1) the conductive threads had to be replaced by thin multi-stranded wires to reduce unwanted electrical resistance and *Shutters* power consumption, and (2) to facilitate construction, it was important to make the louvers modular and easy to replace in the overall textile. Finally, the louvers' overall sizes are determined by the practicality of physically assembling and securing the components to the fabric and the SMA's strength to lift them.

Electronic Design and Control

Shutters is designed to behave like a conventional LED display, where every louver can be individually controlled by addressing its respective column and row, and full images are achieved by multiplexing the whole display. However, *Shutters*' 'pixels' are in fact high current resistors and need to be separated from each other with additional diodes with high voltage bias to prevent current distribution over the whole substrate. The resistance of the conductive threads that distribute power in *Shutters* also play an important role. *Shutters'* firmware has to account for the small power variations required by every louver and set its pulse-width modulation to compensate accordingly, delivering a higher pulse rate to louvers with higher resistance.

Shutters also has a third dimension since its louvers can move inwards and outwards at different angles. This is the kinetic equivalent of bicolor LEDS, but it provides a gradient control of shape and aperture instead of changes in color. Finally, 'pixels' in a kinetic display cannot 'jump' from one state to another; they need to transition from being open to being closed, and vice-versa. This way, gradient scales can be achieved by addressing the louvers at different modulations or counteracting the movement of a louver by powering the SMA on its opposite side.

Shutters circuit design resembles *Sprout I/O*'s, where a matrix of strands is multiplexed and controlled by several MOSFETS. The electronics design and firmware implementation have already been mostly discussed in the previous chapter. However, it is also important to note that the power requirements of SMAs should not be overlooked. Every strand draws roughly 0.6A at 12V to be fully actuated, but since *Shutters* is designed to maximize daylight incidence and heat gain, it can potentially save on other forms of energy. Moreover, since the louvers can preserve their physical position without any applied power, they only need to be actuated once, when changing states, saving on power consumption over longer periods. On the other hand, since the SMA used in *Shutters* changes shape at 60°C, it could be unintentionally triggered by solar heat if the temperature on the textile reached that level, however this seems highly unlikely. Increasing the SMA's phase change temperature would in exchange require more energy when the ambient temperature is lower. *Shutters* power requirements have yet to be fully optimized. Potentially, in the future, the textile could be woven out of photovoltaic threads so that the whole extension of the curtain can be used to harvest energy and hopefully even completely power itself.

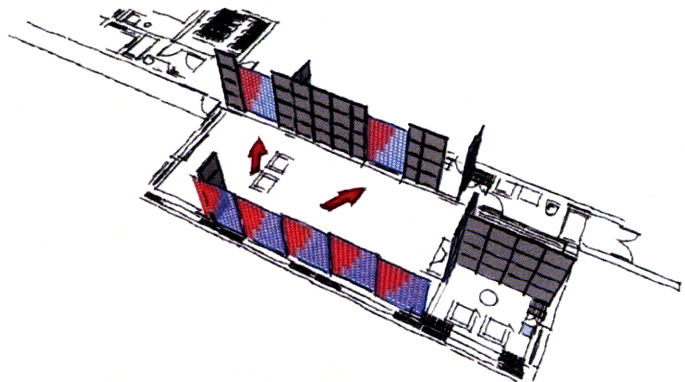


Shutters' louvers positioned at different angles

Application Scenarios

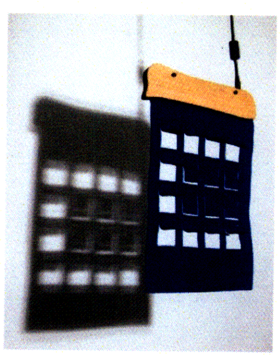
The key to *Shutters'* functionality is in its ability to have a three-state control of environmental exchanges. When the louvers move outwards they allow for ventilation to pass through but, because of their angle, they block daylight. However, when they are bent inwards they allow both ventilation and daylight to come in. Finally, the louvers can rest at a midpoint where they completely block any exchanges with the outside.

