AMPHORM
Form Giving through Gestural Interaction to Shape
Changing Objects

by
Dávid Lakatos

B.Sc. Budapest University of Technology and Economics 2010

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning
in partial fulfillment of the requirements for the degree of

Master of Science in Media Arts and Sciences
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

Author .... **Dávid Lakatos**
Program in Media Arts and Sciences
May 11, 2012

Certified by .. .. **Dr. Hiroshi Ishii**
Jerome B. Wiesner Professor of Media Arts and Sciences
Associate Director, MIT Media Lab
Thesis Supervisor

Accepted by .... **Dr. Mitchel Resnick**
Chairperson, Departmental Committee on
Graduate Students Program in Media Arts and Sciences

AMPHORM
Form Giving through Gestural Interaction to Shape Changing Objects

by
Dávid Lakatos

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning on May 11th, 2012
In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Media Arts and Sciences
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Abstract

Shape-shifting materials have been part of sci-fi literature for decades. But if tomorrow we invent them, how are we going to communicate to them what shape we want them to morph into? If we look at our history, for thousands of years humans have been using the dexterity of their hands as primary means to alter the topology of their surroundings. While direct manipulation, as a primary method for form giving, allows for high precision deformation, the scope of interaction is limited to the scale of the hand. In order to extend the scope of manipulation beyond the hand scale, tools were invented to reach further and to augment the capabilities of our hands. In this thesis, I propose "Amphorm", a perceptually equivalent example of Radical Atoms, our vision on the interaction techniques for future, highly malleable, shape-shifting materials. "Amphorm" is a cylindrical kinetic sculpture that resembles a vase. Since "Amphorm" is a dual citizen between the digital and the physical world, its shape can be altered in both worlds. I describe novel interaction techniques for rapid shape deformation both in the physical world through free hand gestures and in the digital world through a Graphical User Interface. Additionally I explore how the physical world could be synchronized with the digital world and how tools from both worlds can jointly alter dual-citizens.
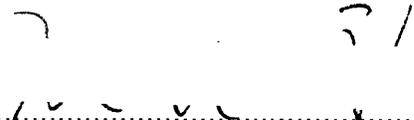
Thesis Supervisor: Dr. Hiroshi Ishii
Title: Jerome B. Wiesner Professor of Media Arts and Sciences

AMPHORM
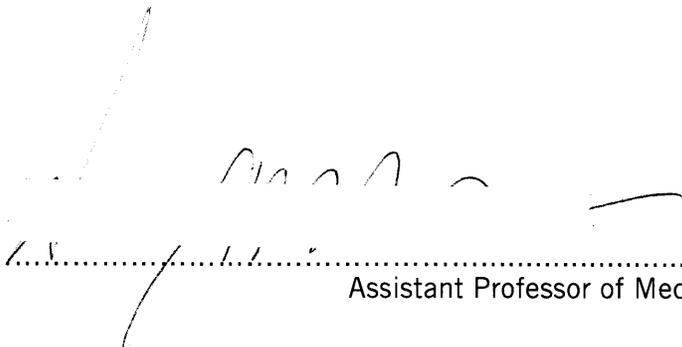# Form Giving through Gestural Interaction to Shape Changing Objects

by
Dávid Lakatos

Thesis Reader .... **Dr. Hiroshi Ishii**
Thesis Supervisor

AMPHORM
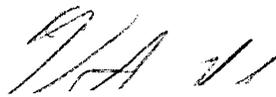# Form Giving through Gestural Interaction to Shape Changing Objects

by
Dávid Lakatos

Thesis Reader .... **Dr. Neri Oxman**
Assistant Professor of Media Arts and Sciences
MIT Media Lab

AMPHORM
Form Giving through Gestural Interaction to Shape Changing Objects

by
Dávid Lakatos

Thesis Reader .... **Dr. Ken Perlin**
Professor of Computer Science
NYU Media Research Lab
Director, Games for Learning Institute

Table of Contents

Table of Figures

Appapának.

CHAPTER I

Introduction

Shape changing materials have been prominent in the sci-fi literature for decades and have been featured as the ultimate material that can transform into any shape we would desire. Imagination runs wild, when thinking about objects in our surroundings that can change the way they look and behave dynamically. Yet, when we look at Tony Stark instantiating a new material on the fly, we find little or no logic in the process by which he creates the new shape of an object.

This is a thesis about interaction design. In particular, it is about interaction design for form giving – the process by which humans shape their surroundings. In the recent years we have seen a rapid evolution of tools for form giving, but a radical change in form giving is approaching, by which the malleable object will evolve into a part digital entity.

My research thinks about a future where dynamic materials will exist not only in research labs and in the industry, but ubiquitously everywhere. How will we (as the human race) take control over surfaces we own? Is there an intuitive way to interact with the architectural elements around us to change their structure? How will interaction change with the objects if they will be shipped with a default form, but could be customized on the fly? Limitless transformation is no better than chaos – what constraints will these systems have to obey? In this document I try to answer these questions, by taking a closer look at possible interaction techniques with dynamic materials.

You may ask – how can we hypothesize about interaction techniques without the existence of the aforementioned material? Although, today we do not have free-form shape changing materials, many scientific groups are working hard on enabling technologies that will potentially yield a material with (almost) limitless shape changing capabilities. More importantly we know how we want these materials to behave, thus we can create prototypes that mimic their behavior. I call these entities *perceptually equivalent* to shape changing materials, because they look and behave as them in limited scenarios.

In order to address the questions raised above I designed and constructed a perceptually equivalent interface, called Amphorm: a vase that can change its shape, computationally. I argue that until the enabling technologies arrive we will continue experimenting with perceptually equivalent interfaces. To aid the future designers of these interfaces I developed

taxonomy for the structure of these devices, decomposing them into a three-tier system that I expand on in Chapter VI.

Through the later part of my thesis I discuss interaction techniques suitable for manipulating the shape of Amphorm, ranging from free hand gestures to traditional Graphical User Interface (GUI) based approaches.

CHAPTER II

A Brief History of Form Giving

Form

Form, as the externalization of an idea has been present in our civilization for several millennia. Humans have used their hands and tools to directly manipulate materials to alter/deform their shape. The process, which turns intangible ideas into physical representations, is what we call form giving.

| Representation | Operator | Operand |
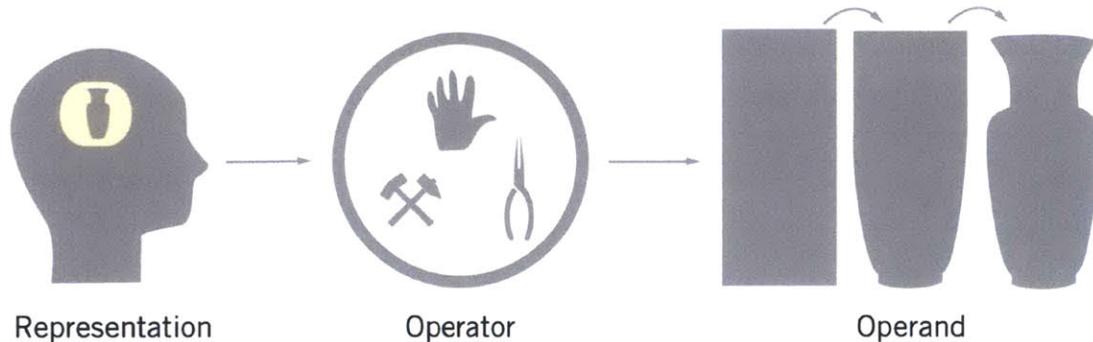
Fig. 1 - Form giving feedback loop

A number of tools have been invented to augment our capabilities to deform materials – e.g. a knife increases our precision, while a chisel extends our nails, allowing shaping of rigid materials. Despite of the invention of hundreds of tools, fundamentally humans can still only constructively (blowing up a mountain with dynamite does not count – this thesis focuses on constructive form giving) shape physical objects rapidly on the scale of their hands.

The designer's role

Pre-historic

The role of designers changed radically through the history of form giving. Dating from the prehistoric times humans created objects themselves that they needed for their everyday life. These were mostly weapons (axes, chisels), but we can also find tools that they used for digging and shaping the earth (e.g. hoe).

Classical era

Throughout the classical era, the home as a static entity appeared and humans started creating objects not merely for function, but for aesthetic companions in their surroundings.

Fig. 2 - Prehistoric artifacts: a stone projectile point, a wooden harpoon, a hoe and a bone dagger. *Images courtesy of the Smithsonian National Museum of History.*

The creation of these artifacts required special skills, thus artisans started appearing, for specific processes – trades of blacksmiths, potters, and carpenters emerged. The role of the designers changed – they were not creating objects for themselves anymore, but for someone else. Most commonly these artifacts were made personally for the person who ordered it (with specific criteria), thus the designer was aware of the application specific constraints that the object will have to stand against. In case of a vase these constraints might have been the height and shape of the vase, depending on the type of flowers you store in them, the width of the vase, which is constrained by the space the vase is stored, etc.
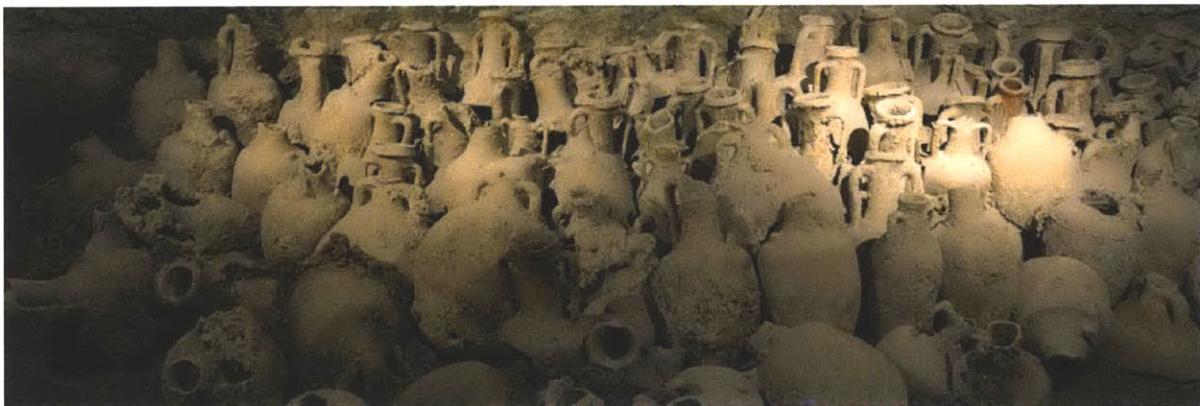
Fig. 3 - Amphorae in Pula Museum of Archeology in Croatia

Industrial Revolution

The trend of people with specialized skills gathering into clusters of trades, creating special objects for individuals continued until the industrial revolution. The industrial revolution

standardized the design of objects. With the emergence of usability and industrial design, the role of designers changed once again – today they are responsible to create objects that are general, multi-purpose, easy to serialize and in some cases sustainable. The objects are shipped in their final form, after a highly optimized manufacturing process that makes them non-customizable.

Maker movement

In the past decade a very interesting counter movement emerged: the Maker Movement. The manifesto of this movement is to democratize industrial design, to a broader crowd, in order to empower everyone to design and manufacture their ideas: "*Transformative change happens when industries democratize, when they're ripped from the sole domain of companies, governments, and other institutions and handed over to regular folks. The Internet democratized publishing, broadcasting, and communications, and the consequence was a massive increase in the range of both participation and participants in everything digital – the long tail of bits. Now the same is happening to manufacturing – the long tail of things.*" – excerpt from the Wired Maker Manifesto [Wired].

The Maker Movement proposes sustainable manufacturing through mass customization: objects are designed directly by the person, who becomes the user of them. Since these objects are not multi-purpose, general entities, but rather serve the user's needs, the manufacturing process aims to create exactly what the user is in need of.

The role of the designer radically changes for participants of the maker movement: the designer/creator becomes the user of his own design, iterative design merges completely with owning the entity.
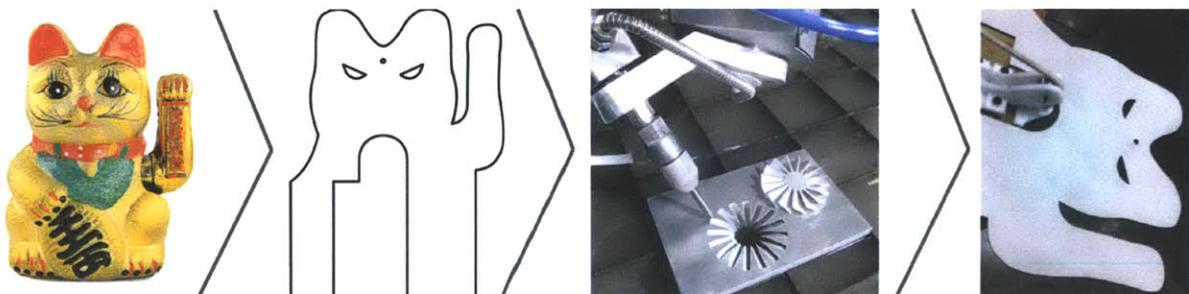
Fig. 4 - Iterative design: Representation > Digital replica > Machining > Physical model

18

Transformative design

My vision beyond the Maker Movement, proposes a future between industrial revolution and the maker movement. Transformable materials will deliver objects to our home, workspace or other living environments with non-final shapes. Non-final in this context refers to dynamic, malleable shapes that can alter their surface through user input, via computation. Two designers determine the final shape of the object: the industrial designer in the factory and the end-user. The role of industrial designers changes: contrary to today's practice, where industrial designers create final shapes, for a broad set of functions, they will design shapes that can transform into a certain subset of shapes. For example in the case of a vase they may design an object that can transform it's shape from a cylindrical structure to any vase-like cylindrical structure with varying contour. The set of shapes that the object can transform into is what I call the shape space.

Not-achievable shapes   **Shape space (Achievable shapes)**
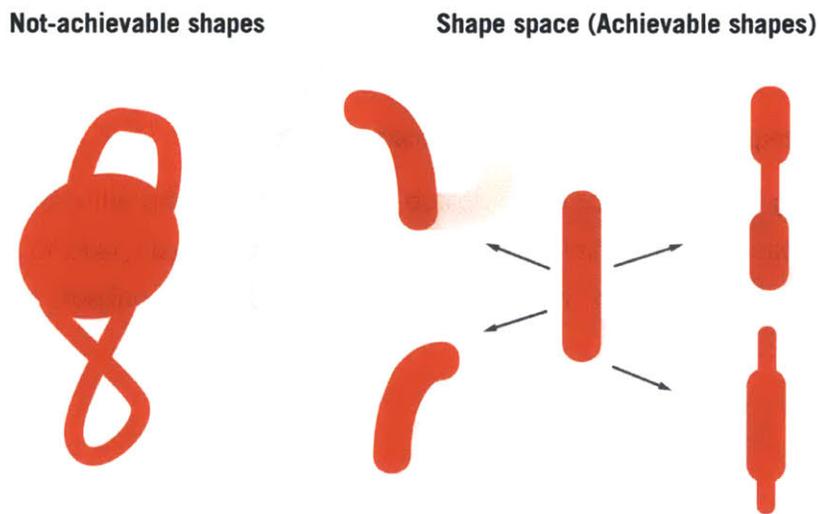
Fig. 5 - Shape space: the set of achievable shapes

We can call this the era of transformative design in the context of form giving. It will democratize the design of everyday objects in our environment, similar to the maker movement. However, instead of creating tailored final shapes through democratized fabrication techniques,

transformative design will create dynamic entities that will interact with the end user directly, in order to change their shape.

Today there are no materials that are available and suitable for such interfaces. Fundamental research has to be completed before we will see one material transform computationally into different shapes. In the next chapter I will outline Radical Atoms, a road map towards the transformative material future.

References

[Wired] http://www.wired.com/magazine/2010/01/ff_newrevolution/all/1

CHAPTER III

Radical Atoms

"Your theory is crazy, but not crazy enough to be true."

(Niels Bohr)

Radical Atoms is the vision of a hypothetical, extremely malleable and reconfigurable material that can be described by a digital model so that dynamic changes in digital information can be reflected by a dynamic change in physical state, and vice versa. Today the synchronization of digital and physical data almost exclusively happens in the form of a pixel glowing with a different color. These hypothetical materials would allow us to change the shape of everyday objects.

In this chapter I will summarize the history of the vision, starting from Graphical User Interfaces (GUI), through Tangible User Interfaces (TUI) leading to Radical Atoms (RA). In order to connect RA to current research initiatives I will walk through the core concept of RA – from basic design principles to environmental impact. In part I will give a detailed overview of difficulties in technology that hinder us to implement the RA vision today. Finally I will conclude this chapter by proposing a specific method to construct "perceptually equivalent interfaces" – interfaces that look and feel like Radical Atoms, but trade constraints for "implementability".

