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ORIGINAL ARTICLE

Shape-changing interfaces

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Abstract The design of physical interfaces has been constrained by the relative akinesis of the material world. Current advances in materials science promise to change this. In this paper, we present a foundation for the design of shape-changing surfaces in human–computer interaction. We provide a survey of shape-changing materials and their primary dynamic properties, define the concept of soft mechanics within an HCI context, and describe a soft mechanical alphabet that provides the kinetic foundation for the design of four design probes: *Surflex*, *SpeakCup*, *Sprout I/O*, and *Shutters*. These probes explore how individual soft mechanical elements can be combined to create large-scale transformable surfaces, which can alter their topology, texture, and permeability. We conclude by providing application themes for shape-changing materials in HCI and directions for future work.

Keywords Form transformation · Shape change · Kinetic · Morph · Tangible interface · Transitive materials · Shape memory alloy · TUI · SMA

1 Introduction

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 [3]. 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. However, while a lot of headway has been made in controlling light to deploy information all around us through visual displays, there is still much to be done to make physical form equally mutable and controllable.

In recent years, tangible interfaces have started to make use of shape change as a way to embody digital information [15]. 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.

In this paper, we present a holistic approach for the design of form transformation in human–computer interaction. We start by looking at the properties and limitations of currently available shape-changing materials and progress toward their application in the design of large-scale surfaces, which can form the electromechanical basis for new human–computer interfaces. However, before looking at the future of shape change, it pays off to briefly look back at the past and understand how the kinetic machines we use today have come to be the way they are.

2 The mechanisms of shape change

Mechanical systems have been around since at least Archimedes' times, and in spite of having evolved considerably up

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to now, benefiting from revolutions in materials, power, and miniaturization, the machines we use today are still very similar to their predecessors. And there is a good reason for this: the capabilities of machines 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 and his work has had a strong and direct impact on the training of engineers which is still influential [9]. Nonetheless, Polhem's machines helped perpetuate an inherent limitation: they were designed to be primarily constructed from materials such as wood or steel, where material rigidity and strength are desirable qualities. Building upon the ancient s*imple machines*, these designs were predicated on the assumption that their mechanical elements are rigid, and that variations on their flexibility and shape hinder functionality by adding unnecessary friction or stress where they are not desired. Materials were seen by Polhem as static substrates from which to build complex systems, rather than dynamic and responsive elements, which could change their properties on demand and adapt to ever-changing design requirements. On the other hand, form and its ability to change in nature are the result of a harmonious orchestration between elements with disparate and changing physical properties. As observed by D'Arcy Thompson, the human body is neither hard nor soft, but a combination of muscles, bones, tendons, and ligaments that make up the complete load-bearing actuation structure that allows us to walk, resist the pull of gravity, or write this document [19].

This material restriction is no longer relevant today but continues to inherently constrain alternative design possibilities, where, for instance, a mechanical element could change the elasticity, shape, or conductivity of its alloys to respond with a more adequate behavior to its changing environment. In the following section, we have gathered a short compendium of the unique properties of shape-changing materials, hoping to shine some light on the new opportunities they offer for the design of mechanical systems.

2.1 Shape-changing materials

Shape-changing materials are materials that undergo a mechanical deformation under the influence of direct or indirect electrical stimuli. They are by nature dynamic, in addition to the static properties that we find in other conventional polymers or alloys. While materials science literature is replete with examples of shape-changing materials, which promise one day to revolutionize the way we build things, most of these materials are in the early stages of development and only a few are sufficiently mature today to be reliably implemented.

2.1.1 *Survey of shape-changing materials*

The comparative table below (Table 1) serves two primary purposes: to give designers a starting point and overview of what material capabilities are available today and, most importantly, to generalize, compare, and extrapolate the