The design of a louver grid is an attempt to improve on traditional shutters to allow for the 'blades' in the same horizontal row to move inwards and outwards, and individually from each other. This flexibility opens the possibility for three important functionalities: (1) precise two-dimensional control of shading, so that the daylight can illuminate different parts of a space and be blocked from others; (2) control of the ventilation between different parts of a space by opening and closing the specific shutters necessary to create wind tunnels, and finally; (3) use of *Shutters* as a soft kinetic and shadow display.



Simulation of *Shutters* controlling airflow. By opening air passages at different parts of the house it is possible to control the path and intensity of ventilation to accommodate the needs of different residents sharing the same space.

In the first scenario, the curtain combines a preprogrammed shading configuration that updates itself over time to maximize heat gain in the winter and minimize it in the summer (according to its geographical location and the position of the sun during the course of the day and the year), while not interfering with the activity of residents. For example, during the winter, the curtain can open itself in the morning to allow the sunlight in, which would heat a room over the course of the day; as the night approaches, it can progressively close itself to prevent thermal losses. A person reading a book, for instance, could also prevent direct sunlight from reaching a table while keeping the rest of the room completely illuminated over the course of a full day. This could be done specifying an area of the curtain that remains closed, while other louvers continue to go through their normal cycle.



Shutters as a kinetic and shadow display

In the second scenario, louvers on the north and south façade can be coordinated to create an airflow on the east side of the house, but prevent it from happening on the west side, creating an intelligent environment that accommodates the preferences of various residents sharing the same space.

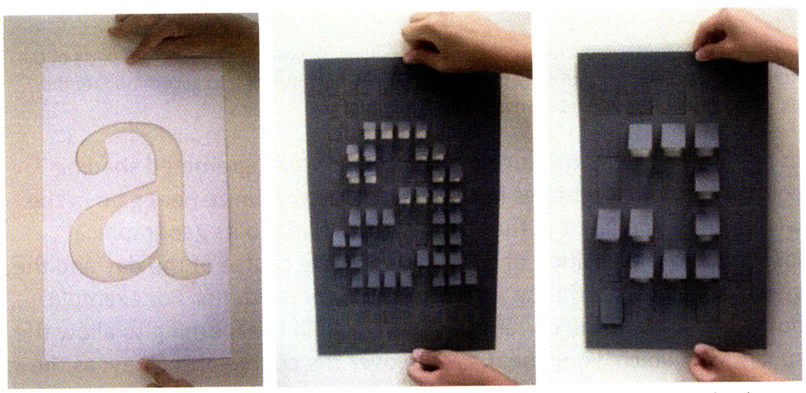
Finally, in the third scenario, since every louver can act as a pixel on an addressable grid, the curtain can be controlled to display images on its surface or project animated shadows on the walls and floor, providing non-obtrusive, ambient information that is relevant to residents. Since the functionality of the curtain is tied to heating and the energy consumption of the house, *Shutters* can function as a kinetic sculpture that provides visual feedback about residents' energy use.

Permeable Surfaces as Kinetic and Shadow Displays

Shutters differs from most displays in two fundamental ways: First, it creates images by regulating the size and angle of perforations distributed over its surface and, second, these perforations can cast controlled shadows over other surfaces. In order to understand how *Shutters* can make effective use of these properties and what its main trade-offs are, I have conducted a series of design explorations.

Resolution

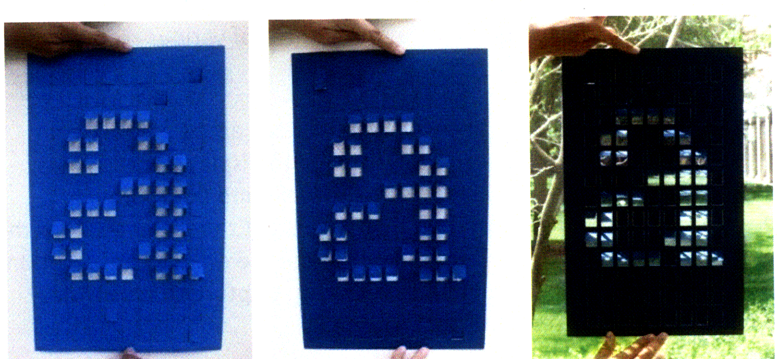
Similar to other display technologies, the number of pixels per area (pixel density) is one of the most important factors affecting the quality of the images *Shutters* can display. The smaller the space between perforations is (known as 'dot pitch' in conventional displays) the better the image quality.



