Print Preview for the Fabrication of Physical Objects

by

David Carr

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Abstract

This work proposes a new class of design and fabrication interfaces for digitally created objects, which the author terms augmented fabrication machines. By enhancing traditional fabrication machines with rich new input and output capabilities, augmented fabrication machines have the potential to ease design iteration, facilitate the incorporation of outside physical objects, and increase the overall transparency of the design and fabrication process—all of which, the author contends, will encourage and improve individuals' use of fabrication technologies for the creation of personal objects.

In addition to introducing the concept of augmented fabrication machines, the second major contribution of this work is its development of Part Preview. Part Preview, in essence, is an augmented fabrication machine application that improves accuracy and usability by incorporating all relevant digital and physical factors such as the toolpath, raw material stock, and machine environment to generate an accurate "preview" of the final object before fabrication takes place.

After reviewing modern digital fabrication technology and outlining the traditional digital object design and fabrication workflow, this work identifies several areas for improvement. The author then discuss two earlier augmented fabrication machine projects, Eat Your Face and CopyCAD, aimed at addressing these shortcomings. This work then turns to a comprehensive discussion of Part Preview, examining its underlying principles and technology in detail. Part Preview's improvements to the functionality and usability of fabrication machines are quantified by way of a user study, which both qualitatively and quantitatively compares processes incorporating Part Preview to the existing design and fabrication workflow.

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Chapter 1

Introduction

The work described in this document is, on its surface, research in the space of digital object design and computer controlled fabrication. The author believes that this work also fits into a broader project, however: one which explores the evolution of human expression in a world where all human activity is increasingly digitized.

In the internet age, many forms of personal expression have become inextricably interwoven with the digital space. Love letters are no longer handwritten and delivered by the postman, but are instead formed on the keyboard and whisked across one of many digital networks to their intended recipient. Increasingly, we share our opinions on politics or the state of the environment not via newspaper editorial but instead on our internet blog. And finally, our most public-facing identities have become our pictures, quotes, and relationship statuses posted on a plurality of social networking hubs.

The de facto consensus on our increasing digitization appears to be a positive one; in general, we seem to want more of it rather than less. The benefits to digitizing our methods of expression–broader reach, greater convenience, and the ability to network and collaborate– have proven to be powerful transformational forces. Interestingly, while intimate communication, public sharing of opinion, and even personal identity have mostly crossed the chasm into the digital realm, the methods by which we create *physical* objects for personal use

and expression largely remain bastions of the analog world. Most objects created for this purpose, especially the more personal ones, are crafted using manual processes that require significant investment of time and resources to acquire. Yet unfortunately, today the prevailing social and economic forces are such that fewer and fewer individuals have the ability to or are willing to dedicate the effort and means necessary to acquire these skills. As a result, as individuals we are less able than ever before to create physical objects for any purpose.

Harnessing the power of digital fabrication has the potential to reverse this trend—to empower individuals to design and create physical objects for their personal use with relative ease. However, while small groups such as the "Maker" community are utilizing digital fabrication technology to design and create objects to scratch every imaginable personal itch, penetration into the mainstream remains small. I believe that the reason for the low levels of personal expression through digital fabrication thus far is two-fold: firstly, the physical machines and underlying technologies for digital fabrication are still somewhat expensive and thus have limited accessibility to the broader public. Secondly, the software and platforms used to design objects digitally are fundamentally mismatched from the natural processes used by humans to conceive physical forms. While both of these problems are of significance, the fabrication machine accessibility problem is slowly yielding to the economies of scale, but the design problem shows little sign of budging.

To address the barriers impeding the design of new objects and their ultimate fabrication via digital means, this thesis proposes a new class of design and fabrication interfaces for digitally created objects, which I call augmented fabrication machines. By augmenting traditional fabrication machines with rich new input and output devices and a new layer of intelligence (computation), augmented fabrication machines facilitate a more natural and intuitive design experience, one with low barriers to iteration and experimentation and a higher degree of usability than enjoyed by traditional methods. Two examples of augmented fabrication machines, discussed in detail later in this work, serve to illustrate the power of this idea. CopyCAD is an application that augments traditional fabrication machines by allowing users to fabricate new objects by "copying" existing physical objects and modifying

their design, all within the machine environment. Part Preview, the project at the core of this work, incorporates all of the relevant digital and physical precursors (including the toolpath, raw material stock, and entire machine environment) to generate an accurate "preview" of the final object before fabrication takes place. Augmented fabrication machines like these allow users to more accurately visualize the fabrication process and results and to harness the power of the machine to aid not only in the execution of a design, but also in the design process itself.

It is my belief that by reconciling the current methods of digital fabrication with the design processes that we as humans more naturally follow, augmented fabrication machines can help to free digital fabrication from its status solely as a tool of the industrial world. By utilizing a more human-centric fabrication process, augmented fabrication machines promote the use of fabrication technologies on a more individual basis, and hence stand poised to facilitate personal expression and creativity through digital fabrication.

1.1 Thesis Overview

Chapter 1: Introduction—you're reading it.

Chapter 2: Background begins by presenting an overview of both traditional and modern digital digital fabrication machines. The essential elements of these machines are presented and then fleshed out using examples from modern fabrication machines. The discussion continues with a description of what the author terms a conventional three-dimensional object design and fabrication work flow. This description is important in so far as it serves as a foil for the later discussion of the natural design process.

Chapter 3: Related Work examines past research and existing products as they relate the the concept of the augmented fabrication machine and also specifically to the Part Preview interface.

Chapter 4: Motivation outlines the industrial past of digital fabrication and the changes that are transforming this technology into a powerful tool for personal expression. The

large obstacles standing in the way of this shift, particularly those related to the design of digital objects, are also described.

Chapter 5: Augmented Fabrication Machines introduces a new platform for the design and fabrication of digitally crafted objects. The purpose, components, and potential benefits of this new environment are explained in detail.

Chapter 6: Part Preview delves deeper into the two particular instances of augmented digital fabrication processes that are the main experimental topic of this work. Both of these processes aim to introduce the familiar HCI concept of what-you-see-is-what-you-get to digital fabrication environment. The chapter ends with a description of the intended user interactions and anticipated benefits associated with each process.

Chapter 7: Part Preview Implementation Details presents the implementation details of the two augmented fabrication machine interfaces constructed for this work. Two test environments, one for each process, were constructed for evaluation by user groups.

Chapter 8: User Evaluation documents the user study conducted to evaluate the merits of the two new augmented fabrication processes in comparison to a conventional control process. The underlying experimental assumptions, study methodology, and aggregated results are presented. An analysis of the results follows these factual details.

Chapter 9: Conclusion generalizes the Part Preview results within the context of augmented machine-based interfaces for digital object design and fabrication. It then presents several opportunities for future work and emphasizes the compelling reasons for engaging in this field of research.

Chapter 2

Background

2.1 Digital Fabrication Processes

To understand the current state of the art in digital fabrication it is important to first understand how existing fabrication machines and their associated workflows traditionally work.

Generally fabrication machines fall into one of two categories, additive or subtractive. Additive machines start with a blank slate and selectively add material where it will exist in the final object. These machines usually function by building up one layer of the object at a time, and stacking each new layer on the previous one. Most three-dimensional printers work this way. Subtractive machines, such as milling machines, function in essentially the opposite manner. These machines start with a piece of raw stock material and use a cutting tool to carve away any portions of the stock that will not be part of the final form. One might also imagine a hybrid machine that employs both processes, simultaneously adding and removing material as deemed most efficient. Such an idea sounds promising, but the author is not aware of any machines that current employ this approach.

Regardless of whether an additive or subtractive process is employed, most fabrication machines employ a fairly standard architecture consisting of a frame or bed, a set of linear

and rotary positioning axes, some sort of end effector that adds or removes material, and lastly a digital control system that interprets a set of instructions that describe how to create the desired object.

As mentioned earlier, almost all modern digital fabrication machines function by following a sequence of digital instructions that describe the process necessary to create the final object. Thus if one desires to create a new object, the generation of this sequence of instructions would seem to be of paramount importance. Of course, one could sit down and manually create this list of instructions line by line. In fact, this method was common in the first few decades of digitally controlled fabrication machines. However, as parts increase beyond relatively basic shapes, this rapidly becomes an overwhelming process. As an example of how quickly things can get out of hand, the list of instructions necessary to carve out the simple circuit board shown below is more than 7000 lines long.
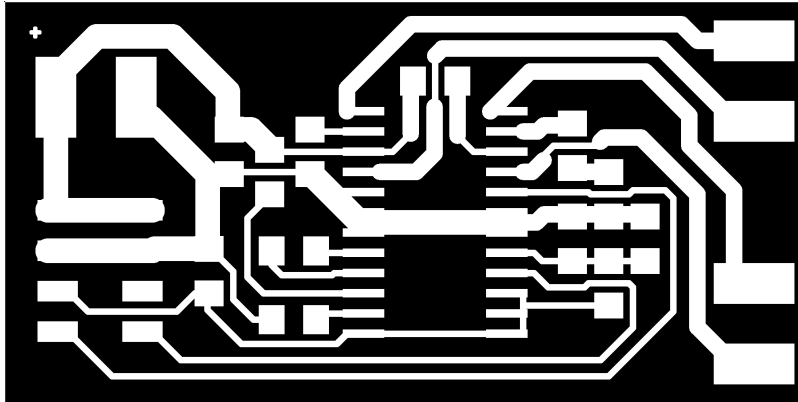
Figure 2-1: A printed circuit board design.

To deal with this problem, computer aided machining (CAM) software was created. CAM software takes a digital model of an object and then uses fabrication process specific algorithms to generate the required list of instructions. As mentioned earlier, for complex parts generating the instruction list or toolpath can become a daunting computational challenge. Fortunately though the problems of toolpath generation have been extensively studied over the last fifty years, and most of the major problems in this space have been solved.

At this point, the tools are in place to turn a digital model of an object into sequence of fabrication instructions, and a variety of fabrication machines are available to create an

actual object by following those instructions. The only piece left is to create the digital model itself, and this is where design software comes into play. Tools used for this process are generally called computer aided design (CAD) tools, and there are as many flavors of CAD software as there are colors in the rainbow.

In most CAD tools, the most fundamental operation is creating two dimensional profiles. Generally the CAD software will provide the user with a set of geometric primitives to use to compose these profiles. These primitives usually include lines, rectangles, circles, arcs, and bezier curves. The location and dimensions of each primitive element are set via a mouse click on screen or by manually entering spatial coordinates on the keyboard. In a two dimensional tool, these shapes are the final output. However, in more sophisticated three dimensional tools, these profiles are used in combinations with mathematical operations such as extrude, revolve, and loft to form three dimensional shapes.

Before ending this chapter, a slightly more detailed discussion of the control systems generally found on fabrication machines may be useful. As mentioned earlier, these control systems are responsible for guiding the fabrication machine through the sequence of steps necessary to create the final object. Oftentimes these instructions take the form of G-codes[1] or one of several similar machine control languages. In general these languages specify a sequence of movements for each machine axis to follow and also intersperse specific commands, perhaps "on" and "off", for the machine end effector (plastic extruder on a three-dimensional printer or cutting spindle on a milling machine). These movements take place in a particular coordinate space, and the alignment of this coordinate system to the machine bed or raw material stock is of particular importance. Colloquially this alignment process is often called zeroing. This name originates from the process where the machine operator sequentially sets the zero position for each machine axis, usually X, Y, and Z.

Chapter 3

Related Work

As discussed in the introduction, the two main contributions of this work are to introduce the concept of the augmented fabrication machine and to develop a specific transparency-aiding [1] augmented fabrication machine application, Part Preview. This section references work related to these two topics, starting with more general augmented reality work and moving towards research specifically related to Part Preview.