Table 1 Properties of shape-changing materials

Material	Direct or indirect electrical stimulus	Keeps shape when stimulus is removed	Displacement	Number of 'memory' states	Force
Shape memory alloy	Heat	No	Large	1 (or 2)	High
Magnetic shape memory alloy (Ni_2MnGa)	Magnetism	No	Large	2	High
Shape memory polymer	Heat	Yes	Large	1	Weak
Piezoelectric ceramic	Electric	No	Small	2	High
Dielectric EAP (e.g. dielectric elastomers (DEs))	Electric	Yes	Large	2	High
Ionic EAP (e.g. Ionic polymer metallic composite (IPMC))	Electric	No	Large	2	High
Magnetostrictive (Terfenol-D)	Magnetism	No	Large	2	High
Electrostrictive (Lead magnesium niobate (PMN))	Electric field	No	Small	2	Small
Thermoplastic	Heat	Yes	Large	1	Weak

core relevant properties, which can help guide the selection and use of these materials. This table is in no way comprehensive. We have purposefully chosen to list the more common and accessible materials. Also, we have 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, due to the difficulty of interfacing them with the control electronics necessary for HCI applications.

2.1.2 Properties of shape-changing materials

In order to clarify how material properties can limit, constrain, and generally affect the design and behavior of shape-changing objects, we list and compare in this section the properties of shape-changing materials that are most relevant to designers today. It is important to note that these properties are intrinsically connected to each other. In order to design a material that maximizes a specific quality, it is crucial to understand how it might affect the performance of other properties.

Deformation S*trength* 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 play a role in determining 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 materials are fast, but non-linear, making it harder to control finer movements with precision.

Number of Memory Shapes: 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.

Transition Quality: 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.

Trainability: The capacity to give a shape-changing material new memorized shapes after it has been fabricated. SMAs can be trained innumerous times, while SMPs can only be trained when they are originally cast.

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 they eventually start gaining a new memory shape and 'forget' 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 electronically actuate the material or measure its degree of transformation.

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 sense touch and gather feedback on how a user modifies or offers resistance to shape change. Several materials are capable of doing this, such as piezoelectric ceramics that can be used as vibration sensors or power-harvesting devices and SMAs that 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, 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 (whether 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.

2.1.3 Shape memory alloys

Due to their market presence, many years of practical use, and strong shape memory effect, SMAs and Nitinol, in particular, are currently the most versatile of the shape-changing materials and have been used for the development of the design probes described in this paper. Alternative materials would have required different control electronics, but the overall electromechanical infrastructure used in their application would have remained the same.

SMAs are thermomechanical alloys that, once treated to acquire a specific shape, have the ability to indefinitely recover from large strains without permanent deformation and remember their original geometry. After undergoing a physical deformation, an SMA wire can be heated through resistive heating to its final transformation temperature (A_f) and regain its original shape.

The shape memory effect (SME) that gives SMA their unique transformational capability is in fact a dual process that combines a transition to a memorized physical form with a transition from a malleable to a rigid state. At ambient temperature SMAs, in their martensite phase, are malleable and can be bent into various shapes, and when heated, to their austenite phase, they become rigid and remember their memorized shape. The diagram below illustrates this relationship (Fig. 1).

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 that produce more work per unit volume than SMAs. Moreover, SMAs present several form factors and can be used as thin films, single-wire linear actuators or be embedded into composites, where its *active memory* can operate in tandem with the *passive memory* of materials such as silicone and polyurethane foam. In the following sections, we focus on the underlying principles that allow shape memory and elasticity changes to support the design of shape-changing surfaces for HCI.

2.2 Soft mechanics

The term *soft mechanics* refers to systems based on the use of shape-changing materials and their composites, which generate kinesis and physical transformation via transitions through different memory and elasticity states.

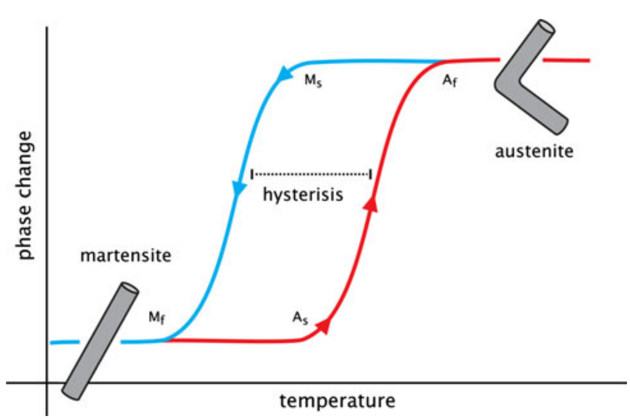


Fig. 1 In its martensite state, the SMA is malleable and can be easily deformed by an applied force; however, when heated, the SMA transitions to its austenite phase, becoming stiff and remembering its 'memorized' shape

Contrary to the machines popularized by Polhem, this ability allows us to 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. *Soft mechanics* is a powerful design approach, opening up novel possibilities for the construction of biomimetic robots [20] that can be squeezed flat to reach inaccessible places and then regain their shape, or for adaptive furniture [7] or wearables where softness and malleability are more appropriate affordances for human interaction [1].