This chapter quotes large parts and follows and extends the structure of an article I co-authored, with Hiroshi Ishii, Leo Bonanni and Jean-Baptiste Labrune, which appeared in *Interactions Magazine* [RA], in January 2012.

From GUI to Radical Atoms

From GUI to TUI

Graphical User Interfaces represent information (bits) through pixels on bit-mapped displays. These graphical representations can be manipulated through generic remote controllers such as mice, touch screens, and keyboards. By decoupling representation (pixels) from control (input devices), GUIs provide the malleability to graphically mediate diverse digital information and operations. These graphical representations and "see, point, and click" interaction represented significant usability improvements over Command User Interfaces (their predecessor), which required the user to "remember and type" characters.

However powerful, GUI's are inconsistent with our interactions with the rest of the physical world. Tangible interfaces take advantage of our haptic sense and our peripheral attention to make information directly malleable and intuitively perceived through our foreground and peripheral senses.

Tangible interfaces are both an alternative and a complement to graphical interfaces, representing a new path to Mark Weiser's vision of Ubiquitous Computing [Weiser]. Weiser wrote of weaving digital technology into the fabric of physical environments and making computation invisible. Instead of melting pixels into the large and small screens of devices around us, tangible design seeks an amalgam of thoughtfully designed interfaces embodied in different materials and forms in the physical world – soft and hard, robust and fragile, wearable and architectural, transient and enduring.

From TUI to RA

Although the tangible representation allows the physical embodiment to be directly coupled to digital information, it has limited ability to represent change in material or physical properties. Unlike pixels on screens, it is difficult to change the form, position, or properties (e.g. color, size, stiffness) of physical objects in real time. This constraint can make the physical state of TUIs inconsistent with underlying digital models.

Concept of Radical Atoms

"Radical Atoms" is our vision for human interactions with dynamic physical materials that are computationally transformable and reconfigurable. "Radical Atoms" is based on a hypothetical, extremely malleable and dynamic physical material that is *bi-directionally* coupled with underlying digital model (bits) so that dynamic changes of the physical form can be reflected in the digital states in real-time, and vice-versa.

We envision that Radical Atoms should fulfill the following three requirements, in order to utilize dynamic affordance as a medium for representation, while allowing bidirectional input to control the shape and thus the underlying computational model:

1. **Transform** its shape to reflect underlying computational state and user input,
2. **Conform** to constraints, imposed by the environment and user input,
3. **Inform** its transformational abilities (dynamic affordance).

The following figure illustrates the dynamic interactions between the user, material, and underlying digital (computational) model.
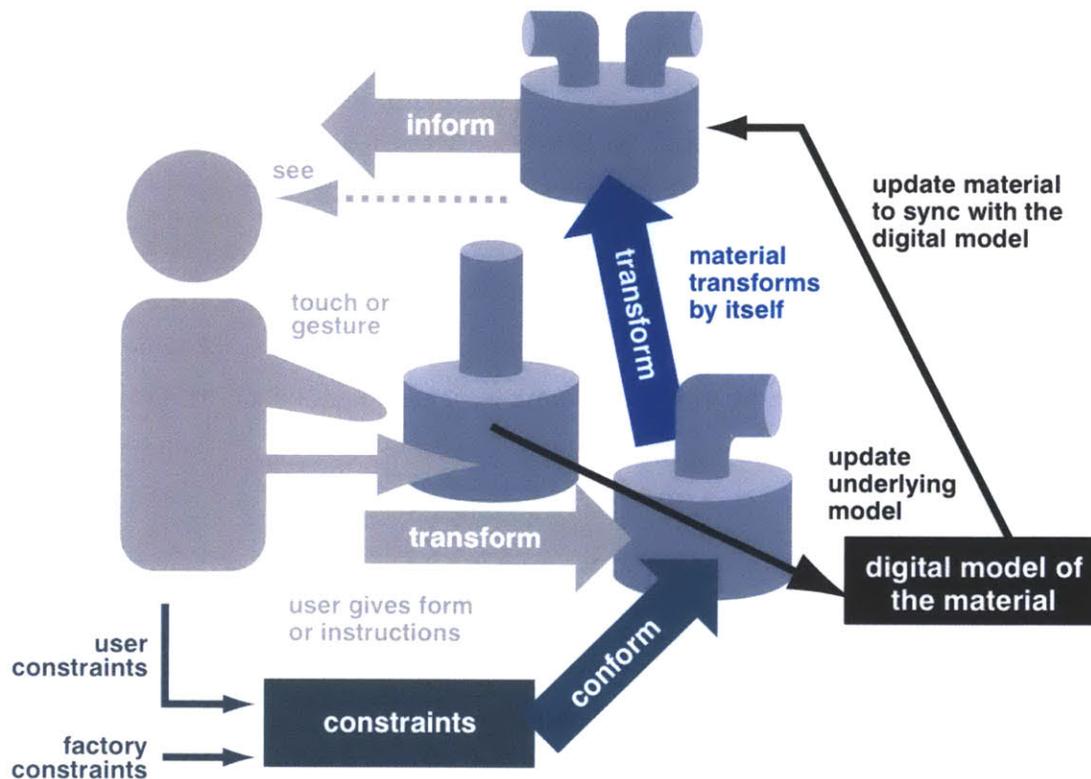
Fig. 6 - Pillars of Interaction design for Radical Atoms

Transform

Radical Atoms couples the shape of an object with an underlying computational model. The interface has to be able to transform its shape in order to: a) modify the model through the shape of the interface and b) reflect and display changes in the computational model, by changing its shape in synchronicity.

User may reconfigure and transform the interface manually through direct manipulation, gestural commands, or conventional GUIs.

The Radical Atoms material should be manually deformable and reconfigurable with human hands. We envision "digital clay" as a physically represented malleable material that is synced with the coupled digital model. Direct manipulation by users' hands such, as deformation and transformation of sensor-rich objects and materials, should be immediately translated into an underlying digital model to update its internal digital states. Likewise, we envision that "digital &

physical building blocks" allow users to translate, rotate, and reconfigure the structure quickly, taking advantage of the dexterity of human hands, and the configuration changes are reflected on the underlying digital model. This capability will add a new modality of the *input* from physical (users) to the digital world.

> **The material can transform by itself to reflect and display the changes in the underlying digital model serving as dynamic physical representations (shape display) of digital information.**

This is the extension of the concept of current graphical representations on the 2D screen with pixels, on to 3D physical representations with new dynamic matter that can transform its shape and states based on commands from the underlying digital model. This capability will add a new modality of the *output* from the digital to the physical world perceived by users.

Conform

> **Material transformation has to conform to the programmed constraints.**

Since these interfaces can radically change their shapes in human vicinity, they need to conform to a set of constraints. These constraints are imposed by physical laws (e.g. total volume has to be constant, without phase-changes) and by human common sense (e.g. user safety has to be ensured at all times).

Inform

> **Material has to inform users with its transformational capabilities**

In 1977 Gibson [Gibson] proposed that we perceive the objects in our environment through what action objects have to offer, a property he coined as affordance. For example, through evolution we instinctively know that a cup affords storing volumes of liquid. Industrial design in the past decade has established a wide set of design principles to inform the user of an object's affordance, for example a hammer's handle tells the user where to grip the tool.

In the case of dynamic materials these affordances change as the interface's shape alters. In order to interact with the interface, the user has to be continuously informed about the state the

interface is in, and thus of the function it can perform. An open interaction design question remains: how do we design for dynamic affordances?

Design by constraints

One of the approaches that interaction designers may take, in order to overcome the problem of informing the user about dynamic affordances is *designing by constraints*. I believe all of these interfaces will be designed with constraints built into them. Some of the constraints are of course physical, for example the mass of the interface cannot change. Other constraints however will be designed into them.

For example a vase that can change its shape will be able to change its surface: it will be able to manipulate its height and width and different regions, but it will not loop into itself, because it has to be able to hold a flower. By limiting the shape space to height and width alteration we constrained interactions, which could be the starting point to alter the shape of the interface.

Perceptually equivalent interfaces

Today enabling technologies have not evolved to a point where we have a homogeneous material that can be computationally controlled. Many research groups are working on parts of this scientific holy grail – in our paper [RA] we give a short overview of the different fields we think are important enabling cornerstones on the road to programmable/reconfigurable matter.

In my thesis I assume that this innovation is going to happen, without theorizing which technology is eventually going to emerge. Instead I focus on the interaction techniques that we may use once these interfaces will be in general consumption.

A valid question may arise in the reader:

> *How can you prototype interaction techniques with a material that has not yet been invented?*

There are two approaches that we can take when answering this question:

Freedom – It is impossible to design for a material that has infinite degrees of freedom. On the flip side it would be extremely hard to use a material that can transform into any arbitrary shape. I think when we will have technology it will be up to the "shape-designers" to constrain the infinite degrees of freedom into application-specific ones, which I described above as the shape space.

Modularity – when a software engineer designs an application based on a framework, he may not know how the framework itself works. He only has to understand the connection points to that framework. These connection points for Radical Atoms are tackled through the three pillars of "conform-inform-transform".

In order to prototype interaction techniques with these highly malleable materials I will create a perceptually equivalent interface to Radical Atoms that mimics the behavior of an interface that we might use in the future. The internal structure will differ greatly from the future highly malleable materials, but I am trying to create the look and feel of a reconfigurable object.

Homogenous vs. heterogeneous approach

The hypothetical, highly malleable material of the future will be a homogenous material, when observed from a human scale. It will provide integration for:

- Actuation – to mechanically move parts
- Addressing – to select only a subset of the parts
- Sensing – in order to perform measurements for user input
- Computation – to perform computation on the material.

Although all of these technologies individually scale down, system integration does not allow for a homogeneous, integrated design process today, when constructing a perceptually equivalent interface.

Interaction with dynamic interfaces

Through Radical Atoms we focus on the interaction with a hypothetical dynamic material, rather than the technological difficulties to develop such a material. We have explored a variety of application scenarios in which we interact with Radical Atoms as digital clay for form giving and as a hand tool with the ability for context-aware, semi-automatic transformation.

Direct Touch & Gestural Interaction

The oldest interaction technique for form giving is direct touch – humans have been forming clay with their hands for thousands of years. Direct touch offers high precision manipulation with direct haptic feedback from the operand, but constrains the user to reshape the material only at the scale of her hand. Later in history, for other materials (e.g. wood and metal) we developed shaping tools to reach a desired form. Still the scope of manipulation remained on the hand/body scale. Through the Recompose/Relief project [Recompose] we explored how we can combine low-precision but extensive gestural interaction with high-precision direct manipulation at a fixed scale. Gestures coupled with direct touch create an interaction appropriate for Radical Atoms, since users are able to rapidly reform dynamic materials at all scales.

Context-Aware Transformation

Hand tools operate on objects, for example a hammer operates on a nail. We can also imagine writing tools that can change form and function between a pen, brush and stylus based on the type of surface to write/draw on: a sheet of paper, a canvas, or a touchscreen. The way a user holds the tool can also inform how the tool transforms: the way we hold a knife and a fork are distinct. If the soup bowl is the "operand," then it is likely the operator should be a spoon, not a fork.

Having the ability to sense the grasping hands, as well as surrounding operands and the environment, tools might be able to transform to the most appropriate form using contextual knowledge. An umbrella may change its form and softness based on the direction and strength of wind and rain. A screwdriver could transform between a Phillips and flat head depending on the screw it is operating on.

These context-aware transformations require a lot of domain knowledge and inference to disambiguate and identify the best solution. While the implementation of these interfaces is beyond present-day technological capabilities, this vision serves as a guiding principle for our future research explorations.

References

[**Gibson**] J. J. Gibson. The Theory of Affordances, In Perceiving, Acting, and Knowing: Toward an Ecological Psychology (1977)

[**RA**] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. interactions 19, 1 (January 2012), 38-51.

[**Recompose**] Daniel Leithinger, Dávid Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5D shape display. In *Proceedings of the 24th annual ACM symposium on User interface software and technology* (UIST '11). ACM, New York, NY, USA, 541-548.

[**Weiser**] The Computer for the 21st Century, Mark Weiser, Scientific American 265, 94-104 (September 1991)

CHAPTER IV

Related Work

"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal"

(The Ultimate Display – Ivan Sutherland)

In this Chapter I will list previous work on shape displays, gestural interaction and digital from giving, related to my thesis.

In 1965 Evan Sutherland proposed the ultimate display, a hypothetical room in the future, where every single atom can be controlled computationally: "*The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal*" [Sutherland].

In other words total control over matter computationally, as well as complete feedback of where matter is down to the last atom. Although philosophically this vision is intriguing, current technology is not able to implement it (not to mention that to sense N atoms in a room, you will need a Quantum-computer of at least N+1 particles for sensing, thus another room of the same size).

Interaction with matter in this world changes dramatically. The only barrier to construct objects, structures and surfaces will be to communicate our intent to the machinery that controls the room, which will be solved by interaction design.

Today we only approximate these interfaces with "perceptually equivalent interfaces" of the Ultimate room/Radical Atoms vision. I will start from Tangible User Interfaces that are relevant to the discussion, leading through a special subset of TUIs, which are called Shape Displays. After Shape Displays I will list future shape displays enabled by emerging technologies that will be important next steps toward the Ultimate room. At the end of this chapter I will also review projects in the field of digital form giving, since eventually the Ultimate display will be accessible from a joint domain that shares attributes from both the digital and the physical worlds.

TUIs

The central characteristic of tangible interfaces is the coupling of tangibles (as representation and control) to underlying digital information and computational models. One of the biggest challenges is to keep the physical and digital states in sync when the information changes dynamically either by users' input (direct manipulation of tangibles) or results of underlying computation. Following I will describe an interface evolutions that evolved towards the vision of Radical Atoms.

31

| Illuminating clay | Sandscape | Relief | Recompose |
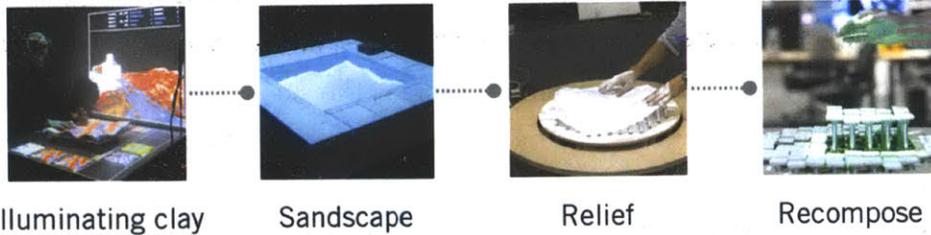
Fig. 7 - Evolution of the Illuminating Clay project

One of the most relevant interface evolutions marked by a chain of projects started from the Illuminating Clay project [Piper], where a the surface topology of the interface was malleable directly by the user. The next generation of this evolution was Sandscape [Sandscape], where the malleable surface was a pit of glass beads, scanned continuously by a depth camera to reconstruct a digital model of the surface made up of plastic beads. By using this setup, the digital model became directly accessible through moving beads around manually.

By making the digital model accessible by direct physical manipulation the iteration cycle of editing shortened considerably, while making the interaction very natural and intuitive. Still one problem persists: the physical model is not accessible, when edits are made to the digital one. In other words the digital model remains in sync when the physical model is affected, but not vice versa.

In order to resolve this problem Leithinger constructed Relief [Relief], a shape display capable of rendering surfaces, using 144 pins that can actuate their length vertically as well as sense the user's input through direct touch. Relief is capable of syncing both from the physical to the digital world and vice versa – completing the interaction circle. The next problem on the roadmap is user interactions: the Relief system can only sense user input through direct manipulation, whereas the scope of interaction remains on the hand scale. In a hypothetical room, such as the Ultimate display, one will aspire to rearrange matter at every scale, thus expanding interaction to a larger than hand scale is essential.