At about half the resolution of the middle image, the letter **a** on the right is completely illegible

Background Contrast and Interference

The contrast between *Shutters* and its background image or pattern is also important. As expected, the greater the contrast between the membrane and its background is, the clearer the displayed images becomes. In the case where the background is not a plain surface or is not static, a greater contrast becomes even more desirable.



In spite of the busy background, the image on the right is clearer due to the higher color contrast

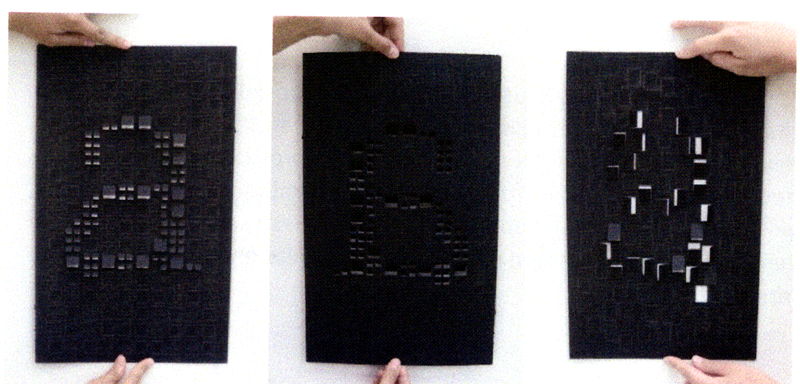
Overall, images look clearer against a plain backdrop and this becomes even more evident when dealing with shadows. In the example below, the grass texture softens the pixel edge and makes the letter **a** harder to see when compared to a shadow cast on plain cement.

The plain background on the left renders a clearer shadow than the textured grass and brick wall surface

Perforation Shape and Distribution

The most unique property of *Shutters* is its perforations and their capacity to influence how images are seen.

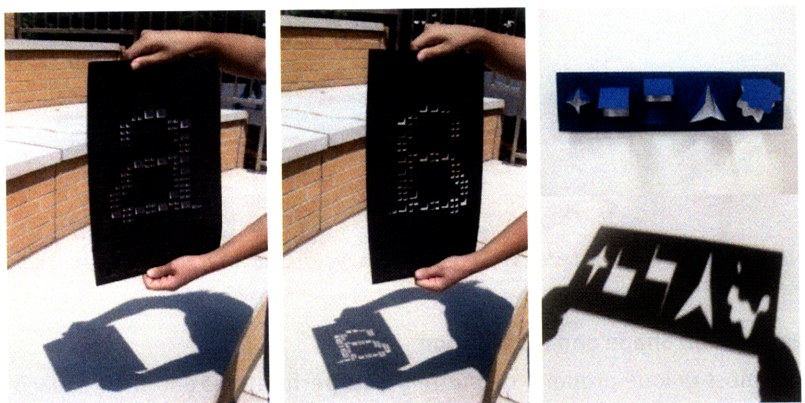
When d*irectly viewed*, there are several perforation properties which can affect the quality of an image, such as: the shape of the louvers; the number of louvers per perforation; the overall alignment of all louvers; the capacity of the upper louvers to cast shadows on lower ones; and the backward or forward orientation of the louvers in relation to the viewer. When *indirectly viewed* – viewed through the cast shadow –, the angle of daylight incidence can considerably distort the shape and size of a shadow pixel.



Symmetry in louver size and distribution are not as relevant as the directions in which louvers open and close

In this image, the perforation orientation plays a great role in how the letter **a** is rendered. However, symmetry in louver size and distribution (random or in a grid) do not seem to be as influential as the direction (up/down or left/right) in which the louvers open and close.