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 that 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.

In a similar fashion to how Polhem extrapolated a mechanical alphabet from the *simple machines* from Ancient times, fully transformable surfaces can be derived from the two basic ways through which real, physical materials deform: *compressions* and *elongations*. These can take place in any three-axis configuration and can be combined to create complex forms.

2.3 Soft mechanical alphabet

In Figs 2, 3, 4, 5, we sketch a *soft mechanical alphabet* for form transformation. They show several variations of how compression and elongation lines can be combined to build simple shape-changing elements.

2.3.1 Individual soft mechanical transformations

In the first set of examples, compressions and elongations operate independently of each other to enlarge and shrink a cube.

2.3.2 Paired soft mechanical transformations

In this set of examples, compressions and elongations act together to bend a surface into different configurations. The number of paired transformations, their angle of orientation, and placement determine the overall transformation effect.

But how exactly can these simple soft mechanical elements be combined to create shape-changing tangible

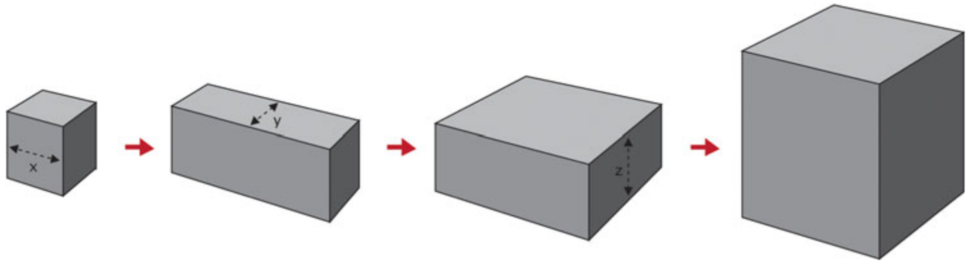


Fig. 2 The *cube* in this image is consecutively elongated in one, two, and three dimensions

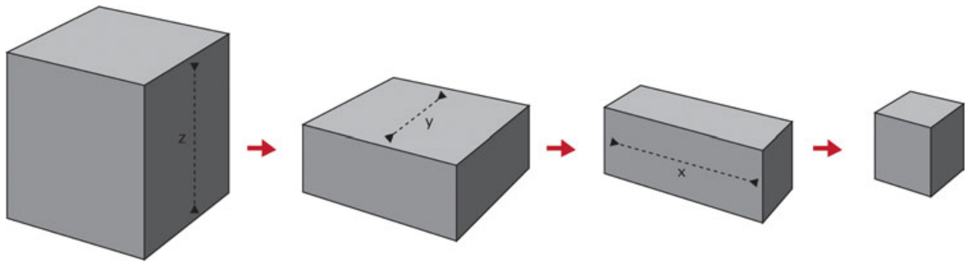


Fig. 3 In this case, the reserve transformation process occurs through compressions in one, two, and three dimensions

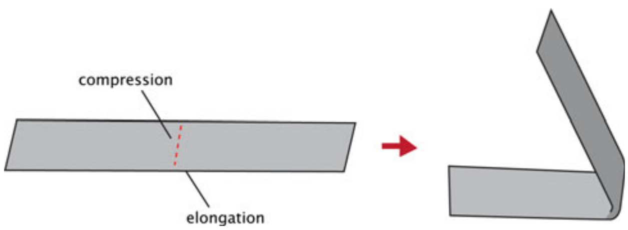


Fig. 4 A single orthogonal line of a paired elongation and compression makes the surface bend

interfaces? In the following section, we discuss how we perceive and interact with physical forms through their surfaces and how these surfaces can physically transform from one shape into another. The inherent topological limitations in their transformations provide the constraints behind the design of *Surflex*, *SpeakCup*, *Sprout I/O*, and *Shutters*.

