1. Introduction

1.1 Motivation

1.1.1 Inspiration

After growing up with frisbees, Barbie dolls, and Tupperware, it's especially hard to imagine that before Bakelite in the early 1900s, we had only natural materials to fashion into the stuff of our everyday lives. The new synthetics changed our material life fundamentally — not only in a practical way, through the near ubiquity of their use; but also in an ideological way, with the revelation that we could actually *create new materials* with qualities unlike any natural substance.

Since Bakelite, countless new synthetic materials have been invented, but most remain popularly undistinguished. Polyethylenes, acrylics, silicones, and so many other appreciably different substances are commonly piled into the same big bin — *plastic*. As such, plastic seems to be infinitely mutable. It can be silky-smooth, pliable or squishy, hard, durable, soft and fuzzy, shiny or matte, colored, patterned, textured, or clear. But once it's fashioned into a particular shape, appearance, and material consistency, those qualities largely remain as prescribed, static and fixed.

What if a plastic substrate could be instructed to change? Materials research is beginning to envision miniature, embedded means of sensing, of switching a material's visual, tactual, and bulk mechanical properties and of actuating its movement. With the eventual fusion of computational algorithms and this fabricated, malleable, programmable material, we would expect another huge practical and philosophical transformation in our lives. The advent of such a *computational plastic* would certainly offer an intriguing newness to any *thing* comprised of it; imagine clay that could be sculpted then instructed to look and feel like either powder coat or patinaed bronze — the implications of such things are still unknowable.

We can think of these computational plastics as a broad class of technologies, each a mixture of programmable behavior and both active and inert encapsulating matter. At the boundaries of their definition are two extremes: one is a completely autonomous computational substrate; the other is a non-material composite of simulation and perfectly mimetic display. In anticipation of the manufacture of the matter-part (and the means of its address and instruction), we can begin to experiment at the more accessible extreme of this alloy's spectrum. From an amalgam of computation and innovative display technologies, both visual and haptic, we might prototype a computational plastic, and begin to contemplate the properties, usefulness, and broader implication of its eventual physical instantiation.

Initially, deploying such a material in interactive computational systems would bring simulation out into the material world, and begin allowing us to apprehend and manipulate purely simulated objects almost as comfortably, skillfully, and artfully as we do real ones. It would also provide designers of interactive systems with the freedom to *embody* purely poetic meaning and idiosyncratic physics in the domain of the physically-based, thus opening up rich new territory for interaction design and artistic experimentation.

1.1.2 Criteria

A good prototype of computational plastic will have several basic properties: it must allow us to shape a surface freely, must admit programmable appearance and behavior, must be available to the senses just like a physical material, and when fashioned into an object, must offer some unique physical affordances for use. The first nontrivial goal of any prototype would be to nominally demonstrate these properties.

The next broad goal would likely be to represent something familiar, simple, and comparable to a physical instantiation. Many past inventions travelled this route to our conceptual apprehension and acceptance; the first celluloid objects imitated the appearance of tortoise-shell, amber, linens and wood, while still being marketed as something that *could* assume innumerable and unimagined forms and colors. In this context, the operative measures of a prototype's success are, generally, whether the eyes are convinced, and whether touch confirms the reality-check.

1.2 Challenge & merits

How might we fulfill these basic prescriptions using computation and display? This question defines the broad engineering challenge of our work. We have approached it using haptic and holographic displays with co-located output, and computational modeling that prescribes its multimodal behavior. Still infant technologies themselves, haptic and holographic displays pose many engineering challenges of their own. Yet, since its earliest demonstration, holography has maintained the quiet promise of striking visual realism. And, less popularly known, haptic displays that stimulate our skin, muscle, and joint senses promise realistic and direct bodily interaction with computational models. Both of these technologies are still developing, and with them comes the potential for more vividly mimetic display.

Why is a purely non-material prototype important to build? There are several answers to this question. First and quite simply, there will always remain something new to imagine and evoke, beyond the boundaries of what can be physically assembled. In that certainty, art and simulation will long have plenty to do. Second, and practically speaking, time and physical resources are spent in fabrication; much of design and experimentation will likely continue to proceed freely and economically in a purely computational environment. Given the first two, the third answer has to do with the need to manifest simulation in our own physical space. During the last two decades, an attempt to qualify our subjective impression of being part of a "virtual" simulated environment grew into the general notion of *presence.* While it's generally agreed that this impression is desirable, it remains hard to qualify — and for *not only* this reason, it is difficult to achieve. Though no evidence squarely shows that the impression of presence affects performance, it may be useful when the understanding of our own body's relationship or interaction with a simulation is important. So while it remains hard for us to wholly tele-occupy a remote space, we may have better success making the simulation present in ours.

1.3 Approach

1.3.1 Three demonstrations

In a suite of three demonstrations described in this dissertation, we combine various holographic displays with a force feedback device, drive them with computational models that together represent the multimodal look and feel of their spatially co-located and metrically-registered output. Through these experiments, we work progressively toward demonstrating all of the previously stated properties that a computational plastic should exhibit.

Each demonstration, *Touch*, *Lathe*, and *Poke*, is named for the primitive functional affordance it offers. In *Touch*, we present static holographic images of simple geometry, reconstructed in front of the hologram plane (in the viewer's space), and precisely co-located with a force model of the same geometry. A participant can visually inspect the holographic image through a wide angle of view while manually inspecting the force model using a hand-held interface. In *Lathe*, we again display holo-haptic images of simple geometry, this time allowing those images to be reshaped by haptic interaction in a dynamic but constrained manner. Finally in *Poke*, we present a holo-haptic image that permits arbitrary reshaping of its reconstructed surface.

Given our haptic and holographic technological underpinnings, we will describe these various implementations from a design and engineering point of view — in fact, the details and rigors of making such systems work comprise the bulk of the effort. In the strictest sense, by relying on such fledgling technologies, *Touch*, *Lathe*, and *Poke* all teeter on the edge of being convincing prototypes of computational plastic. They suffer many visual and haptic display limitations and also exhibit lag due to the enormous computational burden of hologram computation. But, by rendering three-dimensional computational models into physical space that we can literally see, touch, lathe, and poke, this work gives us a solid early glimpse of this new idea and marks a path for future and better approaches.

1.4 Organization

This dissertation begins in chapter 2 by discussing fundamental design issues for spatial interactive systems using novel means of input and display. We first review current thought about how vision (independently and in concert with other sensory modalities) informs both perception and action. We conclude the chapter by proposing a new behavior-based classification of interactive space, useful for designing systems that employ spatial display and bodily interaction. Chapter 3 offers a sampling of many and diverse research efforts related by the desire to conjoin eyes and hands at the simulation interface, and outlines the requirements for an idealized holo-haptic approach.

We continue in chapter 4 by describing important developments in the field of display holography and providing an overview of its fundamentals. We identify basic challenges to interactive display using electro-holography, and describe some existing techniques to address them. We introduce an important new technique that allows us to arbitrarily modify the image by making only local changes in the computed holographic fringe pattern (rather than completely regenerating it). Next, we motivate and describe the implementation and performance of the systems *Touch*, *Lathe*, and *Poke* in chapters 5, 6, and 7, respectively. These systems combine computational force models with the holographic techniques described in chapter 4, and address many of the visual-haptic workspace design considerations identified in chapters 2 and 3.

In chapter 8, we identify and discuss some easy and hard problems involved in producing the "perfectly mimetic" display needed for a simulation to qualify as a bona fide computational plastic. We conclude by summarizing the research contributions represented in this work, describing the overall strengths and weaknesses of our current demonstrations, and indicate directions of future research.