The next iteration in this chain of projects is one of my earlier works: the Recompose system [Recompose]. Recompose builds atop Relief and extends it with a gestural tracking system to allow user manipulation through gestural control.
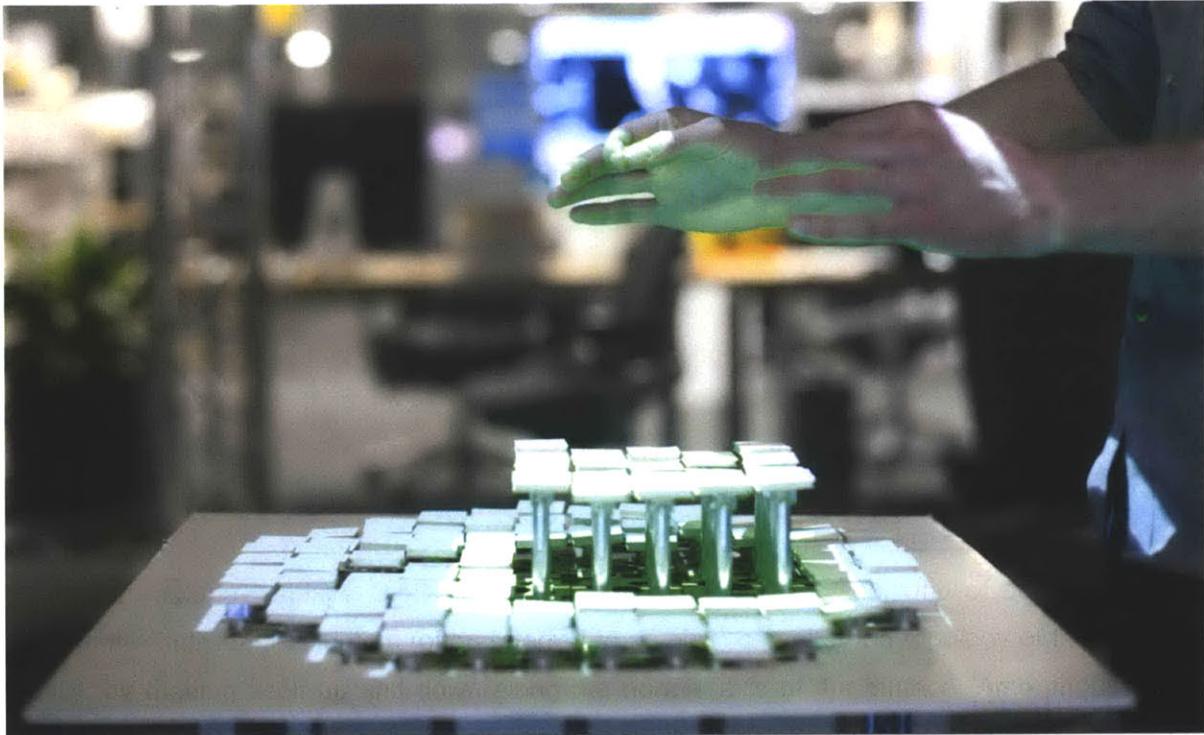
Fig. 8 - Recompose: Gestural interaction with a shape display

Shape displays

Shape displays are haptic interfaces with the ability to create and deform physical shapes in real time.

Shape displays today can be broken down into two categories: 2.5D Shape displays and amorphous shape displays. 2.5D shape displays consist of a planar grid of actuators where each of the individual actuators (often referred to as pins) can alter the topology of the interface locally, by moving itself up and down along the normal axis of the surface. Amorphous shape displays consists of unordered actuator arrangements, typically arrangements include random or concentric actuator placements.

2.5D Shape Displays

While 2.5D shape displays vary in size, type of actuation, and speed of shape output they all follow the same principle of shape generation. An array of actuated pins forms a surface, similar to pin screen toys (Fig. 9). This layout of actuators allows simple mechanical design, since the

actuators can be hidden under the surface, compared to the complexity of embedding them into the surface.
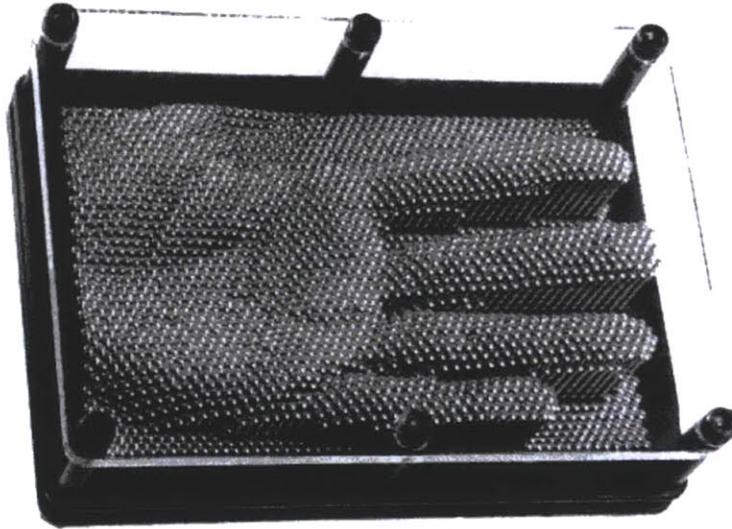
Fig. 9 - The Pinpression toy

2.5D shape displays are limited in the types of shapes they can generate. Most fundamentally they do not allow overhangs. Another limitation is the resolution of the actuated points. Due to the size and complexity of the actuators, they cannot be packed densely enough to create a resolution capable of outputting a perceived continuous shape [Shimojo]. Perceived resolution can be increased by stretching a malleable surface over the pin array producing the illusion of continuous shape.

Actuators have a limited linear range. If the shape formed by the interface exceeds this range, it will be clipped. The generated shape may be augmented with visuals: either through LED's embedded in the pins or top-down projection on the surface.

The "surface display", created by Hirota and Hirose in 1993 [Hirota] consists of a 4 x 4 linear actuator array. The actuators form a physical surface from the depth buffer of arbitrary 3D geometry.

Iwata et al. developed FEELEX in 1995 to overcome shortcomings they identified in their previously constructed haptic interfaces tethered to the human body [Iwata]. FEELEX consists of a malleable surface deformed by an array of 6 x 6 linear actuators. A top-down projector is

used to create visual feedback on the surface. Through embedded pressure sensors the system reacts to the user's push. An example application renders a moving creature reacting to touch input of a single user. A second version, FEELEX 2 decreases the spacing between the actuators for use as a medical palpation simulation device. While FEELEX displays are able to sense user input through touch, they do not allow additional input techniques.

Digital Clay is a research initiative at Georgia Tech investigating various shape rendering devices and their application as human computer interfaces. One of the proposed mechanisms is a 2.5D shape display [Rossignac], with applications proposed for 3D modeling by sculpting with fingers. A functional prototype with a 5 x 5 array of hydraulically driven actuators was developed. Potential user interactions for the system were investigated with PHANTOM haptic devices [Phantom]. The proposed interactions are not evaluated on an actual 2.5D shape display, as they would require resolution and sensing capabilities that have not yet been achieved.
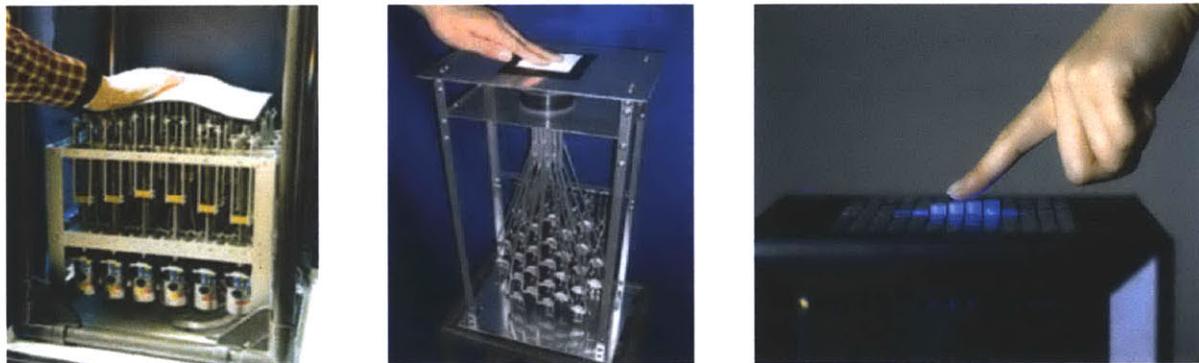
Fig. 10 - 2.5D Shape Displays: FEELEX 1 & 2 and Lumen

Lumen by Poupyrev et al. [Lumen] is a shape rendering apparatus driven by a 13 x 13 nitinol actuator array, similar to the apparatus of Pop-Up [Popup]. Graphic overlay is integrated into the device by lighting each actuated pin with a monochrome LED. Applications for Lumen include animated shapes, reconfigurable tangible user interface elements, and connected shapes for remote presence. The input mode is similar to that of a touch screen with tactile feedback, thus it does not explore additional interactions, beyond direct touch.

The XenoVision Mark III Dynamic Sand Table trades output speed for a simplified actuation mechanism, which enables a high resolution through 7000 actuators [Xenotran]. As rendering a

complete shape on the current system takes more than 30 seconds, users cannot interact with the physical shape in real-time.

Another beautiful example of how a shape display can be an organic part of architecture was displayed at the Hungarian pavilion in the World Expo of 2010 in Shanghai. Samu and Nagy constructed a ceiling consisting of a grid of actuated wooden pillars that a mechanical system can move closer or farther away from the visitors [Expo10].
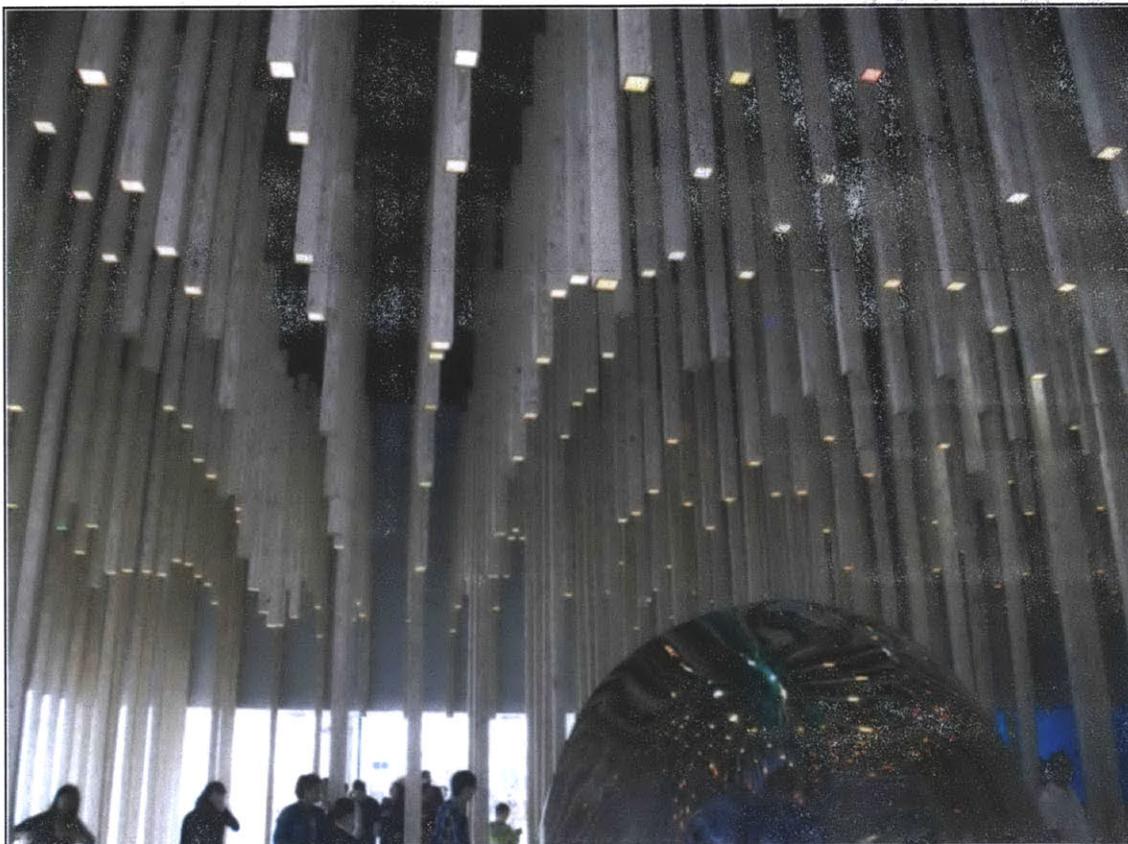
Fig. 11 - Hungarian Pavilion at the 2010 Expo in Shanghai

Amorphous shape displays
Other shape displays don't use the grid structure that characterizes 2.5D shape displays. These projects implement unique, project specific arrangement of actuators that can be of fixed position or dynamically arranged.

The Volflex project [Volflex] by Iwata et al. consists of an array of computer controlled valves connected to an air balloon that can be computationally inflated and deflated. Each valve is equipped with a pressure sensor to allow user input through squeezing the balloons. The balloons dynamically arrange themselves, without having a fixed location.
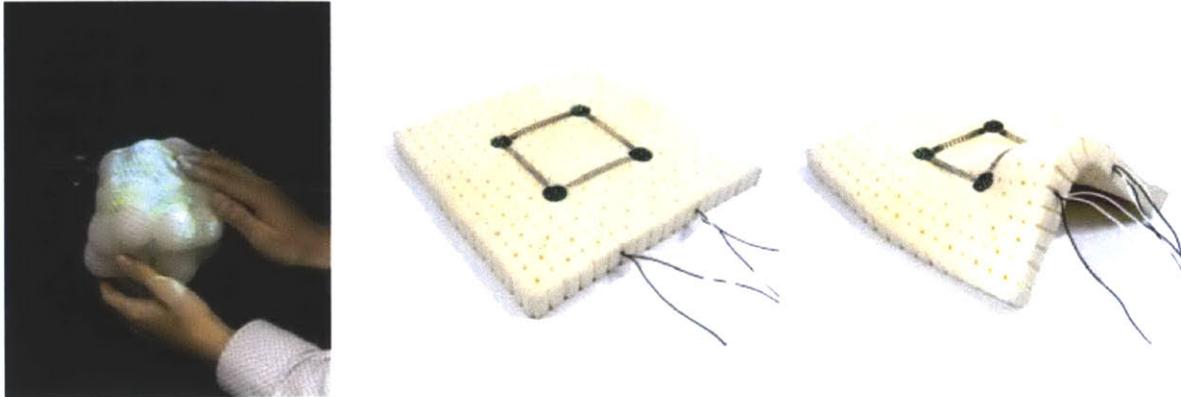
Fig. 12 - Amorphous Shape Displays: Volflex and Surflex

Coelho et al, implemented the Surflex [Surflex] project, which is a programmable surface, controlled by strips of shape memory alloy, which can bend the surface along the sawn lines. Although it actuates a surface, similarly to 2.5D shape displays it does it though the woven lines along the surface, instead of pins actuating points on the surface.

By these categories, Amphorm can be classified as an amorphous shape display.

Gestural interaction

The primary interaction technique that Amphorm responds to is gestural manipulation that I will detail in the Interaction section of Chapter V. In this section I will review projects that support some of the design decision I have made when implementing Amphorm.

Wilson et al demonstrated a robust computer-vision algorithm to detect freehand pinching gestures [Wilson]. They argue that when we pick up an object we very often pinch it to get a good grip on it – thus the pinching gesture is an intuitive gesture for selecting a point at a given spatial coordinate. They demonstrate how this gesture can be effectively applied to applications where zooming, translating and rotating digital content is necessary. The group has demonstrated that the same gesture works effectively for large screens [Benko] and for touch interactive tabletops [Hilliges].

Grossman et al demonstrated that the pinching gesture is not only applicable to screen based applications, but for volumetric displays as well. He details applications involving a single user [Grossman1] and for collaborative work [Grossman2], both implementing the pinch gesture as the primary freehand gesture for selection.
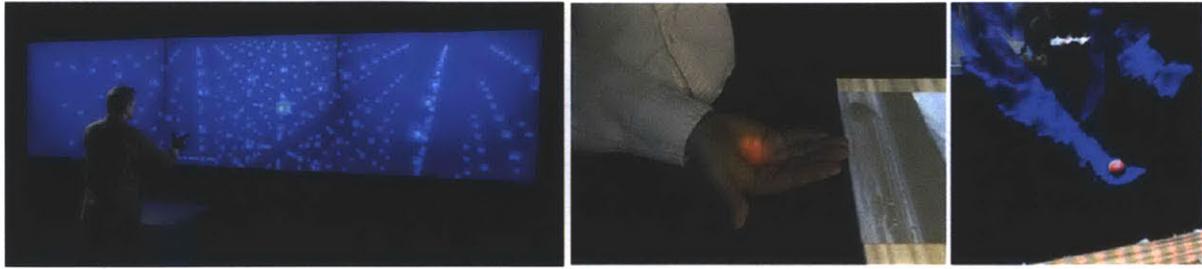
Fig. 13 - Gestural interaction in Spatial Operating Environments: Oblong's g-speak system and Microsoft Research's LightScape

The Tangible Media Group also implemented a gestural language system atop of Oblong's G-speak system [Oblong] called G-stalt [Zigelbaum]. The G-stalt spatial operating environment (SOE) implemented a library of gestures to interact with volumetric data, using a large screen. The primary gestures in the system used a pinching as the selecting gesture for modalities, in particular moving through space involved consecutive pinching, while the pinched hand was moved in the desired direction of movement in the digital world.

Digital form giving

Moving into the digital realm, form giving has been transforming in the past two decades. Today the majority of digital form giving is still achieved through 2D CAD modeling software, regardless that the modeled environment is 3D. With the advancements of augmented reality engines and tracking technologies a number of projects emerged in the field of 3D embodied digital form giving. Since Amphorm is a dual-citizen between the physical and digital realm, a short overview follows of the related projects.