3 From materials to surfaces

Norman defines affordances as action possibilities that are readily perceivable by an actor [14]. Affordances invite, guide, and limit users to particular action. When we interact with the physical world, we interpret affordances from the form, texture, or color of 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, the "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" [17]. Surfaces are also discussed relative to the operations performed on them (e.g. painting, carving, finishing) as well as the materials manipulated by these operations. We can also identify surfaces through their haptic qualities (e.g. soft, smooth, cold) or their spatial relationships (e.g. surfaces on the wall, floor, or enveloping objects).

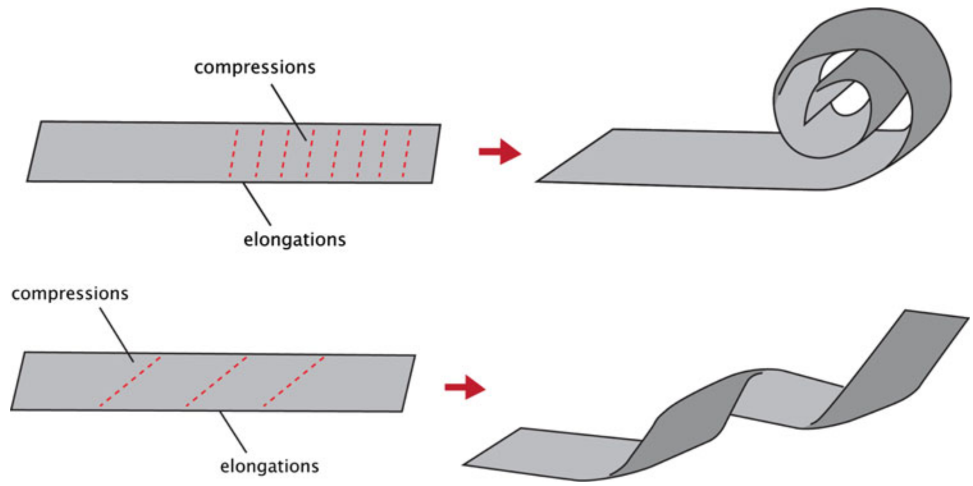
Simply put, surfaces are the boundaries through which we interact with things—where things end and begin, where things are separated from space, other things, and ourselves. Ultimately, surface boundaries define physical forms and how we perceive and interact with their transformation. Here, we look at how surfaces can be deformed to make up complex shapes.

3.1 Shape-changing surfaces

At a basic level, surfaces are very simple and only have four distinct shapes: flat, convex, concave, and saddle-shaped. 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. The simple compression and elongation transformations described in the soft mechanical alphabet can be combined to create each of the four surface types, and these surfaces as consequence can then be tiled together to create any physical form and transform it, as long as topological equivalences are preserved (Fig. 6).

In mathematics, surfaces capable of transforming into one another are considered to be homeomorphic or topologically equivalent. Two spaces are topologically equivalent if they can be continuously stretched and deformed

Fig. 5 A series of parallel orthogonal lines of elongation and compression make the surface curl (*top*). Parallel diagonal lines give the surface a helical shape (*bottom*)



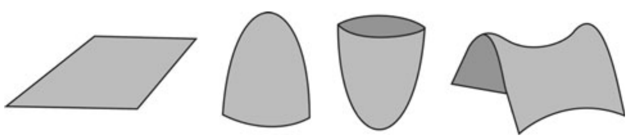


Fig. 6 Surfaces shapes: flat, convex, concave, and saddle-shaped

into another without cutting or joining distinct parts. A common example is the topological equivalence of a donut and a mug. A sufficiently pliable donut 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 cutting or joining. 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 transformable surfaces without having to resort to constructive or destructive processes, such as punching holes or stitching surfaces together (Fig. 7).

In the digital realm, these limitations do not exist and a surface is generally regarded as a two-dimensional programmatic field: an "immaterial and pliable two-dimensional datum with no depth or internal structure" [18]. Digital surfaces are unconcerned by gravity, construction, and traditional distinctions between surface and structure. In the physical world, things are quite different and physical surfaces are constrained by their topological and material limitations, as well as external forces such as gravity and user control.

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. The design of *Surflex*, *SpeakCup*, *Sprout I/O,* and *Shutters* is partially motivated by these constraints and the possibilities leveraged by different transformation types.

