Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions

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ABSTRACT
Shape change is increasingly used in physical user interfaces, both as input and output. Yet, the progress made and the key research questions for shape-changing interfaces are rarely analyzed systematically. We review a sample of existing work on shape-changing interfaces to address these shortcomings. We identify eight types of shape that are transformed in various ways to serve both functional and hedonic design purposes. Interaction with shape-changing interfaces is simple and rarely merges input and output. Three questions are discussed based on the review: (a) which design purposes may shape-changing interfaces be used for, (b) which parts of the design space are not well understood, and (c) why studying user experience with shape-changing interfaces is important.

Author Keywords
Shape-changing interfaces; shape displays; organic user interfaces; actuated interfaces; non-visual actuators

ACM Classification Keywords
H5.2. Information interfaces and presentation (e.g., HCI): User Interfaces---Haptic I/O, Input Devices and strategies, Interaction styles.

General Terms
Human Factors

INTRODUCTION
The ability of objects to change shape plays a key role in nature (e.g., the Southern White-faced Owl can enlarge its body to scare enemies or shrink it to appear as a tree branch), in design (e.g., the invention of self-inflating life vests), in architecture (e.g., buildings that automatically reconfigure offices based on occupants' habits), as well as in many other fields. The research area of shape-changing interfaces aims at using some of these qualities to enhance our interaction with digital information.

Examples of shape-changing interfaces include displaying directions on a mobile phone through deformations of its shape [15], a foam surface with embedded shape-memory alloys that may be programmed to change shape [10], a water faucet that uses changing postures to raise awareness about water consumption [48], and buttons capable of modifying their shape [12]. Recent reviews contain many other examples (see [9,37]).

In spite of the inventiveness of these examples, we see a number of limitations of the research on shape-changing interfaces. First, the literature mainly contains point designs. Few papers survey the design space for shape-changing interfaces, so as to put existing work into perspective and identify underexplored directions. Second, research on shape-changing interfaces is mostly a technical enterprise. The psychological and artistic aspects of shape change are rarely discussed. Third, research in shape-changing interfaces rarely focuses on interaction and does not relate shape change to models of interaction (e.g., on reality-based interaction [24] or tangible user interfaces [11,49]).

The aim of this paper is to review existing research on shape-changing interfaces. We analyze the change in shape, the dynamics of change, the interaction, and the design purposes. Based on the review of these parameters of the design space, we discuss open research questions and under-researched areas. For practitioners, the paper aims at providing an overview of the design possibilities in shape-changing interfaces. For researchers, the benefit of the paper is to outline open research questions.

SCOPE AND MOTIVATION
The interfaces relevant to the present paper have been discussed under different headings: Actuated Interfaces [37], Kinetic Interaction [34], Organic User Interfaces [9], Kinetic Organic Interfaces [34], Pro-active Architecture [31] and Computational Composites [50]. The present paper discusses these together under the phrase shape-changing interface. A shape-changing interface uses physical change of shape as input or output. We follow earlier work that has used self-actuated change as a defining characteristic for such interfaces [37]. Additionally, we require that the self-actuation must be controllable so that the object can return to its initial state and repeat the shape change. Interfaces that cannot directly control their shape are thus left out of

this paper. Finally, we are concerned only with non-WIMP types of interfaces and non-desktop hardware.

Previous papers have begun to characterize the potential of interfaces using shape change. In 2008, Communications of the ACM ran a special issue on organic user interfaces [52], the TEI conference has featured several overviews of shape-changing interfaces [37], and Coelho and Zigelbaum [9] recently reviewed the potential of shape-changing materials to HCI, focusing in particular on technology for invoking shape change.

Compared to these earlier reviews, the present paper offers three novelties. First, we base our review on a selection of 44 papers on shape change. We collected these by browsing proceedings of relevant conferences, following references in and citations to well-known papers on shape change, and searching the reference lists of the reviews mentioned above. The list of papers is available from the authors. Second, we discuss four aspects of shape change: the change in shape, the dynamics of change, the interaction, and its purpose. Previous reviews have only focused on a subset of these. Third, we discuss state-of-the-art, as well as open research questions and blind spots. In particular, existing reviews have mostly been about technology; we try to complement this by also focusing on the experience of using shape-changing interfaces.

TYPES OF CHANGE IN SHAPE

This section presents an overview of the types of change in shape that are used in the papers informing this review (see Figure 1). The types are changes in: *orientation, form, volume, texture, viscosity, spatiality, adding/subtracting*, and *permeability*. Changes in viscosity and spatiality do not necessarily deform objects (i.e., change shape in a strong sense), but are included because they may lead to the experience of shape change.

Changes in *orientation* distort the original shape through rotations or changes in direction, while preserving the recognisability of the original form. Orientation is a widely used means to establish shape change [6,33,39,44,48]. The Thrifty Faucet [48] communicates information on water consumption and hygiene to the user through deforming its shape into various postures, using changes in rotation and direction.

