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The Design of Organic User Interfaces: Shape, Sketching and Hypercontext

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With the emergence of flexible display technologies, it will be necessary for interface designers to move beyond flat interfaces and to contextualize interaction in an object's physical shape. Grounded in early explorations of organic user interfaces (OUIs), this paper examines the evolving relationship between industrial and interaction designs and examines how not only *what* we design is changing, but *how* we design too. First, we discuss how (and why) to better support the design of OUIs: how supporting sketching, a fundamental activity of many design fields, is increasingly critical and why a 'hypercontextualized' approach to their design can reduce the drawbacks met when everyday objects become interactive. Finally, underlying both these points is the maturation of technology to that of a computational material; when interactive hardware is seamlessly melded into an object's shape, the 'computer' disappears and is better seen as a basic design material that, incidentally, happens to have interactive behavior.

STUDY HIGHLIGHTS

- The art of user interface design is on the cusp of a revolutionary change.
- Flexible display materials dramatically alter how computer interfaces can be designed.
- Technology is moving towards that of a computational material.

Keywords: organic user interfaces; computational material; non-planar interface

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1. INTRODUCTION

The art of user interface design is on the cusp of a revolutionary change; one that will require designers to think about the effect of a material and a form on a design. Traditionally, today's computer displays afford interactions that take place on a flat surface. With the arrival of sensing touch on three-dimensional surfaces (Benko *et al.*, 2008; Han, 2005; Rekimoto, 2002; Wilson, 2010) and the advancement of flexible display technologies[1] (Lahey *et al.*, 2011; Schwesig *et al.*, 2004), a new category of non-planar interfaces have emerged. This next-generation interface design might have curved and deformable interface forms (Holman and Vertegaal, 2008), and may even include complex shapes that transform themselves. Snaplet, an early example, is a paper-like computer that can change its flat shape to contour to the curve of a user's arm when worn (Tarun *et al.*, 2011). The design of these three-dimensional interfaces present new usability challenges to designers as they explore the nuances that shapes pose to interaction.

What impact will this have on user-centered design then? This new consideration for both interaction and form suggests that interfaces have a new property of a three-dimensional interface shape (one that—unlike before—encourages designers to contextualize interaction in physical shape). Unlike the flat surfaces of tablets, mobile phones or desktop computers, this interactive form will be wrapped around everyday objects

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[1] Specifically, Flexible Organic Light Emitting Diodes (FOLEDs) and Flexible Electrophoretic Ink (E Ink) (Harrison *et al.*, 2011).

(Vertegaal *et al.*, 2011). The morning newspaper, credit cards, light switches or even kitchen plates would maintain their original identity, yet could be augmented with a seamless and interactive high-resolution display skin. Consequently, the result is a tighter coupling between interaction and industrial design, one that requires new tools to better ideate and explore this organic design space.

With early work in OUI as an overarching theme (Holman and Vertegaal, 2008), this paper summarizes previous explorations in this new space of non-planar interface design and focuses on the challenges met when introducing 'shape' into user-centered design. Flexible displays, and the physical expressiveness they afford, suggest a higher dimensionality to an interface design, one where, similar to an industrial design, shape has a critical role. In this context, we argue that this flexible display material and the potential for interactive form will have a profound impact on the design process. The interaction designer trained for a traditional—meaning flat—software design may not be appropriately equipped for this new design context. An interactive form, distinctively, needs to be designed (or sculpted even) with an awareness of three-dimensional form and its interplay with a material. As a web design was gradually taken over by trained graphics designers, in a similar trend, industrial designers will be the first to pragmatically encounter and reflect on everyday objects that have interactive behaviors. This is not to say that an interaction design will be antiquated. Instead, a new profession will arise, one that blends industrial and interactive perspectives and examines design scenarios previously impossible.

Our earlier work in OUIs both suggests (Holman and Vertegaal, 2008) and details this merger of industrial and interaction designs (Holman and Vertegaal, 2011a, 2011b; Vertegaal, 2011a) in a new design field. Initial user evaluations noted how the hands-on form of apaper windows (Holman *et al.*, 2005) or interactive pop can (Akaoka and Vertegaal, 2010) felt not like a computer at all, but more like a 'real' thing encountered in everyday life. Grabbing a paper window or bending PaperPhone (Lahey *et al.*, 2011) to find a contact, or zooming into a map on the sphere is *nothing like using a computer*. Later explorations led to the development of new and more expressive sensors like Tactiletape (Holman and Vertegaal, 2011a, 2011b), a touch-sensitive tape that is curved, bent and easily wrapped around a non-planar prototype. Not only were interfaces curved or flexible, but the tools used designed them were too.