3.1   Augmented Three Dimensional Visualization

Augmented reality technologies are frequently used to visualize three dimensional models of objects. The first class of these technologies utilizes physical markers or object recognition to attach digitally generated graphics to physical items. A good example of this first approach is the Lego Digital Box,[2] which uses a camera and screen equipped kiosk to superimpose three dimensional animations of Lego models over the model's box when it is held in front of the unit. Another approach to augmented reality visualization tracks the user's gaze and position, and then uses that information to render an image that correctly represents the view of an object from that perspective. The pCubee perspective corrected handheld

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[1] In this context, increasing transparency enables the user to better visualize the inner workings and final result of the digital fabrication process.

cubic display[3] is a project that takes this approach. Both approaches to augmented reality visualization in this section could be applied to digital fabrication applications. However I have not encountered any such work that does so in the physical environment of a fabrication machine.

3.2 Augmented Two Dimensional Visualization

Projection-based augmented reality visualization tools have been applied to fabrication machines in the past. Companies including SL Laser[4] and Carter Products[5] have developed products that display components of machine motion paths directly on the machine surface. These products use a laser beam to create vector drawings of part outlines and potentially other simple part features. This approach has merit in that it allows direct visualization of some machine motion elements relative to the raw material and machine bed. However, these products fall short in a few ways. First, the choice of vector graphics limits the visualization to very simple part features and does not permit a full preview of the motion path itself. This incomplete view leaves the potential for incorrect motion paths or collisions to go undetected. It is also difficult or impossible to display information about travel in the third dimension, which limits these products ability to accurately represent three dimensional objects. Lastly, these products lack deep integration into the machines to which they are connected. For example, no such systems allow the path to be dynamically positioned by the user to achieve accurate alignment.

3.3 Augmented Design

Augmented reality tools have also been applied to digital design tasks. The Urp[6] project allows a user to design a city layout by positioning physical models of buildings on a table while a ceiling-mounted projector displays their calculated shadows and wind speed effects on the same surface. Sandscape[7] and Relief[8] allow users to manipulate sand in a box or an array of actuated plungers, respectively, to design a landscape. As with Urp, a

down firing projector displays relevant augmented reality graphics on the materials as they are manipulated during the design process. These projects are interesting in that they combine a physical design task with an augmented reality overlay, a modality which may be useful in an augmented fabrication machine interface. However, this work takes place in an environment isolated from the fabrication context, and therefore provides little opportunity to consider the physical realities and implications of the fabrication process during the design phase.

CopyCAD[9] is a past collaboration intended to create an augmented design and fabrication environment. It enables users to design and digitally fabricate new objects by simply combining and modifying existing physical items. A full description of CopyCAD can be found in Chapter 5.

3.4 Fabrication Machine Crash and Injury Detection

Augmented fabrication machines as described in this work incorporate some intelligent behaviors designed to avoid, or at least react to, erroneous commands or unintended situations such as collisions with fixed objects or machine components. Some existing fabrication machines also incorporate features related to this idea. Certain large format CNC routers manufactured by the Thermwood company[10] have the ability to detect when the moving portion of the machine has unexpectedly collided with another object and halt operation. Also, SawStop[11] has created a line of woodworking table saws that can sense if the operator's flesh comes in contact with the spinning blade. When contact is detected, the blade can be stopped within milliseconds to reduce the potential for injury.

3.5 Toolpath Preview

Many fabrication machine control programs incorporate on-screen visualization of the machine motion path. Examples of such programs include the Enhanced Machine Controller[12]

and PartWorks[13]. While these programs do an admirable job of visualizing the motion path, they often fail to include the raw material to be processed, and sometimes do not even show the machine itself. In the cases where the material is shown, the position and size of the material are usually manually entered, and it can be difficult or impossible to display stock with non-trivial shapes (eg: a piece of raw material from which another part has been previously cut). Lastly, because they are confined to the computer screen, these programs are inherently less intuitive than a presentation that places the visualization directly on the machine working surface.

3.6   Automatic Zeroing Technology

Another pertinent area of prior work is automatic zeroing technology. A subset of production environment fabrication machines incorporate features ranging in sophistication from manually assisted single axis zeroing[14] to sophisticated touch probes that measure the inserted raw stock and compensate for errors in positioning and flatness[15]. In certain contexts, these features can be quite effective at reducing errors related to manual zeroing. However these technologies fail to address errors stemming from faulty object design, erroneous motion paths, or the insertion of the wrong size raw material. Part Preview improves on these systems by addressing all of these problems and also provides users much higher visibility into the fabrication process.

3.7   Other Related Work

Eat Your Face[16] is an early application of the augmented fabrication machine concept that makes it possible for a user to rapidly create an edible three dimensional chocolate model of their face. The entire process requires no conventional software tools and can be completed in two to three minutes. The Eat Your Face project is described in more detail in Chapter 5.

The CopyCAD and Eat Your Face projects were both constructed on top of a low cost digital fabrication platform called the Mantis Machine[17]. The Mantis machine provides a full three axis motion platform and interchangeable tool heads for under one hundred dollars to facilitate research and experimentation in personal applications of digital fabrication.

Chapter 4

Motivation

4.1 Digital Fabrication

The narrowest definition of digital fabrication is that it is a process and set of associated tools for turning a digital representation of an object into physical form. This definition is problematic, however, in that it leaves out the process of *creating* this initial digital representation. Oftentimes, the creation of this digital representation consumes more time and energy than the mechanical fabrication of the object itself. Thus, for the purposes of this thesis, the term digital fabrication will refer both to the creation of the digital representation of an object, henceforth called "design", and to the methods and tools required to actualize that form as a physical item, henceforth called fabrication.

Thus, digital fabrication is the process by which we first **design** the digital representation of an object to be created, and then **fabricate** the newly designed physical object itself.

A simple equation that encapsulates this process:

$$\text{design tools} + \text{fabrication technology} = \text{physical object}$$

It is important to remember that both design tools and fabrication technologies are inputs

to this equation. All too often we focus heavily on one of these inputs while neglecting the other. To be successful in advancing digital fabrication, both must be given due process.

4.2 The Rise of Digital Fabrication

Digital fabrication is not at all a new thing. Arguably digital fabrication began when Gordon Brown of the MIT Servomechanisms Laboratory first connected a digital computer to an industrial milling machine in the early 1950s. Since then, this form of digital fabrication, computer controlled machining (also CNC machining), has been a major force in a very large number of research and manufacturing activities. Of course, digital fabrication is by no means limited to computer controlled machining. Many other technologies have been developed including:

- Laser cutting

- 3D printing

- Plasma cutting

- Digital assemblers

- Hot wire cutting

- Ion deposition

- Robotic bricklaying

As with computer controlled machining, most if not all of these processes were initially developed to serve in the research and development laboratory or on the factory floor. Only recently have digital fabrication technologies begun to be used in significant quantity to create objects for personal expression rather than profit. This group of *personal* digital fabricators is still small in number but growing rapidly. The initial forays into digital fabrication for personal expression were largely lead by hobbyists and tinkers developing

home versions of industrial computer controlled machining centers[18]. This group was soon joined by a few artists and visionaries who saw potential in this new application of digital fabrication and began further experiments[19]. Most recently, a new group calling themselves Makers has grown phenomenally and focused enormous attention on digital fabrication as a means to create any object one desires[20].

Two factors are largely responsible for the expansion of digital fabrication into personal digital fabrication. First, two predominant digital fabrication technologies, computer controlled machining and three-dimensional printing, are reaching the point on the commoditization curve where they are financially within reach for small scale groups and even individuals[17][21]. Secondly, the rise of the internet has enabled individuals interested in digital fabrication to form communities that serve as hubs for social encouragement and technology sharing. The Maker community in particular has used digital fabrication to create an incredibly wide range of physical objects as a form of personal expression. However in spite of the enthusiasm clearly exhibited by the Makers, the overall population outside this small group has thus far been slow to adopt digital fabrication for personal use. I believe that this limited penetration of digital fabrication into the mainstream is not a reflection of the masses lack of desire to leverage digital technology to create physical objects, but rather an indication of how difficult and expensive it can be to use modern digital fabrication to do anything at all.

Coming back to the core digital fabrication equation, for digital fabrication to gain mainstream acceptance as a means for physical expression I believe two things are required:

1. It must be easy to design the digital representation of the physical object a user wishes to create.

2. The means of turning this digital representation into the final physical object must be democratic and widely available.

Today we are making much better progress towards achieving the second than the first.

4.3   Design of Digital Objects

The current design process for digital objects is one shaped largely by history and the limitations of early technology. It follows a rigid linear path: the design of the object is digitally captured, the design is post-processed into machine-readable instructions, and these instructions are then sent to a digital fabrication machine to be executed. Rather than accept a variety of forms of expression, the design capture environment forces the user to think of the object design in terms of a fixed set of geometric primitives and mathematical operations. This capture process is usually cumbersome and time consuming, and by virtue of its high overhead penalizes iteration. Furthermore, if an outside object is to be involved in the design process, it also must be painstakingly digitally modeled. Collectively, these limitations result in an overall process that is inflexible and poorly matched to the basic steps involved in human creativity and innovation.

This traditional design process has been able to persist in its semi-broken state because its primary users to date—industry—have the developed the organization, training, and other resources necessary to forcibly overcome its inherent friction, and as a whole lack sufficient impetus to spur major paradigm changes. On the other hand, individual users looking to use modern design tools for personal reasons rather large scale financial gain, often find the inherent friction in these design tools too great to overcome. From their perspective, conventional digital design tools are a hindrance rather than an aid to expression.

4.4   Towards Natural Design

As I've asserted above, and will now reiterate, if digital fabrication is to succeed in enabling rich human physical expression, we must significantly improve the usability and accessibility of our methods for designing objects digitally. At present, the state of the art in the process for digitally designing physical objects is simply too broken to be effective for a broad audience. In particular, the digital object design process needs to be reconciled with the design process that we as humans naturally follow. The previous section mentioned several

areas in which the current process is particularly off track: ease of expression, ease of iteration, the incorporation of outside objects, and finally transparency.

The personal computer has long been the traditional environment for digitally designing objects. However, in spite of more than thirty years of active research and development, digital design tools on this platform are largely deficient as described above. Accordingly, its time to rethink how the design platform can help us address these issues.

Chapter 5

Augmented Fabrication Machines

5.1 Introduction

In this chapter, I propose the augmented fabrication machine as a way to address some of the problems associated with the traditional digital object design and fabrication process. This concept does not refer to a single "entity"; rather an augmented fabrication machine is composed of, first, a base fabrication machine (such as a ShopBot) and, second, a collection of three core components that collectively form a more intuitive platform for the entire digital fabrication process. These three core components are (1) a rich new set of input and output devices located in the machine environment, (2) a dedicated computation engine, and (3) an ecosystem of machine-based applications designed to address a wide variety of digital fabrication needs.

5.2 Input and Output

Traditional personal computer-based methods for the design of physical objects limit their interface to a relatively spartan set of input and output devices. These devices consist predominantly of a two dimensional screen, a keyboard, a mouse, and, occasionally, a

multiple degree of freedom input device such as a 3D Connexion Space Navigator[22]. With the exception of the multiple degree of freedom input device, these devices are a product of the legacy of other personal computer applications and none are particularly well suited for three dimensional input or output.

In rethinking the digital design platform, my goal has been to incorporate devices much more suited for the task at hand, namely moving three dimensional objects in and out of the digital realm. In the spirit of promoting freedom and ease of expression, a wide variety of such devices should be made available to the user. The following is a short non-exhaustive list of input and output devices that have been used or appear to be a good fit for an augmented fabrication machine platform. The devices indicated with an asterisk are already in use in my augmented fabrication machine research.