Form changes are defined by transformations that preserve the approximate volume of the shape while changing its overall form [10,26,27,32,33,47,56]. Horev's Morphing Harddisk concept [20] changes form by sucking in or blowing up a cube shape, thereby hiding or revealing the cube's skeleton structure. The concept applies the form change to visualize information about harddisk activity, synchronization, and the remaining space on the harddisk. Another example is the Shape-Changing Mobile [17], a mock-up phone that changes its form by using a set of small motors embedded in a flexible chassis.

Changes in *volume* maintain the approximate form and are used in some shape-changing interfaces [16,26,32,59]. The Inflatable Mouse [26] uses change in volume, through inflating and deflating a form, in order to accommodate both fitting into the PC card slot on a computer and having the volume of a comfortable, ergonomic mouse. Although the inflatable mouse changes form to some extent, the most pronounced change is in the change of volume.

Textural changes are small changes on the surface of the shape that add visual and tactile properties without affecting

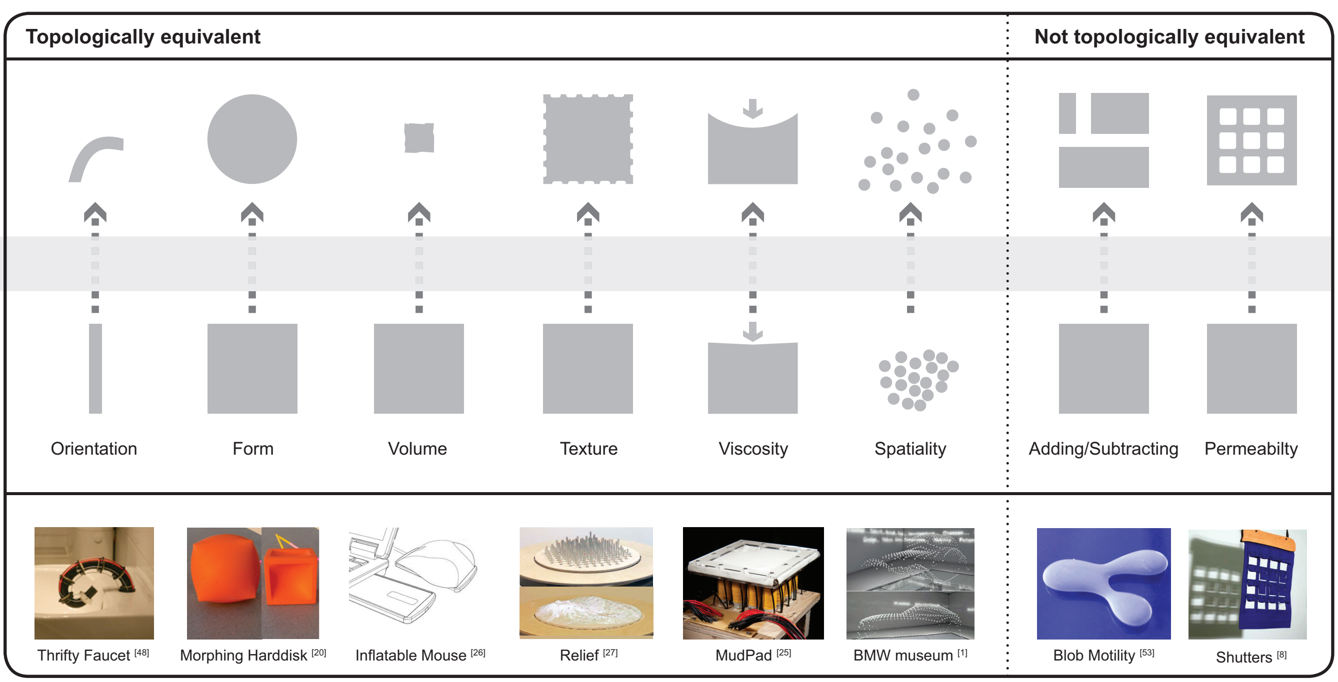

Figure 1. Types of shape change.

the overall form [4,7,12,21,23,38,40,44]. The surface of Leithinger and Ishii's [27] Relief is actuated by an array of 120 motorized pins, which allow users to create and experience digital models of, for instance, a geographical terrain. The pins are covered with lycra, which causes movements of the individual pins to be perceived as textural changes on the surface.

Changes in *viscosity* can result in both physical shape changes and in the illusion of shape change, where the viscosity changes while the original form is maintained. Mudpad [25] uses changes in viscosity as haptic output for a multi-touch surface. The change in viscosity is for instance used for the play button feedback: When the play button is pressed it becomes fluid and the user's finger sinks in. As the music starts playing, a tactile representation of the music's amplitude can be felt on the button. The viscosity change of the surface causes an illusion of the interface changing shape, as users perceive the surface as shifting between hard, soft, and vibrating. In the sample of papers, only Mudpad exploits this means of shape change.

Changes in *spatiality* do not automatically create the illusion of shape change. A change of one element's position in space does not create the illusion of shape change, as the change is typically seen as a repositioning in space. The illusion of shape change through spatial repositioning depends on individual elements being seen as part of a collective structure. When multiple elements are repositioned spatially, they may be perceived as part of the same structure. Like schools of fish group in spherical formations to confuse enemies, changes in the spatial position of individual elements changes the composite form. The only example of shape change through spatial repositioning in the sample of papers is the Kinetic sculpture at the BMW museum in Munich [1] illustrated in Figure 2. The sculpture consists of 714 metal spheres that can be repositioned vertically and thereby lead to perception of a composite form, rather than of individual elements.