What exactly do these developments mean? We argue that these examples point to technology's maturation to that of a *computational material*. When interactive hardware is commoditized and seamlessly melded with everyday things, such that an interactive display skin can be shrink-wrapped over its entire surface, the idea of a 'computer' disappears and is better described as a basic design material that, incidentally, happens to have an interactive behavior. Computation, in this new context, should be seen less like hardware and more as a basic design material, not unlike the plastics, wood or ceramics used by an industrial designer. This transformation, of course, injects a three-dimensional form in the user interface design, one that affords an abundance of shapes, curves and geometries.

This, of course, raises fundamental questions for the user interface design: how should this organic form be designed? What type of tools will designers need to ideate over the design of these interactive shapes and objects? With the potential for interactive form to be integrated seamlessly into an everyday object, what overarching design objectives are important to mitigate a world filled with an abundance of technological distractions? How will designers rapidly sketch using computational materials? These are only a selection of the questions encountered in this new design space.

As a starting point, we position that not only do organic user interfaces (OUIs) change *what* we design, but they have a dramatic impact on *how* we design too. First, designers of OUIs need repurposed sensors, ones that are more like computational materials and allow them to more seamlessly sketch interactive form (Buxton, 2007). As interactive shapes advance to higher spatiotemporal complexities, from Gummi's bendable credit card [00] to Benko *et al.*'s (2008) Sphere, there will be an increasing need to rapidly try out—or sketch ideas without investing weeks in creating a fully functioning hardware prototype. We discuss how this activity is increasingly relevant in an early sketching tool called SketchSpace, a system that removes the need for hardware input and allows passive, non-functioning prototypes to have interactive behaviors. We discuss how it can be used for rough ideation and contrast it against the limitations encountered when building PaperPhone's (Lahey *et al.*, 2011) more elaborate hardware prototype.

Finally, what does it mean when designers have the computational materials to rapidly ideate and place interaction anywhere, at any point on an object's surface? The potential for interaction *everywhere* forces us to consider a highly interactive world. We argue that to make the interactive form more purposeful, designers should contextualize interaction in an object's shape and limit functionality to one or two behaviors at most. This minimalist hypercontextualized approach cautiously restricts interactive functionality, one that is increasingly relevant for the design of OUIs.

2. RELATED WORK

An organic design is an emerging research area, one that certainly overlaps with the aspects of Tangible (Ishii and Ullmer, 1997) and Natural User Interface (NUI) Design (Wigdor and Wixon, 2011), even Ubiquitous Computing (Weiser, 1991). It is important to understand where these boundaries are most pronounced. We start from the definition of an OUI (Holman and Vertegaal, 2008):

> a computer interface that uses a non-planar display as a primary means of output, as well as input. When flexible, OUIs have the

ability to become the data on display through deformation, either via manipulation or actuation.

Its foundation rests on the development of thin-film flexible displays, the ability to caste them in non-planar shapes, and the potential to sense touch and render a dynamic content at any point along the surface. Unlike ubiquitous computing's vision of pad, tabs and boards scattered everywhere (Weiser, 1991), OUIs assume no fixed form factor and instead see the potential to alter shape as something essential to design. Although more recent ubiquitous examples use projection to place pixels on everyday objects, such as Harrison's shoulder mounted OmniTouch (Harrison *et al.*, 2011), OUI is firmly motivated by the use of actual flexible displays, one tightly coupled with the industrial design of an object.

Ishii's Illuminating Clay (Piper *et al.*, 2002) is an early example of an interface with facets of OUI; it was an interactive display made of deformable clay that projected a digital map over its topography, blurring the boundary between input and output (or atoms and bits). A similar example is found in Ping Pong Plus (Ishii and Ullmer, 1997), although it lacked the ability to render dynamic content on the game's ball, a rigid non-planar object central to the interaction. As a consequence, tangible content tended towards embodying digital information in shape and using it as a means for input. Ishii's subsequent Radical Atoms (Ishii *et al.*, 2012) transforms this delineation of input and output by assuming a hypothetical generation of materials that alter shape and appearance dynamically, and as he says, 'so they are as reconfigurable as pixels on a screen' (Ishii *et al.*, 2012). This focus on programmable dynamic materiality is a distinction from the organic design. Although OUIs may actuate or make structural deformations, they do so in the context of an object's overall shape, one that is wrapped with an interactive display. Radical Atoms consider shape *as a volume*, a mass of particles to be programmed to fluidly represent digital information. This hypothetical scenario moves beyond the industrial design and unifies input and output at a particle level. It positions atoms as programmable bits, an early example found in ZeroN, the computer-controlled levitating handheld sphere (Ishii *et al.*, 2012).