- Depth cameras*

- Three dimensional displays

- Rotary knobs*

- Multiple degree of freedom input devices*

- Direct manipulation input devices

- Two dimensional cameras*

- Finger and pen trackers*

5.3 Computation Engine

Computation is an essential part of the augmented fabrication machine platform for two reasons: (1) it provides execution resources for applications running on the platform, and (2) it allows us to endow the augmented fabrication machine environment with a sense of "intelligence". As the role of providing application execution resources is relatively straightforward, the rest of this section is dedicated to the concept of intelligence.

In the natural world even the most basic living creatures integrate sensing and computation in such a way as to form some degree of intelligence. Such creatures generally avoid colliding with themselves or with other fixed objects, and rarely proceed into obviously hopeless situations, or persist in actions that they have found to be grievously injurious to their health.

By these standards, modern fabrication machines seem grossly unintelligent. For example consider the following:

1. Why does a two hundred thousand dollar five axis machining center frequently crash into itself?

2. Why does a state of the art three dimensional printer stubbornly continue to print when a substantial portion of the job has adhered itself to the print head and is being dragged around the print chamber?

3. Best of all—why does the laser cutter continue to attempt to operate *when it is on fire?*

The answer to all of these questions is that these machines lack the sensing capacity, computational resources, and necessary algorithms to implement the most basic intelligent functions.

Augmented fabrication machines by their definition contain all of these prerequisites for intelligence and therefore should attempt to behave intelligently to the maximum extent possible. To do otherwise is frankly irresponsible, and sometimes downright dangerous. In the scenarios described above unintelligent machines at best destroy the parts being fabricated. However they often also damage themselves or their surrounding environment in the process, and occasionally they do the worst and hurt or injure nearby humans. Clearly these are unacceptable behaviors for machines expected to broadly proliferate throughout society.

5.4 Applications

Applications, such as the CopyCAD application described below, are a key to success for the augmented fabrication machine platform. Applications have the potential to provide the platform with the means to combine rich input and output, computation, and user input into an overall satisfying digital fabrication experience. The breadth of possible applications means that augmented fabrication machines can grow and evolve to meet a wide variety of foreseen and unforeseen user needs. This is especially important in an environment were maximizing the potential for personal expression is a primary goal. Also, an open platform like the augmented fabrication machine supports the development of applications by outside users and thereby facilitates the creation of a market with low barriers to entry to all comers. The financials of this market can then fuel a powerful economic engine that helps the platform to grow, evolve, and maintain relevance as time marches onwards.

The nascent state of the augmented fabrication machines makes it difficult to say with much detail or authority what the primary applications on a augmented fabrication machine platform might be. However, it is possible to discuss few applications that have already been developed and illustrate how they serve the objectives of a natural process for digital fabrication.

5.4.1 Eat Your Face

I initially developed "Eat Your Face" as a standalone demonstration of the capabilities of the Mantis Machine discussed earlier[16]. However, as this demonstration developed, Eat Your Face essentially became the first augmented fabrication machine application. In Eat Your Face, a user places his head in a hole that faces a three dimensional laser scanner, after his head (or whatever other object) is scanned, the Mantis machine carves the three dimensional form of his face into a block of dark chocolate—which the user, of course, can then eat.

When considered in the context of digital fabrication, Eat Your Face is a radical departure

Figure 5-1: Eat Your Face.

from the traditional digital design process. No interaction with computer aided design software or computer aided manufacturing tools is required. The complete steps of the process are:

1. Place a fresh block of chocolate in the machine.

2. Smile for the laser face scanner.

3. Press the start button.

One might argue that the relatively constrained scope of Eat Your Face's functionality might limit its overall appeal or constrain the creative potential of its users. Thus far, though, that does not seem to be the case. To date, over 170 chocolate "faces" have been created, and some of those faces have been quite creative indeed—looking like all manner of body parts, found objects, and even a live ferret.

5.4.2 CopyCAD

Following Eat Your Face, I collaborated with Sean Follmer of the Tangible Media Group[23], and Emily Lovell of Hi-Lo Tech[24] to create CopyCAD[9]. CopyCAD demonstrates the idea that many interesting new objects can be created by simply combining existing objects and making simple modifications to their form. This project once again augmented the Mantis milling machine, this time by adding a two-dimensional camera and projector facing downwards towards the machine bed. The machine bed also featured a laser net system that allowed finger touches in the bed area to be localized by the overhead camera.

Work Area
Projected Context Menu
Laser Line Projectors
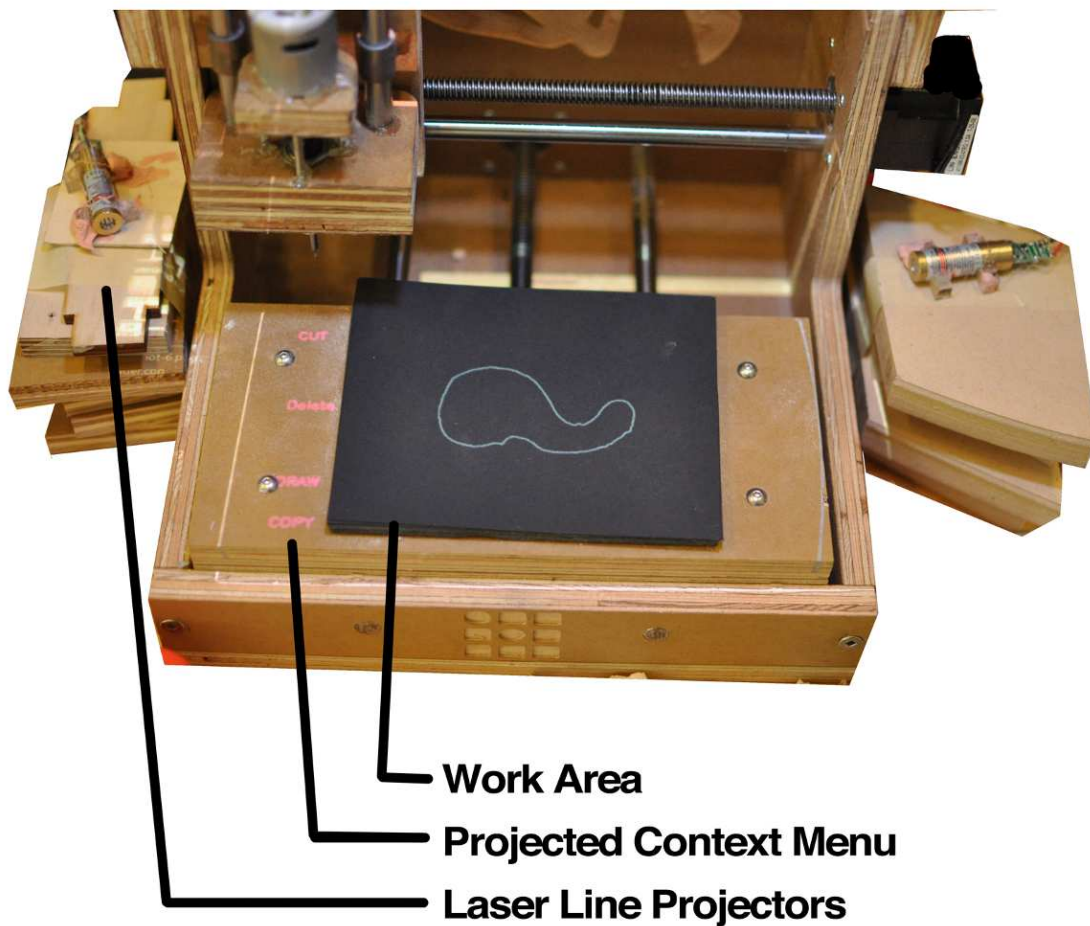
Figure 5-2: CopyCAD.

One use case for CopyCAD involves a user who desires to create a pair of leaf shaped

earrings out of some colored wood. To accomplish this task, the user first secures the piece of wood to the machine bed. She then positions an actual leaf on top of the portion of the wood she would like to use. Upon command, CopyCAD detects the outline of the leaf and uses the projection system to project the detected contour back down onto the leaf and wood. If the user is satisfied, she may remove the leaf and continue. If not, she can touch the leaf contour, use the augmented reality pop-up menu to delete it, and try again. Once the leaf contour has been captured as desired, she can use a colored pen or pencil to draw additional details, such as the earring hole, onto the wood surface. CopyCAD is able to visually recognize these features in the same manner as the leaf outline. Finally, once all shapes and details have been drawn or captured from outside objects, the user can press the start button, and the machine will cut the new earring out of the supplied wood.

As with Eat Your Face, the CopyCAD design process departs significantly from that of traditional design tools. In a traditional CAD environment, it would be extremely difficult both to recreate the irregular natural shape of a found leaf and to incorporate any hand drawn details. With CopyCAD, both of these tasks are greatly simplified, and there are few barriers to iteration and experimentation. CopyCAD encourages freedom of expression because virtually any object, photograph, or sketch that will fit in the machine can be used in the design. If the outcome of any design experiment is unsatisfactory, it can easily be undone. It is interesting to note that many personal digital fabrication tasks, like the earring creation above, do not require three or four decimal places of precision to obtain good results. This runs contrary to many of the industrial applications for which digital fabrication is traditionally utilized. In CopyCAD we opted to trade away this unnecessary precision in the vision system in order to enable much greater flexibility in input media.

The last major triumph of CopyCAD is transparency. The design of an object using Copy-CAD takes place on top of (and in position on) the material from which it will be cut. This enables even material defects, such as a knot in the wood, to easily be incorporated into the design. With CopyCAD, what you see is truly what you get.

Chapter 6

Part Preview

6.1   Introduction

After building Eat Your Face and CopyCAD, I wanted to create an augmented fabrication machine application that would demonstrate the potential of an augmented fabrication machine platform to improve the digital fabrication process even when used in conjunction with a traditional digital design process. This application, Part Preview, was born from the realization that the what-you-see-is-what-you-get aspect of CopyCAD was independently powerful and could be used in a more general environment.

In Part Preview, the digital representation of the object and the physical environment in which it will take form are explicitly mixed together. By including all of the relevant digital and physical precursors to the final object in this mixture, an accurate visual preview of the final object can be created. Such a preview increases the transparency of the fabrication process and allows errors and other items of note, to be seen prior to investing in the final act of fabrication. When done correctly, this increase in transparency also speeds iteration because for many applications it eliminates the need to actually create an object to see where changes are required. In addition to providing a preview of the final object, Part Preview can also replace cumbersome and error prone setup procedures, such as zeroing, required by traditional fabrication machines. By eliminating these tasks, Part Preview

also makes substantial contributions to ease of use and reduces the potential for wasted materials, equipment damage, and operator injury caused by improper machine setup.

Part Preview recognizes that digital fabrication does not take place in a vacuum; even after the form of an object has been digitally finalized, the design process is not complete. The final physical object is also a product of material chosen to fabricate it from, as well as the physical fabrication machine environment. In sum, the design process for digital fabrication can continue all the way to the moment the object becomes physical—all proceeding steps including material selection, stock positioning, and configuration of the machine can also part of the design process.

This section introduces two approaches for implementing the Part Preview application: the projection-based interface and the depth camera-based interface. In the rest of this chapter and the next, the design and implementation of each of these approaches is detailed. Following that, I present the setup and results of a user study designed to evaluate their relative performance.