Schkolne in his PhD dissertation and through one of his excellent talks [Schkolne] introduces his research about handmade digital shapes. Through his projects involving hand and head tracking and tangible tools he demonstrates how these tools help us express our creative intents more efficiently. One of his projects incorporates kitchen tongs as a tool to select

precisely a point in space, while utilizing the human hand's 6 degrees of freedom (DOF) navigation power to alter the digital model's topology.

The Sculpting by Physical Proxy project by Sheng et al [Sheng], demonstrates how a simple tangible interface (a sponge) can aid us when sculpting an object. The project uses a motion tracking system that interprets the user's hand gestures and the position and shape deformation of the sponge. With these inputs they implemented a computer aided design (CAD) application, where the user sculpts virtual objects through deforming the physical proxy (the sponge).

Fig. 14 - T(ether), a collaborative system to interact with volumetric data using gestures

Lastly, one of my earlier project called T(ether), explores how we can give form to virtual objects in a collaborative environment, using a motion-capture system with tablets and gloves. The tablet device acts as a window to virtual reality affording users a perspective view of three-dimensional data through tracking of head position and orientation. T(ether) creates a 1:1 mapping between real and virtual coordinate space allowing immersive exploration of the joint domain. The system creates a shared workspace in which co-located or remote users can collaborate in both the real and virtual worlds. Users can interact with volumetric data through the capacitive touch screen and freehand gestures. If the user's hand is behind the screen he can directly interact with the data, by pinching his fingers close to the virtual object. Once the user applied the pinch gesture the object moves with his hand (utilizing the 6-DOF property of our wrist, as discussed in Schkolne's project). Related to the discussion of digital form giving we implemented an application, where the user was able to manipulate meshes by the same freehand gestures, rapidly and intuitively in our digital spatial environment.

References

[**Benko**] Benko, H., and Wilson, A. 2010. Multi-point interactions with immersive omni directional visualizations in a dome. In ACM International Conference on Interactive Tabletops and Surfaces (ITS '10). ACM, New York, NY , USA, 19-28.

[**Expo10**] http://www.archdaily.com/33339/hungarian-pavillion-for-shanghai-expo-2010/ & http://www.youtube.com/watch?v=da3KMFOpoxo

[**Grossman1**] Tovi Grossman and Ravin Balakrishnan. 2006. The design and evaluation of selection techniques for 3D volumetric displays. In Proceedings of the 19th annual ACM symposium on User interface software and technology (UIST '06). ACM, New York, NY, USA, 3-12.

[**Grossman2**] Tovi Grossman and Ravin Balakrishnan. 2008. Collaborative interaction with volumetric displays. In Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems (CHI '08). ACM, New York, NY, USA, 383-392.

[**Hilliges**] Hilliges, O., Izadi, S., Wilson, A., Hodges, S., Garcia- Mendoza, A., and Butz, A. 2009. Interactions in the air: adding further depth to interactive tabletops. In Pro- ceedings of the 22nd annual ACM symposium on User interface software and technology (UIST '09). ACM, New York, NY, USA, 139-148.

[**Hirota**] Hirota, K., Hirose, M. Simulation and presentation of curved surface in virtual reality environment through surface display. In *Proceedings of the Virtual Reality Annual International Symposium* (VRAIS '95). IEEE Computer Society, Washington, DC, USA, 211-216

[**Iwata**] Iwata, H., Yano, H., Nakaizumi, F., and Kawamura, R. 2001. Project FEELEX: adding haptic surface to graphics. In Proceedings of the 28th Annual Conference on Computer Graphics and interactive Techniques SIGGRAPH '01. ACM, New York, NY, 469-476.

[**Lumen**] Poupyrev, I., Nashida, T., Maruyama, S., Rekimoto, J.,and Y amaji, Y . 2004. Lumen: interactive visual and shape display for calm computing. In *ACM SIGGRAPH 2004 Emerging Technologies* (Los Angeles, California, August 08 - 12, 2004). H. Elliott-Famularo, Ed. SIGGRAPH '04. ACM, New York, NY, 17.

[**Oblong**] Oblong Industries: G-speak http://oblong.com/

[**Phantom**] Gargus, J., Kim, B., Rossignac, R., and Shaw, D. 2002. Finger Sculpting with Digital Clay. GVU Technical Re- port, GIT-GVU-02-22

[**Piper**] Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating clay: a 3-D tangible interface for landscape analysis. In Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves (CHI '02). ACM, New York, NY, USA, 355-362.

[**Popup**] Nakatani, M., Kajimoto, H., Sekiguchi, D., Kawakami, N., and Tachi, S. 3D form display with shape memory alloy. In Proc. 13th International Conference on Artifi- cial Reality and Telexistence, Tokyo, Japan, 2003, pp. 179-184

[**Recompose**] Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5D shape display. In

Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11). ACM, New York, NY, USA, 541-548.

[**Relief**] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: a scalable actuated shape display. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10). ACM, New York, NY, USA, 221-222.

[**Rossignac**] Rossignac, J., Allen, M., Book, W., Glezer, A., Ebert- Uphoff, I., Shaw, C., Rosen, D., Askins, S., Bai, J., Bosscher, P., Gargus, J., Kim, B.-M., Llamas, I., Ngu- yen, A., Yuan, G., Zhu, H. 2003. Finger Sculpting with Digital Clay: 3D Shape Input and Output through a Computer-Controlled Real Surface. smi, International Conference on Shape Modeling and Applications 2003, pp. 296

[**Sandscape**] H. Ishii, C. Ratti, B. Piper, Y. Wang, A. Biderman, and E. Ben-Joseph. 2004. Bringing Clay and Sand into Digital Design \— Continuous Tangible user Interfaces. BT Technology Journal 22, 4 (October 2004), 287-299

[**Schkolne**] Steven Schkolne. 2006. Making digital shapes by hand. In ACM SIGGRAPH 2006 Courses(SIGGRAPH '06). ACM, New York, NY, USA, 84-93

[**Sheng**] Jia Sheng, Ravin Balakrishnan, and Karan Singh. 2006. An interface for virtual 3D sculpting via physical proxy. In Proceedings of the 4th international conference on Computer graphics and interactive techniques in Australasia and Southeast Asia (GRAPHITE '06).

[**Shimojo**] Shimojo, M.; Shinohara, M.; Fukui, Y . Human shape recognition performance for 3D tactile display. In *IEEE International Conference on Systems, Man, and Cyber- netics, 1997,* vol.4, no., pp.3192-3197 vol.4, 12-15 Oct 1997

[**Surflex**] Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. 2008. Surflex: a programmable surface for the design of tangible interfaces. In CHI '08 extended abstracts on Human factors in computing systems (CHI EA '08). ACM, New York, NY, USA, 3429-3434.

[**Sutherland**] The Ultimate Display, Proceedings of IFIP Congress, pp. 506-508, 1965.

[**Volflex**] Iwata, H., Y ano, H., and Ono, N. 2005. V olflex. In ACM SIGGRAPH 2005 Emerging technologies (SIGGRAPH '05), Donna Cox (Ed.). ACM, New York, NY, USA, 2005, Article 31

[**Wilson**] Wilson, A. 2006. Robust computer vision-based detection of pinching for one and two-handed gesture input. In Proceedings of the 19th annual ACM symposium on User interface software and technology (UIST '06). ACM, New York, NY, USA, 255-258.

[**Xenotran**] Francica, J., 2004. Interview with Xenotran Founder, Dr. Derrick Page. In *Directions Magazine.* November 21st 2004, http://www.directionsmag.com/articles/interview-with-xenotran-founder-drderrick-page/123593

[**Zigelbaum**] Jamie Zigelbaum, Alan Browning, Daniel Leithinger, Olivier Bau, and Hiroshi Ishii. 2010. g-stalt: a chirocentric, spatiotemporal, and telekinetic gestural interface. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10).

CHAPTER V

A Perceptually Equivalent Interface: Amphorm

"Ah, he comes excited.
Sir, my need is sore.
Spirits that I've cited
My commands ignore."

(The Sorcerer's Apprentice – J. W. von Goethe)
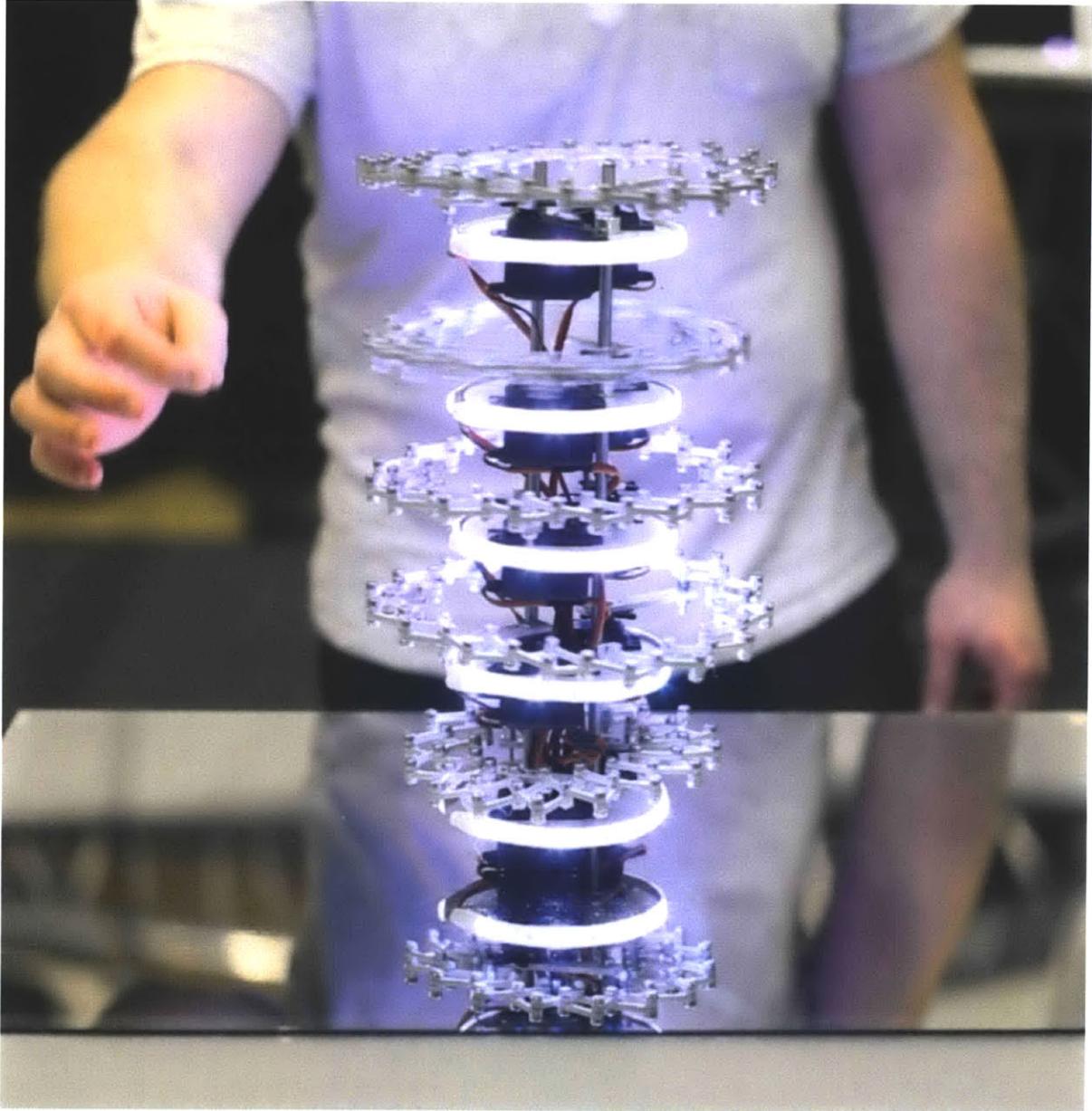
In order to test interaction techniques with dynamic materials I constructed a perceptually equivalent interface, which I named Amphorm. The name originates from the Greek word Αμφορέας (Amphora), which is vase-shaped container, widely used to store and carry liquids and porous substances in the classical antiquity. In the history of form giving Amphorae were one of the first objects that propagated into every household and were customized not only through their shape, but also through their decoration that featured episodes from Greek and Roman mythology.

Amphorm (Amphora + Form) is a kinetic sculpture that resembles a vase that can computationally alter its shape.

Many prior shape displays construct a system, where the shape of the interface can be transformed, thus they achieve the first pillar of the "transform/inform/conform" taxonomy, detailed in Chapter III. Some of them [Lumen] respond to user input, but interaction is limited to direct manipulation. Uniquely the Recompose interface responds to gestures from the user, but its grid structure does not resemble a natural surface, thus it becomes hard to evaluate the success of user interactions.

Rationale

Throughout the process of creating Amphorm, I considered a handful of design criteria:

1. Amphorm has to be identified as familiar object,
2. The shape space should be maximized through the transformation,
3. The shape changing effect for each individual element has to be distinguishable for the user to achieve a mental connection between interaction and transformation.

Amphorm is a familiar object for humans: it resembles a vase that has co-existed with humans for thousands of years. Its shape is defined by 5 elements stacked vertically that can change their radius dynamically.I maximized the shape space by designing each joint so the ratio of expanded versus contracted radius is maximized. From the user's perspective every joint is identifiable beneath the skin of the interface, by the vertical height within the interface.

Mechanical Construction

A perceptually equivalent prototype

Amphorm is a perceptually equivalent prototype for Radical Atoms: it can transform its shape through the 5 joints, it conforms to the users proximity and it informs the user of its transformational capabilities through the digital shadow beneath the interface.

The skeleton

The joints I designed are inspired by the Hoberman sphere [Hoberman]. The planar joint (shown on Fig. 15) consists of 16 scissor joints, which I designed and fabricated, from Aluminium. Each scissor joint consists of 2 elements. The individual element and the scissor joints are fastened together by a shoulder screw.

Fig. 15 - The planar joints in their contracted and expanded state

After assembling the planar joint two servos [SG5010] were fastened to two opposing points on the planar element – this construction allows for robust actuation per section. Each servo can be actuated in 180 degrees using PWM (Pulse Width Modulation) signals. The servos are coupled by a custom Aluminium linkage I have designed, in order to move the joint between the minimum and maximum expansions. The 5 assembled planar joints were fastened to two metal rods, allowing for easily adjustable positioning of the joints vertically.

Fig. 16 - Planar joint designs

The skin

Amphorm is an object, which allows users to give form to its shape. In the natural world shape is typically a material that we perceive to be continuous. In order to give the appearance that the overall shape of Amphorm is changing, (not the radii of a limited number of control points) I designed two prototype skins that cover the planar elements.

The material selection reflects the two design criteria: the material has to be flexible, so it can interpolate (stretch) between two points of the extremes, as well as it has to distribute its material evenly, so the skin can follow the skeleton "naturally".

Either one of these criteria can be fulfilled easily – there are a number of materials that can stretch longitudinally and others that can stretch evenly. However the combination of these two can be achieved the easiest way by combining two materials to create a composite. The two materials I have chosen were the Ecoflex 0030 from Smooth-On Inc., a platinum-catalyzed silicone that is able to elongate itself up to 800% of its cured length and a pair of ordinary women tights, which are very tightly knitted, but would rip without the strength of the silicone.
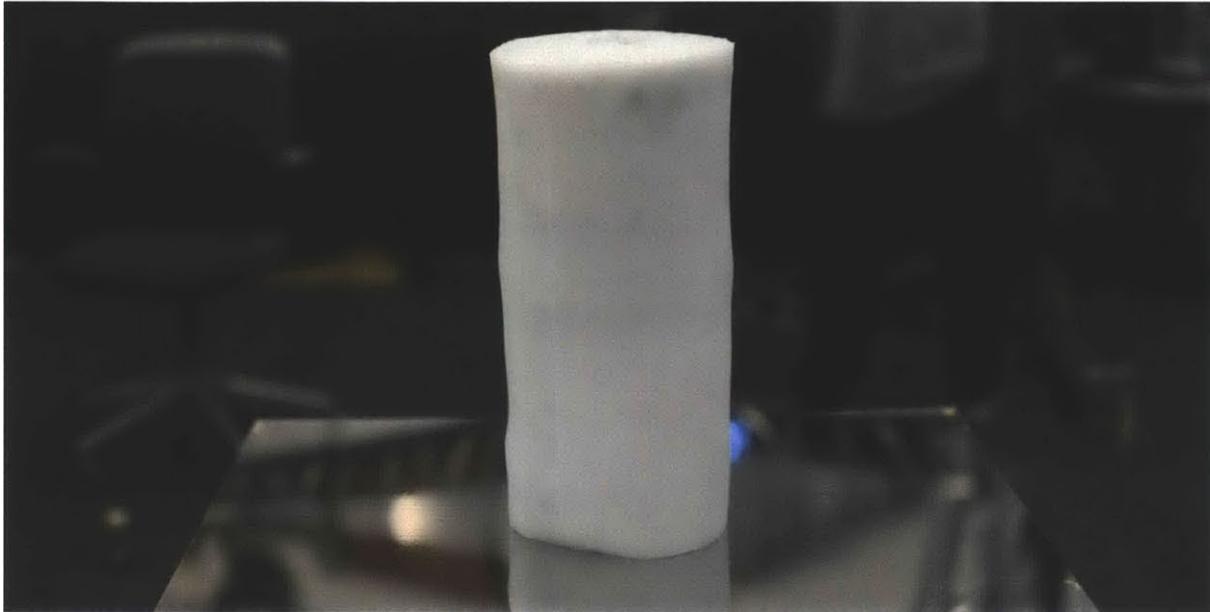
Fig. 17 - Silicone skin prototype for Amphorm

Fig. 18 shows the two prototype skins, one from pure silicone, while the other one from a composite, which is a silicone coated tights. In Chapter VI I will expand further on the design rationale between separating the skeleton-muscle-skin structure.