The shape of the perforations, the direction in which they open (backward or forward), and the angle of incident light also affect how images are displayed. The left and center images below provide a comparison between louvers which are opened perpendicular or parallel to the sunlight. While both images are clear on the actual display, the shadows they cast are completely different. Finally, the image on the right illustrates how variations in perforation shape also affect the cast shadows.



In the left image, louvers are oriented perpendicular to the sunlight, while in the center they are parallel, resulting in completely different shadows. The image on the right presents different perforations

Future design studies will include a more direct exploration of how louver motion influences the quality of the image displayed; in particular, looking to determine what is the ideal speed for a louver to move. This is important since the pixels are not necessarily blinking pixels on a screen, but objects that need to transitionally pass through different open and closed states to reach a desired position.

Conclusion

This chapter describes *Shutters*, a curtain composed of actuated louvers that can be individually addressed for precise control of ventilation, daylight incidence and information display. It provides construction details and use scenarios for kinetic textile membranes. In the future, I will explore the coupling of *Shutters* with different sensing systems that can track people's position in a house to optimize energy savings and interaction.

9 Conclusion and Future Forms

Form transformation is not a new topic in design, but it remains largely unexplored in human-computer interaction due to its technical challenges and a clear understanding of its potential benefits. One of this thesis' main contributions is the unraveling of a cohesive thread that connects the behavior of responsive materials to the design and application of transformable interactive surfaces.

Chapter 3 discusses how responsive materials — materials that can alter their own properties or transform energy from one form to another — and their composites can be used for embedding interaction into every surface, while preserving a rich set of material affordances. This discussion focused particularly on shape changing materials through a short survey of their different properties. The goal was to make some of the design trade-offs more apparent and help guide the material selection process. Hopefully, by gaining a better understanding of how these unique properties are used by designers, materials scientists can invent better and more efficient materials.

In spite of their limitations, shape memory alloys (SMAs) are currently the most accessible and versatile of these materials and *chapter 4* explains their properties and how to design and control shape changing composites. I purposefully drifted away from an extensive material characterization towards a more hands-on and practical design approach in order to make this knowledge more accessible for designers at large.

Chapter 5 looks at the concept of soft mechanics and how shape changing materials challenge the rigidity of traditional mechanical systems by generating kinesis via transitions through different shape memories and elasticity states. Moreover, it looks at how simple material compression and elongations along different axes are the building blocks for creating complex shape changing surfaces, which can be used in human-computer interaction to reveal the functionality of things, display data, as well as guide and limit user interaction. Future work in this area should extend the soft mechanical alphabet sketched in chapter 5 and develop the CAD tools for automating the design and selection of soft mechanical elements, which will allow surfaces to transition from one shape to another. Consequently, research also needs to be done to define how to best power and control a complex array of these elements so they can work together.

Surfaces are instrumental to how we perceive and interact with physical things but their ability to function as computer interfaces is inherently limited by their material and homemorphic constraints. *Chapter 6: Surflex, Chapter 7: Sprout I/O* and *Chapter 8: Shutters* address these limitations by exploring three distinct subject areas in the design of form transformation: topology, texture and permeability, respectively.

Surflex proposes a material architecture through which a surface can produce large shape changes and adopt different topologies. A considerable amount of research still needs to be done to improve its design and overcome some of its physical limitations and these are discussed in more details in chapter 6. Additionally, future research might also want to address how to break *Surflex's* homeomorphism and continuity by creating a shape changing surface that can be sliced and spliced back together. A solution could be found in using a tiling architecture and replacing *Surflex's* circuit boards for electromechanical connectors. This way *Surflex* could transform itself from a flat surface to a porous membrane or Möbius strip. A modular architecture would also allow for the easy replacement of components as they wear out and break.

Sprout I/O, on the other hand, focuses on changing the tactile and visual qualities of the surface through a shape changing texture, rather than its overall topology. Future iterations need to considerably shrink the size of *Sprout I/O's* strands so that shape change can be perceived as a transformation in surface finish, rather than changes in the protrusions coming off of the surface. Future work also needs to completely implement a dense co-located sensing and actuation grid, potentially exploring approaches where the sensing electrodes are embedded on *Sprout I/O's* main substrate rather than its strands.