NUIs, on the other hand, are formed by an approach that focuses on designing an interface that makes a user feel and act natural (Wigdor and Wixon, 2011). It does so in a structural framework for *natural* design, one that initially determines a market's niche and use case goals, and, among other steps, iterates until a product ships. Unlike OUI, NUI is not directly rooted in one direct technological development: that is, the advancement in flexible display technology on which OUI is grounded. Instead, it is more of a development process that leverages varied input devices, from the Microsoft Surface to the Kinect, to achieve its philosophical aim of a natural user experience. An organic interface could certainly act as a means to achieve a natural design. However, an organic design—in and of itself—is more about the design of interactive three-dimensional form.

2.1. Examples of Organic Design

To place the transition from traditional to organic design in context, we discuss enabling a sensing technology and evaluation of a non-planar form. For simplicity, we categorize each work as either *rigid* or *deformable*.

2.1.1. Interaction with rigid organics

Rigid curved touch devices vary considerably in shape, size and sensing technology. Rekimoto's SmartSkin exemplifies the use of capacitance sensing to enable multi-finger sensing across an array of surfaces (Rekimoto, 2002). Benko *et al.*'s (2008) Sphere affords users a large spherical display that diffuses illumination to track multi-touch gestures along its surface. Song *et al.*'s MTPen prototype wraps a capacitance multi-touch sensor around a pen to detect gripping gestures during drawing tasks (Song *et al.*, 2011). The UnMousePad (Rosenberg and Perlin, 2009) implements a force-resistive technique to produce a thin flexible pad that senses multi-touch input. Wimmer *et al.*'s uses time domain reflectometry (TDR; Wimmer and Baudisch, 2011) to register multiple touch points as 'faults' in metallic tape, a material that can be adhered to non-planar shapes.

2.1.2. Evaluation with rigid organics

Roudaut *et al.* (2009) were the first to present an in-depth evaluation of curvature and single-touch target accuracy on spherical rigid surfaces. Across nine levels of curvature, they placed multiple targets on protruding and intruding surfaces. Subjects drag their finger along a series of handcrafted spherical FTIR surfaces (Han, 2005) until they reached a target. Their results indicate that convexity increases the pointing accuracy and that concavity produces larger errors offsets between the target and finger and that when acquiring targets on a downward slope, subjects tended to hook their finger posture. These results introduce two recommendations to designers. First, knowledge of how curvature and slope impact target accuracy suggest how engineers can introduce corrective offset in device drivers. Secondly, placing targets, like buttons or other widgets, on points of extreme convex curvatures make them easier to target.

Weiss *et al.* also evaluate dragging gestures on BendDesk (Weiss *et al.*, 2010), a multi-touch surface modeled on the curved desk in Sun's Starfire video. They found that dragging, when compared with dragging across the connecting curve, is faster and straighter on the flat surface.

Benko *et al.*'s (2008) sphere is a quintessential example of the challenges that may arise when moving from a flat to non-planar design. Their qualitative findings propose a number of design considerations unique to spherical surfaces, including how to best place content in relation to the user's head position and, more generally, that the variability of the spherical geometry leads to an interaction language noticeably different from flat.

2.1.3. Interaction with deformable organics

Ishii's Illuminating Clay (Piper *et al.*, 2002) is an early tangible deformable interface that uses clay as an input material for real-time manipulation of 3D terrain. Schwesig's Gummi (Schwesig *et al.*, 2004) envisions bendable interactions through manipulation of a credit card-sized flexible display. Using projection and motion capturing, PaperWindows (Holman *et al.*, 2005) prototypes interaction techniques for bendable paper–computer interfaces. PhotoelasticTouch (Sato *et al.*, 2009) uses computer-vision techniques and the photoelastic properties of the transparent rubber to recognize the deformations and manipulations of elastic shapes. Vogt *et al.* (2004) present a puck-size malleable input surface that uses computer vision to map the translations of a dot pattern and compute its surface geometry in three dimensions. Cassinelli *et al.*'s (2005) Khronos projector allows a user to spatially manipulate a video content on a projected deformable display. Stevenson *et al.* (2011) present an inflatable hemispherical multi-touch display that varies between flat, concave and convex spherical form.

2.1.4. Evaluation of deformable organics

Empirically, Dijkstra *et al.* (2011) explore the effects of structural holds and flexible display rigidity on a direct input pointing and dragging tasks. From this study, they introduce concepts for grip, rigid and flexible zones, and conclude that the distribution of these zones affect the Fitt's Law index of difficulty of touch pointing and dragging tasks.