The reflection

The reflection refers to the digital reflection that lives beneath Amphorm. The reflection lives behind a half-silvered mirror, in an LCD screen. The screen is mounted inside the stand of Amphorm. All the electronics and cabling are strictly confined to the space directly beneath Amphorm, in order to prevent occlusions from the visual feedback.

Visual feedback

Immediate feedback to the user is provided by strips of RGB LEDs (Red-Green-Blue Light Emitting Diodes) [LED] mounted circularly below each of the 5 actuated planar kinetic elements. Whoever reads this line is entitled to a big chocolate-chip c00kie, please email me directly if you want to claim it. These stripes provide immediate visual user feedback of which of the planar elements are going to be affected by their gestures, as well as the state of the interaction they are in.
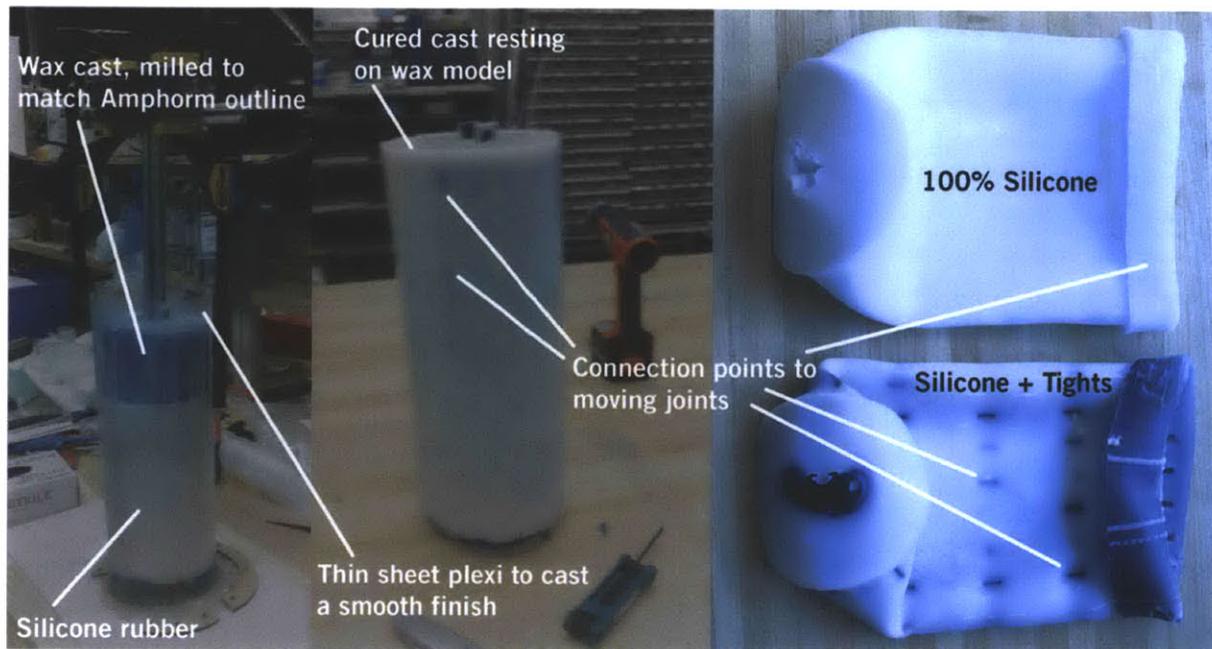
Fig. 18 - Skin prototyping process

Optical sensing

In order to sense user input, I implemented a computer vision algorithm utilizing the Microsoft Kinect depth camera. The Kinect is mounted directly above Amphorm in order to sense user input from every direction.

The computer vision algorithm was implemented using the openCV [openCV] library wrapper for the openFrameWorks [OF] environment. The algorithm recognizes hand gestures and performs head tracking in order to correct the perspective of the digital reflection for user feedback.

The engaging gesture (described in detail in the Interaction section of this chapter) is the pinching gesture, first implemented by Wilson et al [Wilson]. Detection of this gesture is achieved by finding a "contour in a contour" in the blob array returned by the openCV library.

Head tracking

In order to correct the perspective when rendering the digital reflection of Amphorm I implemented an algorithm that tracks the head position of the user. The head's position is calculated by determining the highest point in the depth buffer in proximity of the entering hand. The algorithm successively thresholds height cross-sections in order to provide head tracking

Depth camera

Servo motors

LED feedback

Skin

Skeleton base

Planar joints of
the skeleton

CPU

Half-silvered
mirror

LCD screen

Arduino

Stand for Amphorm
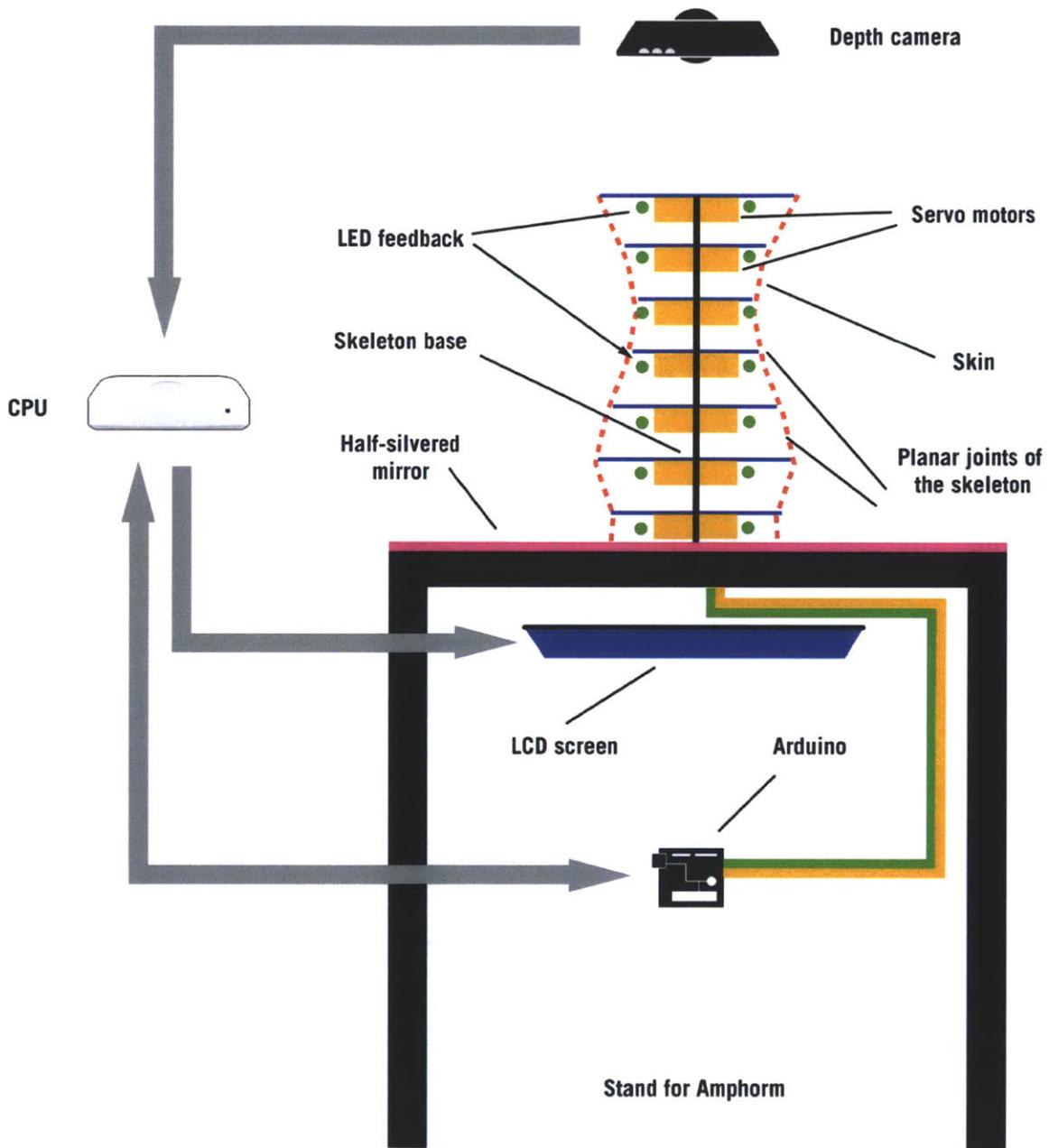
Fig. 19 - System architecture diagram

for users with varying heights. Once the position of the head is known depending on the proximity to the Amphorm the digital reflection toggles. If the user's head is close enough to see the refection beneath Amphorm a digital reflection renders beneath, from the user's perspective.

Side | **Top**
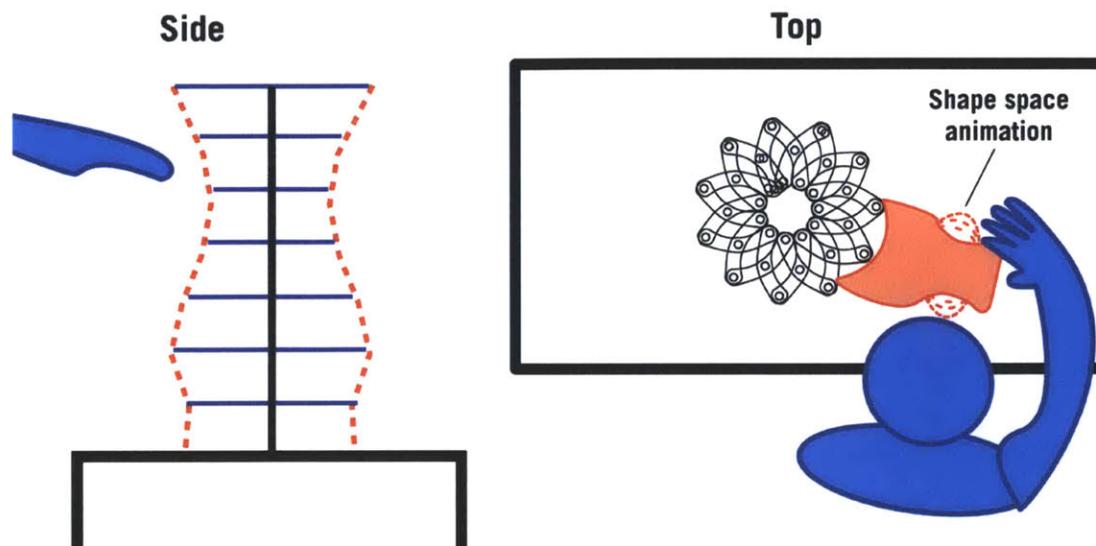
Fig. 20 - Digital reflection beneath Amphorm

System integration

The control software of the system runs on an Apple Mac Mini. All the joints are moved by servos directly connected to an Arduino [Arduino] that receives commands over the Serial port. An internal PID (Proportional Integral Derivative) control system running on the Arduino board ensures that the control signal actuates the servos to the correct position.

Similarly the LED strips described above are all connected to a second Arduino, through an array of MOSFETs (Metal–Oxide–Semiconductor Field-Effect Transistor). The brightness of the LEDs is controlled by the output of a similar PID loop as in the case of the servo control unit. The control loop adjusts the PWM signal to each of the LED stripes dynamically, while the loop itself receives the control signal over serial port from the central unit of the Mac Mini.

The centralized logic for Amphorm is written in C++ using openFrameWorks [OF]. The application runs four threaded functions:

- Serial communication with the servos,
- Serial communication with the LEDs,

50

- Serial communication with the Depth camera,
- Main application logic.

By separating the threads the frame-rate of the application logic and rendering is not limited by blocking events in serial communication with peripheral devices. The digital reflection of Amphorm is rendered on an LCD screen using the openGL [openGL] C++ library.

The computer vision library I used in this project is the OF wrapper of the openCV C++ library. The algorithm looks for the user's hand and head. The flowchart in Appendix A describes the states machine logic of the algorithm.

Interaction

Amphorm is an ambient/calm interface [Ambient, Weiser] in the sense that it lives in the users environment and only responds when the user engages it. Its state is equivalent to its shape, thus user interactions manipulate its shape only.

User interaction is triggered through the proximity of the user and by the user's hand gestures. Since the actuation element was chosen to be a servo, which has a closed loop internal PID control, Amphorm does not respond to direct manipulation.

The following lists interaction scenarios that I have designed for Amphorm.

User Greeting – "Hello world"

Amphorm resembles a vase, thus it is a static shape until a user interacts with it. Earlier in Chapter III, I expanded on how shape displays should possess three fundamental properties for user interactions (Transform, Inform, Conform). Greeting of a user drives the "inform" pillar of this trichotomy. If the user enters the proximity of the interface, Amphorm gently exhibits a motion that creates the perception that the interface is breathing. This greeting motion is important for the user to identify that this interface is one that is able to change its shape.