All the types of shape change mentioned above are topological equivalent, meaning shapes that can pass from one form to another through continuous deformation, without dividing or joining elements (the left part of Figure 1). Next we describe changes that are not topologically equivalent, for instance because shapes are being split, united, or perforated. However, interfaces rarely use such changes because few materials are capable of producing them.

Shape change through *adding or subtracting* is achieved by transformations that unite or divide elements, while being able to return to the initial shape or shapes. The Blob Motility [53] is an example of an interface that explores the possibilities of creating shape changes that break homeomorphism, through using a magnetic fluid as an interface that is able to split, merged, and moulded into organic shapes through changes in the magnetic field.

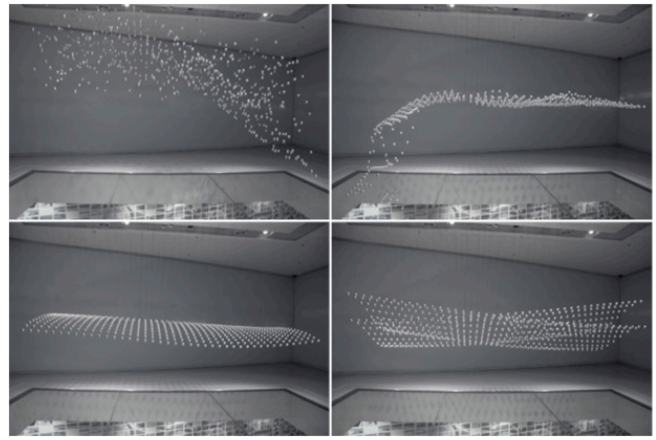

Figure 2. BMW museum kinetic sculpture [1].

Changes in *permeability* are defined by transformations, where the shape is perforated, but able to return to its initial shape. Permeable transformations offer interesting design possibilities, for instance for creating architecture that allow regulation of ventilation flow, daylight intake, or visual privacy. However, current materials are not able to realize this ideal. Shutters [9] imitates a permeable transformation, where parts of a surface can open and close to regulate the flow of air and light. Although the example does not break the homeomorphism of the surface, the imitation exemplifies the potential of permeable transformations.

TYPES OF TRANSFORMATION

In the previous section, we described the endpoints of a change in shape; this section describes the phase between endpoints. We characterize the transformations using the work of Vaughan [51] and its adaptation by Young et al. [55]. Figure 3 shows the kinetic parameters of transformations at the bottom; the top of the figure illustrates how transformations are perceived (expressive parameters).

Kinetic Parameters

Kinetic parameters are physical specifications of the transformation (e.g., speed, tempo, frequency). They include:

Velocity: Describes the speed, acceleration, tempo, vibration, and frequency of an object's movement. The Inflatable Mouse [26] uses changes in tempo and intensity of its up and down movement to express various emotions. Shutters [8] seeks to determine what is the ideal speed for a louver to move. MudPad [25] describes the speed of the changes in viscosity of the interface, being able to switch back and forth within 5 ms.

Path: Describes the movement pattern of a transformation, and thus the line that an object moves along, and whether that movement is smooth/jerky, linear/curved, continuous/intermittent, or pattern/random. Togler and colleagues [48] use a series of images to describe different movement patterns of the Thrifty Facet.

Direction: Describes the directions in which the object moves. The BMW museum kinetic sculpture [1] uses simple up and down movements to create the fluid shape-changing sculpture.

Space: Describes the use of space by the interface, including scale change and form change. In the InSync hard drive [20] the space transformation is described as follows: "Two of the prototype adjacent planes were sliding in parallel to each other, causing the envelope to twist in a way that appeared as if the cube lost its alignment." (p. 27).

A few papers describe these parameters in detail. Shape-changing Mobiles [17] include precise details of how the back plate of the mobile phone change by "…tilting of its back plate by 10° into each direction, extending by up to 15mm in depth" (p. 3077). Several papers mention kinetic changes [5,31,48], but provide few details on how the transformation occurs. It is thus hard to discuss in depth how transformations happen. One reason seems to be that movements often are complex and thus hard to express in text. Videos might provide raw information about the transformation used. For Shade Pixel [21], for example, a video is available that shows the prototype, contextualizes it in relation to related work, and explains its technical construction. Videos are not, however, available for all papers in the sample and often do not focus on illustrating transformations.

Expressive Parameters

Expressive parameters account for how the effect of the kinetic parameters is perceived. A fast, pumping motion might be experienced as agitated; slow, flowing movements might be experienced as similar to grass moved by the wind. The expressive parameters are divided into two types: association and adjectives.

Association

This type of expressivity is about the associations generated by the transformation, in particular whether it is perceived as mechanical or organic. Several of the reviewed papers seek to give "life" to the interfaces through movement. Often papers do not distinguish whether the goal is anthropomorphic or zoomorphic. Togler and colleagues [48] describe The Thrifty Faucet, which "move and behave in life-like manners" (p. 43) and the authors emphasize how continual, small movements "enriched the impression of a living object" (p. 44). In the Inflatable Mouse, life is expressed as a heartbeat, which can alter tempo to create tension [26]. Along the same line, other examples aim to create interfaces that appear to be "living" [6,23,48].