6.2 Projection-Based Interface

6.2.1 Overview

The projection-based interface allows users to preview an object's final form before fabrication by projecting a digital visualization of the object onto the machine bed. At its core, this approach has two steps. The first is to form a two dimensional image that represents the critical details of the object to be created and also any relevant aspects of the digital fabrication technology used to create it, such as cutter size or machine motion constraints. This two dimensional image is then projected onto the fabrication machine bed, and thus also onto the raw material stock and any other items in the machine environment. The projection system is calibrated in such a way that the location and scale of the projected image correspond exactly to the final position and orientation of the final object, if fabrication were to start at that instant. Because the projected image is inherently only two
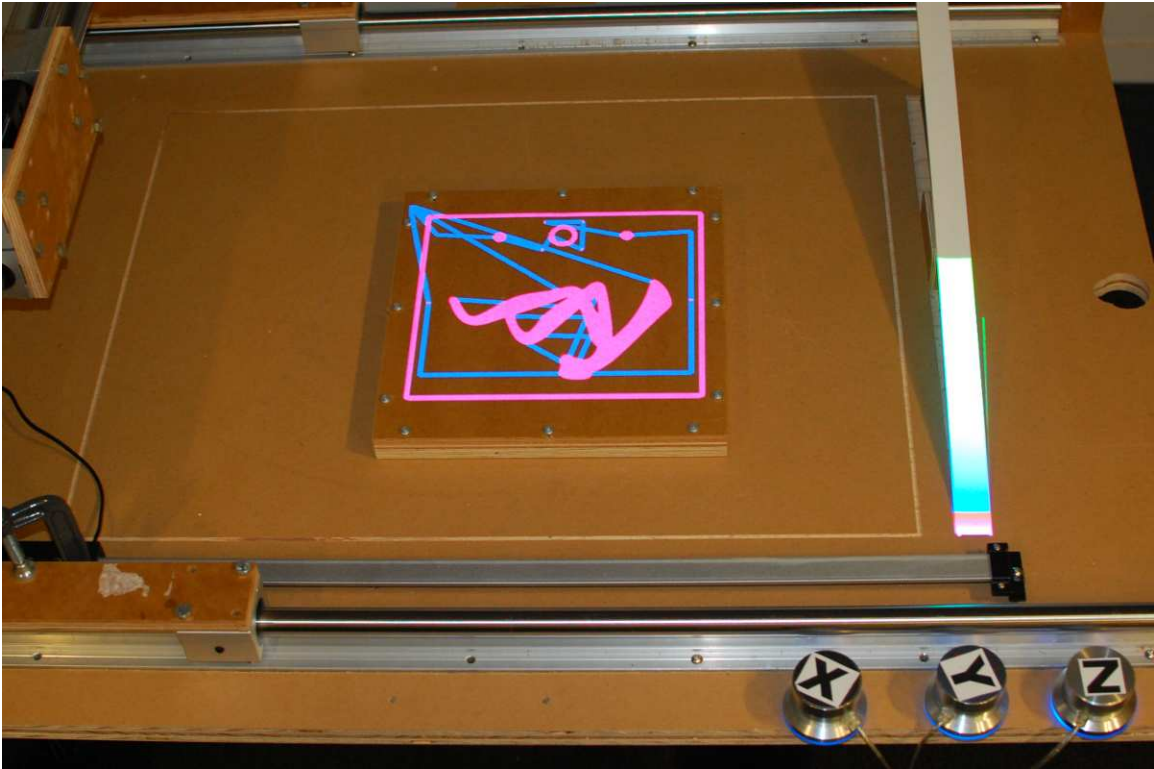
Figure 6-1: Projection-based interface.

dimensional, vertical height is encoded using a color scale. To help translate this scale into physical heights, a sloped depth reference ramp is located at the side of the machine bed. The full color scale is also projected onto this ramp to provide a physical reference for the height of any color. A set of three knobs are also provided alongside the machine bed. These knobs enable the user to position the final object (and projected image) to any position inside the working volume of the machine.

6.2.2 Intended Interaction

The intended use of the projection-based approach starts with the digital representation of the object being created. This representation is loaded into the projection-based interface application and the visual image of the final object is generated. The user can then directly view the object in full scale on the machine bed and raw material stock. If the object preview reveals a design defect, the user can make any necessary modifications and then

reload the modified digital object representation into the preview application.

Once the object design is satisfactory, the user can then use the three knobs to place the preview image over the desired portion of the raw stock. Fabrication issues such as an undersized piece of raw material, or a defective toolpath are easily recognized at this stage. Finally with the design and position of the object visually confirmed, the user presses the start button. Upon this action, the projection-based interface application computes and loads the proper toolpath offsets into the fabrication machine controller and the fabrication process commences.

6.3 Depth Camera-Based Interface
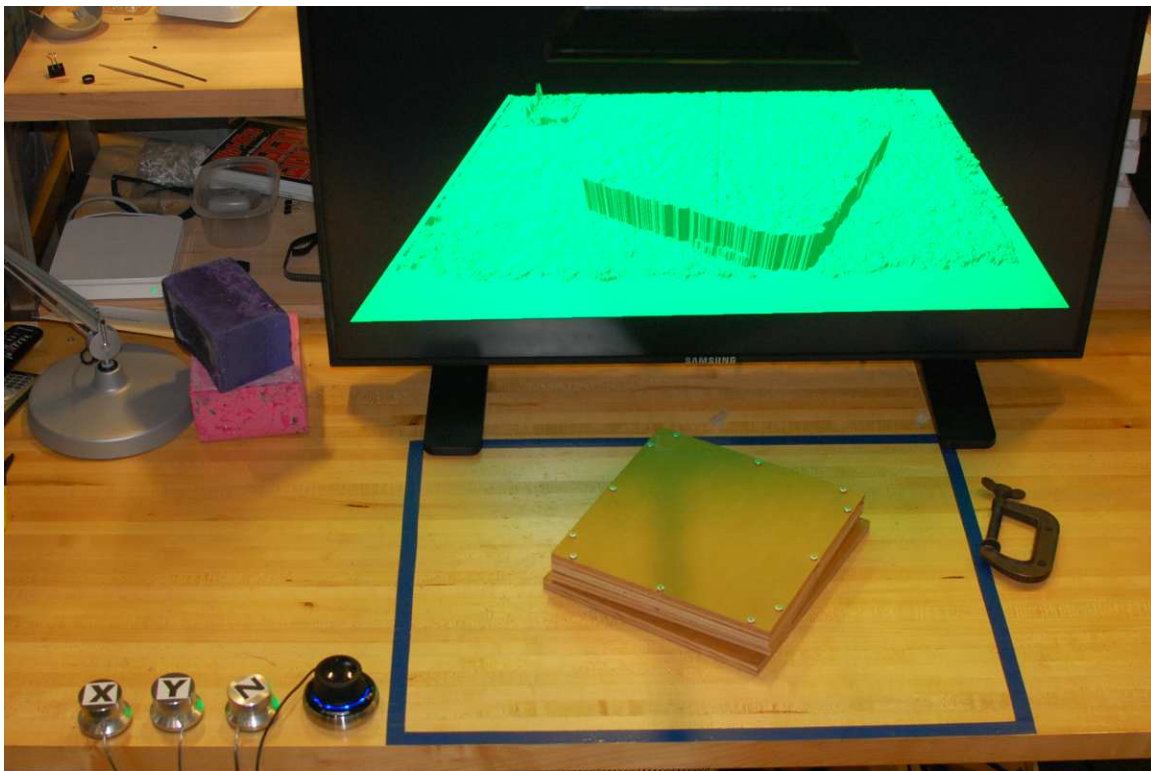
Figure 6-2: Depth camera-based interface.

6.3.1 Overview

The depth camera-based interface works by creating a three dimensional model of the raw material stock and machine environment, and then overlaying on top of this model a real-time machining simulation of the final object. The depth camera-based process begins with a depth camera mounted above the fabrication machine bed that creates an accurate three-dimensional digital model of the raw material stock and machine environment. This model is then used in conjunction with the digital representation of the objected to be created to compute a three-dimensional model of the final object form—accounting for the raw stock and machine environment presented.

The calculated model of the final object is displayed on a large LCD screen adjacent to the fabrication machine bed. Three knobs similar to those used in the previous application can be used to adjust the X, Y, and Z positions of the final object in the machine working volume. The calculated final object result is updated in real time as any position changes are made. To facilitate navigation of the final object on the LCD screen, a multiple degree of freedom input device is also provided.

6.3.2 Intended Interaction

Just as with the previous projection-based approach, use of the depth camera-based application starts by loading the digital representation of the object to be created. With the object is loaded, the user presses a button that triggers the depth camera mounted above the machine bed to acquire a three dimensional model of the raw material stock and machine environment. Once the machine environment has been captured, the large LCD display begins to show the calculated form of the final object. The user then positions the final object inside the raw stock using the three control knobs. The user can also use the multiple degree of freedom controller to rotate the view of the final object into order to examine it from any angle or perspective.

The fabrication simulation shown on the LCD screen not only simulates fabrication of the final object in real time; it also displays an accurate model of the of entire fabrication

machine environment. Common problems such as collisions with clamps or fixtures are readily visible and thus preventable. When all necessary modifications and adjustments have been made, the user presses the start button, position offsets are loaded into the fabrication machine controller, and production of the final object begins.

6.3.3   Approach Comparison

	Projection-based	Camera-based
Display environment	Machine bed	LCD display
X, Y axis object visualization	2D projection	Screen-based 3D graphics
Z axis object visualization	Depth-to-color mapping	Screen-based 3D graphics
Machine path indication	Direct projection	Implicit from final form
Stock texture visible	Yes	No

Table 6.1: Projection-based and Camera-based Approach Comparison.

Chapter 7

Part Preview Implementation Details

In the previous chapter, I introduced two approaches for implementing the Part Preview application. This chapter provides additional details regarding the implementation of both the projection-based and depth camera-based interfaces.

7.1 Projection-Based Interface

7.1.1 System Overview

The projection-based system consists of a simulated milling machine, a ceiling mounted computer projector, a depth ramp display, a set of axis control knobs, a laptop computer, and several software programs. Figure 7-1 shows a general overview of the system.

The flow of data through the projection-based system begins with a textual description of the fabrication machine toolpath stored in a file. A preprocessor script then parses this textual toolpath and generates a new grid-based spatial representation of the machine movements. The interface rendering software offsets this spatial based representation in the
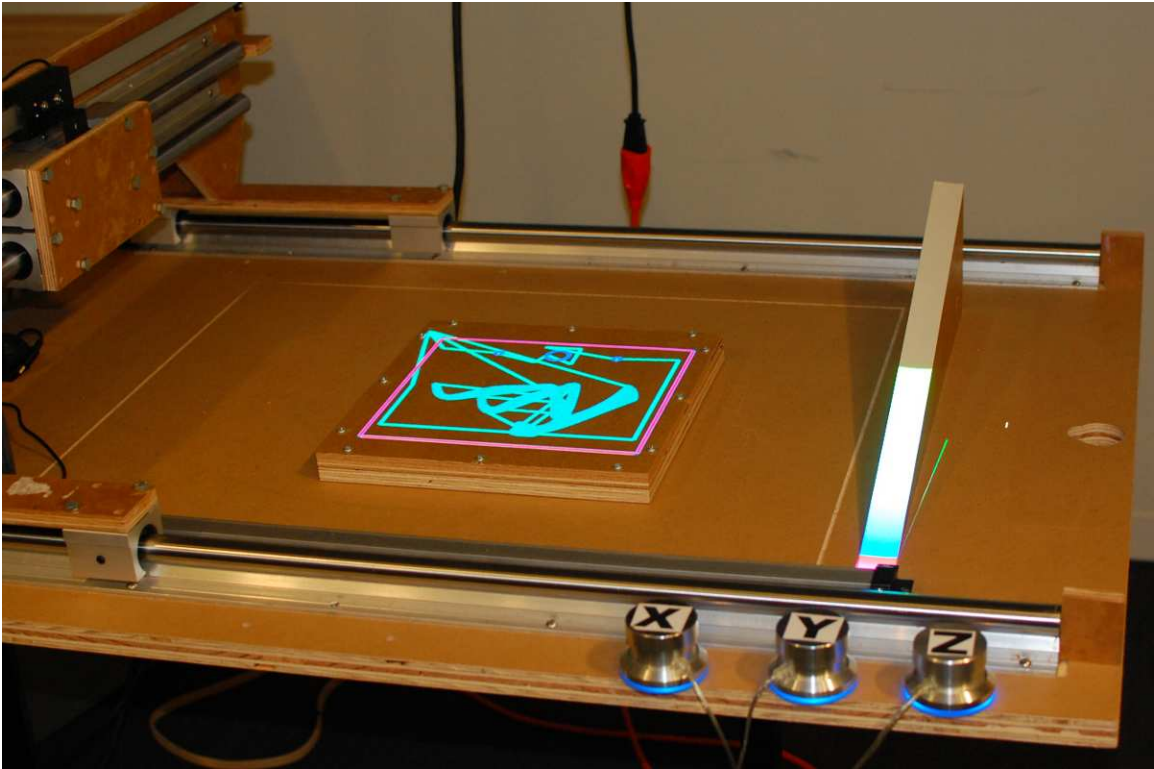
Figure 7-1: Projection-Based System Overview.