4 Topology, texture, and permeability

According to how we perceive and interact with surfaces, and taking into account the homeomorphic limitations of materials, surface transformations can be divided into three separate types:

- *Topological transformations*, where the complete surface has a modifiable curvature and a combination of compression and elongation lines can give it any continuous shape.
- *Textural transformations*, where small shape changes at the surface boundary can give a surface new visual and tactile properties, without affecting its overall shape.
- *Permeable transformations*, where the porosity of a surface can be controlled to regulate its transparency and the exchanges between two spaces, ultimately breaking its homeomorphism.

These distinctions are relevant here in so far as they hint at how different transformations can support or hinder new interaction possibilities. For instance, *Surflex* proposes a material architecture in which a surface can adopt any topology by combining compression and elongations in the principal directions, much alike NURB-based digital surfaces. However, its design is limited by the fact that it cannot break its homeomorphic continuity. *SpeakCup* uses topology changes as a form of input, where user-activated shape changes can reveal different metaphors and trigger related functionalities. *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

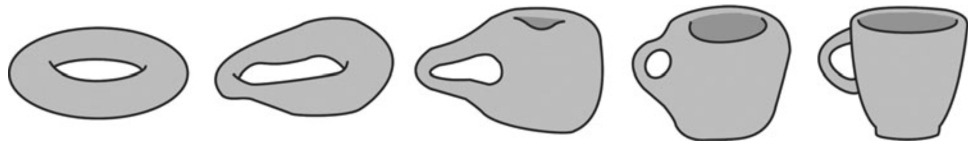


Fig. 7 A pliable donut can be reshaped into a cup in a homomorphic transformation. [12]

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 using small controllable perforations to modulate the permeability between two spaces.

4.1 Surflex: topology

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 (Fig. 8) [5].

4.1.1 Dynamic output forms

Today, designers have a variety of additive and subtractive fabrication techniques available to them, such as laser sintering or CNC milling, to visualize and physically create virtual objects at high resolutions. 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.

Researchers have sought to address this issue by creating kinetic surfaces and interfaces for physically manipulating and visualizing digital information. *Aegis Hyposurface* [8] and *Lumen* [15] are examples of two interfaces that use an array of pistons and linear actuators to display kinetic and three-dimensional images. 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. *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 deformations in three dimensions.

4.1.2 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 (PCBs) each, which are connected to each other through 8 SMA springs arranged on an x,y grid.

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 splines' control vertices. In order to build a physical spline-based curve, these control vertices cannot float autonomously and need to be located on the surface itself. To address this problem, Surflex uses an array of SMA strands arranged in opposing U and V directions, which act as soft mechanics compression elements that pull the surface's vertices together (in this case, small circuit boards attached to the surface itself). When the SMA cools down to the ambient temperature and reaches its 'malleable' state, the foam becomes stronger than the SMA and forces the composite back to the foam's original shape. Acting as soft mechanics elongation elements, the foam uses its passive shape memory to counteract the SMAs actuation (Fig. 9).

By combining horizontal (x) and vertical (y) compressions, it is possible to bend the foam composite into any

Fig. 8 Surflex's surface deformation in three steps

shape in the *z*-plane, which allows for a range of surface deformations as broad as the ones we find in virtual surfaces.

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.

4.1.3 Application

We are currently developing two main applications for this technology: the real-time computer modeling of objects and programmable acoustics.

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. Walls could not only be updated overtime to reflect changes in its usage but they could even be 'played' in a similar way to how a musician plays an instrument.

4.2 SpeakCup: topology

SpeakCup is 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. When molded into a concave shape, *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 (Fig. 10) [21].

In this design probe, we were interested in exploring two primary surface types (concave and convex) and passive shape change as a means to incorporate physical metaphor or analogy into devices. Form in *SpeakCup* not only communicates different functionalities, but it is also used to trigger different events, in this case, recording or reproducing sound.