Shutters breaks the surface continuity of the previous projects by using small controllable perforations to modulate the permeability and environmental exchanges between two spaces. As I complete *Shutters* next design iteration, the focus will shift from its technical implementation to more directed studies of its effectiveness at controlling daylight and ventilation, and most importantly how people can use *Shutters* on a daily basis in their living environments and work spaces.

The ability of things to physically transform is still relatively unexplored and there is a long way to go before we can fully understand how these technologies will permeate our lives. To conclude this thesis, I will outline future directions this research can take, describing the sorts of technology that it may enable one day.

Shape Change Parametric Design

As shape changing materials improve, the need to simulate their transformational properties will only increase. Current parametric design tools allow for the creation of complex three dimensional forms, which can adapt in response to changing conditions and parameters, or provide multiple design variations based on a set of defined rules.

Future design tools will need to extend this potential for adaptability and support the design of physically transformable forms. Designers should be able to create an object's initial and final state, and automate the selection of structural and soft mechanical elements necessary to generate a transformation between these two states. Additionally, rather than designing the transformations per se, a designer could simply define initial form requisites and allow their physical creations to develop in the real world, towards unexpected and more optimal shapes.

These tools should also include a shape changing material database which would allow designers to select materials according to properties such as speed, strength, power requirements etc. Omissions in this database would also inform the need for new materials and help guide future research.

Open Source Forms

With the advent of rapid prototyping, open source design has been transitioning from the world of software to that of physical things. Today it is possible to browse through and download freely available designs for laser cutting or 3D printing almost any kind of object. Within the same philosophy of open source software, these designs can be used, modified and shared.

However, open source approaches applied to hardware and rapid-prototyping have a clear disadvantage: all design iterations have a material cost and their resulting physical object cannot be modified with the same modularity and compartmentalization that pure software allows.

It is not hard to imagine a future where we will be able to automatically download a new firmware that describes not only the behaviors and functionalities, but also the forms of the physical things we own. Similar to how firmware updates today bring in new functionalities or security patches, these objects will also be able to physically update themselves. Parallel to this, users will be able to modify these physical forms themselves, in response to new contexts of use or personal interests, and share their designs with others: creating a dynamic economy around the improvement and sharing of physically transformable devices.

Morphable Interfaces and Just-In-Time Affordances

A promising application domain for shape changing surfaces is the design of physical interfaces that can physically change to accommodate different uses and contexts. When compared to the versatility of graphical user interfaces, the greatest drawback of tangible user interfaces today is their physical limitation and the fact that they impose single purpose functionalities. However, as TUIs become fully capable of changing shape and reconfiguring themselves, the dichotomy between graphical and tangible user interfaces will become increasingly obsolete and these limitations will most likely be overcome.