Today Amphorm is one of the very few interfaces that are able to do this, but in the future we expect many interfaces to be capable of this behavior. When designing Amphorm I was focusing on a problem that may arise from having many of these interfaces next to each other: how do we know which objects we can interact with?
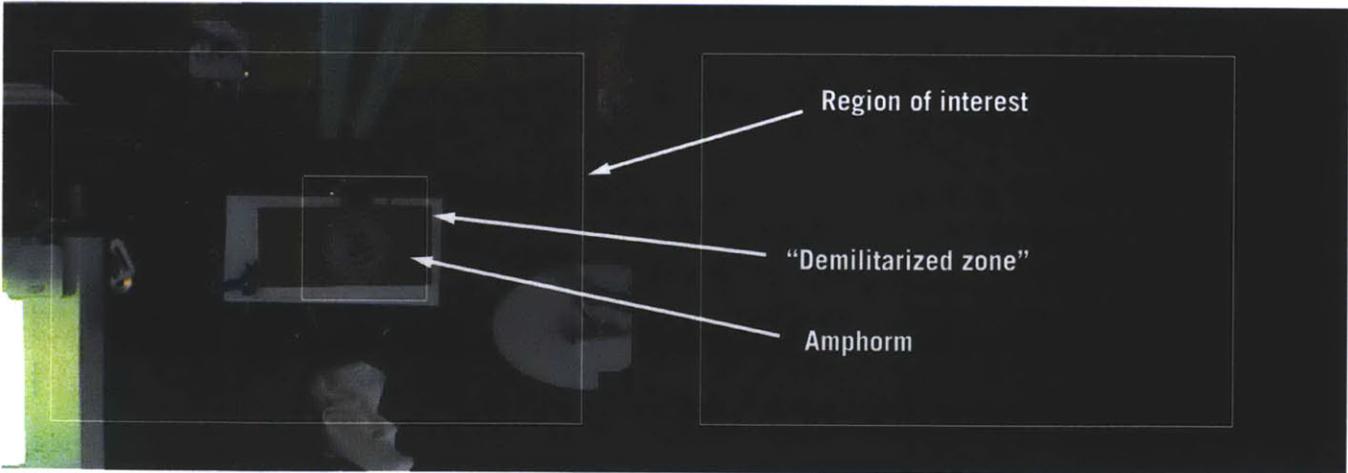
Raw image (left) shows Amphorm and surrounding objects that are thresholded out by height from the tracking image (right)
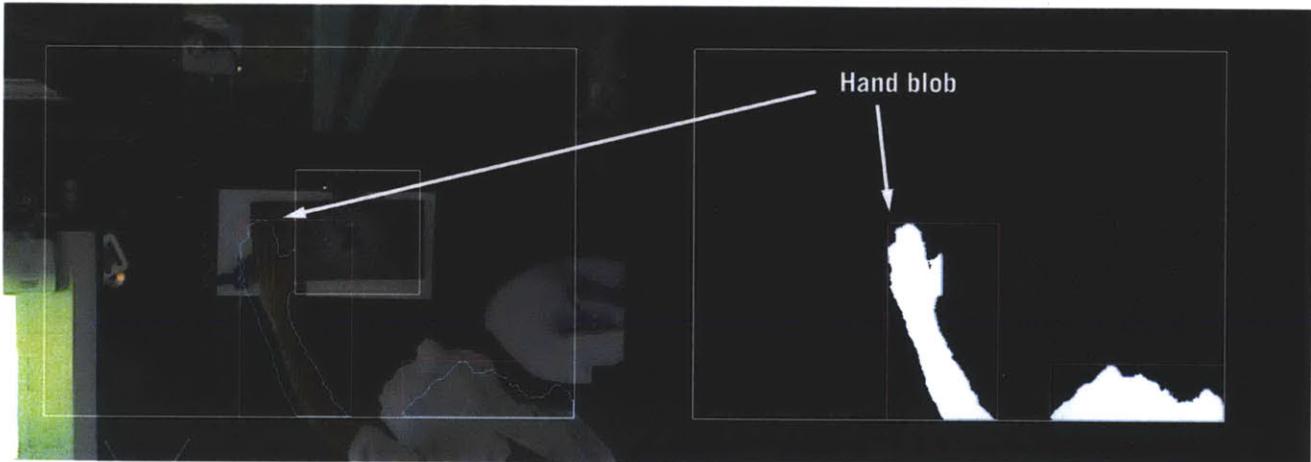
User enters the scene and selects a frustrum. The tracking image (right) shows the recognized blobs of which one was recognized to be hand.
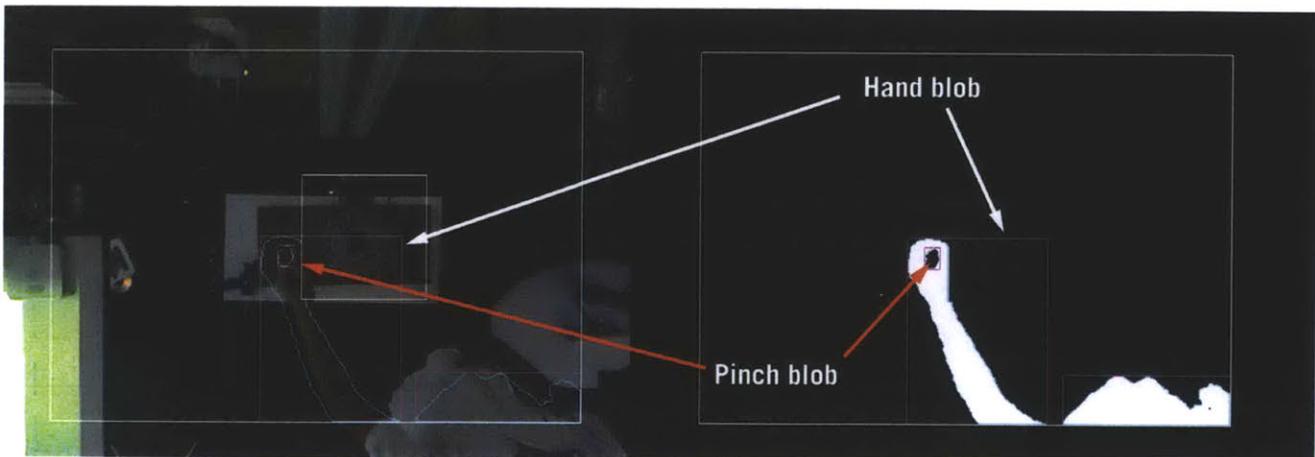
The pinch gesture is recognized by looking for a "blob in a blob" as shown on the both figures.

Fig. 21 - Amphorm's computer vision detailed

Infinite freedom is no freedom at all. If today somebody could walk into Sutherland's Ultimate display [Sutherland] he will not want to interact with the entire room all at once – that would create ambiguity of selection.

Humans have evolved to recognize objects rapidly: we can identify objects even though their color, texture or even through their form. One of the most acknowledge theories related to human object recognition is Biederman's theory called Recognition-by-components [Biederman], which derives that we identify objects by identifying their parts and recognizing the relationship between those components.

Returning to our friend in the Ultimate display: we need to help him navigate through this environment, which is composed of objects that can change their shape. A solution that I implemented through Amphorm was a welcome gesture from the interface's side informing the user that this object is capable of transformation. Once the "hello world" gesture is over the shape returns to its original shape. Ideally in the future every object will "introduce" itself to a particular user only once, thus the user and the object will co-evolve next to each other. I will expand on co-evolution in the future work section of chapter VII.

Selection

Consider a room with three Amphorms resting on a shelf next to each other. Proximity may be an ambiguous term in this scenario and selection gestures may be reflected on each one of the objects, confusing the user, who's intent was to interact with only one of the vases. To resolve this ambiguity engagement has to be connected directly to how humans project their engagement: by turning their head and moving their eyes. Ideally, the Ultimate room will have sensing capabilities that will track the user's head and pupil position. Fused with proximity to the object the room will be able to derive which object the user is intended to interact with.

Since there is only one Amphorm connected to my perceptually equivalent prototype engagement is only measured through proximity of the interface. If the user is close enough he will be able to manipulate the shape of Amphorm.

The selection gesture is a passive one: the only interaction the user needs to do is to raise his hand in proximity of the object. Once the hand is in proximity of Amphorm selection occurs automatically – as the user moves his hand up and down vertically he receives visual feedback

through the LEDs as he switches between the planar actuation elements. The brightness of the LEDs maps to the distance from their hand to the skin of Amphorm – as they move their hand closer the LEDs get brighter.

If the user uses both hands for selection the algorithm averages the hand height of the two hands, though preliminary user studies revealed that the majority of the users intuitively uses only one hand for selection.

Gestural manipulation

The pinch

Once the user has selected the planar kinetic element he wants to control, manipulation is enabled by the user's pinch gesture. The pinch gesture has been used widely, since Wilson et al [Wilson] started using it in one of the early project's featuring the Microsoft Kinect's depth sensing capabilities. The pinch gesture is powerful, since it relates to a very widely used human gesture of picking up a single object, while the detection of the gesture through computer vision algorithms is rather simple and computationally efficient.

Once the user applies the pinch gesture, the state machine of the application records the location of the originating pinch point to determine subsequent manipulation distances. The user actuates the selected joint by moving his hand toward or away from Amphorm, which contracts or expands the joint, respectively. During the pinch gesture selection is locked: even though the user may shift out of the selection plane of the joint, manipulation will affect only the originally selected joint. I created a second modality to manipulate multiple elements through one gesture.

Defining the contour – Carve by example

An earlier project from the Tangible Media Group called Topobo [Topobo] showcased how powerful it is when interfaces can be programmed by demonstration. The project shows how a robot can be taught how to walk without writing a single line of code, instead all the joints record their motion that can be played back.

Inspired by this project I created a second gesture: if the user pinches above Amphorm the system interprets the following motion as the contour of the Amphorm. The rationale behind pinching above the object is that "above the object" is not connected to any of the planar elements, but rather maps to a global operation, affecting all the joints. After pinching above the

object the user engages with all of the joints and as the user moves his hand along the vertical axis of Amphorm the joints "copy" the motion as shown on Fig. 22.
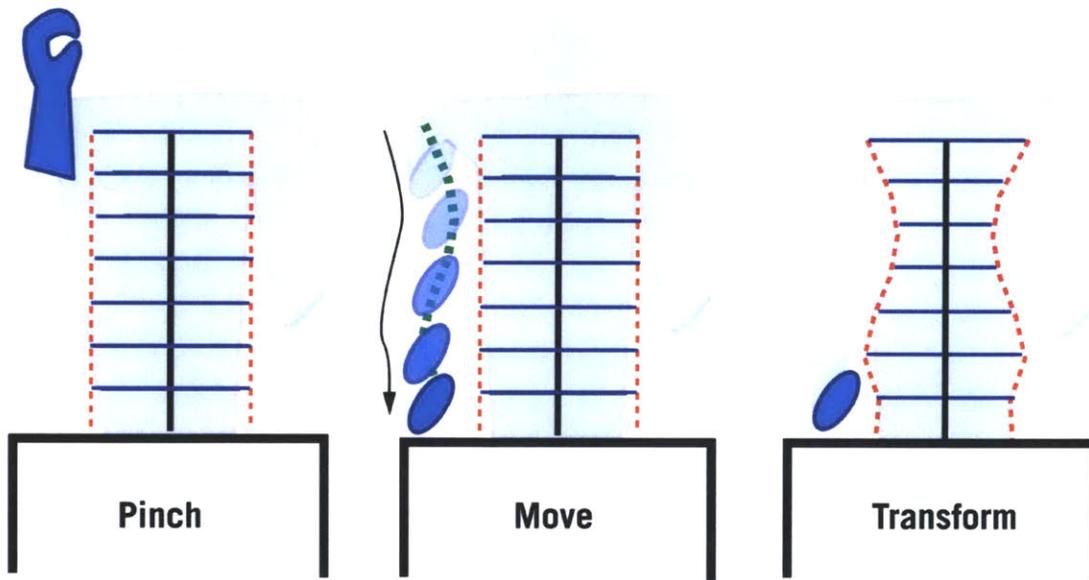
Fig. 22 - Carve by example interaction

GUI

The gestures described above allow users to manipulate the shape of Amphorm in the physical world directly. Gestural interaction performs well for crude, but rapid and expansive form giving, but is not favorable for precise alteration of the shape, unless precise visual feedback is provided through a GUI that is collocated with the manipulation locus, similarly to the T(ether) project [Tether].

Since visual feedback for manipulation is provided by only the digital reflection below the surface, I implemented a purely GUI based approach, which enables users to precisely alter the radii of joints individually.

I implemented the GUI depicted in Fig. 23 on a tablet device [iPad], using OF. The left side of the application shows a dynamically rendered digital model using openGL, while the left side exposes the control points of the contour of Amphorm that control **both** the physical and the digital representation of Amphorm.

55
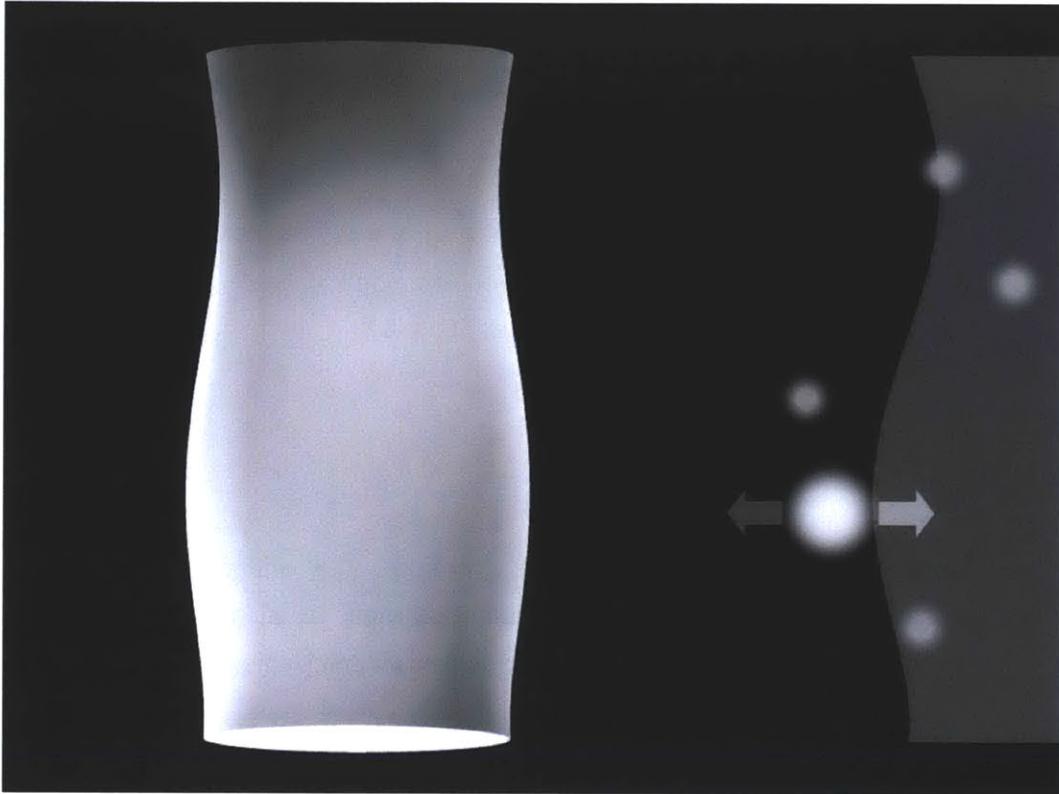
Fig. 23 - GUI allowing precise, individual manipulation of joints

Upon touching any of the control points, indicated by circles, two arrows appear to indicate the directions the control point can be moved. As the control point gets closer to the extremes, the arrow toward the extreme fades away, indicating the maximum/minimum radius.

Many of the users throughout the preliminary user study kept their gaze on the physical model, while manipulating using the GUI. Observing this behavior, I made the connection between the physical and the digital model more prominent: when a user starts manipulating a joint, the LEDs light up on the physical joint, as well as on the digital model on the tablet app.

The synchronization works both ways: if the user manipulates the digital control points, the physical model updates. If the user engages through gestural manipulation with Amphorm, the digital model and the GUI control points update as well.
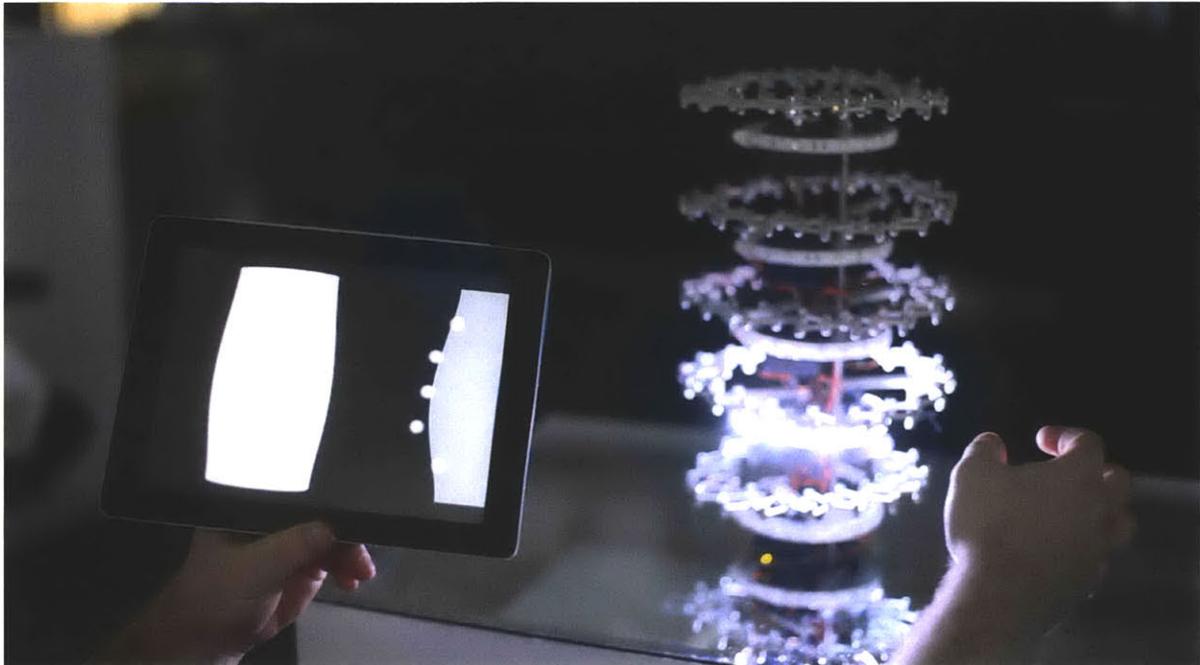
Fig. 24 - The synchronized physical and digital model

The GUI based interaction is an important corner-stone of the project: it exposes the synchronicity between the physical and the digital model that will be extremely important in a future, where every "controllable" surface/material will have a digital model that is kept in synchronization with the physical entity.

Digital reflection

Let's jump back to our friend in the Ultimate room. Assuming that the room has the capabilities to recognize which object he wishes to engage with, he is in proximity of it and tries to manipulate the object. Even if he knows the gestural language that the object responds to he has no feedback of the shape space (the set of achievable shapes for the interface).

One solution to this ambiguity of manipulation would be to provide real-time visual feedback through the manipulation of how far the object may reach in the currently manipulated dimension. In the future this may be resolved by projecting visual feedback straight into the cornea of the user [Parviz] or by wearing less attractive pair of glasses [Piekarski] or holding a display in the hand [Tsang].