Other researchers seek to use movement to embody the interface with a sense of nature. The movements of Slow Furl [47] are described as a glazier, a frozen river, a landscape, a cloud formation, and an ice wall. In the case of Bamboostic [31], the movement of the individual mechanical "trees" creates the "feel of a rather natural landscape" (p. 76).

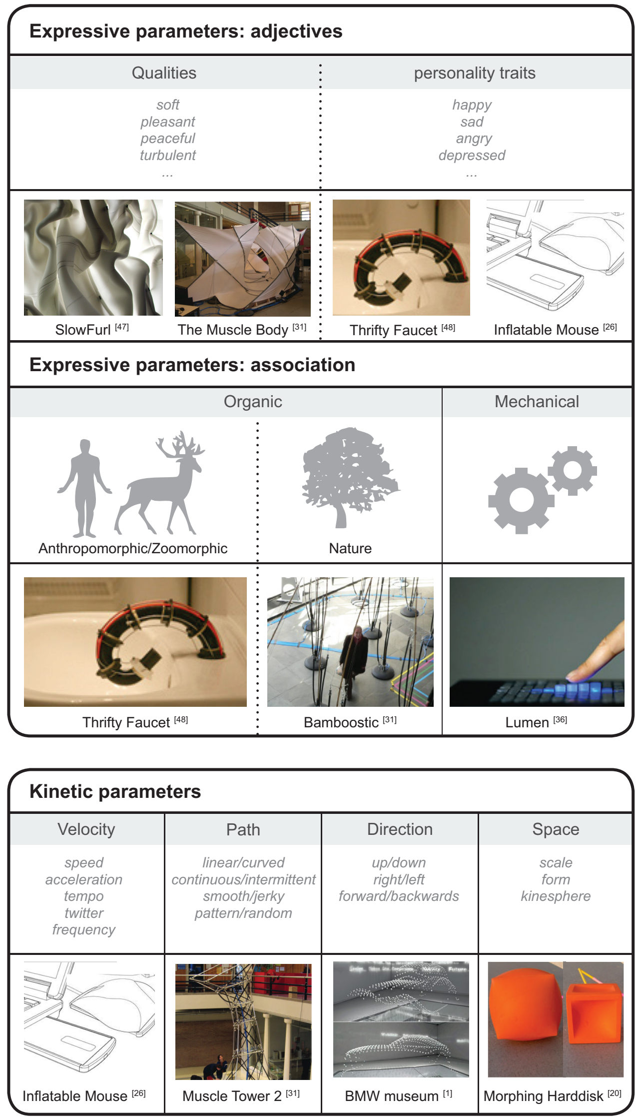

Figure 3. Transformation vocabulary.

Mechanical characteristics are less sought in shape-changing interfaces, possibly because researchers seek to answer the question "what would computers look like if they were more curved, flexible and delicate" [19]. Although a more organic sense is sought, some of the examples might be perceived as mechanical. In Kinematics [32] the two types of kinematic blocks, one shape changing and one rotating, move with repetitive and jerky movements, which give the movement a mechanical feel.

Adjectives

Adjectives describe what type of traits and qualities are ascribed to the movements. The category is divided into *qualities* and *personality traits*. If an interface transforms with a continuous smooth movement, it can be perceived as having pleasant and peaceful *qualities*. Likewise, the movement can be ascribed certain *personality traits*, by associating the movement with the interface being, for instance, relaxed or tired.

The Thrifty Faucet [48] seeks to ascribe personality traits to the faucet through movements. It moves between poses being intended as curious, seeking, or rejecting [48]. Ambient Life [18] aims at giving life to mobile phones and uses, for example, movements of "excitement" to get the user's attention. Oosterhuis and Biloria describe the movements made possible by the muscle wire as soft luxuriant undulations [31], and thus use adjectives to characterize the movement.

The expressive parameters above are often combined, serving both to describe the user experience of transformations and to account for the designer's intentions with the movements. Expressive descriptions that recount the designer's intention with the movements tend to be rather subjective and provide little information about the movements necessary to obtain it. Furthermore, it is rare to see studies of how users actually experience the prototypes. Such studies would allow us to see or validate if the intended experience materializes. Exceptions include The Thrifty Faucet [48] and Topobo [39], both of which report evaluations of how users perceive the movements.

INTERACTION

Next, we survey how shape-changing interfaces use physical transformation as input and output. In the reviewed sample of papers, we see three approaches to interaction (see Figure 4): *No interaction* where shape change is used solely as output, *indirect interaction* where shape change occurs based on implicit input, and *direct interaction* where shape change is used as both input and output.

Shape-changing interfaces have the potential to create a bidirectional relationship between the physical and the digital: The shape can be changed both physically by the user (as a means of input) and digitally by the interface (as a means of output). *Direct interaction* takes advantage of this bidirectional relationship, and in some cases *indirect interaction* also uses digital input to change the physical form. However, the majority of reviewed examples only use shape change as a means of output, focusing on the ability to alter the physical shape.