X, Y, and Z axes as commanded by the user. Also, as its name suggests, the rendering software continuously generates a color-coded-depth graphic of the offset toolpath which is fed to the ceiling mounted computer projector. The ceiling mounted projector projects a high brightness image downward onto the machine bed and depth ramp display below. Three knobs mounted at the side of the machine bed allow the user to control the toolpath position relative to the machine in the X, Y, and Z axes.

7.1.2 Simulated Milling Machine

For the user evaluation, the projection-based system was implemented on a milling machine mockup. At the center of this mockup is a machine bed that is approximately 18x24 inches. Linear rails run along two sides of the bed to form the machine X axis and support a moving gantry. The gantry itself supports the machine Y and Z axes. All machine axes are unpowered, but are fitted with linear encoders to allow the current position of each axis to
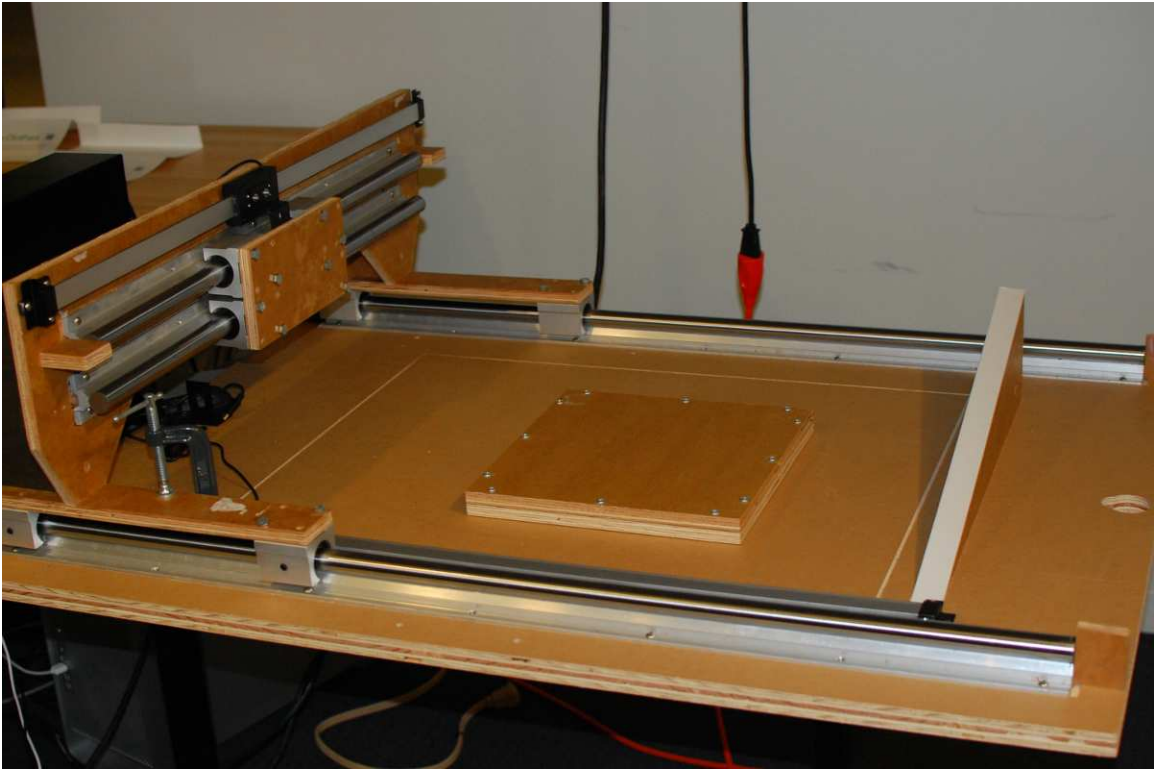
Figure 7-2: Simulated Milling Machine.

be measured. The axes allow travel of approximately 24 inches in X, 18 inches in Y, and 6 inches in Z. Objects as tall as 5 inches may pass underneath the gantry structure. The simulated machine bed was supported so that it was approximately at waist height during the user evaluation.

7.1.3   Computer Projector

For the user evaluation, an Optima computer projector was positioned above the simulated milling machine bed using a custom fabricated ceiling mount. The projector is a high brightness DLP based unit and provides approximately 3,600 lumens of output. This high brightness level is important to ensure a good quality image when working with darkly colored or non-reflective stock material. The height and zoom level of the projector were chosen such that the projected image completely covered the working area of the machine and also the area of the depth ramp display. Careful efforts were made to ensure that

the projected image was square relative to the working area of the machine and that any keystone distortion was eliminated.

7.1.4 Interface Computer

All software for the projection-based interface is executed on a nearby laptop computer. This computer is equipped with an Intel T2400 processor, Intel 945GM on-board graphics, and 2.5GB of RAM. The computer supplies video to the ceiling mounted projector via a VGA interface, and receives input from the user via the three USB connected knobs. During the user trials, the computer was positioned so that it was outside the immediate area of the simulated milling machine and so that it's primary screen was not visible to the user.

7.1.5 Axis Control Knobs

Figure 7-3: Griffen Powermate knob.

Three knobs were provided to the user to control the toolpath X, Y, and Z axis offsets. Griffen Powermate[25] knobs with approximately 75 detents per revolution were used for this purpose. On the X and Y axes, one detent corresponded to 0.03 inches of toolpath offset. On the Z axis, each detent corresponded to 0.01 inches of toolpath offset. Large axis labels were affixed to the top of each knob. The three knobs were positioned in a line, but the user was permitted to relocate them as desired. A software deamon, gizmod[26], was used to map movements of each knob into keypress events.

7.1.6   Depth Ramp Display
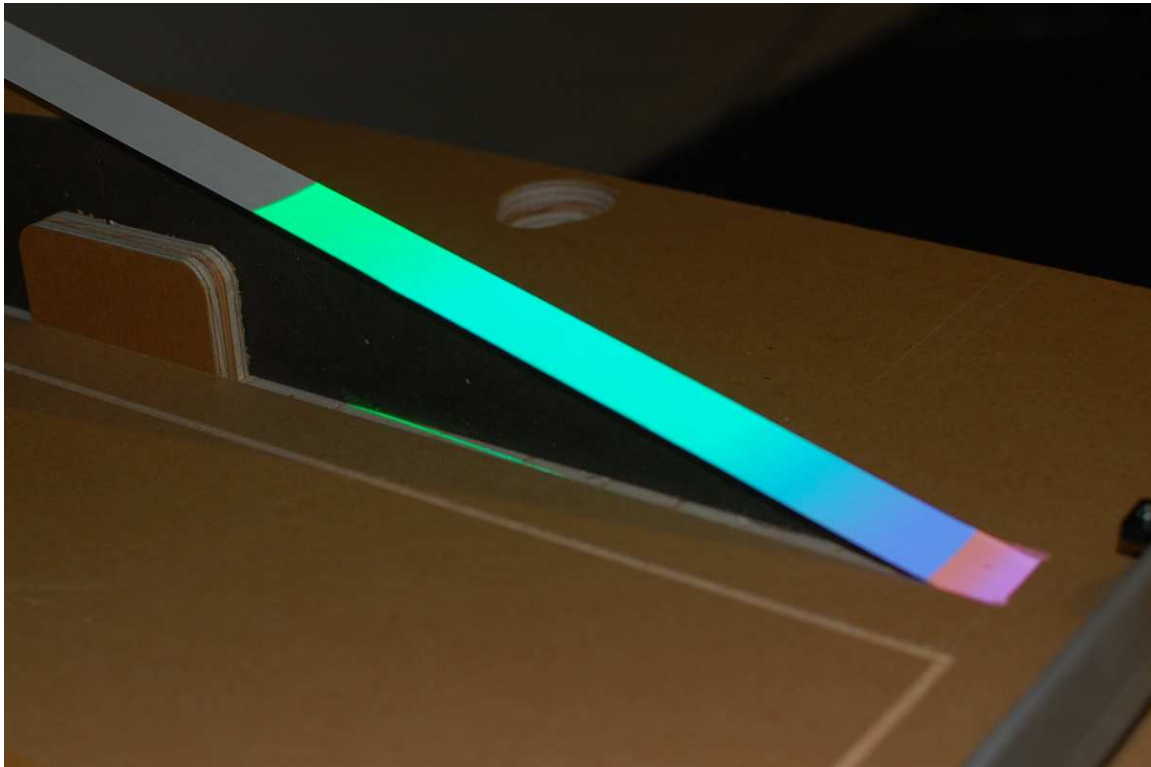
Figure 7-4: Depth Ramp Display.

The depth ramp display consists of a sloped wedge with a white surface located at one edge of the simulated milling machine bed. One end of the sloped surface is located approximately 0.1 inches below the simulated milling machine bed surface, while the other end is located approximately 4 inches above the nominal bed surface. In the projection based interface,

toolpath Z height at any position is mapped to a gradient or other color scale. During use, this color scale is projected onto the sloped surface of the display so that the physical height of any color along the scale can be directly perceived by the user.

7.1.7 Toolpath Preprocessor

The toolpath preprocessor is a script written in Python[27] that transforms the fabrication machine native toolpath format into a binary grid based format that can be used by the main interface software. Because the user evaluation was conducted using a ShopBot Tools CNC mill[28] as a control, the projection based interface system was designed to process the OpenSBP[29] textual toolpath format used by that system. The preprocessor transforms this textual toolpath into a two dimensional grid that encodes the furthest (deepest) the Z axis will travel at each point. This operation generally requires between five and fifteen seconds on the machine described above.

7.1.8 Interface Software

The main interface software executes whenever a user is interacting with the projection-based system. This software loads the grid-based toolpath representation created by the toolpath preprocessor and renders an offset and color mapped version for the projector. User input from the axis manipulation knobs continuously update the toolpath offsets for the X, Y, and Z axes. This software also generates the depth-to-color mapping graphics that are projected onto the depth ramp display. Once the user is satisfied with the displayed toolpath configuration and position, the interface software loads the appropriate toolpath offsets into the fabrication machine control software so that the fabrication cycle can commence.

7.2 Depth Camera-Based Interface

7.2.1 System Overview

The depth camera-based system consists of a simulated fabrication machine environment, an overhead mounted depth camera, a large LCD display, a multiple degree of freedom input device, a set of axis control knobs, a desktop computer, and several software programs. Figure 7-5 shows a general overview of the system.

The flow of data through the depth camera-based system also begins with a textual representation of the fabrication machine toolpath. The depth mask generator software then converts this toolpath into a three dimensional "depth mask." Concurrently, the system uses the overhead depth camera to construct a three dimensional digital model of the raw material stock and the surrounding machine environment. The interface software then combines (essentially subtracts) the precomputed depth mask from the machine environment model to produce a three dimensional model of the final object. This model is displayed on the large LCD screen and can be explored using the multiple degree of freedom interface. The user can also use the three axis control knobs to adjust the relative position of the depth mask (object) to the machine environment.

7.2.2 Simulated Machine Environment

For the user study, the depth camera-based system was installed in a simulated fabrication machine environment. This environment was formed by a large wooden table with an 18 x 24 inch "bed" marked off with blue tape. The table height was approximately 30 inches from the floor.