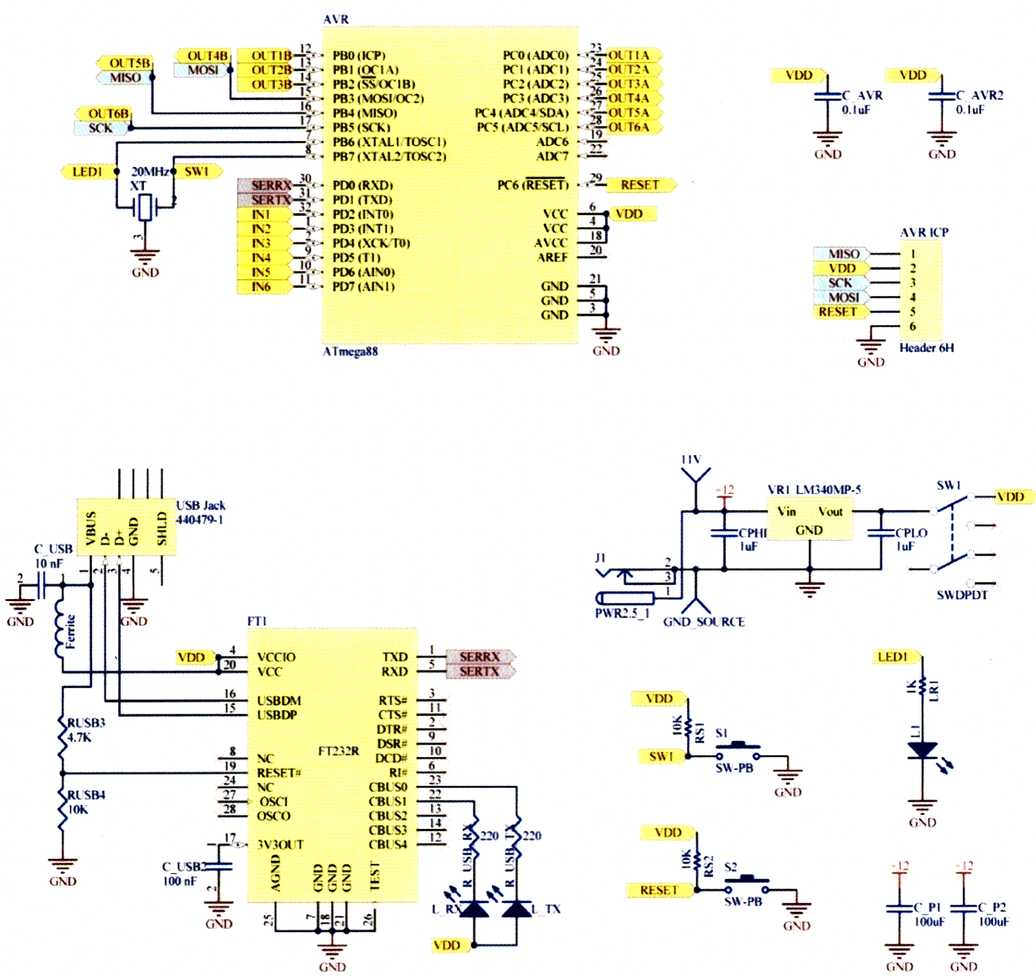
Devices that provide different functionalities according to how they are used are becoming increasingly common today. Consumer electronic devices, such as Apple's iPhone, can turn off its screens when held up to a users' ear, cameras can use their orientation to switch between portrait and landscape mode, and researchers are exploring ways to use grasp recognition (a passive measurement of device orientation and user hand placement) to make devices switch between different functionalities (Taylor & Bove, 2008).