Shape-changing Output - No Interaction

The category of shape-changing interfaces without interaction uses shape change solely as output and disregards user input [4,5,6,8,21].

Some of these interfaces change shape in order to display digital information in physical form, either visually or haptically. For example, Shutters [8] and Shade Pixel [21] use a limited number of "pixels" to communicate with the user, while BubbleWrap [4] vibrates a set of electromagnetic actuators to provide haptic feedback.

Other interfaces use shape change more randomly without attempting to convey information. SlowFurl [47] changes in its own rhythm, engaging a "geological time of imperceptible flow" (p. 2). Likewise, Skorpions [6] (four different kinetic garments) and Vilkas [5] (a kinetic dress) all change shape autonomously and independently of the users' actions.

Indirect Interaction

The interfaces employing indirect interaction use shape change as output, but base the change in shape on implicit

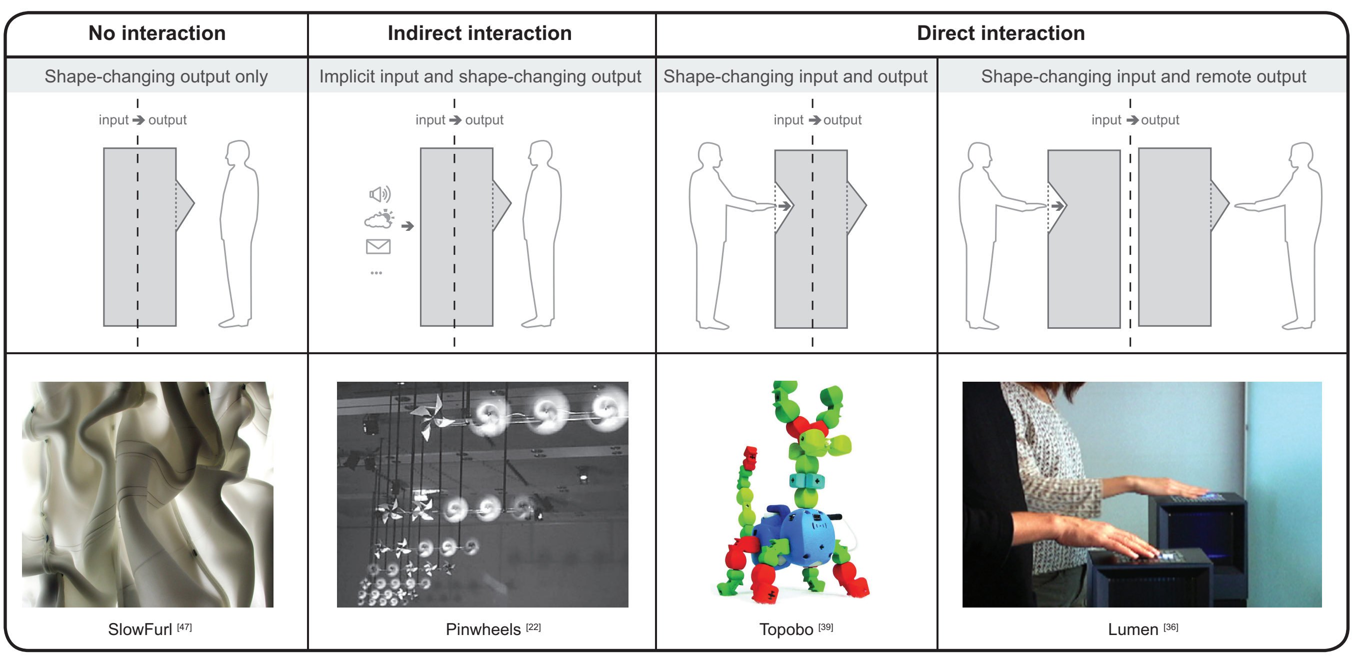

Figure 4. Three approaches to interacting with shape-changing interfaces.

input. We characterize input as implicit, when users may not realize that their actions are being used as input. The Pinwheels installation [22] exemplifies this approach. In Pinwheels, the system monitors human behaviour in its environment and spins its wheels when certain activities occur (e.g., when a person uses the elevator or sends an e-mail). Similarly, Murmur [41], a sonic sculpture, responds to sound input from its surroundings. Oosterhuis and Biloria employ implicit input as the basis for their proactive architectural spaces [31], the muscle projects (Muscle Tower, Muscle Body, Muscle Space and Bamboostic). All of these interfaces respond implicitly to the users' movements in the installation space.

Direct Interaction: Merging Input and Output

This category is defined by interfaces that use shape change both as input and output. The user interacts intentionally with the system through deforming the shape, while changes in shape are simultaneously used as output [20,26,36]. Within the reviewed papers, two approaches to using shape change as input and output exist: *action and reaction* and *input and output.*

With the *action and reaction* approach*,* the user transforms the shape, which triggers a shape transformation corresponding to the one that the user inputs. For example, the InSync' harddisk [20] must be twisted in order for it to be re-synced. As the synchronization progresses, the twisted cube realigns by slowly twisting back to its initial cubical shape. In Bodyscape [35], a kinetically transformable meshed textile interface, and Topobo [39], a kinetic toy, the user can record an action through transforming the shape and a corresponding movement is played back.