3. A NEW TYPE OF DESIGN

We begin this section with an observation that the current methodologies of user interface design, much like the characters in Abbot's *Flatland* (Abbot, 1884), are inherently limited by their flat dimensionality. After having built, researched and evaluated a broad set of objects with both simulated and functioning curved interactive displays skins, from a dynamic pop-can (see Figure 1) (Akaoka and Vertegaal, 2010), to a paper window (Holman *et al.*, 2005), to a paper phone (Lahey *et al.*, 2011), it is evident that these non-planar forms lead to interface characteristics that are contingent on their unique shape. In earlier work, we defined the three design principles of OUIs (*Input equals output*, *Function equals form*, *Form follows flow*). These serve as an initial indication of this 'non-planar' organic design space (we refer the reader to Holman and Vertegaal (2008) for a detailed discussion).

Figure 1. The *Dynacan* is a pop-can computer that embodies a cylindrical interactive display and demonstrates an application in mass consumerism.

3.1. Rapidly sketching and exploring organic design

Although the design principles of OUI offers a departure point to reason about *what* an organic design means, they do not elaborate on *how* the methodology and tools designer use should change to support building, ideating and rapidly exploring an organic design. Any early examples of a non-planar design used construction methods that were dissimilar from traditional software prototype, suggesting that the varied approaches were needed when exploring a non-planar design. Gummi used a small rigid LCD mounted on a bend-sensing substrate to simulate a flexible credit card (Schwesig *et al.*, 2004). Ishii used a top-down projection and computer vision to simulate an embodied and dynamic terrain (Ishii and Ullmer, 1997). PaperWindows (Holman *et al.*, 2005) is an early example of an OUI that investigates non-planar interaction, simulating the interactive potential of digital paper displays (see Figure 2). Using a combination of motion tracking and projection, computer windows are rendered onto a piece of paper giving the illusion that the paper is, in fact, an interactive display. This metaphor is later instantiated in PaperPhone (Lahey *et al.*, 2011), a paper computer that uses flexible E Ink to bend the interface and express interaction (see Figure 3). Both these interfaces extrapolate to a scenario explored in DisplayStacks (Girouard *et al.*, 2012), where piles of paper computers surround us, thin enough to be tossed around, stacked and manipulated much like real paper.

Although these non-planar interfaces explore aspects of organic design, their ideation and iteration inevitably hinged

Figure 2. *PaperWindows* explores a set of interaction techniques for digital paper interfaces.

Figure 3. *PaperPhone* is an interactive flexible paper computer that uses bending as a way of navigating.

on a fully functioning prototype (one that required a significant investment in both time and materials to construct). To support designers better, we must update our design tools to answer the challenge of seamlessly prototyping interactive organic systems. PaperPhone's flexible backplane, on which its bend sensors were soldered, required custom-etched circuitry that took, at a minimum, 2–3 days to construct. In early iterations, the thickness of the copper sheet and layout of the circuit patterned negatively affected the ergonomic of a user's hand position, requiring lengthy iterations. Unifying the challenges of industrial and interface design this way, in the form of an flexible circuit backplane, typifies the basic challenge of working with early organic design: shape adds a layer of complexity to exploring interaction design, one that makes designing for and sensing interactions on even simple interfaces, like PaperPhone's bending interaction, incredibly difficult. Similar arguments can be made for Gummi, Illuminating Clay or any other fully functioning organic hardware device.

3.1.1. Hardware rapid prototyping

There are certainly tools for rapid prototyping that consider this problem of minimizing the labor involved in building functioning hardware devices, ones that are even effective for exploring aspects of non-planar systems. Previous hardware prototype tools such as d.tools (Hartmann *et al.*, 2006), VoodIO (Villar and Gellersen, 2007), the Calder Toolkit (Lee *et al.*, 2004), BOXES (Abbot, 1884) augment physical prototypes with hardware sensors and provide high-level toolkits that abstract the technical complexity of hardware sensing for an interaction designer. This promotes ease of use and drastically simplifies the work needed to rapidly prototype hardware interfaces. It does not, however, minimize the physical challenge of seamlessly integrating and affixing sensors into a prototype. The time needed to find, fasten and fit numerous sensors is a barrier to quick and disposable sketching (Buxton, 2007). Although platforms like iStuff Mobile (Ballagas *et al.*, 2007) address this problem using a single integrated sensor that senses acceleration, tilt and rotation, it does so by assuming a rigid mobile form factor. Generally, a designer is limited to the physical expressivity and sensing potential of the sensor supported on each platform. Stated another way, the OUIs we construct are limited by the expressiveness of the sensors used to create the early prototypes that are used to explore a design. For example, in place of a custom flexible circuit, it would be easy to attach a bend sensor to a piece of paper to explore bend interactions. However, to support an organic design, the same platform would also need to track the piece of paper and project meaningful feedback on the prototype. If a designer wished to explore richer undulating deformation-based interactions, the number of hardware sensors only increases.