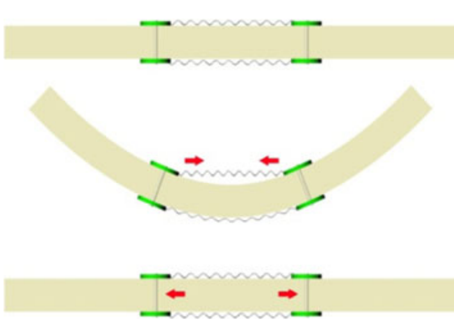


Fig. 9 Surflex deformation diagram

Fig. 10 Speak Cup in play mode

4.2.1 Dynamic input forms

Using shape change as an input to computational systems is nothing new, the mouse changes shape when you click it and so do keyboards. Shape change is the dominant form of human–machine interaction, but in most cases the change in form and the action incurring the change are only loosely connected to the desired response. Hutchins, Hollan, and Norman described this as *the gulf of execution* [10]; in other words, it is the gap between a user's goals for action and the means to execute those goals. Interfaces (by definition and observation) get in between users and their goals (Fig. 11).

In *SpeakCup*, we bridge form and functionality by imagining sound as a metaphor for a physical substance that can be *contained* and *absorbed* by a surface. *SpeakCup*'s silicone disk has seven holes on one of its faces. Deforming it into a concave shape, so that the holes are located inside of a cup, triggers the sound recording. Once the sound is *absorbed*, red LEDs pulse within its body, indicating the presence of sound. When the user removes pressure from *SpeakCup*, it springs back to its original flat shape. To playback the recorded sound, the user then presses *SpeakCup* in the opposite direction, pushing the holes so that they are located on the outside of a convex shape, releasing the stored sound.

4.2.2 Engineering SpeakCup

SpeakCup's body is made from a 5.5" disk of platinum cure silicone rubber, which gives it the *passive shape memory* to return to its original shape. A ring of aluminum is embedded inside the outer rim of the disk so that *SpeakCup*'s deformation is constrained and remains round,

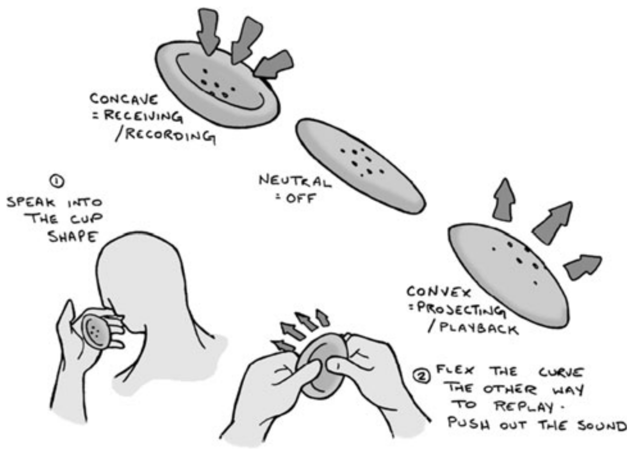


Fig. 11 Speak Cup interaction design

forcing the soft mechanics lines of compression and elongation to radiate in circles from SpeakCup's center.

A PCB embedded in the silicon disk is outfitted with control electronics and LEDs and is wired to an external computer that controls the recording and playback functions. Finally, an embedded flex sensor is used to sense the user deformation and trigger the appropriate behavior.

4.2.3 Application

SpeakCup is a simple interface for sound recording and playback but similar interface techniques could be used for a number of other applications. For instance, the *Kronos Projector* [2] is an example of an application where shape change can serve as a compelling input technique. Users of the *Kronos Projector* view video on a vertical sheet of deformable material, and by physically deforming different areas of the screen, they can replay segments of earlier video frames. In this case, shape change input is used to create a poetic association between time and space distortions.

4.3 Sprout I/O: texture

Sprout I/O is a textural 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. Rather than modifying a surface's overall topology, shape change in this case is used to generate dynamic surface properties at an object's physical boundary with the external world [4].

4.3.1 Dynamic texture

Surface properties, such as texture, can play an important role in how users perceive objects' affordances and interact with the information they convey. Small shape deformations on a surface can not only modify how surfaces feel to the touch but also modulate light reflectance, color and give us audio and visual feedback of how objects react when in contact with one another. Additionally, since texture plays a crucial role in how the surface qualities of an object are perceived, it can also enhance or counteract the overall perception of form (Fig. 12).

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 generally accepted 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 [11]. Through techniques such as cross-hatching, 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. In fact, 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 oriented in the direction of maximum normal curvature, also known as the first principal direction [11].