Whereas the *action and reaction* approach employs a turn-taking relationship between the shape-changing input and output, many systems use *input and output* that are not directly related. In the Inflatable Mouse [26], users can input through shape change, either by squeezing the sides or pressing the top of the mouse, thereby manipulating the shape of the mouse. Simultaneously, the mouse may be deformed as means of output by inflating or deflating the shape. This is used for expressing a heartbeat, which could be applied to create tension while playing a game or inform the user of program errors and system warnings. This example uses both shape changing input and output, but in a decoupled manner. Another example is Sprout I/O [7], an array of soft and kinetic textile strands, that uses shape memory alloys both to sense touch and move to display images and animations.

Direct Interaction: Remotely Merging Input and Output

The direct interactions described in the previous category may also be used for linking remotely located interfaces. In this way, the shape changes performed on one interface are transferred to an identical interface, where they are reproduced. One of the applications of the Lumen display [36] uses two separate displays, in order to establish haptic communication between remote participants. The setup allows users to remotely touch and draw simple traces on each other's hand using the Lumen shape display.

PURPOSES OF SHAPE CHANGE

One way to understand shape-changing interfaces is to understand the purpose with which they are designed (i.e., the aims and goals pursued by designers and researchers). In this section we review the purposes as stated by the authors of the papers we review. Typically, the purposes are stated in abstracts, descriptions of prototypes, conclusions, or application scenarios. In the sample of papers, we see four main purposes of using shape change: *functional, hedonic, explorative*, and supplying the field with *toolkits* for designing shape-changing interfaces (Figure 5). Many papers address more than one purpose, but for the sake of mapping the design space of shape-changing interfaces, we discuss each of the four purposes separately in the following sections.

Functional Aims of Shape Change

Within the sample of papers we found a number of specific functional purposes for using shape change, which we present below. In the majority of cases, the purpose reflects the designers' intentions rather than studies of how users experienced the interfaces.

The main functional purpose of applying shape change is to *communicate information* (e.g., [8,17]). Shape change is here used to encode information in a more expressive or efficient manner. Shape-changing Mobiles [17], for instance, uses changes in thickness of the phone to guide users to move in a particular direction, by making the phone slightly thinner in the direction in which to move. In other cases, changes in shape are used as "information displays" [8, p. 13] or to "visualize information" [21, p. 1].

Dynamic affordances are another functional purpose, where shape change is used to communicate possibilities for action. As an example, Harrison and Hudson [12] use pneumatics to add physical shape to buttons, allowing for dynamic affordances depending on digital content. Papers in our review use phrases like "just-in-time affordances" [10, p. 3433] and "dynamic ergonomics" [17, p. 3077].

Another functional purpose of shape change is to use it for providing *haptic feedback* [4,7,12,25,27]. One aim of using shape change as haptic feedback is to provide tactility to touch displays. BubbleWrap [4] uses electromagnetic actuators enclosed in fabric to provide haptic information by making the surface bulge or vibrate or by changing its firmness. Whereas the interfaces mentioned above use haptic feedback to improve usability, systems like Super Cilia Skin [38] and Lumen [36] use haptic feedback for more explorative purposes. Here, haptic feedback is used to create social presence by recording the interactions of one user and play them back either locally or on remotely placed device.

Some research prototypes use the capability to change shape because it is a *practical* solution to a problem. One example of this is the Inflatable Mouse [26] that can be inflated to the size of a regular mouse and deflated in order to fit inside a PC card slot. Another example is Shutters [8], where the permeability of a fabric is changed by opening small louvers in the fabric to change daylight intake and ventilation.

Several papers describe the use of shape-changing interfaces for *construction* [32], where the user can assemble a dynamic form and manipulate it. Both Kinematics [32] and Topobo [39] allow users to construct different shape-changing kinetic structures through assembling parts.

Hedonic Aims of Shape Change

A number of design goals of shape-changing interfaces are hedonic, that is, focus primarily on non-instrumental goals [3,13] such as stimulation, aesthetics, identification, and fun. An illustrative example of such a hedonic aim is found in Pinwheels: "Pinwheels acted as kinetic sculptures that are beautiful and poetic in and of themselves" [22, p. 112]. Below we present the specific hedonic aims.

Several papers use shape change for *aesthetical* aims [5,26,48]. The interfaces in the aesthetics category derive from domains such as fashion [6], art [40], and architecture [47].

Another frequent use of shape change technologies is to engender *emotion* (e.g., [26,48]). A commonly used approach to portray emotions is to use organic and life-like movements. The Inflatable Mouse [21] simulates breathing to "express the motion of taking a nap when it is not in use." [26, p. 213]. The Thrifty Faucet [48] is neither functional nor aesthetic. Rather, by ascribing life-like behaviour to the faucet, Togler and colleagues sought to "step into dialogue with the user" (p. 43) and communicate emotions through motions and postures. In the case of the faucet, emotional responses from users have been studied empirically [48].