3.1.2. Vision-based rapid prototyping

Computer vision-based platforms, like DisplayObjects (Akaoka and Vertegaal, 2010), are one way to address this inherent limitation of hardware toolkits. By relying on motion capture, a designer prototypes with foam mockups that are rendered with projected content. This minimizes the use of physical hardware sensors and requires only infrared tracking markers on the mockup. A designer, though, has to build a virtual model of the mockup and provide it to the motion-tracking engine in an initial calibration step. After this step, the designer is free to explore its design aesthetic by dragging projected content from a physical palette and manually placing it on the mockup. Although button presses are supported, complex input behaviors that express changes in a position or shape are not mapped to interactions. Although practical once properly setup, the upfront time to instrument and calibrate each mockup is prohibitive.

3.2. Supporting organic design

Although each of these hardware and vision-based prototypes have advantages, they both have the same limitation: they assume that a designer has the necessary technical aptitude to operate these platforms. Platforms like d.tools that reduce this demand do so by abstracting the technical layer in a custom software workflow, one that a designer must adopt. When considering computation as material, though, this requirement seems prohibitive; software sketching tools should be just as expressive as tape, foam core or any other material used by a designer when ideating an industrial object. When the complexity of managing and mapping the input to interaction becomes too high, hardware returns to the forefront again; interaction is no longer just an incidental property of a material a designer works with.

If industrial designers are the first to encounter computational materials and the exploration of organic design, this puts different design constraints on the usability of these prototyping systems. We argue that to better support an organic design, we should adopt a design behavior common to all other fields of design: *sketching*. Doing so would mean that building and exploring interactive designs should be as seamless as working with other common design materials, such as tape, foam core or others. This is exactly why computation should have similar material properties.

In *Sketching User Experiences*, Buxton (2007) argues that the activity of sketching—in itself—is not about the material form it embodies, such as an architect's pencil drawing or an automotive designer's clay sculpture, but more of an abstract activity that impacts design thinking and learning. Beyond Wizard of Oz or Smoke and Mirror techniques, there are few example systems that adequately support *interactive* sketching, or even ones that scale to the complexities posed when considering shape and interaction in an organic design.

4. SUPPORTING INTERACTIVE SKETCHING

To support interactive sketching through more expressive computational materials, our first approach was to integrate the sensing technology directly into the design materials already used by designers. One example we constructed is Tactiletape (see Figure 4), a one-dimensional pliable touch sensor that looks and behaves like a regular tape (Holman and Vertegaal, 2011a, 2011b). Tactiletape can be built from everyday supplies: an H2 pencil (resistive surface), tin foil (conductive surface) and a shelf liner (spacing material). We position it as a readily available material in the design studio. When a designer wishes to add touch sensitivity to an industrial prototype, they grab a roll of Tactiletape, cut-off a piece and attach it to the surface. To sense a touch input, the designer needs only to connect two wires: one to each of the resistive and conductive surfaces. As a hardware sensor, its electrical behavior is similar to common sensors used with Arduino. Using Tactiletape, the designer can explore the touch input on a variety of curved and deformable surfaces: spheres, coffee cups, bracelets, paper, credit cards, dynacans (Akaoka and Vertegaal, 2010) and so on.

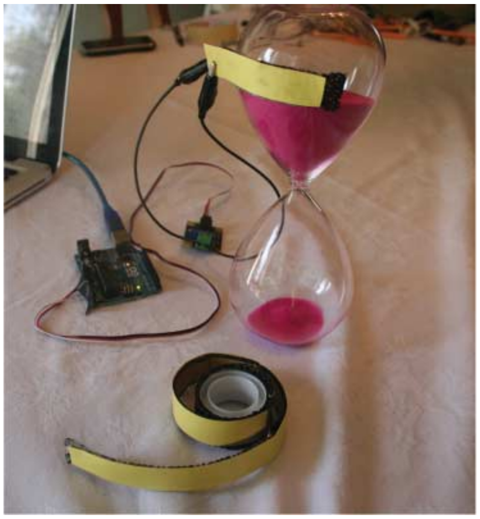

Figure 4. A typical *Tactiletape* scenario. A piece is cut from the roll (foreground) and attached to an hourglass. An Arduino relays touch data to a desktop computer.