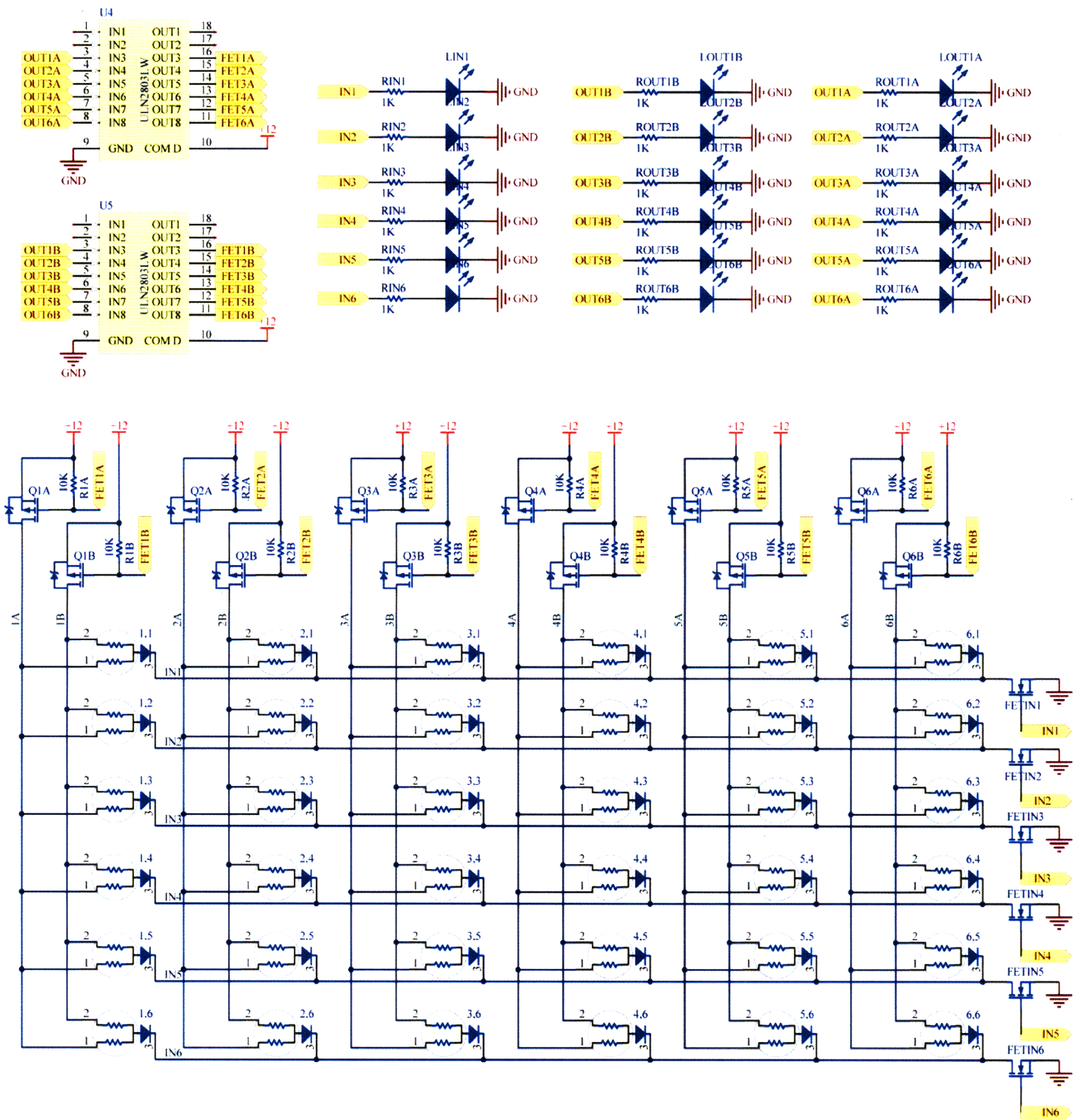
In a similar vein to how animal forms are the evolutionary result of forces such as gravity or surface tension, the form-generating forces behind tangible interfaces will be an amalgamation of a panoply of contextual information, body language, gestures and user interests. As a result, objects and spaces will be able to physically adapt to different conditions of use and respond with *just-in-time affordances*, ultimately supporting more rich and enticing human-computer interactions which could not have been initially predicted by their designers.