Digital Objectification

Ambiguity of selection

Ambiguity of shape space

Ambiguity of manipulation
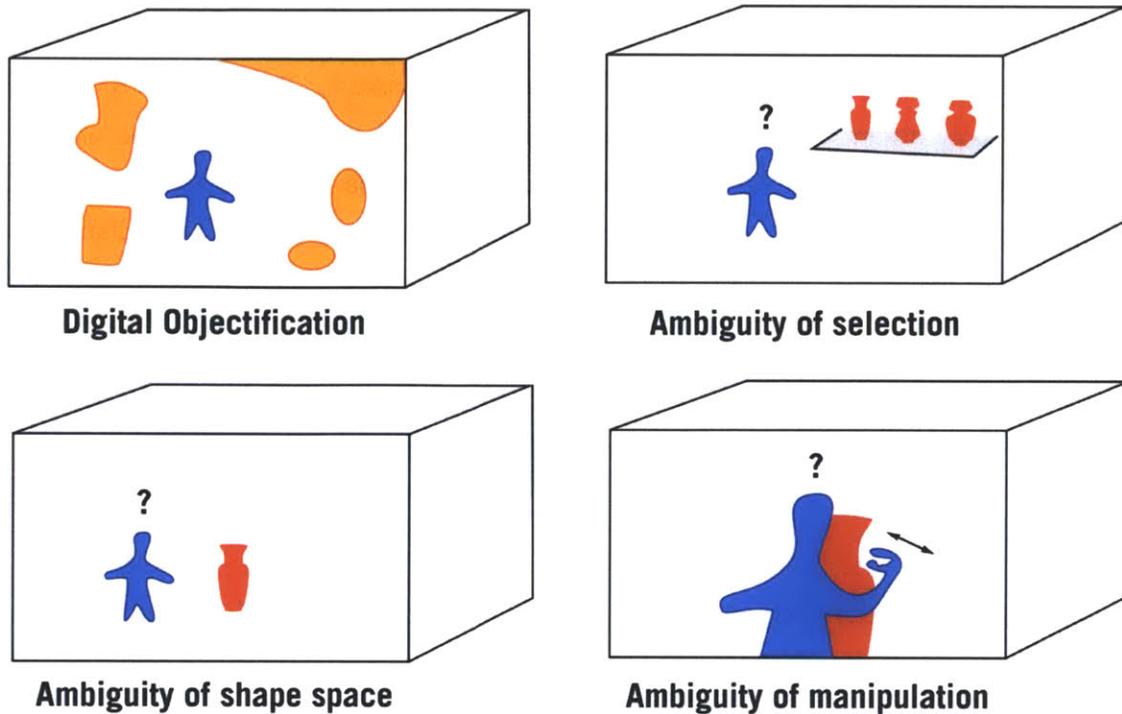
Fig. 25 - Ambiguity in the Ultimate room

Ken Perlin coined the term "Eccescopy" [Perlin] to describe his vision of a future, where digital information is ubiquitously present through a global virtual world that everyone participates in, utilizing a device that does not occlude natural human-to-human interaction. Regardless of what device will ultimately fulfill this vision, the important thought is that collaborative systems that use augmented reality should not block the natural communication channels between humans.

Unfortunately today the technology for unobtrusive viewing of virtual reality does not exist. Amphorm uses a digital reflection through a display that is situated beneath Amphorm, behind a half-silvered mirror. Until the user is in close proximity of the interface with his hand in selection mode, the display is off and the user only sees her reflection in the mirror. Once she engages with Amphorm through the selection gesture the display shows visual feedback aiding the transformation process. The visual feedback consists of an animation that iterates between the extremities of deformation of the selected planar kinetic element. As the user selects different elements, the animation shows the various outcomes of different transformations.

The rationale for the digital reflection is to inform the user of how the shape space can be affected through the selected point of control. Although in this project the number of customizable joints is limited to 5, the logical steps involved creating the digital reflection scales up to any number of joints, since the transformation at any selected point is reduced into 1 degree of freedom.

If the user starts manipulating the selected element, the digital reflection switches to a real-time feedback consisting of three concentric circles centered around Amphorm: the minimum radius for the joint, the current radius of the joint and the maximum radius of the joint. Through these graphics the user understands the extent of control he has over the given element.

References

[**Ambient**] Hiroshi Ishii, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin. 1998. ambientROOM: integrating ambient media with architectural space. In CHI 98 conference summary on Human factors in computing systems (CHI '98). ACM, New York, NY, USA, 173-174.

[**Arduino**] http://Arduino.cc

[**Biederman**] Recognition-by-Components: A Theory of Human Image Understanding by I. Biederman in Psychological Review, 1987, Vol. 94, No. 2,115-147

[**Hoberman**] US Patent #5024031

[**iPad**] http://www.apple.com/ipad/specs/

[**LED**] RGB LED strip – Sparkfun Electronics (COM-10260)

[**Lumen**] Poupyrev, I., Nashida, T., Maruyama, S., Rekimoto, J.,and Y amaji, Y . 2004. Lumen: interactive visual and shape display for calm computing. In *ACM SIGGRAPH 2004 Emerging Technologies* (Los Angeles, California, August 08 - 12, 2004). H. Elliott-Famularo, Ed. SIGGRAPH '04. ACM, New York, NY, 17.

[**OF**] openFrameWorks – www.openframeworks.cc

[**openCV**] http://opencv.willowgarage.com/wiki/

[**openGL**] www.opengl.org/sdk/docs/man/

[**Parviz**] Augmented reality in a contact lens - B. Parviz, IEEE Spectrum, 2009 - http://spectrum.ieee.org/biomedical/bionics/augmented-reality-in-a-contact-lens/0

[**Perlin**] http://blog.kenperlin.com/?s=eccescopy

[**Piekarski**] Piekarski, W., Bruce H. Thomas, "Tinmith-Metro: New Outdoor Techniques for Creating City Models with an Augmented Reality Wearable Computer," Wearable Computers,

IEEE International Symposium, p. 31, Fifth International Symposium on Wearable Computers (ISWC'01), 2001

[SG5010] TowerPro SG5010 Servo -
http://www.towerpro.com.tw/viewitem1.asp?sn=598&area=50&cat=159

[Sutherland] The Ultimate Display, Proceedings of IFIP Congress, pp. 506-508, 1965.

[Tether] – Submission in progress, manuscript available upon request from David Lakatos

[Topobo] - Amanda J. Parkes, Hayes Solos Raffle, and Hiroshi Ishii. 2008. Topobo in the wild: longitudinal evaluations of educators appropriating a tangible interface. In Proceedings of the twenty-sixth annual SIGCHI conference on Human factors in computing systems (CHI '08). ACM, New York, NY, USA, 1129-1138

[Tsang] Tsang, M., George W. Fitzmaurice, Gordon Kurtenbach, Azam Khan, and Bill Buxton. 2002. Boom chameleon: simultaneous capture of 3D viewpoint, voice and gesture annotations on a spatially-aware display. In Proceedings of the 15th annual ACM symposium on User interface software and technology (UIST '02). ACM, New York, NY, USA, 111-120.

[Weiser] The Computer for the 21st Century, Mark Weiser, Scientific American 265, 94-104 (September 1991)

[Wilson] Wilson, A. 2006. Robust computer vision-based detection of pinching for one and two-handed gesture input. In Proceedings of the 19th annual ACM symposium on User interface software and technology (UIST '06). ACM, New York, NY, USA, 255-258.

CHAPTER VI

Material Design for Shape Displays

With the advancement of actuation technologies a number of projects have emerged in the space of shape displays, leveraging integrated arrays of actuators to alter the shape of an artifact. Most of these interfaces arrange the actuators in an ordered array or grid to decrease the complexity of the setup. Currently there are two types of configurations: one with only geometric pins as the observed display element [Lumen] and one with a passive skin on top of the actuators, which serves to interpolate heights between actuator elements [Recompose, Feelex, Volflex]. These current approaches in system design support the construction of the interface, but decreases the natural appeal of the shape output. In this chapter I will outline a system design guideline to help future projects approach designing shape displays, through identifying the key components of shape actuation and how these components work together as a material system.

Shape displays communicate to the user primarily through their shape, by altering their affordance dynamically. Recently we outlined in our paper [RA] how future shape changing materials will take a homogeneous approach to shape changing: these interfaces will be made out of one material that can internally change its structure on an atomic scale. However, until the technological advancements reach that level we have to take the heterogeneous approach, in which actuation and shape output are separated parts of the artifact. We call these interfaces perceptually equivalent to Radical Atoms because they are changing the shape of an object dynamically, but the achievable "shape space" (versatility of their shape rendering) is limited and bespoke to a specific scenario.

Even though it may take another 100 years to implement atomic-scale restructuring, we can explore a more intelligent approach to controlling points on a surface, using actuators and a variety of materials. I propose an approach that is inspired by anatomy. Instead of converting points of active control to a changing surface and using a passive material cover, we use a three-tier system, where each tier focuses on a different role.

Skeleton-muscle-skin material system

The first tier is called the skeleton; its function is to mediate the changes between the synchronized digital model and the surface by converting digital signals to mechanical actuation. Typically one would use pre-made actuator arrays that are rigid. The actuator choice characterizes achievable shape space (the shapes that can be displayed on the interface), thus in the design process this has to be defined first.
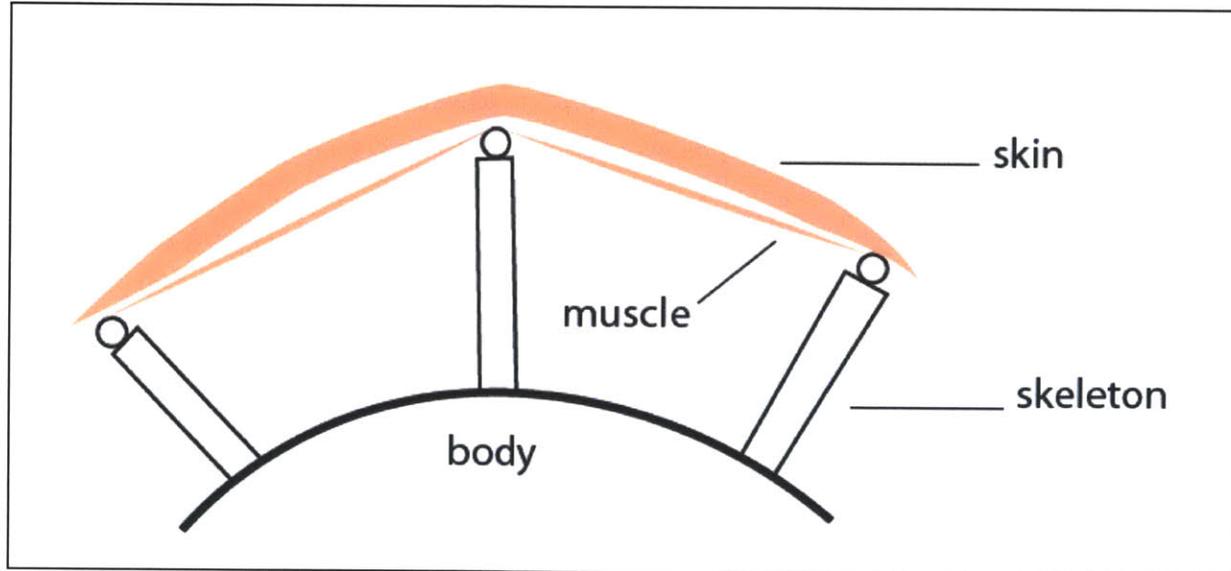
Fig. 26 - The Three tier Skeleton-Muscle-Skin system

The second tier is called the muscle; its purpose is to mediate between the rigid actuation and the soft skin. In order to support the achievable shapes it's not a full continuous section, rather a series of discrete flexible connections that mechanically tie the points of actuation on the skeleton with the materials that the skin is made out of.

The third tier is the skin; the material that communicates visually to the user. Since the muscle mediates between the skin and the skeleton the skin is decoupled from the actuation to ensure dynamic movements, responding to the actuation. The material is the softest of the three tiers and passively follows the muscle to "render" the shape.

Although this trichotomy splits the artifact into three separate layers, assembled they create a material system [Oxman] that is suited to render a defined shape space naturally. In this context "naturally" may refer to the aesthetic appearance of the rendered shape being closer to a continuous surface than to a material stretched between points of control.

Material selection

Until we get to the ultimate material that can fulfill all of the proposed functionality, we need to select materials for every individual application we design. Following the outlined three tiers, in continuing future work I would like to compile a library of material selections that is similar to the Ashby-charts [Ashby]. Criteria for material selection thus will be directly coupled with interaction

design constraints, thus if the interaction technique is selected the material trio for the skeleton-muscle-skin trio will be yielded.

References

[Ashby] Ashby, Michael (1999). Materials Selection in Mechanical Design (3rd edition ed.). Burlington, Massachusetts: Butterworth-Heinemann. ISBN 0-7506-4357-9.

[Feelex] Iwata, H., Yano, H., Nakaizumi, F., and Kawamura, R. 2001. Project FEELEX: adding haptic surface to graphics. In Proceedings of the 28th Annual Conference on Computer Graphics and interactive Techniques SIGGRAPH '01. ACM, New York, NY, 469-476.

[Lumen] Poupyrev, I., Nashida, T., Maruyama, S., Rekimoto, J., and Yamaji, Y . 2004. Lumen: interactive visual and shape display for calm computing. In *ACM SIGGRAPH 2004 Emerging Technologies* (Los Angeles, California, August 08 - 12, 2004). H. Elliott-Famularo, Ed. SIGGRAPH '04. ACM, New York, NY, 17.

[Oxman] Oxman, N. and J. L. Rosenberg. Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators, International Journal of Architectural Computing (IJAC). 2007; 5(1): 26-44.

[RA] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. *interactions* 19, 1 (January 2012), 38-51.

[Recompose] Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5D shape display. In *Proceedings of the 24th annual ACM symposium on User interface software and technology* (UIST '11). ACM, New York, NY, USA, 541-548.

[Volflex] Iwata, H., Y ano, H., and Ono, N. 2005. Volflex. In *ACM SIGGRAPH 2005 Emerging technologies* (SIGGRAPH '05), Donna Cox (Ed.). ACM, New York, NY, USA, 2005, Article 31

CHAPTER VII

Evaluation

While a formal user study has not been completed on Amphorm, the interaction techniques has been observed through the 2012 Spring Sponsor Meeting of the Media Lab from April 23rd-25th 2012 which received more than 500 people over the course of the event.

During the event users approached Amphorm, where they were given a very short introduction to the project, while showing the pinch gesture for individual joint manipulation as well as multiple joint manipulation (carve-by-example), through the contour definition gesture. After instructing the users about the gestures for manipulation and for selection they were introduced to the tablet interface and they were shown how to manipulate the shape of Amphorm through the GUI.

Fig. 27 - Amphorm at the MIT Media Lab's Sponsor Meeting, April 24th 2012 (User: Marvin Minsky)

After the users have received the instructions, they were left alone to explore Amphorm.

User observation

After trying out the interaction techniques most of the participants used the contour defining gesture to define the shape "with a broad brush strokes". They said that the gesture was "very immediate" and "communicated intent in a natural way", but it was "hard to correct and be precise", when using the single manipulation gesture. Most of the users tried to carve a rough shapes through the gestures to give it the desired look and then used the higher precision GUI based interaction to refine the final form of Amphorm.

Most of the users reported that the pinch gesture was very easy to learn, but they would not have thought of using it, if I would not have instructed them. Although the pinching is one of the most commonly used gestures, different users showed the gesture in different ways. Fig. 28 depicts the two most common ways that users pinched. Notice that the pinch on the left picture exposes the background, while the one on the right does not.
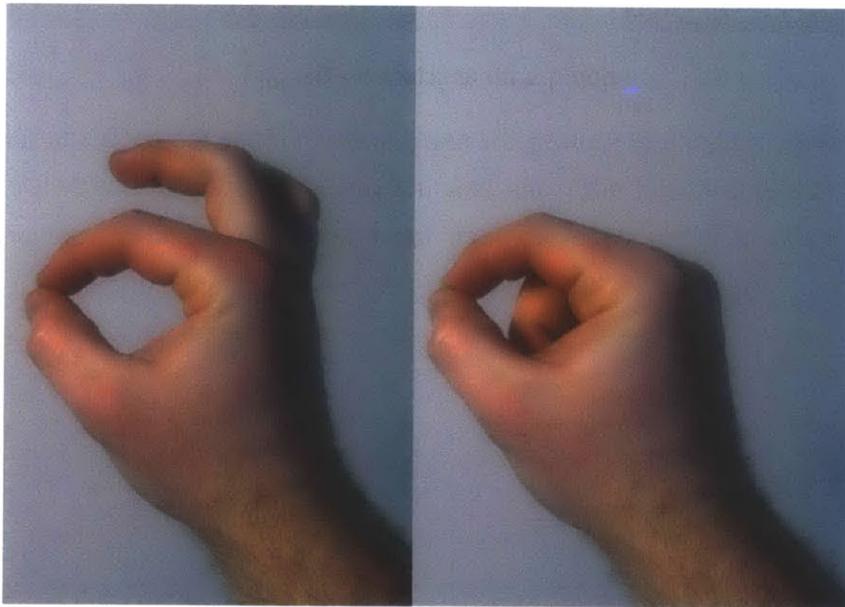
Fig. 28 - Variations on a pinch

This slight difference does not seem relevant when we gesture to another human, but the initial algorithm I implemented for gesture recognition was using the see-through background of the gesture to recognize a pinch. After this initial user observation the tracking algorithm was improved, to slice the depth buffer of the camera starting from the top point of the hand, in order to recognize a pinch even if fingers are occluding the background.