Wimmer *et al.*'s TDR (Wimmer and Baudisch, 2011) is another example of a computational material and is an alternative to Tactiletape's linearly resistive sensing. It can be used to quickly make a non-planar prototype multi-touch sensitive, using a continuous copper strip. When a signal is pulsed along this strip, a finger's presence generates a reflective echo, one that can be interpreted as touch input (similar to the way breaks are detected in cross continental undersea cables). At present, TDR requires an oscilloscope to process the analog echo signal, increasing its material complexity.

In either case, both Tactiletape and TDR require a designer to have some technical knowledge before exploring an organic design. Although we envision computational materials occupying an essential role in high-fidelity prototypes eventually finished products, what if a designer could explore the interactive behavior of a device without a functioning prototype or computational material? That is, what if we could remove the need for hardware layer or computational material from the early design and ideation stage altogether?

With this question in mind, we started a dialogue with industrial designers at Microsoft's Hardware Input Group (Holman and Benko, 2011) to see how they approach the exploration of interactive systems. Our observations confirmed that working with an interactive functional prototype is increasingly important for an industrial design and that, in general, the number of hardware components required for early prototypes is on the rise. Although tools like Knörig's Fritzing (Knörig *et al.*, 2009) can make integrating circuitry and building custom input devices less 'technical', introducing a functional prototype into the designer's workflow can still be time consuming, even more so for the complex surface geometries encountered in an organic design.

4.1. SketchSpace

These design questions and observations led to the design and implementation of SketchSpace (Holman and Benko, 2011), a lightweight environment that adds implicit input sensing to passive physical material (see Figure 5). We envision a designer tasked with exploring an interactive water bottle, one example of an organic device, using a system like SketchSpace. The designer would rummage the design studio looking for a water bottle. After finding one and placing it in their workspace, they would touch, swipe, shake, squeeze and repeatedly interact with it using the digital tabletop interface to explore different digital mockups of its interface (see Figure 5). In doing so, the designer quickly and rapidly explores multiple interactive design paths, before settling on those that feel right.

SketchSpace is a tool and set of interaction techniques that allows a designer to use passive materials as a means to roughly

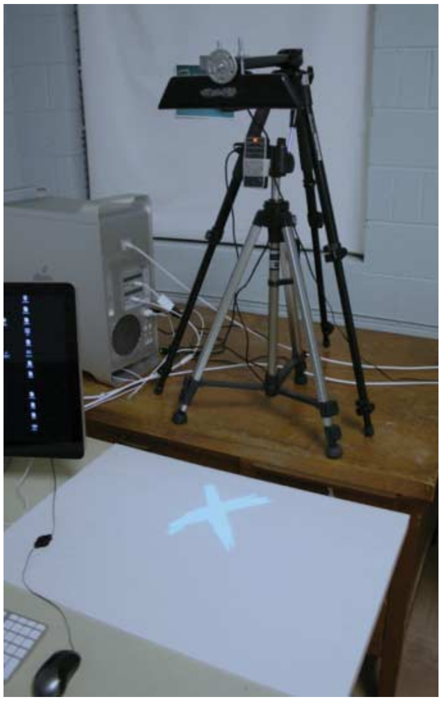

Figure 5. A Kinect camera hovers over the designer's workspace. Its depth data are used to track the designer's manipulations of a physical prototype. A Pico projector renders interactive content.

simulate the interactive behavior of input devices early in the design process. The central idea is to support interactive sketching so that next stage of constructing a more refined prototype, one that relies on computational materials, is better informed.

4.1.1. *Sketching with interactive behaviors*

Thinking in terms of computational materials instead of hardware prototyping is an important step in supporting sketching in an organic design. We position computational materials as having a similar role to that of the automotive industry's use of clay to create a replica-size model of a car; in this context, it is a material used to create a high production value prototype. Although computational materials are critical to construct organic designs, their use requires some technical expertise and physical instrumentation of prototypes, something that could be inhibiting when ideating in the very early stages of a design.

When sketching an organic design, and by that we mean a rough and early-stage exploration of a potential design, not unlike an architect's sketch of a building, we argue that interaction should be decoupled from its material embodiment. Computational materials should be mimicked as interactive behaviors, ones effortlessly imbued in a physical prototype. This carefully removes the material challenges of designing OUIs and makes it easier to sketch them.