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 [16]. While systems such as this enable a rich set of interaction scenarios, their level of kinesis and material affordances are limited. In *Sprout I/O*, actuation is part of the material itself, rather than depending on an external mechanism such as an electromagnet.

4.3.2 Engineering sprout I/O

Sprout I/O is composed of a grid of 36 textile strands (6 rows and 6 columns) that resemble grass blades. Each strand is made of a fabric and SMA composite and can bend in two directions (backward and forward). In this case, a paired soft mechanics line of compression and elongation is located midway through a strand. When the strands are aligned up straight, the surface feels rough to the touch, and when they curve down, it feels smoother. Since the two faces of a strand are made of different color fabrics, their motion can transition the surface from a dark green to a light green color.

To create a strand that could move in two directions, we 'bond sewed' a complex SMA shape onto both sides of a felt strand. To guarantee that shear between the different

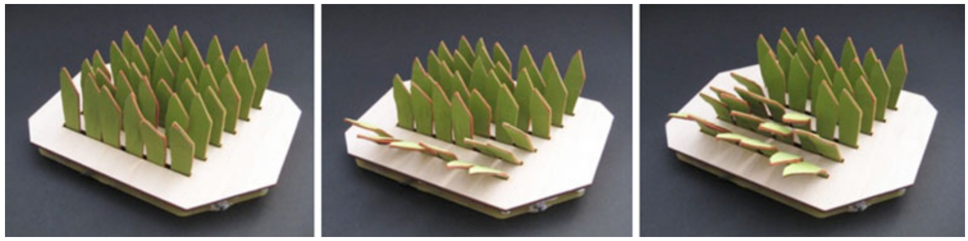


Fig. 12 Sprout I/O animation steps

composite laminates would not hinder actuation, a stretchy fabric was used as the external substrate. 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. While the SMA gives two-directional movement to this composite, the fabric provides structure, as well as visual and tactile quality (Fig. 13).

4.3.3 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, we 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. In contrast to SpeakCup, the user input is sensed by simply touching the strands, rather than physically deforming the whole object.

4.3.4 Application scenarios

Apart from functioning as a new kind of soft and non-emissive display, applications for this technology could take many forms. We 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 displays for advertisement and to provide information about a game or 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.

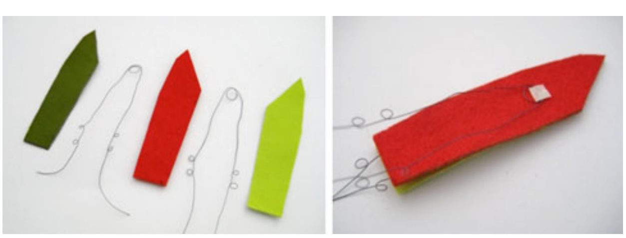


Fig. 13 Sprout I/O strand construction details

4.4 Shutters: permeability

Shutters is a curtain composed of a grid of actuated louvers (or shutters), which can be individually controlled to move inwards and outwards, regulating shading, ventilation, and displaying images and animations, either through its physical shape changes or by casting shadows in external surfaces [6].

While *Surflex* and *SpeakCup* change topologically and *Sprout I/O* changes texturally, *Shutters*, on the other hand, changes permeability—the third type of form transformation. In *Shutters*, we create perforations in a continuous surface to break its homeomorphism. The resulting apertures are regulated to control the boundary between two distinct spaces, examining how kinetic membranes can be used to blur their physical boundary, rather than just modulate topological relationships (Fig. 14).

4.4.1 Dynamic permeability

Architecture provides a compelling need for a permeable membrane that can physically transform itself to simultaneously accommodate multiple conditions and functionalities. Spaces are 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 flow, daylight intake, or visual privacy. Moreover, people's use of space is complex and changes frequently, raising the need for an

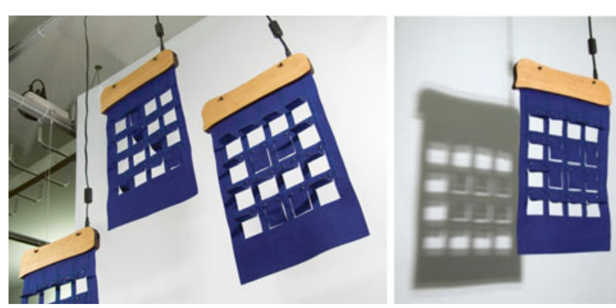


Fig. 14 Shutters as a kinetic and shadow display

environmental control system which is equally flexible, and capable of adapting to its users.