Appendix

Sprout I/O Schematic

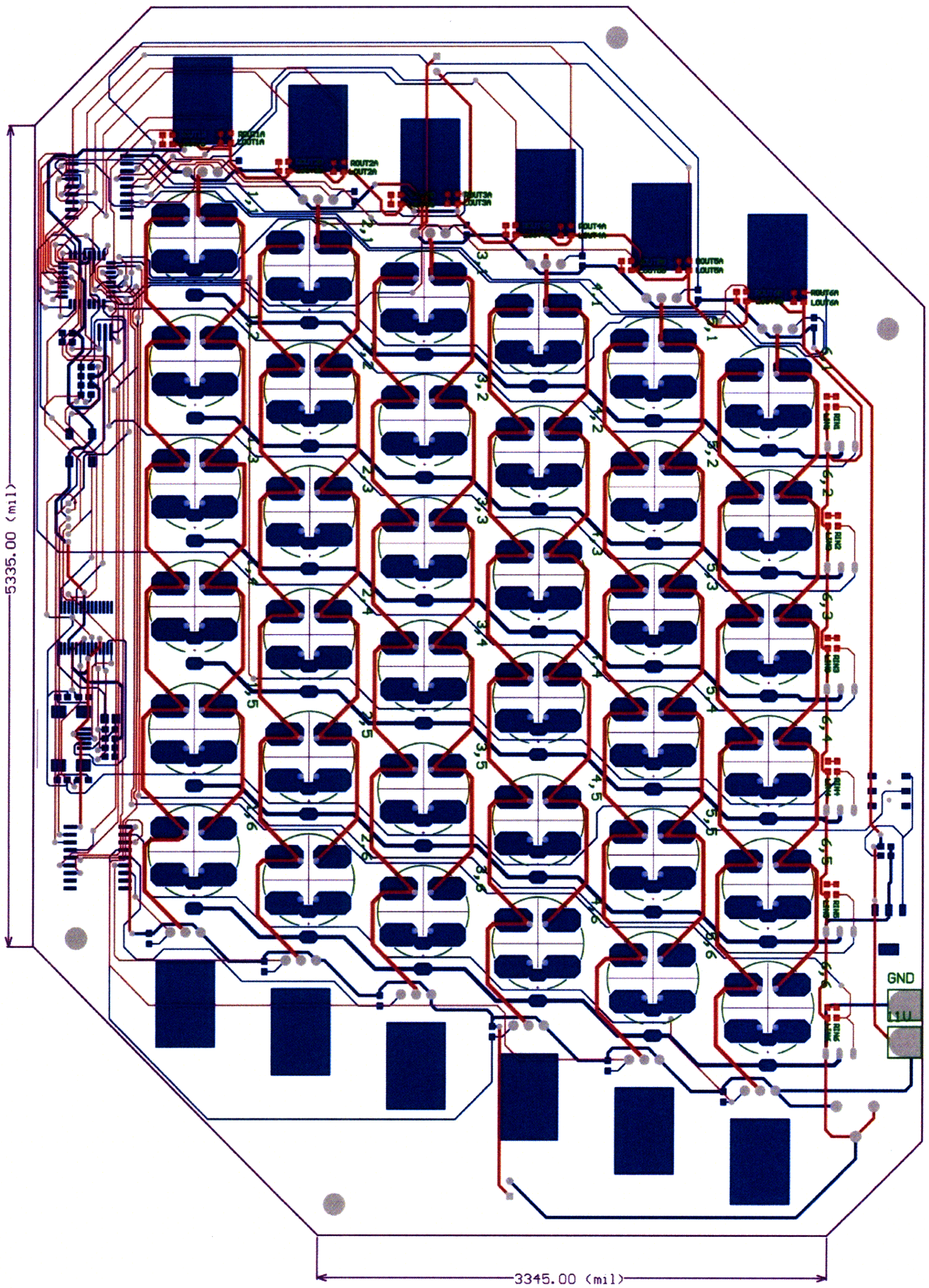
Surflex and *Shutters*' circuit design resembles that of *Sprout I/O*; however, in both of these projects the diode array is distributed across the shape changing surface, rather than being located on the circuit board.





U4
ULN2803LW
IN1 IN2 IN3 IN4 IN5 IN6 IN7 IN8
OUT1 OUT2 OUT3 OUT4 OUT5 OUT6 OUT7 OUT8
GND COM D
OUT1A OUT2A OUT3A OUT4A OUT5A OUT6A
FET1A FET2A FET3A FET4A FET5A FET6A
U5
OUT1B OUT2B OUT3B OUT4B OUT5B OUT6B
FET1B FET2B FET3B FET4B FET5B FET6B
GND
+12
LIN1
LOUT1B
LOUT1A
RIN1 RIN2 RIN3 RIN4 RIN5 RIN6
ROUT1B ROUT2B ROUT3B ROUT4B ROUT5B ROUT6B
ROUT1A ROUT2A ROUT3A ROUT4A ROUT5A ROUT6A
1K
Q1A Q2A Q3A Q4A Q5A Q6A
Q1B Q2B Q3B Q4B Q5B Q6B
R1A R2A R3A R4A R5A R6A
R1B R2B R3B R4B R5B R6B
10K
1A 1B 2A 2B 3A 3B 4A 4B 5A 5B 6A 6B
FETIN1 FETIN2 FETIN3 FETIN4 FETIN5 FETIN6

Sprout I/O Circuit Board Layout



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