Stimulation and provocation are also pursued as design goals [6,31]. One prominent purpose of using shape change is to challenge our understanding of materiality. This use is illustrated by Oosterhuis and Biloria with their Muscle Projects [31]. By incorporating interactivity as a key component, they seek to "suggest and provoke the possibilities of engaging with space" (p. 75) and to "break the stereotype of the façade of a building as a barrier separating the interior from the external environment" (p. 78).

Explorative

Some papers report on conceptual experiments with shape-changing materials and technologies. Their goals are typically technical and aim at increasing our understanding of the materials involved in shape change. Examples of such explorations have concerned soap bubbles [45], shape memory alloys [10], silicone [44], and the use of ferrofluid [25]. Few focus on exploring the design potential of shape change unencumbered by technical limitations. SpeakCup [56], however, explores the design potential of shape change in relation to simplicity.

Toolkits for Programming Shape Change

A few papers discuss shape change in terms of toolkits for programming it. Bosu [33] is an example of this aim. Bosu makes it possible to iteratively experiment with shape actuation by making it possible to use soft materials to record and play back motion in 3-D space.

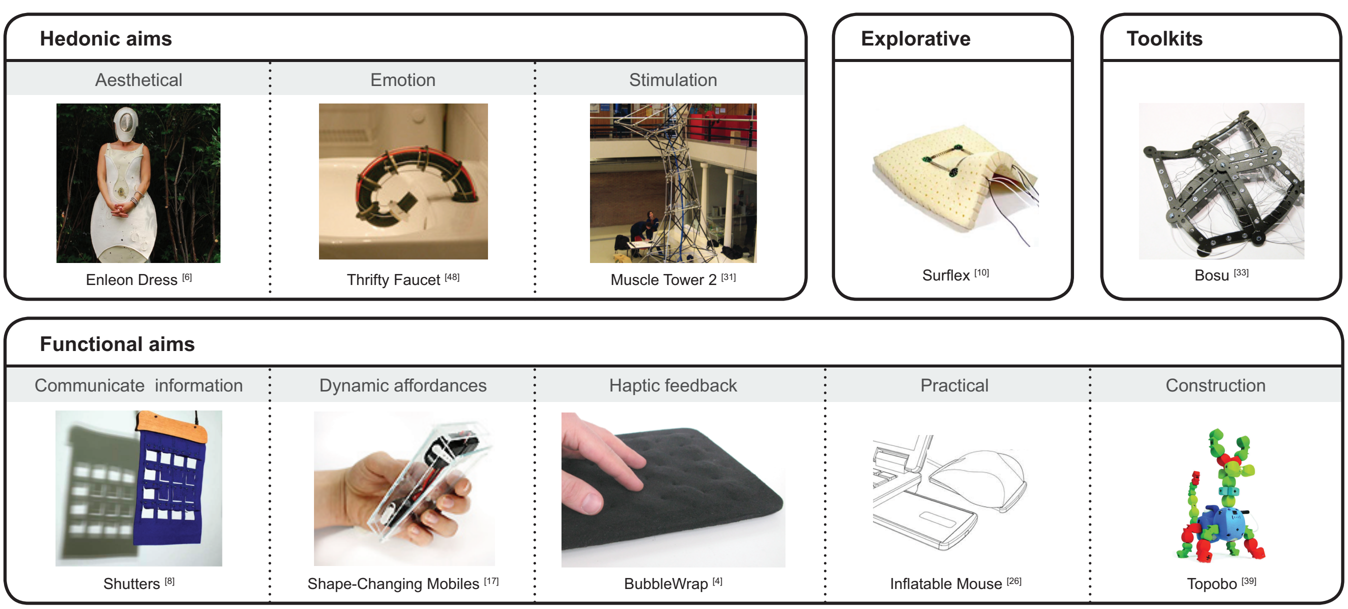

Figure 5. Four purposes of using shape change.

DISCUSSION AND CONCLUSION

We have reviewed 44 papers on shape-changing interfaces in order to outline the design space and provide a basis for discussing open research questions. Papers were analyzed with respect to which aspects of shape they manipulated (e.g., form, volume) and how transformation between shapes was achieved (e.g., animation type). We also discussed the broad types of interaction (e.g., integrated input/output) and the purpose intended with shape-changing interfaces (e.g., communication, artistic expression). Three questions spring from the review, which we discuss next.

The Purpose of Shape Change

The first question concerns the purpose to which designers put shape-changing interfaces. We have shown how many purposes are pursued in the literature, something not brought up in previous reviews of shape-changing interfaces [9,35]. Each purpose raises different questions on the suitability of using shape change and on how to assess whether the purpose was successful.

Many of the interfaces we have discussed aim to communicate information. Surprisingly few of them, however, answer the question whether shape change is a good modality for accurate and precise communication. Shade Pixel [21] for instance, has a resolution of 7×11 pixels; Shutters [8] offers 4×4. As communication devices in a strict sense, are these resolutions interesting? Limited bandwidth communication can be very rich (e.g., the 12Pixel project, [54]), but we would like to see more discussion of the viability of this particular purpose. For instance, what is the inherent communication quality of shape and transformation? What is the potential of ambiguity, subtleness, growth, or related shape notions for designing expressive and engaging interfaces?