7.2.3 LCD Display

A 42 inch Samsung LCD display was mounted at the rear of the machine environment. This display presents a three dimensional model of the final object to the user. This on-screen
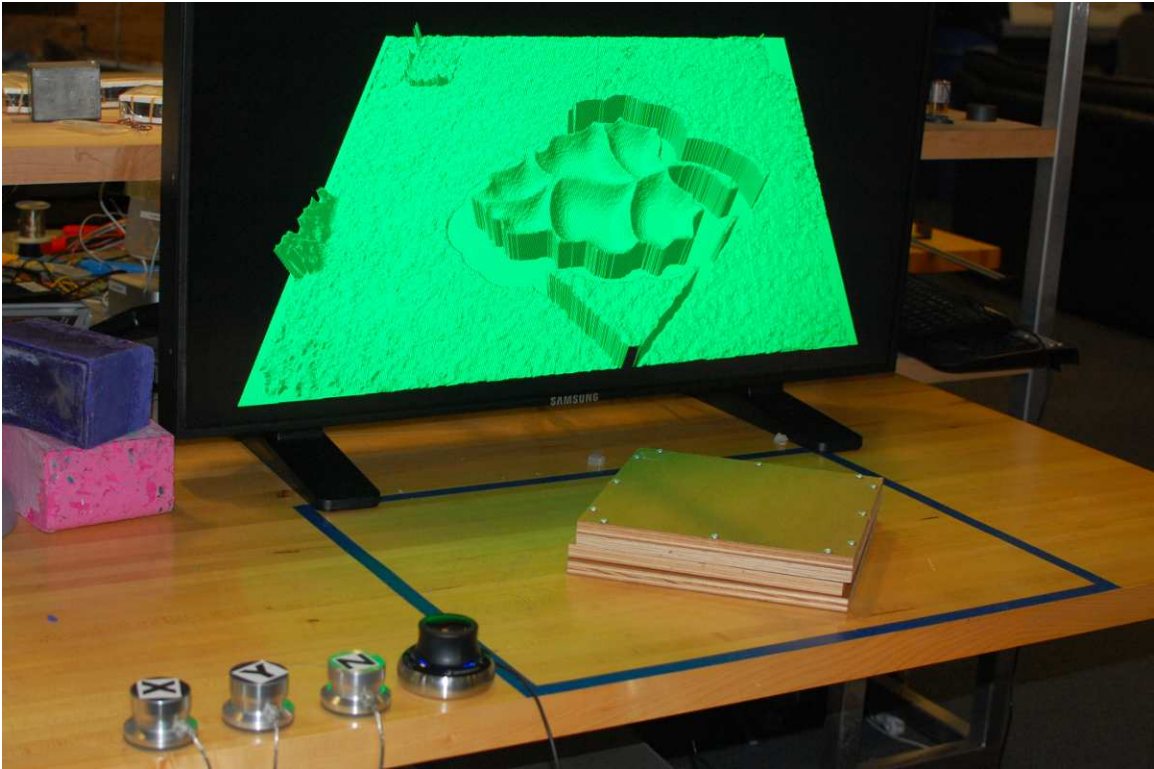
Figure 7-5: Depth-Camera Based System Overview.

model is updated in real time in response to user inputs.

7.2.4 Interface Computer

The software for the depth camera-based interface executed on a desktop computer located under the simulated machine environment surface. This computer was equipped with two Intel Xenon 5160 processors, a nVidia GeForce 7300 graphics card, and 3GB of RAM. The computer supplied video to the Samsung LCD display and received input from the user via the multiple degree of freedom input device and the three USB connected knobs.

7.2.5 Axis Control Knobs

The depth camera-based interface used the same three Griffen Powermate knobs as the projection-based interface for manipulation of the X, Y, and Z axis offsets. These knobs
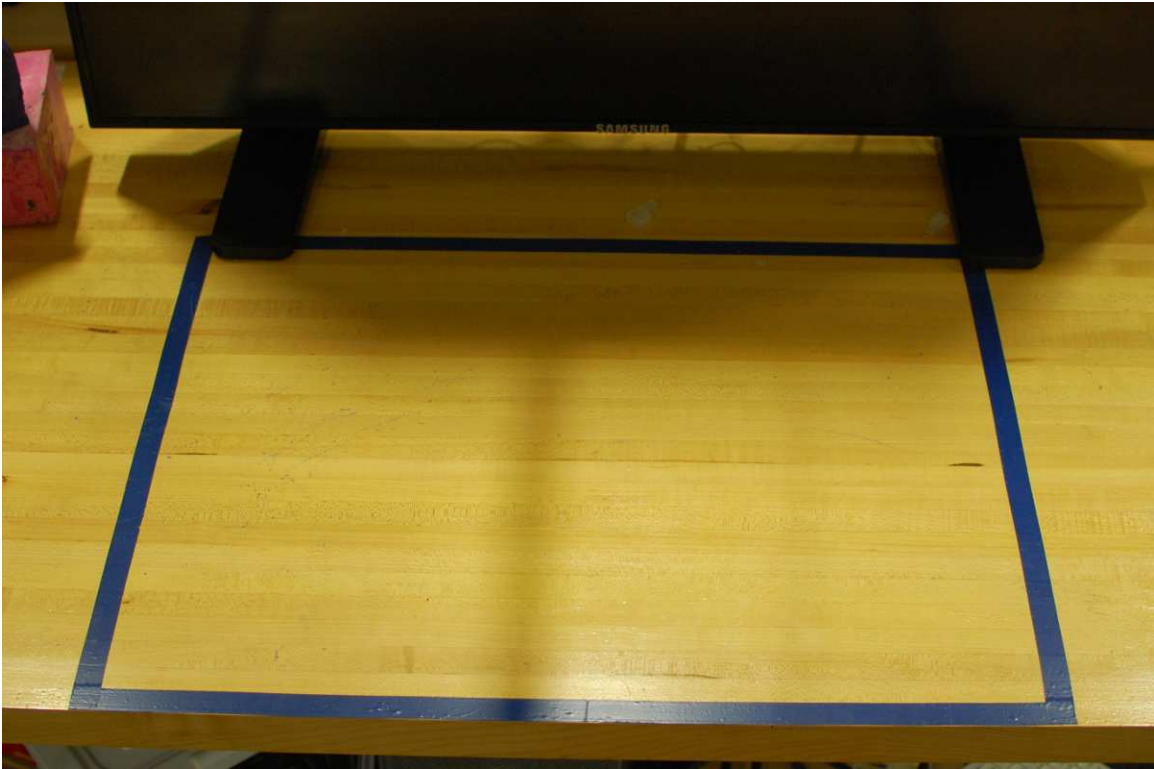
Figure 7-6: Simulated Machine Environment.

feature an integral button that can be actuated by pressing downward on the knob itself. In the depth camera-based interface, pressing any of these three buttons caused the depth camera to capture a new digital model of the machine environment.

7.2.6   Display Control Interface

The depth camera-based interface provided a 3dConnexion SpaceNavigator multiple degree of freedom input device to facilitate manipulation of the onscreen three dimensional model. This input device features six degrees of freedom (X, Y, Z, roll, pitch, yaw) but only pitch and yaw were utilized to control the on screen display. Experimental interfaces using more than pitch and yaw were found to be confusing and difficult to use. A piece of software called spacenavd[30] was used to decode the proprietary knob messages into events that could be utilized by the main interface software.

Figure 7-7: SpaceNavigator.

7.2.7   Depth Mask Generator

The depth mask generator is a piece of software that accepts an OpenSBP format toolpath and from that generates a "depth mask" consisting of Z axis depths spaced on a regular grid. These depths represent the maximum depth that the cutting tool will reach over that point in space while executing the toolpath. This depth mask can then be applied to a height map of the raw material stock to produce a three dimensional model of the resulting final object. This approach to realtime machining simulation is similar to the one described by Saito[31].

The algorithm used to generate the depth mask permits arbitrary tool geometries to be specified and could also be trivially modified to work with an additive process. The software itself is a minimally-optimized python implementation of the algorithm described above yet still executes in ten to thirty seconds on the desktop machine described previously.

7.2.8   Interface Software

At start, the interface software for the depth camera-based system loads three input files: a three dimensional grid representing the baseline height of the empty machine working area,

another grid representing the latest depth camera image including the machine working area with stock, clamps, etc. in place, and lastly the depth mask grid generated above by the depth mask generator. The interface software then subtracts the machine environment height map from the baseline height map to produce an accurate three dimensional model of the objects on machine bed.

This model of the machine environment and the previously loaded depth mask are the two inputs to the real time machining simulation process. The simulation starts by offsetting the toolpath depth mask as commanded by the three axis knobs. Then the offset version of the mask is overlaid on the the model of the machine environment. For each location in the machine environment, the height of the depth mask and the machine environment model are compared, and the minimum value stored in the final result height map.

This model of the final object is then prepared for display on the LCD screen. First, it is converted into a set of vertices for rendering via OpenGL on the machine video card. Then inputs from the SpaceNavigator are integrated to calculate a transformation matrix that positions the model in the orientation requested by the user. Finally the vertices are rendered and displayed on screen.

Chapter 8

User Evaluation

8.1 Overview

The principle objective of the user evaluation was to determine whether fabrication machine users felt a higher level of confidence when using the two Part Preview augmented machine interfaces to perform several common digital fabrication tasks as compared to a conventional fabrication machine interfaces. [1] In order to provide an experimental control, the evaluated tasks were also performed using a conventional digital fabrication machine interface. Tasks tested during the evaluation included the following:

1. Correctly setting the X, Y, and Z axis zero positions to produce a functional final object.

2. Evaluating whether the maximum cutting depth would be satisfactory.

3. Forming an understanding of the general area in which the machine would travel.

4. Verifying that the machine would not collide with clamps, fixtures, and other obstacles in the machine environment.

5. Verifying the final object would be cut from the correct portion of the raw material.

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[1]Part Preview is a specific augmented fabrication machine application. It's goals are subset of the overall goals for the augmented fabrication machine concept.

8.2   User Selection

A group of approximately twenty graduate students of varying backgrounds were invited to participate in the evaluation. This group was selected to include individuals with digital fabrication experience levels ranging from complete beginner to very experienced. Of the initial group contacted, twelve individuals agreed to participate in the evaluation. Unfortunately, due to availability issues of the ShopBot conventional fabrication machine[28] used as a control, only seven subjects were able to complete the full evaluation.

8.3   Experimental Procedure

8.3.1   Toolpath Generation

Each experimental trial began with the process of producing a toolpath for the ShopBot computer controlled milling machine. This process was intended to familiarize subjects with the model of the object to be fabricated and also to serve as an introduction or refresher to conventional digital fabrication machine techniques. For this task, a digital representation of a sample part to be fabricated was provided to the participant. The study investigator then guided the user through the use of the PartWorks toolpath generation software[13], the general concepts of fabrication machine coordinates and zeroing, and answered any questions posed by the user.