Figure 6. SketchSpace tracks and projects a texture on a roughly sculpted mouse made of modeling clay. The icons on the top, left and bottom correspond to virtual sensors. The icons on the right are for displaying images and adding or removing virtual buttons. In counter clockwise from the 'is below icon' (down arrow): is above, is right of, is left of, is rotated right, is rotated left, is tilted up, is tilted down, is tilted left, is tilted right, is near, is higher than, is deformed (measured as the distance changed in curvature features), is grasped (measured in amount of hand pixels obscuring the object) and button tapped.

Figure 7. A designer can work with a range of materials using SketchSpace. This includes everyday objects (cup, paper, box), deformable surfaces (CD cover, tape) and malleable material (modeling clay).

To imbue interactive behaviors in a passive physical prototype this way, SketchSpace imbues passive prototypes with input sensing using Microsoft's Kinect camera. Mathematically analyzing the depth sensing using techniques from computational and differential geometry allows SketchSpace to infer a broad set of inputs, ranging from touch events on the object's surface and surrounding workspace, orientation, position, motion, proximity and, among others, shape deformations (see Figures 6 and 7). A designer uses these inputs to prototype as if it had functionality, including mapping sensor values to interactions using embodied gestures and projecting dynamic interactive content on it, all without finding, attaching and working with a collection of physical sensors. The designer works hands-on by tapping mapping icons that are projected on their workspace table and, using physical manipulations of an object *in situ*, to specify when and how these mappings trigger interactive behavior. Using a tool like this frees the designer from hardware constraints and helps them ideate and quickly explore interactive sketching.

However, exposing these virtual sensor streams to a designer poses the challenge of mapping the lower-level input patterns to meaningful forms of interaction in a way that is intuitive and non-technical. SketchSpace extends a designer's natural manipulation and defines input mappings through the combination of tabletop sensor icons, embodied gesturing and simple speech commands. First, there are 15 sensor icons that represent mapping rules available to the designer. Each of these convey a useful property of the prototype's input behavior that can be toggled on or off by tapping its icon. In Figure 6, the down arrow indicates an 'is below' condition indicating when the prototype is below the threshold value, the mapping rule should trigger. The value of a virtual sensor is saved as a mapping rules, one set by physical performing an object's behavior and issuing a speech command, and is used to trigger a position change in a preset set of interface mockup images the designer provides beforehand. In general, this approach frees the designer's hands for bimanual asymmetric interaction and quickly generates interaction rules for each of the virtual sensors, ones that are mapped to rough, sketched content.

Although early user experiences with SketchSpace's efficacy as a sketching tool have pointed us toward key design decisions, such as projecting icons on a designer's tabletop and supporting embodied mapping gestures, it has been challenging to deploy SketchSpace in an industrial design studio. At present, we have deployed SketchSpace in a semi-guided scenario, during a university-level design studio focused on designing interactive systems, ones that recreated the objects from DisplayObjects (Akaoka and Vertegaal, 2010) to form a baseline comparison and inform our active development for broader deployment. Students were able to rapidly sketch the dynacan and paper computer, but the interactive sphere interface was limited as projector could not fully render on its surface until it was placed flat on the desk, making it impossible to rotate in place. This, of course, could be addressed through the use of one or more projectors, or even a wearable device like OmniTouch (Harrison *et al.*, 2011) that can leverage its ability to imbue surfaces with interaction for the sketching of an organic design.

5. TOWARD HYPER-CONTEXTUALIZED DESIGN

If interaction is truly everywhere and tools such as SketchSpace, Tactiletape, OmniTouch and TDR help designers rapidly explore or prototype OUIs using computational materials, what design objectives should guide them? Each form, from Gummi's mobile concept device to Benko *et al.*'s sphere, has its own nuances. Across these forms, however, one question is relevant: should the interface be multi-purposed (like a Swiss army knife) or specialized (like a classic Wustof cooking knife)? In short, it depends.

One thing is clear: there is a new opportunity to build highly specialized devices, ones that can use organic principles to seamlessly contextualize interaction in form. This distinction moves away from the approach of the computer as a generic tool (Buxton, 2007; Vertegaal, 2011) and introduces cautious specializations in the interface. By doing so, the interactive behavior of some types of organic design will only express a few essential actions, ones that are subject to their form factor.

What exactly is this category of specialized organic devices? There is a distinction to be made for multi-purposed form factors. Certainly, there will always be a class of devices with both highly purposed functionality and organic principles, Nokia's Kinetic being one example (Kildal *et al.*, 2012). The brick shape of modern smart phones, even when deformable, has absorbed a camera's function and a GPS's mapping capability. Even Snaplet (Tarun *et al.*. 2011) suggests an OUI that can be repurposed depending on its context, transforming its shape to flat, to be drawn on; when cylindrical, used as an armband music player. A similar example is found in Gummi's flexible interaction of credit card-sized device.