As discussed earlier, many shape-changing interfaces use life-like movements (e.g., [48]; see also [42]). But what is the purpose of life-like movements, besides serving as design inspiration? Further, whereas life-like technology is often pursued early in the life cycle of a technology, its later utility is sometimes questioned. We suggest future research to be clearer about the purposes and benefits of imitation of life; the papers in the present sample are not.

Our classification of purpose was cumbersome and proceeded on limited information; few papers succeed in articulating the design aim of using shape change and making plain why that purpose is better accomplished with shape change, rather than another interaction style (say, a tangible user interface or direct manipulation). Recent reviews of tangible user interfaces (e.g., [43]) have begun a careful, data-driven discussion of the purposes and tasks for which tangibility is suitable. We suggest future research to do the same for shape-changing interfaces.

The Design Space of Shape Change

The second question concerns the design space of shape change, as exemplified by the sampled papers.

Undoubtedly, what we have called transformation is a key aspect of making shape-changing interfaces useful and usable, just as transformation is part of the magic of animation [46]. Unfortunately, current descriptions (incl. videos) do not give sufficient detail to discuss this aspect of shape-changing interfaces in depth. Also, we have seen no systematic exploration of how different types of transformation may be used and to what effects.

We have attempted to outline the design space of shape-changing interfaces; others have provided complementary accounts (e.g., [9,35]). Whereas individual papers combine design space parameters, we see no systematic attempt to explore this space and investigate new combinations of purpose, shapes, transformations, and input/output configurations. Future work should do so, possibly using a design research approach [57,58], which seems ideal for exploring design opportunities, yet curiously underused in work on shape-changing interfaces. One benefit of exploring the field through design would be to illustrate how shape-changing interfaces can integrate into and benefit from different use contexts, as well as gaining an understanding of how shape-changing interfaces can enter people's lives in new and unexpected ways.

At the level of modeling interaction, Parkes [33,35] has discussed how shape-changing interfaces advance tangible user interfaces. We would like to see this discussion followed up by further studies on, for instance, hybrid materiality, that is, the combination of structural stable parts of shape and more malleable parts [33]. Thus, at the level of modeling the distinct characteristics of shape-changing interfaces and exploring them through design-based research, we have seen no systematic approaches in our sample. Finally, the relation between input and output in the present sample of shape-changing interfaces is underexplored.

User Experience and Shape Change

The third question we wish to raise is about users' experience with shape change. Overall, about one fourth of the papers in our sample evaluate users' reactions to the interfaces; in our view, many of these offer valuable insights [12,16]. On the one hand, this percentage may be seen as adequate for a technology-driven field in its early stages. On the other hand, many evaluations are sketchy and based on exhibitions or workshops. Few papers in our sample build on recent progress in conceptualizing and studying user experience [13,29]. This is unfortunate for three reasons. First, it is unclear whether the designer's conceptual model (in the terms of Norman [30]) is in agreement with what is being experienced by the user. Thus, we do not know enough about whether the many purposes that designers imagine for shape-changing interfaces will materialize in user studies or in real use. Second, many questions on the utility of particular transformations, shapes, or purposes are empirical. For instance, one potential of shape-changing interfaces is to allow for dynamic affordances, that is, perceived action possibilities that change with changes in shape. To our knowledge, however, how users experience dynamic affordances has not been investigated. Third, shape-changing interfaces are a case in point with respect to Bannon's [2] recent critique of the HCI field as having too little of a human-centred focus. A key objective for future research is to generate more, high-quality data on the user experience with shape-changing interfaces.

Let us suggest two ways of how to generate such data. One way is about understanding the vocabulary of shape-changing interfaces and how this may be used. As an analogy, studies of graphical perception have long investigated the expressivity and accuracy of graphical marks (e.g., [14,28]). Similarly, we would find it highly valuable to see in-depth studies of the expressivity of the eight shape types outlined earlier as well as of how to transform among them. Another way is to study overall reactions to interfaces, in particular to involve users' tasks (or aspirations for experiences) and user context. The current literature rarely discusses suitable tasks for shape-changing interfaces and we found no investigations of how use context may impact the performance of and preference for shape-changing interfaces.

Limitations

We have argued in the introduction that the present review's strengths are to build on a solid base of papers and to discuss shape-changing interfaces in a broader manner than existing reviews. However, it has several limitations. First, we have established the sample of studies in an ad hoc way, based on references in and citations to well-known papers on shape change. A more systematic review could complement this approach. Second, the research on shape change is multidisciplinary, bordering fields and traditions where research papers are rarely the prime documentation of designs and prototypes. A different approach to obtaining descriptions (e.g., video, catalogue entries, exhibitions) of shape-changing interfaces would be complementary and, we believe, valuable. Finally, the reader may object that the discussion ignores that shape-changing interfaces is a primarily technology-driven research area; the discussion above about purpose and user experience is therefore irrelevant. We disagree. One reason is similar to that offered by Bannon [2], another is that we believe that the research suggestions above are likely to improve our understanding of shape-changing interfaces markedly, in turn informing the necessary technical development of such interfaces.

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