Most buildings present some form of adjustable sun-shading element or technique (also referred to from French as *brise-soleil* or *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 weather conditions and season. 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 replaced 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.

Using a shape-changing material to control its apertures, *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 non-intrusive way.

4.4.2 Engineering shutters

Shutters is primarily built from a natural wool felt sheet, laser cut to create a grid of 16 louvers (4 rows and 4 columns). Each louver can be individually controlled to move inwards and outwards regulating their aperture within a 180° shape change. Similar to *Sprout I/O*, the soft mechanics lines of compression and elongation are placed midway through a louver causing them to deform orthogonally to Shutters' surface and creating its regulated apertures. *Shutters* is constructed out of fabric so as to be flexible and easy to manipulate, while still embodying the conventional functionalities of external façade elements.

The actuation mechanism in *Shutters* is also similar to that of *Sprout I/O*, where SMA strands are embedded within the fabric substrate and electrically heated by multiplexing specific rows and columns, similar to the design of a conventional LED display. However, '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. Moreover, *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.

4.4.3 Application

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 due to 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 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 regulate airflow; and finally, (3) use of *Shutters* as a soft kinetic and shadow display.

5 Interacting with shape-changing interfaces

In this section, we look at the different ways in which users can interact with shape-changing interfaces and how they can be used as a tool to enrich human–computer interaction.

As far as interaction affordances are concerned, shape change can be described as physical deformations that 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 changes as in *Surflex* and *SpeakCup*; (2) the external surface quality changes as in *Sprout I/O*; (3) homeomorphic changes as in *Shutters*; and (4) any combination of these changes. These transformations can be perceived directly or, as in the case of *Shutters,* indirectly through changes to external elements such as wind and light.

In response to a deformation exerted by a user, transformable shapes can develop the following kinds of interaction with a user:

- 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.
- Objects can respond with force-feedback and counteract the user's deformation.
- Objects do not respond at all, recording the user's action and applying it in some other place or context.
- Objects can constrain and limit the deformation imposed by the user.

Additionally, we have identified three ways in which shape change can be used in human–computer interfaces.

5.1 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 space. But as forms become dynamic, they start to reflect dynamic functionalities. One example is Fan and Schodek's shape memory polymer chair [7]. Another example is *Haptic Chameleon,* a dial for navigating video content that can change shape to communicate different functionalities to a user. A circular dial advances the video continuously (frame-by-frame) while a rectangular-shaped dial advances it scene-by-scene [13].

5.2 Dynamic forms as a physical representation for dynamic data

Another scenario is the use of form transformation as a representation for dynamic data. Shape-changing interfaces can communicate information by: (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.

These methods 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. *Lumen,* described earlier, is an example of a display that use kinesis as a way to change shape and display information. *Lumen* can communicate data to a user visually or through tactile feedback [15].

5.3 Dynamic forms guide and limit dynamic physical interactions

Physical constraints are sometimes pointed out as being a drawback of tangible interfaces when compared to the more versatile graphical UIs [13]. However, these constraints can help a user learn an interface or system; they can be catered to support specific tasks or goals; and 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 [17].

These scenarios are not comprehensive. 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.

6 Conclusion and future forms

Shape change is not a new topic in design, but it remains largely unexplored in human–computer interaction due to technical challenges and the relative lack of information regarding its value. Shape-changing materials present exciting new opportunities in HCI. To conclude this paper, we will outline some possible directions for future research.

6.1 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 will require tools to automate the selection of the soft mechanical elements necessary to generate a transformation between multiple forms.

6.2 Morphable interfaces

A promising application domain for shape-changing surfaces is the design of physical interfaces that can physically change to accommodate different users, uses, and contexts. When compared to the versatility of graphical user interfaces, one of the drawbacks for tangible user interfaces is their physical limitations and the fact that they are rarely generalizable or scalable. 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 could be overcome. With advances in shape-changing materials, tangible interfaces could dynamically morph to accommodate contextual information, body language, gestures, and user interests perhaps mimicking the way that animal forms are the evolutionary result of forces such as gravity or surface tension [19].

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