8.3.2   Control Task

After the subject had successfully generated a valid ShopBot toolpath from the digital object representation, evaluation proceeded with a control task using the ShopBot. The subject was given a piece of raw material measuring approximately 12x12x2 inches. A number of screws were located around the outside of the raw material approximately 1/2 inch from the edge. The raw material was placed on the machine bed, and basic operation of the machine control interface was demonstrated. Subjects were then asked to zero the machine X, Y,
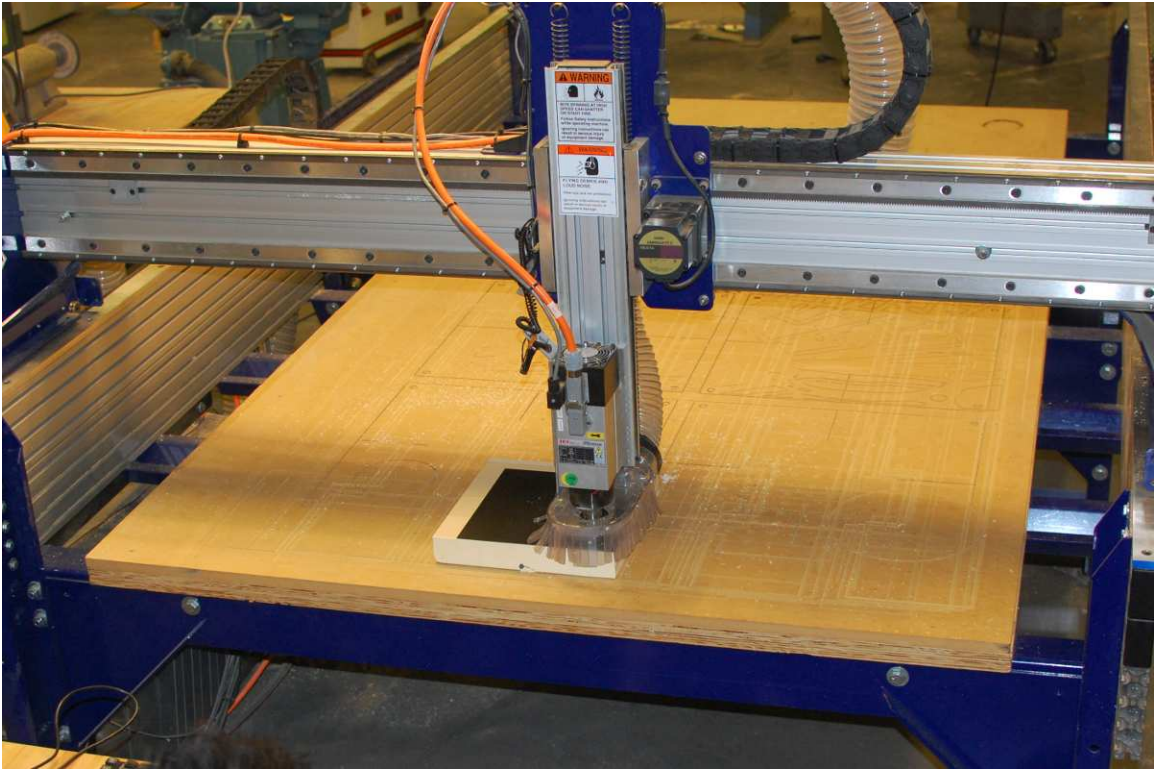
Figure 8-1: Control Task Setup.

and Z axes such that the previously generated toolpath would properly produce the desired final object. It was also emphasized that care should be taken to prevent to machine cutter from striking the screws around the edge of the raw stock. Once the participant had finished configuring the machine to his or her satisfaction, the investigator determined whether the final object would have been successfully created. The results of this evaluation were not disclosed to the subject.

8.3.3 Projection-Based Interface Task

After completion of the control task, participants were asked to complete two more fabrication machine setup tasks, one using the projection-based machine interface, and the other using the depth camera-based machine interface. The order of these tasks was randomized. The experimental test setup used for the digital-into-physical task was configured as described in the previous chapter. To start, the same toolpath used in the control task was
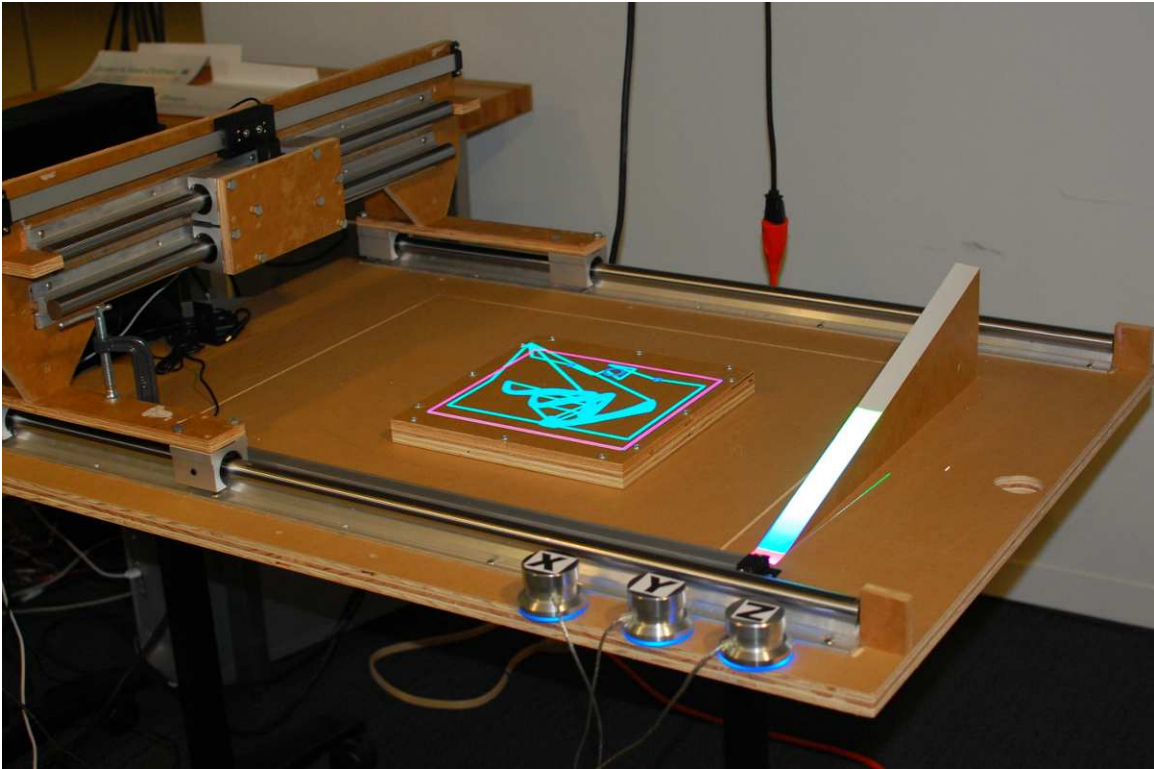
Figure 8-2: Projection-Based Task Setup.

loaded into the physical-into-digital system. Subsequently, the subject was given the same piece of raw material stock from the control task and asked to place it on the bed of the simulated milling machine. Then the operation of the digital-into-physical system including the meaning of the projected graphics, interpretation of the depth ramp display, and use of the X, Y, and Z axis manipulation knobs was explained. Once the subject understood how to use the system, he or she was asked to position the toolpath relative to the raw material and machine bed to produce the final object. Once the subject determined that the toolpath was positioned as desired, the task was complete.

8.3.4   Depth Camera-Based Task

The depth camera-based task began with an overview of the general operation the interface. This was followed with demonstrations of how to use the multiple degree of freedom interface, depth camera trigger, and axis positioning knobs. For this task, a three dimensional
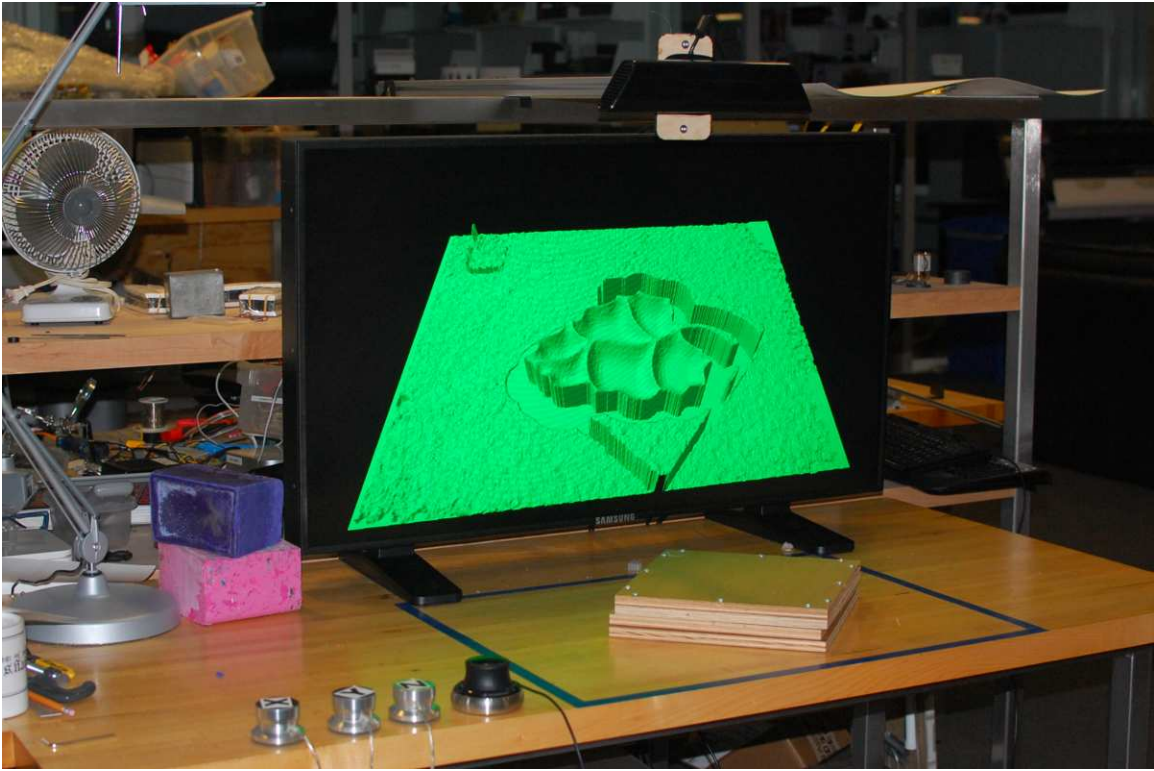
Figure 8-3: Depth Camera-Based Task Setup.

model of a leaf shaped bowl was substituted for the model used in the control and digital-into-physical tasks. The thickness of the material stock was also increased to approximately three inches. The subject was then asked to once again position the raw material stock and the toolpath to generate the final object.

8.3.5   Study Questionnaire

After the completion of all three evaluation tasks, subjects were presented with a short questionnaire. This questionnaire contained questions pertaining to the subject's confidence level while completing each of the three tasks. The full text of the questionnaire is available in the appendix. After completing the questionnaire, subjects were also given a chance to ask questions about the study and to provide any addition feedback.

8.4   Results

Aspect	Control	Projection	Camera
Proper cutting depth selected	4.0	4.3	3.9
Understood machine travel area	3.4	4.9	3.3
No collisions would occur	2.6	4.1	3.3
Cut from correct stock portion	3.4	4.9	3.9
Object successfully created	3.1	4.3	3.7
Ease of use rating	2.1	4.4	3.3

Confidence: 1=Least...5=Most

Table 8.1: Summarized User Evaluation Results.
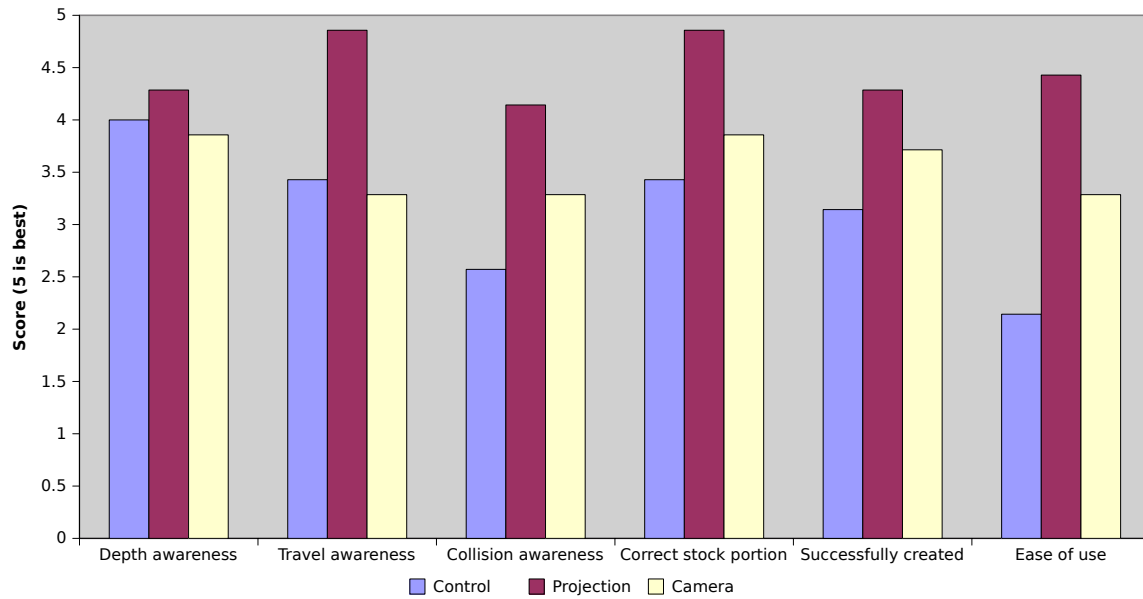
Figure 8-4: Graphical User Evaluation Results.