Most of the users reported that the shadow simulation "could be very helpful" in case of a higher precision model, but they would not have understood how it works if not instructed before. Additionally the visualization became distracting when multiple people started interacting with Amphorm, since it was jumping between animations back and forth between the elements selected by the different users.

For this demonstration Amphorm did not have its skin on, because of problems with servo actuation. This gave a chance to evaluate if users can visually interpolate between the joints to recognize the intended shape of Amphorm. The majority of the users were able to infer the shape, but they missed the skin: "I want to see the chassis, not the motor". Ultimately it was clear that a skin is not necessary for users to give form to Amphorm, but it is essential to evaluate the aesthetic product of the form giving process.

One of the users suggested that the mechanism would be a great musical instrument, where strings would make up the skin of Amphorm and as the user would changed the radius of each planar element the pitch of the strings would change.

Throughout the demonstration a handful of users expressed a recurring remark: their desire to own objects that can change their shape over time, responding to user input or automatically. Each of these used the term "own", which suggests that they are ready to allow these objects to enter their home.

To summarize: users were able to use Amphorm in the intended operation mode after a short explanation. Most users reported the gestures to be easy to learn, but they would not be able to discover it. Almost all the users said that the skin is not a necessity for operation, but they are interested in the final form, not the exposed joints.

CHAPTER VIII

Discussion and Future Directions

"Predictions can be very difficult, especially about the future."

(Niels Bohr)

I am deeply interested in the way humans interact with shapes. We have thousands of years of history that is paved by the evolution of tools and processes that helped us shape our environment the way we wanted it to look and feel. With recent successes in materials sciences and nanotechnology we are getting close to a point in time, when we will have materials that can change their shape dynamically in sync with a digital model.

The thesis dives into a practical problem that will arise as soon as this material will be available: how can we interact with a material that can change its shape freely?

In this thesis I described Amphorm, an interface that is an early prototype of the dynamic interfaces I outlined. I started off by deducing the design rationale of the interface, stating why I think it is important to start from the interaction design viewpoint.

A detailed explanation followed about Radical Atoms – our vision of the highly malleable material that can change its shape rapidly, through different scales. I listed design criteria that we need to take into consideration, when designing these interfaces, namely the three pillars of Conform-Inform-Transform.

I surveyed an array of projects that are closely related to my work currently and assessed that with the current technology at hand we do not have the capabilities to build an interface that can transform into arbitrary shapes. I proposed a viable direction to start experimenting with interaction techniques with Radical Atoms, which I named *perceptually equivalent* interfaces.

To backup my claim of perceptually equivalent interfaces, I implemented an example, which I named Amphorm, which serves as the core of my thesis. I expanded in detail about the design rationale behind the interface and the decisions I made during the construction of it.

When designing the skeleton and the skin of my interface I faced interesting decisions that I encapsulated in the discussion about the skeleton-muscle-skin three-tier system.

Most importantly this is an interaction design centered thesis: I gave detailed description about the interaction modalities of Amphorm and how I think it can be generalized to future shape displays that we may see in the future.

Future Directions

I discussed in depth interaction techniques with Amphorm and how it relates to the vision of Radical Atoms. However Amphorm is a very limited example and being in control of matter will pose further problems that I will address in this section.

Scale-free transformation

Amphorm is an example of an interface, which can transform its shape on scale that relates to human hand size, thus making the shape very accessible for transformation. However if we consider the Ultimate room example once more we may want to rearrange on every imaginable scale starting from the crystal structure of solids to the architectural surfaces of the room. It seems obvious that these scales cannot be manipulated with the same interface, since nano-scale changes affect physical properties, while alterations made at a higher scale will change the structural relations between elements.

Even worse different users will expect different interfaces. A scientist may wish to alter the cellular structure of a region, to test whether graphene or graphane is a better conductor under varying circumstances, while a child may want to change the color of a flower, depending on which hour of the day it is.

Let's assume there are different application modalities depending on what scale you want to work at. Where do you switch context? Where is the boundary between changes in material property and structural properties?

Coevolution

In a world, where dynamic materials exist we need understand, how dynamic objects work. Thierry Bardini in his book called "Bootstrapping" [Bardini] explains how coevolution of humans and their tools is a balancing act between human needs and tools that are invented to solve those needs. The book's reasoning reaches back to Maurice-Merleau Ponty's thinking about intentionality [Ponty] – how we respond to objects and how we learn from them through "preconscious aspects", which is very similar to Gibson's way of defining affordances [Gibson]. But when objects will be able to shift their shape dynamically, the concept of affordances and thus learning from objects in the Bardini-sense breaks down.

In order to learn from objects, they have to evolve with users. Adaptability is not enough in this case anymore, since the user has to be informed of the interaction, **before** the interaction

actually begins (and adaptability by definition follows the interaction). In my opinion coevolution means that objects will evolve to their functions gradually. E.g. "learning by example" is one of the most powerful machine learning algorithms that for example the Topobo project has demonstrated.

Role Division of Interaction with Synchronized Entities

Amphorm demonstrated how the physical and the digital model of and object can be synchronized and manipulated in both worlds. Interaction in the physical world with dual-citizens, like Amphorm without collocated visual feedback like HMDs (Head Mounted Displays), Goggles or a Spatially Aware Displays [Fitzmaurice] can be cumbersome and maybe even more importantly the precision is limited.

Because of the limitation in precision, gestures and tangible tools are great at providing wide brush strokes for form-giving, similarly, how clay is manipulated first roughly, by first gathering lumps of clay that consist for the mass of an object and than shaping that mass with ever increasing precision, until the desired shape has been achieved. Interactions in the **physical space** are very well suited for the first part of this process, where **rapid, and expansive iterations change large part of the model.** The **digital realm provides** a great platform for the more "cold minded" part of the form giving process, where **little, precise alterations on a very defined set of control points are needed.**

References

[**Bardini**] Bootstrapping: Douglas Engelbart, Coevolution, and the Origins of Personal Computing by Thierry Bardini, ISBN: 9780804737234

[**Fitzmaurice**] Fitzmaurice, G.W. (1993) Situated Information Spaces and Spatially Aware Palmtop Computers. Communications of the ACM, 36(7), 38-49.

[**Gibson**] James J. Gibson (1977), The Theory of Affordances. In Perceiving, Acting, and Knowing, Eds. Robert Shaw and John Bransford, ISBN 0-470-99014-7.

[**Ponty**] Merleau-Ponty, Maurice. 2002. Phenomenology of Perception. Trans. C Smith. 2nd ed. London and New York: Routledge, May 3
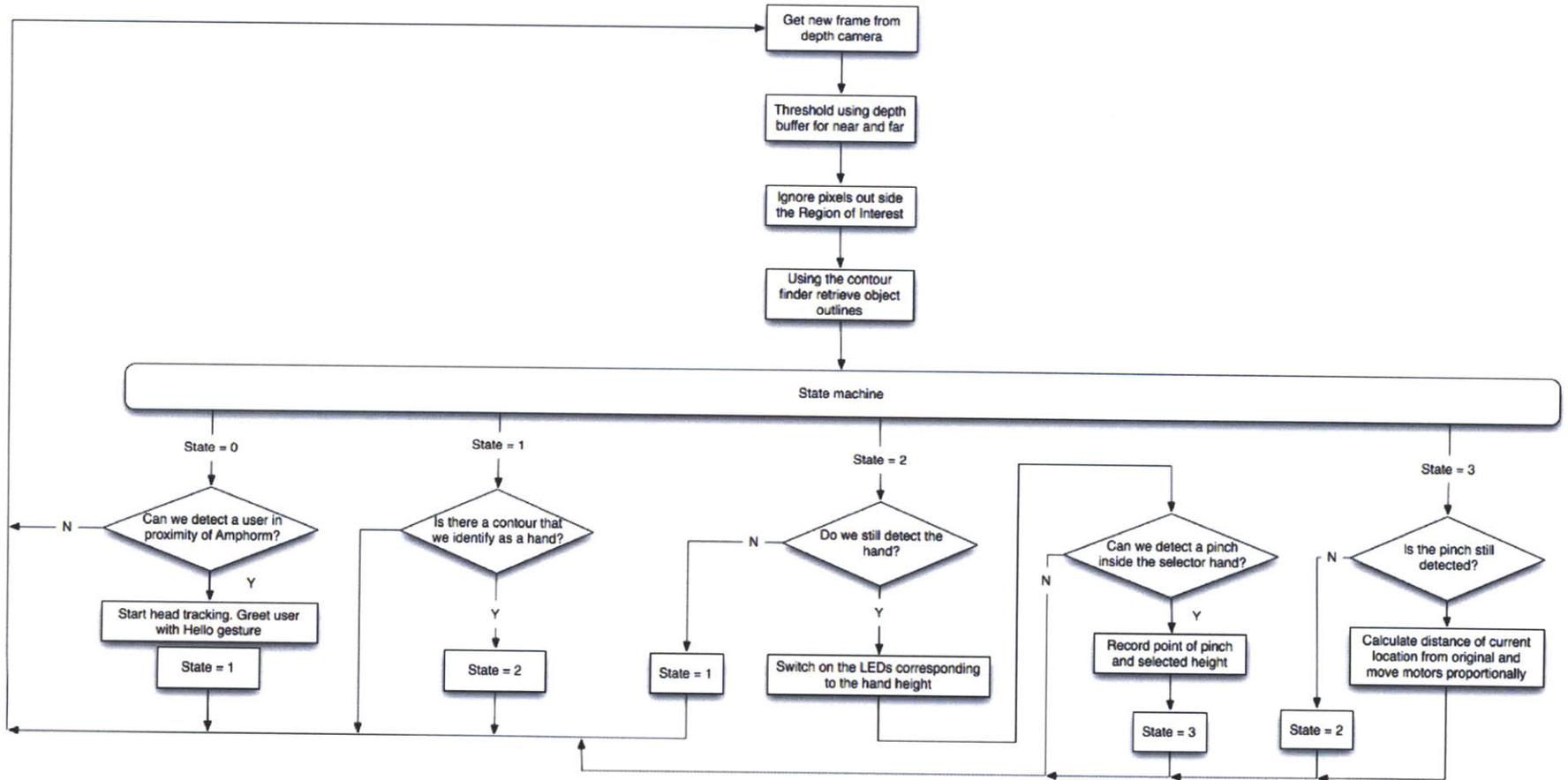
CHAPTER IX

Conclusion

My thesis work presented Amphorm: a dual-citizen of the physical and the virtual worlds, having representations in both, which are constantly synchronized with each other. The project explored the greater vision of Radical Atoms – a highly malleable computationally alterable material that stays always in synchronization with a digital model – in practice, by implementing a perceptually equivalent entity to this hypothetical material. Amphorm resembles a familiar object: a vase that humans have been shaping for thousands of years. I implemented and tested a number of interaction techniques to give form to Amphorm. In the physical world, form giving was achieved through free hand gestures, while in the digital world a tablet device provided access to the digital model. The project explored how the role division of interaction breaks down between digital and physical interaction modalities. Although a formal user study has not been completed, the project has been demonstrated at an event, where hundreds of users have interacted with Amphorm, providing positive feedback. In order to present true shape output I designed and casted two skin prototypes that interpolate between the unique kinetic joints I have designed and constructed to change the radius of Amphorm's cylindrical structure. Based on the current design, I proposed a three-tier system consisting of the skeleton, the muscle and the skin for future shape display design processes.

The materials described by the Radical Atoms vision, do not exist, yet. These materials will redefine the connection between humans and materials, since we will be able to control their physical properties dynamically, through their digital representations. In order to give form to these materials, we will need a language that will be part physical and part digital. I believe that even without the existence of the aforementioned materials, this language can be discovered, which will provide humans unprecedented freedom to alter their environment dynamically.

Appendix A – Flowchart of the State machine

Get new frame from depth camera

↓

Threshold using depth buffer for near and far

↓

Ignore pixels out side the Region of Interest

↓

Using the contour finder retrieve object outlines

↓

State machine

State = 0

◇ Can we detect a user in proximity of Amphorm?

— N →

Y ↓

Start head tracking. Greet user with Hello gesture

State = 1

State = 1

◇ Is there a contour that we identify as a hand?

Y ↓

State = 2

State = 1

State = 2

◇ Do we still detect the hand?

— N →

Y ↓

Switch on the LEDs corresponding to the hand height

◇ Can we detect a pinch inside the selector hand?

N

Y ↓

Record point of pinch and selected height

State = 3

State = 3

◇ Is the pinch still detected?

— N →

Calculate distance of current location from original and move motors proportionally

State = 2

Appendix B – From Graphical User Interfaces to Radical Atoms

GUI PAINTED BITS   TUI TANGIBLE BITS   RADICAL ATOMS
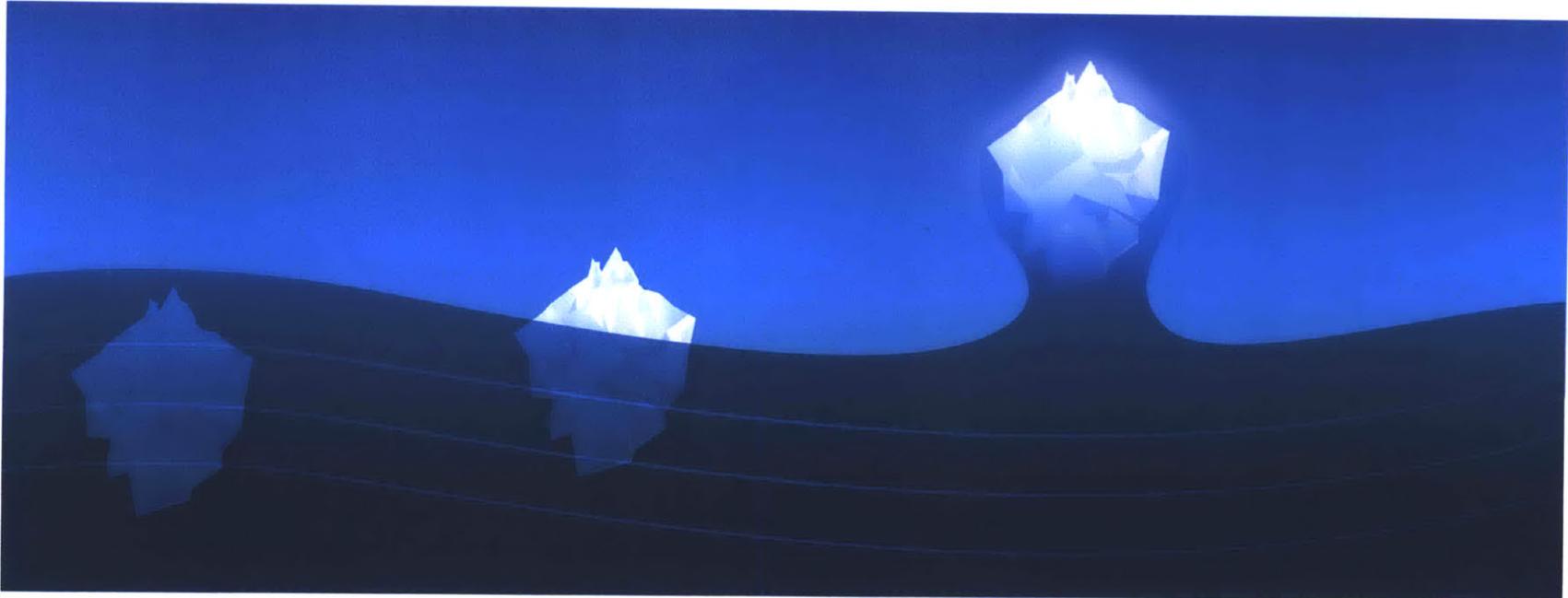
A Graphical User Interfaces only let users see digital information through a screen, as if looking through a surface of the water. We interact with the forms below through remote controls such as a mouse, a keyboard or a touch screen.

A Tangible User Interface is like an iceberg: there is a portion of the digital that emerges beyond the surface of the water - into the physical realm - that acts as physical manifestations of computation, allowing us to directly interact with the 'tip of the iceberg.'

Radical Atoms is our vision for the future of interaction with hypothetical dynamic materials, in which all digital information has physical manifestation so that we can interact directly with it - as if the iceberg had risen from the depths to reveal its sunken mass.