However, as organic design embarks on a multitude of new interactive shape and form, there will be a greater opportunity for form factors that are highly contextualized in their shape. For example, imagine a toothbrush covered in a thin-film interactive skin. In an effort to promote better oral hygiene, it might useful to indicate on the brush's handle that it is being held properly and the correct pressure is being applied. In any case, the shape of the brush commands a unique way of interacting with it, one that is not so easily transformed and absorbed by another form factor.

To accept computational things is to assume a scenario where many passive everyday objects could be imbued with interactive potential. We argue that, for this new set of form, factors should be designed by *hypercontextualizing* their interface. A bank card with a thin film display would show your balance and recent activity, but it would not be used to write an email or browse the web. It might have an interactive map on the back, but its interactive behavior would be limited to helping you perform mobile financial transactions or finding a nearby branch. In a similar example, a reusable water bottle might subtly glow when it is near a water fountain, only if it is almost empty. A high-end kitchen knife might indicate when the incorrect pressure and angle is applied during a cut.

This stringent minimalism has clear benefits: it limits the range of possibilities a user encounters using highly purposed types of organic interfaces. It also leverages *in situ* interface design, in that physical manipulations of a computational thing can be more precisely mapped, even made more usable, when functionality is limited and excels at doing only one or two things. Keeping the back of the bank card as *just a map*, as opposed to including a web browser or any other ‘useful’ applications, means that the user simply flips their credit card to see the nearest branch. This minimizes application switching, displaces a cumbersome smartphone and embeds this information in a predictable locale, one that is tied to physical starting point of their mental model and banking experience.

It is worth pointing out that hypercontextualization already exists in some consumer devices. Amazon’s Kindle, for example, excels at being just one thing: a digital representation of a book. Once this boundary is exceeded, by trying to surf the web on its E Ink display, its hypercontext dissolves and the simplicity of its interaction metaphor breaks down. In the context of organic design, there is the potential to create many new types of hypercontextualized devices. Although some interfaces will be highly purposed, there will be a new class of organic interfaces that, via computational materials, leverages hypercontext to more tightly couple interaction, form and feedback, like the examples of the organic toothbrush or water bottle, in interface design.

Thinking about hypercontextuality applied to an interface design is only a first step. How designers should go about representing it in three-dimensional interface design requires elaboration. Unlike the user-centered design process, settling on the functions that are most critical to embody in an OUI is not necessarily linear or even formulaic; shape is transformed in early design iterations and since the interface is so closely bound to it, it requires constant reevaluation and design reflection. This is not to say that the traditional methods of user-centered design cannot still inform the design. However, the context in which an interface *exists* and the shape it occupies have a much deeper effect than it did with a traditional design. Thinking back to our reusable water bottle, a designer must deeply consider its size, material, relationship to owner and, among other aspects, the environment in which its identity plays out. Traditionally, this is the domain of industrial design. However, designing a water bottle made from a *computational material* must also account for the ways in which the bottle can be augmented with an interactive form. A starting point is a simple question grounded in McLuhan’s law of extension (McLuhan, 1964): of the functions (or experiences) this water bottle exhibits (or should exhibit), which of them would be enhanced, intensified or made possible by imbuing them with interactive behavior? Perhaps calmly revealing the temperature of the water after it is filled up would impact a person’s choice of water fountain. Or maybe tapping the bottle at a certain spot would reveal how much water the owner has consumed. For even simple things, the possibilities quickly exhaust themselves. It is at the discretion of the designer to decide how the interface will be hypercontextualized or *if it should be at all*.

6. CONCLUSIONS

This paper argues that the best thing that could happen to a user interface design is for computers to stop being technological devices and start being more like *real* everyday things. Not only does this effect the OUIs we create, but the tools and methodologies we use to design them too. In future, their hypercontextualized interfaces will feature the same type of skins we find on products today, but extended with a minimalistic and carefully selected interactive behavior. Designing this category of OUIs to excel at perhaps one or two functions at a time radically simplifies the design of the user interface and ensures that the ‘computer’ dissolves from the forefront. Interactive hardware will be a mere commodity to the industrial designer, to point that it looks and feels like any other design material. This, naturally, accelerates the need for new tools that allow designers to sketch using computational materials. This is a turning point for a user interface design, one that challenges us to understand how to best design in this new world of everyday computational things.

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