Chapter 9

Conclusion

9.1 Evaluation Analysis

As the user evaluation results demonstrate, Part Preview has the potential to significantly improve users' experiences in the later stages of the digital fabrication process. In every tested category, the projection-based method resulted in higher reported user confidence levels. The camera-based method also fared well, besting the control in four of six tested categories. Part Preview also made significant gains in the important overall ease of use category, with projection-based approach scoring an average of 4.4 compared to the control's 2.1. Lastly, while the study dataset was small, the probability of a successful fabrication outcome rose from approximately 43 percent with the conventional methods to 100 percent with either Part Preview method. This result is significant in that a higher probability of successful outcomes both increases the utility of a digital fabrication machine, and also further reinforces the higher confidence levels experienced using the Part Preview interfaces. Notably, since no fabrication failures occurred with Part Preview Interfaces, users likely avoided several instances of wasted material, possible machine damage, or even the potential for injury.

In light of these results it seems Part Preview was largely successful in achieving its goals of improving the transparency of the digital fabrication process, bolstering user confidence, and

avoiding the potential negative consequences of fabrication failures. Equally significantly, the success of Part Preview serves as further evidence of the value of augmented fabrication machine interfaces—even when used in conjunction with existing fabrication machines and conventional digital fabrication process.

This result is important from a bootstrapping perspective because it provides motivation for personal and industrial users alike to invest in augmented fabrication machine infrastructure. Once in place, this infrastructure can then serve as a stepping stone towards the development and dissemination of more radical augmented fabrication machine applications—and doing so bring us that much closer to the vision of widespread physical expression through digital fabrication.

9.2 Future Work

9.2.1 Part Preview

Projection-based Method

A common comment during the user evaluation was that judging the height of a particular location was difficult using the projection based method. The main reason for this difficultly seemed to be that precisely matching up a color in the preview projection and its mate on the depth ramp indicator color gradient was challenging.

One solution to this problem would be to switch the height representation from a continuous color gradient to a stepped series of discrete colors. This effectively quantizes the information and potentially reduces the number of heights that can be displayed, but in doing so makes it easier to individually pick out any given altitude. The steps in the height scale could be uniform like on a topographical map. Another approach to choosing the step locations would be to use a flat surface detection algorithm to intelligently choose the threshold heights. These thresholds would be chosen to align with significant features in

the environment such as the bed surface, the top of the stock, the maximum height of any obstructions, etc.

Another potential solution to the height indication problem would be to add a method to touch or otherwise designate a location whose height the user wishes to examine more closely. It would then be possible to display a graphical water level line on the environment that indicates which features are above and below the selected height. This information could also be duplicated on the depth ramp indicator itself.

Depth Camera-based Method

The most common criticism of the depth camera-based method was that on occasion it was challenging to identify the boundaries of the raw material stock in some situations, such as when the object being created extended beyond the boundaries of the stock. In this situation, it would be useful to display a wireframe or ghost representation of the original stock on the display in addition to the final form of the finished object. It would then be much easier to visualize which areas of the stock would be cut away and which would remain.

Another potential improvement the the depth-camera based method would be to display the motion path of the machine in addition to the final part shape. This motion data can currently only be determined implicitly (ie: when the path intersects something in the machine environment.) A few users stated that seeing this motion information would make them more comfortable that no collisions were going to occur during fabrication.

A Hybrid Method

In some respects the projection-based method and the depth-camera based methods have complementary strengths. The projection-based method was found to be very effective in helping users to understand how the machine would move in the X-Y plane. However, there was more uncertainty around the height of the machine cutter. On the other hand,

the depth-camera based method is well suited to displaying relative height information, especially if the user rotates the preview model to view it from the side. Combining both methods in the same machine environment would enable users to leverage the best aspects of both preview methods to form an even clearer picture of the digital fabrication process.

9.2.2 Augmented Fabrication Machines

Future work is needed to flesh out all three aspects of the augmented fabrication machine concept—input and output, intelligence, and applications.

Input and Output

Rich interaction is at the heart of a successfully digital fabrication experience, and this interaction is made possible by incorporating a wide variety of expressive input and output devices into the fabrication environment. This thesis presented a list of potential input and output devices, and also work utilizing a substantial majority of those listed. However, the presented list is far from complete and even for devices on the list, very little of their potential capabilities have been explored. Thus the exploration of these devices and the user interactions they enable remains a promising area for future work.

Intelligence

Outside of their design capabilities, intelligence is one of the major factors setting augmented fabrication machines apart from their more conventional brethren. Digital fabrication machines often wield rapidly rotating sharp cutters, high intensity laser beams, or other potentially harmful tools. Today relatively few safeguards are in place to ensure that stock is not wasted, the machines themselves are not damaged, and that the digital fabricators themselves remain unscathed. I believe that as digital fabrication moves more into the mainstream it will become more and more important that strong guarantees can be made about what our machines will and will not do. Technologies like SawStop[11] are

excellent solutions to narrow problems, but as the sensing and computational capabilities of augmented fabrication machines continue to increase we should expect more.

Applications

This thesis has presented three early augmented fabrication machine applications—Eat Your Face, CopyCAD, and Part Preview. Each of these applications marks a different potential space in which augmented fabrication machines can be effective tools. These three lights are dim points across a vast landscape of potential applications that need to be probed, explored, and thoroughly mapped. In particular, I believe that Eat Your Face, CopyCAD, and other similar projects have demonstrated that new approaches to the object design process can radically improve the expressiveness and accessibility of digital fabrication. These and other new design approaches should to be developed, evaluated, and remixed again. It won't be easy to radically transform the way that objects are digitally designed, but this transformation is desperately needed by personal and industrial users alike.

9.3 Contributions

This work has introduced the concept of the augmented fabrication machine as an enabling step towards more prolific use of digital fabrication technology for personal expression. It also studied an augmented fabrication machine application, Part Preview, which was shown to reduce the incidence of fabrication process failures and their associated negative consequences. Part Preview also increased users' reported confidence levels in the five studied areas and improved overall ease of use relative to the control fabrication machine. In addition to demonstrating the direct value of Part Preview, these results show that the augmented fabrication machine concept has the potential to significantly improve the digital fabrication user experience.

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Appendix A

User Evaluation Questionnaire

Print Preview for Digital Fabrication Machines Questionnaire Page 1
Please circle the appropriate response.

How would you classify a your experience with digital fabrication, CNC machines, 3D printers?

Beginner   Intermediate   Advanced

When "zeroing" the conventional fabrication machine:

How confident were you that the machine would cut all way through the material, but not excessively into the machine bed?

Not confident   Somewhat confident   Confident
1   **2**   **3**   **4**   **5**

How confident were you that you knew where the machine would travel?

Not confident   Somewhat confident   Confident
1   **2**   **3**   **4**   **5**

How confident were you that the machine would not collide with screw, clamps, fixtures, other items in the working area of the machine?

Not confident   Somewhat confident   Confident
1   **2**   **3**   **4**   **5**

How confident were you that the object would be cut from the correct portion of the raw stock ?

Not confident   Somewhat confident   Confident
1   **2**   **3**   **4**   **5**

How confident were you that the object would be successfully created?

Not confident   Somewhat confident   Confident
1   **2**   **3**   **4**   **5**

How would you rate the ease of use of this method?

Difficult   Easy
1   2   3   4   5

Print Preview for Digital Fabrication Machines Questionnaire Page 2
Please circle the appropriate response.

When using the projection based print preview method:

How confident were you that the machine would cut all way through the material, but not excessively into the machine bed?

Not confident		Somewhat confident		Confident
1	**2**	**3**	**4**	**5**

How confident were you that you knew where the machine would travel?

Not confident		Somewhat confident		Confident
1	**2**	**3**	**4**	**5**

How confident were you that the machine would not collide with screw, clamps, fixtures, other items in the working area of the machine?

Not confident		Somewhat confident		Confident
1	**2**	**3**	**4**	**5**

How confident were you that the object would be cut from the correct portion of the raw stock?

Not confident		Somewhat confident		Confident
1	**2**	**3**	**4**	**5**

How confident were you that the object would be successfully created?

Not confident		Somewhat confident		Confident
1	**2**	**3**	**4**	**5**

How would you rate the ease of use of this method?

Difficult				Easy
1	**2**	**3**	**4**	**5**

Please circle the appropriate response.

When using the computer based print preview method:

How confident were you that the machine would cut all way through the material, but not excessively into the machine bed?

Not confident		Somewhat confident		Confident
1	2	3	4	5

How confident were you that you knew where the machine would travel?

Not confident		Somewhat confident		Confident
1	2	3	4	5

How confident were you that the machine would not collide with screw, clamps, fixtures, other items in the working area of the machine?

Not confident		Somewhat confident		Confident
1	2	3	4	5

How confident were you that the object would be cut from the correct portion of the raw stock?

Not confident		Somewhat confident		Confident
1	2	3	4	5

How confident were you that the object would be successfully created?

Not confident		Somewhat confident		Confident
1	2	3	4	5

How would you rate the ease of use of this method?

Difficult				Easy
1	2	3	4	5

Appendix B

User Evaluation Results

Control Trial Confidence Scores

Aspect	1=Least...5=Most							Avg.
Proper cutting depth selected	5	3	5	4	3	4	4	**4.0**
Understood machine travel area	4	4	3	3	2	4	4	**3.4**
No collisions would occur	1	4	3	1	2	3	4	**2.6**
Cut from correct stock portion	2	4	4	4	2	4	4	**3.4**
Object successfully created	2	3	4	3	3	3	4	**3.1**
Ease of use rating	3	3	1	2	1	3	2	**2.1**

Projection-based Trial Confidence Scores

Aspect	1=Least...5=Most							Avg.
Proper cutting depth selected	3	5	5	5	5	3	4	**4.3**
Understood machine travel area	5	5	5	4	5	5	5	**4.9**
No collisions would occur	4	4	4	3	5	4	5	**4.1**
Cut from correct stock portion	4	5	5	5	5	5	5	**4.9**
Object successfully created	4	5	4	5	4	4	4	**4.3**
Ease of use rating	5	5	5	4	4	4	4	**4.4**

Depth Camera-based Trial Confidence Scores

Aspect	1=Least...5=Most							Avg.
Proper cutting depth selected	3	3	5	4	4	5	3	**3.9**
Understood machine travel area	3	5	4	2	1	5	3	**3.3**
No collisions would occur	2	3	3	1	5	5	4	**3.3**
Cut from correct stock portion	3	5	5	3	4	4	3	**3.9**
Object successfully created	3	4	5	3	4	5	2	**3.7**
Ease of use rating	2	4	4	3	3	4	3	**3.3**

Table B.1: Full User Evaluation Results.